Faim Finite Element Analysis Manual

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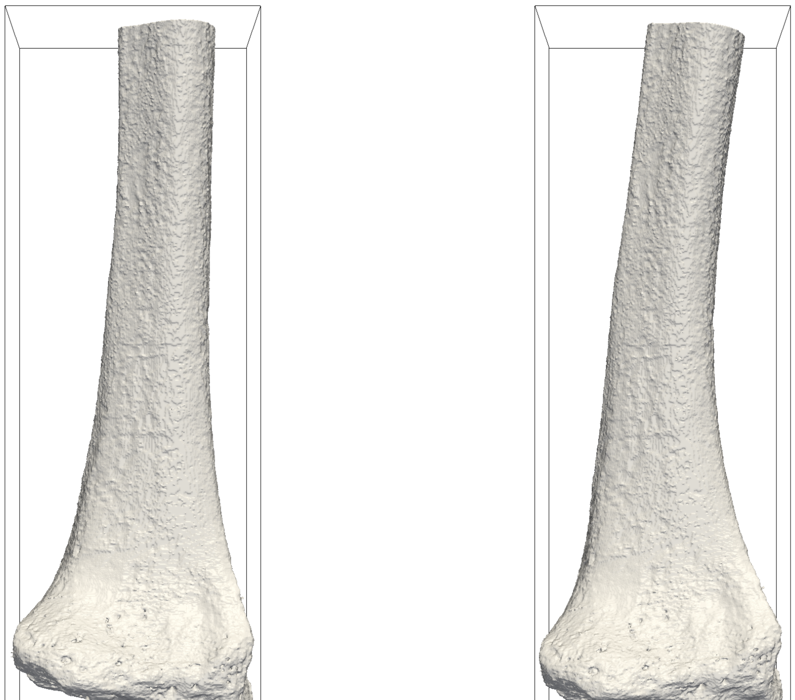

Version 8.0

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Contents

Chapter 1

Introduction

Overview

Faim is a finite element solver optimized for solid mechanics simulations of bone, including strength and stiffness determinations, directly from three-dimensional medical image data such as micro-CT. Faim uses the mesh-free method, which is a highly memory efficient method of finite element analysis. This makes it possible to solve finite element models with very large numbers of degrees of freedom derived directly from high resolution scans.

The Faim Finite Element solver has an established record of being used in scientific studies. See the bibliography for selected studies.

How to read this manual

- If you need to install Faim, refer to Installation in this chapter.
- Experienced users may want to read Section 1.3, and then go directly to the sections indicated there.
- For new users, start by reading the section Section 1.5. This will give you an overview of finite element analysis and the Numerics88 software tools.
- Next, we recommend that you jump first to An introductory tutorial: compressing a solid cube. It will take you through the typical steps of generating a model, verifying it, solving it, and analyzing the results. This is a good introduction to how everything fits together, and will help to put things into context.
- The intervening chapters (before the Tutorials chapter) should be used as reference material. You probably don't want to read them from beginning to end in one sitting with the intention of retaining everything. However, you should at least skim through them, to be aware of the possibilities and options, as well as the limitations and potential pitfalls.
- If you are a user who is familiar with `n88modelgenerator` and who is interested in creating your own custom models, start with the tutorial, Compressing a cube revisited using vtkbone. And then move on to the more advanced tutorials dealing with `vtkbone`.

What is new in version 8

Version 8 introduces the following new features:

- *Material arrays* and a solver specifically designed to be memory-efficent in the case of a large number of material definitions. See Efficient Handling of Large Numbers of Material Definitions.

- A new convergence measure, *convergence sets*, which makes it easier to select a meaningful tolerance. Practically speaking, this means that certain types of models (*e.g.* compression tests) will now terminate in substantially fewer iterations. See Convergence measure in the section Solving linear models.
- A new method of specifying materials to `n88modelgenerator`, which allows for the specification of multiple materials, and of fully anisotropic materials. Previously, these cases required using `vtkbone`. See Material definitions file.
- A tool to generate smaller models from exisiting models that are reasonable approximations, but with many fewer elements. This is useful for getting fast approximate solutions to large problems. See n88coarsen.

Installation

In version 8, the installation of Faim is more modular than in previous versions.

Install the solvers and n88modelgenerator

The solvers and n88modelgenerator are the commercial components of Faim. They are the only parts of Faim that require a license file to run. They are bundled together and are installed using the installers that can be downloaded from http://numerics88.com/-downloads/ .

Linux The Linux installer will be named something like `faim-8.0-linux.sh`. It can be installed with the following command for a single user:

```
bash faim-8.0-linux.sh
```

For a system-wide installation, add `sudo`:

```
sudo bash faim-8.0-linux.sh
```

If you want to specify a particular install location, use the `--prefix` flag, for example

```
bash faim-8.0-linux.sh --prefix=$HOME/Numerics88
```

Windows The Windows installer will be named something like `faim-8.0-windows.exe`. Simply run it to install.

macOS The Mac installer is a disk image with a name like `faim-8.0-windows.dmg`. Double-click to mount it, and then drag the Faim icon to the Applications folder, or to any other convenient location.

For all operating systems, it is possible to install Faim either system-wide using an administrator account, or to install it for a single user, for which administrator rights are not needed. It is also possible to install it multiple times on a single machine, so that each user has their own installation. The installation directory can also be freely renamed and moved around.

How to run the solvers

To run the solvers and n88modelgenerator, you may use any of the following methods:

1. Run them with the complete path. For example

   ```
   /path/to/faim/installation/n88modelgenerator
   ```

   or, on Windows

   ```
   "c:\Program Files\Faim 8.0\n88modelgenerator"
   ```

2. Permanently add the directory where they are installed to your PATH variable. The exact method depends on your operating system.

3. Run the script `setenv` in a Terminal (or Command Prompt on Windows) to set the PATH just for that Terminal. On Linux and macOS, this is done as follows

   ```
   source /path/to/faim/installation/setenv
   ```

   On Windows, if you are using a Command Prompt, then you can run

   ```
   "c:\Program Files\Faim 8.0\setenv.bat"
   ```

   while for Windows PowerShell, the equivalent is

   ```
   . "c:\Program Files\Faim 8.0\setenv.ps1"
   ```

Note
In version 8, the solvers and n88modelgenerator are statically linked. Setting `LD_LIBRARY_PATH` (Linux) or `DYLD_LIBRARY_PATH` (macOS) is no longer required.

Install a license file

To receive a license file, you must run one of the Faim programs with the --license_check option, and send the resulting UUID to skboyd@ucalgary.ca. For example,

```
> n88modelgenerator --license_check
n88modelgenerator Version 8.0
Copyright (c) 2010-2016, Numerics88 Solutions Ltd.
Host UUID is DFD0727B-89AA-4808-B03F-E73E80ABFE64
```

When you receive a license file, which is a short text file, you can copy it to one of several possible locations where the software can find it. These locations are:

1. a subdirectory `licenses` of the installation directory, or
2. the location specified by the environment variable `NUMERICS88_LICENSE_DIR`, if set,
3. for an individual user, a directory `Numerics88/licenses` (`Numerics88\licenses` on Windows) in their home directory, or
4. on Linux, `/etc/numerics88/licenses`, or
5. on macOS, `/Library/Application Support/Numerics88/licenses`, or `$HOME/Library/Application Support/Numerics88/licenses`, or
6. on macOS, `/Users/Shared/Numerics88/licenses`.

You may have multiple license files installed at once.

Install n88tools and vtkbone

The solvers and n88modelgenerator are most conveniently used together with a collection a command-line utilities called `n88tools`. `n88tools` is implemented in Python, and depends on the library `vtkbone`. Additionally, `vtkbone` can be used create custom model generation and processing scripts in Python, as will be discussed in a subsequent chapter.

`n88tools` and `vtkbone` are open-source. If you wish, you can download the source code from https://github.com/Numerics88/- and compile them yourself, using whatever installation of Python is most convenient for you. Most users however, will not want to go through the hassle of compiling them. The quickest way to install them is via Anaconda Python, which is supported on Linux, Windows, and macOS. An advantage of using Anaconda Python is that the very large repository of mathematical and scientific Python packages available in Anaconda Python can be used together with Faim. To install `n88tools` and `vtkbone` in Anaconda Python, follow these steps:

1. Install Anaconda Python from https://www.continuum.io/downloads . It is also possible to install Miniconda (http://conda.pydata.o miniconda.html). Miniconda is identical to Anaconda, except that instead of starting with a very large set of installed python packages, it starts with a minimal set. You can of course add or subtract packages to suit your needs. Anaconda Python can be installed either system-wide, or just for an individual user. Faim works with either arrangement.

2. Create an Anaconda environment in which to run Faim. To learn about Anaconda environments, we recommend that you take the conda test drive at http://conda.pydata.org/docs/test-drive.html . Creating an Anaconda environment for Faim is optional; you could alternatively install `n88tools` and `vtkbone` directly in the root environment of Anaconda. However, using a dedicated enivornment greatly helps with avoiding possible conflicts, where for example `vtkbone` may want a specific version of a dependency, while some other Python package that you want to use requires a different version of the same dependency. In addition, you can create separate environments for different versions of `n88tools` and `vtkbone`, and easily switch between them. To create an Anaconda environment named `faim-8.0` and install `n88tools` version 8.0 and `vtkbone` all in one step, run the following command:

   ```
   conda create --name faim-8.0 --channel numerics88 python=2.7 n88tools=8.0
   ```

To use `n88tools`, you simply activate the Anaconda environment. On Linux and macOS, this is done with

```
source activate faim-8.0
```

On Windows, the command is

```
activate faim-8.0
```

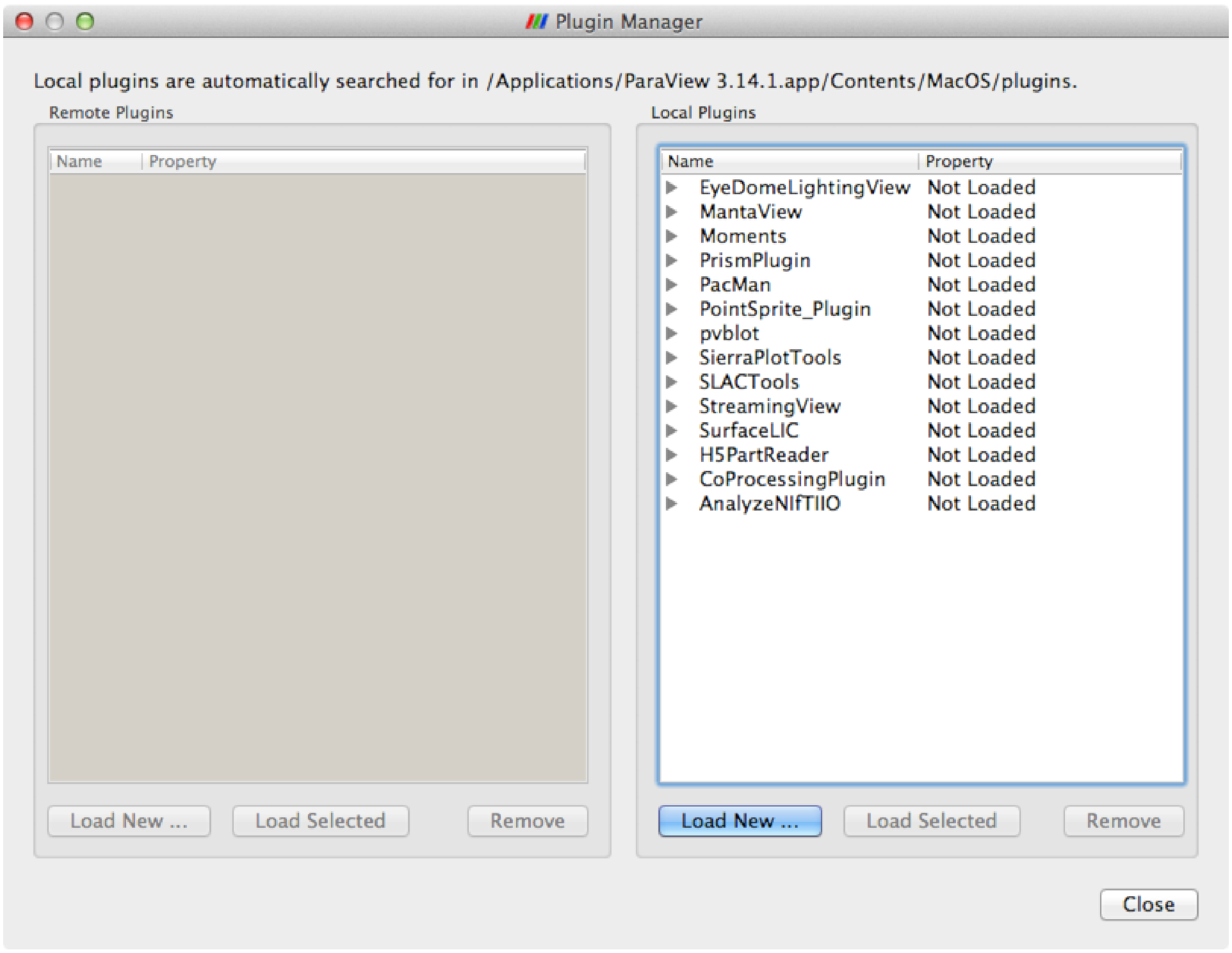
You will have to activate the environment in each Terminal (or Command Prompt) in which you want to use Faim.

Install the Numerics88 plugins for ParaView

ParaView can used for interactive rendering of Faim finite elements models. For this purpose, Numerics88 provides plugins for ParaView. These allow ParaView to open `n88model` files (as well as Scanco AIM files). The plugins can be downloaded from http://numerics88.com/downloads/ . You can unzip the plugins into any convenient directory, and you can move and rename the plugin directory as you like.

Important
The ParaView plugins are specific to a particular version of ParaView and can not be loaded into a different version of ParaView.

To load the plugins, open ParaView, and select the menu item Tools → Manage Plugins. The Plugin Manager will appear, as shown in Figure 1.


Plugin Manager

Local plugins are automatically searched for in /Applications/ParaView 3.14.1.app/Contents/MacOS/plugins.

Remote Plugins

Name	Property

Local Plugins

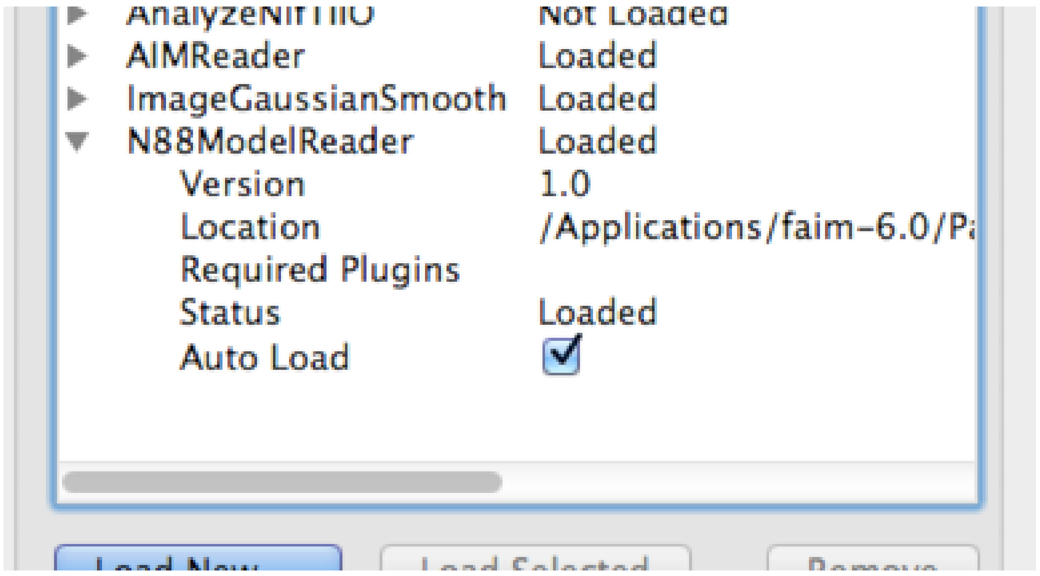
Name	Property
EyeDomeLightingView	Not Loaded
MantaView	Not Loaded
Moments	Not Loaded
PrismPlugin	Not Loaded
PacMan	Not Loaded
PointSprite_Plugin	Not Loaded
pvblot	Not Loaded
SierraPlotTools	Not Loaded
SLACTools	Not Loaded
StreamingView	Not Loaded
SurfaceLIC	Not Loaded
H5PartReader	Not Loaded
CoProcessingPlugin	Not Loaded
AnalyzeNIfTIIO	Not Loaded

Figure 1.1: ParaView's Plugin Manager

Click Load New... and navigate to the location of the plugins. Select one of the plugins, and then click OK. You will need to repeat this for each of the plugins, in particular for

- `libAIMReader`,
- `libImageGaussianSmooth` and
- `libN88ModelReader`.

They are now loaded, and you should be able to read to corresponding file formats. For more convenient future use, you may want to select `Auto Load` for each. To do this, click on the arrow beside the plugin in the Plugin Manager, and make sure that `Auto Load` is selected. This is shown in Figure 2.



▶ AnalyzeNIfTIIO	Not Loaded
▶ AIMReader	Loaded
▶ ImageGaussianSmooth	Loaded
▼ N88ModelReader	Loaded
Version	1.0
Location	/Applications/faim-6.0/Pa
Required Plugins	
Status	Loaded
Auto Load	✓

Figure 1.2: Selecting Auto Load in ParaView's Plugin Manager

Additional downloads

A PDF version of this manual can be downloaded from http://numerics88.com/documentation/ .

Example data files, together with scripts for the tutorials in this manual, can be downloaded from http://numerics88.com/-downloads/ .

Work flow for finite element analysis

There are several steps involved in applying finite element analysis to 3D medical image data. These steps are diagrammed in Figure 3. Generally they can be categorized as pre-processing, solving, and post-processing. Faim integrates these steps to simplify the work flow as much as possible, while retaining flexibility and customizability in preparing, solving and analyzing finite element problems derived from micro-CT data.

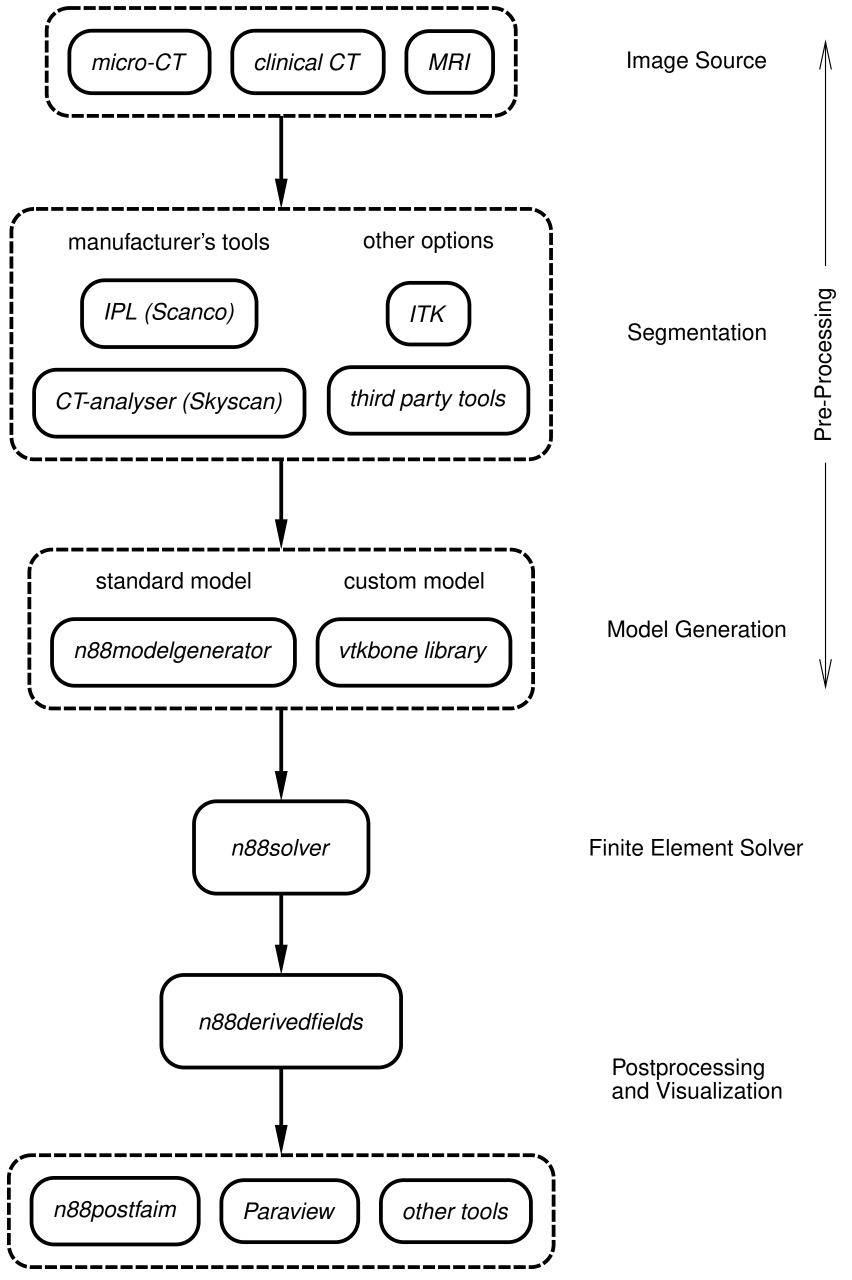


Figure 1.3: Work flow for FE analysis of micro-CT data.

Segmentation

The first step is to segment your 3D medical image data. Although in principle any type of 3D image data can be analyzed, we focus on the use of micro-CT images of bone here. During segmentation, bone and other relevant structures in the CT image are labelled and identified. Segmentation is a very broad and complex field. Because of this, Numerics88 software does not attempt to provide all solutions. Instead, we recommend that you use the segmentation tool provided by the manufacturer of your medical image equipment. This has the advantage that it will be well-integrated into the scanning workflow. In the case of Scanco systems, the tool is *Image Processing Language (IPL)*; for Skyscan systems, *CT-analyzer* provides segmentation functionality.

In cases where your segmentation problem is unusually tricky and beyond the abilities of the manufacturer's tools, there are many third party solutions available.

Whichever tool you use to perform the segmentation, the result should be a 3D image file with integer values. These integer values are referred to as "Material IDs", because they will subsequently be associated with abstract mathematical material models. Material ID zero indicates background material (often air, but sometimes also other material, such as marrow in bone) that can be assumed to have negligible stiffness. Voxels with material ID zero will not be converted to elements in the FE model. Other values can be associated freely with particular materials or material properties as required.

Model generation

Model generation is the process of converting a segmented image to a geometrical representation suitable for finite element analysis, complete with suitable constraints such as displacement boundary conditions and applied loads.

A number of steps are required for complete model generation.

Meshing
Meshing is the process of creating a geometric representation of the model as a collection of finite elements. For micro-CT data, we typically convert each voxel in the input image to a hexahedral (box-shaped) element in the FE model. Each of the corners of the voxel becomes a node in the FE model. Voxels labelled as background (*e.g.* 0) are ignored.

Tip
There may be scenarios in which it is desirable to have FE models that have elements smaller or larger than the voxels of the available image. Larger elements lead to smaller FE models (*i.e.* fewer degrees of freedom) which may solve faster, at the expense of accuracy. Smaller elements allow the forces and displacements to vary more smoothly (that is, with higher resolution) in the FE model, at the cost of increased solution time and memory requirements. To alter the FE model from the original 3D image, one typically resamples the original image to the desired resolution employing some sort of interpolation.

Material Assignment
Material assignment is the process of mapping material IDs to mathematical models for material properties. For example, an isotropic material is specified by its Young's modulus (E) and Poisson's ratio (ν).

Assigning Boundary Conditions and Applied Loads
Boundary conditions and applied loads implement a specific mechanical test. The tool used will typically translate a desired physical action, such as a force or a displacement applied to a specific surface, into a set of constraints on a set of nodes or elements.

Faim provides two tools for model generation:

n88modelgenerator
`n88modelgenerator` is a program that can generate a number of standard tests (e.g. axial compression, confined compression, etc…). `n88modelgenerator` has a number of options that allow for flexibility in tweaking these standard models. `n88modelgenerator` is the easiest method of generating models.

vtkbone
`vtkbone` is a collection of custom VTK objects that you can use for creating models, and is a more advanced alternative to using `n88modelgenerator`. In order to use them, you need to write a program or script (typically in Python). Some learning curve is therefore involved, as well as the time to write, debug and test your programs. The advantage is nearly infinite customizability. VTK objects, including `vtkbone` objects, are designed to be easily chained together into execution pipelines. In this documention, we will give many examples of using `vtkbone` in Python scripts.

Finite element solver

The finite element solver takes the input model and calculates a solution of the displacements and forces on all the nodes, subject to the specified constraints.

As finite element models derived from micro-CT can be very large, the memory efficiency and speed of the solver are important. Faim uses a mesh-free preconditioned conjugate gradient iterative solver. This type of solver is highly memory efficient.

Note

Faim is currently limited to small-strain solutions of models with linear and elastoplastic material definitions. This is adequate for most bone biomechanics modelling purposes, as bone undergoes very little strain before failure. However, if you need to accurately model large deformations, the Faim solver is not an appropriate tool.

Post-processing and visualization

Post-processing and visualization can take many different forms, depending on the goals of your analysis. For example, you may want to identify locations of stress variations, in which case, a visualization tool is likely the best approach. Or, you may want to obtain a basic output such as an overall stiffness. A number of common post-processing operations are performed by Faim.

Visualization is important even in cases where ultimately you want one or more quantitative values. Visualization provides a conceptual overview of the solution, and may allow one to quickly identify incorrect or invalid results due to some deficiency in the input model. Many visualization software packages exist. If you don't have an existing favourite package, we recommend the use of ParaView, which is an open-source solution from Kitware. The Faim distribution includes plug-ins for ParaView which allow ParaView to directly open Faim file types.

Units in Faim

Faim is intrinsically unitless; you may use any system of units that are self-consistent.

Nearly all micro-CT systems use length units of millimetres (mm). With forces in Newtons (N), the consistent units for pressure are then megapascals (MPa), as $1\text{N}/(1\text{mm})^2 = 1\text{MPa}$. Young's modulus is an example of a quantity that has units of pressure. In the examples, we will consistently use these units (mm, N, MPa).

Chapter 2

Preparing Finite Element Models With n88modelger

Running n88modelgenerator

n88modelgenerator is a tool to create a number of different standard mechanical test simulations directly from segmented 3D images. This tool is designed to be simple to use and in many cases, requires no more than specifying a test type and an input file, like this

```
n88modelgenerator --test=axial mydata.aim
```

This will generate a file `mydata.n88model` that is suitable as input to the Faim solver.

Tip
For an introduction to n88modelgenerator, we recommend that you start first with An introductory tutorial: compressing a solid cube. Getting your hands dirty as it were with the program is often the best way to learn. Once you have some familiarity with the program, the following documentation will be make much more sense.

The models produced by n88modelgenerator can be modified and tuned by specifying a number of optional parameters. For example, here n88modelgenerator is run to create an axial test with a specified compressive strain and Young's modulus:

```
n88modelgenerator --test=axial --normal_strain=-0.01 --youngs_modulus=6829 test25a.aim
```

Parameters can be specified either on the command line, or in a configuration file. Command line arguments must be preceded with a double dash (`--`). The argument value can be separated from the argument name with either an equals sign (=) or a space. A complete list of all possible arguments is given in the Command Reference chapter. You can also run n88modelgenerator with the `--help` option to get a complete list of possible parameters. All parameters except the input file name are optional; a default value will be used for unspecified parameters. To use a configuration file, run n88modelgenerator as follows.

```
n88modelgenerator --config=mytest.conf test25a.aim
```

Here we are specifying the name of the input file on the command line. This is convenient if we want to use the same configuration file for multiple input files. It is also possible to specify the name of the input file in the configuration file, using the option input_-file. The output file name is left unspecified, so a default value will be used (`test25a_axial.n88model` in this case), but it can also be specified either on the command line or in the configuration file if desired.

The configuration file format is one line per option: the parameter name (without leading dashes), followed by the equals character (=), followed by the parameter value. Lines beginning with # are ignored. The following configuration file is exactly equivalent to the example above using command line parameters.

Example configuration file for n88modelgenerator

```
# This is the example configuration file "mytest.conf"
test                           = axial
normal_strain                  = -0.01
youngs_modulus                 = 6829
```

Note
If a parameter is specified on both the command line and in a configuration file, the command line value takes precedence.

n88modelgenerator can accept several different input file formats. Refer to the Command Reference chapter for details.

Tip
If you have an input image in a different format, there are many possible solutions. One is to convert the file format, possibly with ParaView, which can read a large number of formats. VTK can also be used to convert many image files. For example, the following python script will convert a MetaImage format file to a VTK `.vti` file.

```
import vtk
reader = vtk.vtkMetaImageReader()
reader.SetFileName ("test.mhd")
writer = vtk.vtkXMLImageDataWriter()
writer.SetFileName ("test.vti")
writer.SetInputConnection (reader.GetOutputPort())
writer.Update()
```

For more information on scripting, refer to Preparing Finite Element Models With vtkbone.

Test orientation

To allow for flexibility in defining the orientation of applied tests, two coordinate frames are defined:

Data Frame
The Data Frame is the coordinate frame of the data. The input and output data use the same coordinate system.

Test Frame
The Test Frame is the coordinate frame in which the test boundary conditions are applied. Tests are defined with a constant orientation in the Test Frame.

The relationship between the Test Frame and the Data Frame is set by the value of the parameter test_axis according to the following figure. In the figure, the red-colored axis is the test axis. What this implies exactly depends on the kind of test that is being applied. For example, for a compression test, the direction of compression is along the test axis. The test axis is always the z axis in the Test Frame, and always equal to value of the parameter test_axis in the Data Frame. The default value for `test_axis` is z ; for this case the Test Frame and the Data Frame coincide, as shown.

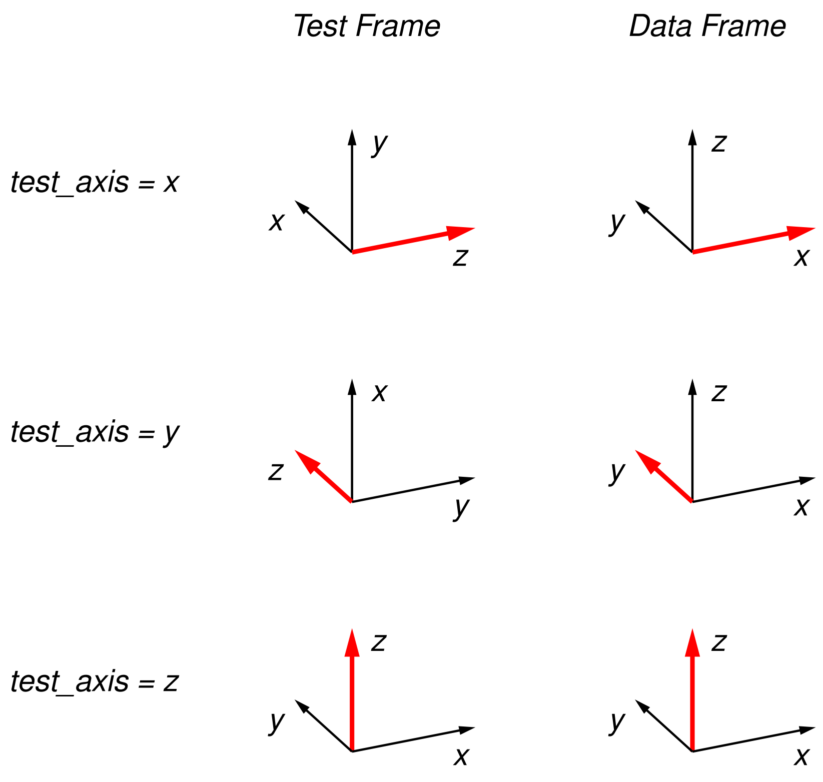


Figure 2.1: Coordinate frames Test Frame and Data Frame as set by the option test_axis.

In the test descriptions, references to “Top” refer to the maximum z surface in the Test Frame; References to “Bottom” refer to the minimum z surface in the Test Frame. Likewise “Sides” refers to the surfaces normal to the x and y axes in the Test Frame.

The Test Frame is used only for the specification of tests (*i.e.* a specific configuration of boundary conditions and applied loads) within n88modelgenerator and `vtkbone`. When the model is written to disk as an `n88model` file, it is encoded with reference to the original Data Frame. As a consequence post-processing and visualization are in the original Data Frame.

Note
In terms of rotations, for a setting of test axis = *x*, the transformation from the Test Frame to the Data Frame is a rotation of -90º about the *x* axis, followed by a -90º rotation about the *z'* axis. For a setting of test axis = *y*, the transformation from the Test Frame to the Data Frame is a rotation of 90º about the y axis, followed by a 90º rotation about the *z'* axis. These transformation sequences are of course not unique. For most applications, it is not necessary to know these transformations; it should be sufficient to refer to Figure 4.

Standard tests

Important
Axis directions in the following test descriptions are in the Test Frame. All the standard tests can be applied along any axis of the data by specifying test_axis, as described in the previous section.

Uniaxial test

A uniaxial test is a compression (or tension) test with a fixed displacement or force applied along the z axis. Two boundary conditions are applied:

1. Nodes on the bottom surface are fixed in the *z* direction, but free in the *x* and *y* directions.
2. Nodes on the top surface are subject to a fixed displacement in the *z* direction. No constraints are applied to the *x* and *y* directions.

A uniaxial test is shown in Figure 5, along with other types of compression tests. The coordinate system shown in the figure is the Test Frame. A uniaxial test is distinguished from an axial test (described below) by the fact that nodes on the top and bottom surfaces are unconstrained laterally. This corresponds to zero contact friction.

The amount of displacement applied to the top surface can be specified by either the normal_strain or displacement parameters.

Important
Uniaxial models are under-constrained since, as defined, arbitrary lateral motion, and arbitrary rotation about the *z* axis of the entire model are permitted. This results in a singular system of equations. A "pin" may be added to prevent these motions. See pin parameter. However, Faim will find a (non-unique) solution even without a pin, and in fact typically does so faster in the absence of a pin. A pin should always be added if you want to use an algebraic solver, or if you intend to compare the absolute positions of multiple solved models. Alternatively, you can register the solved models before comparing absolute positions.

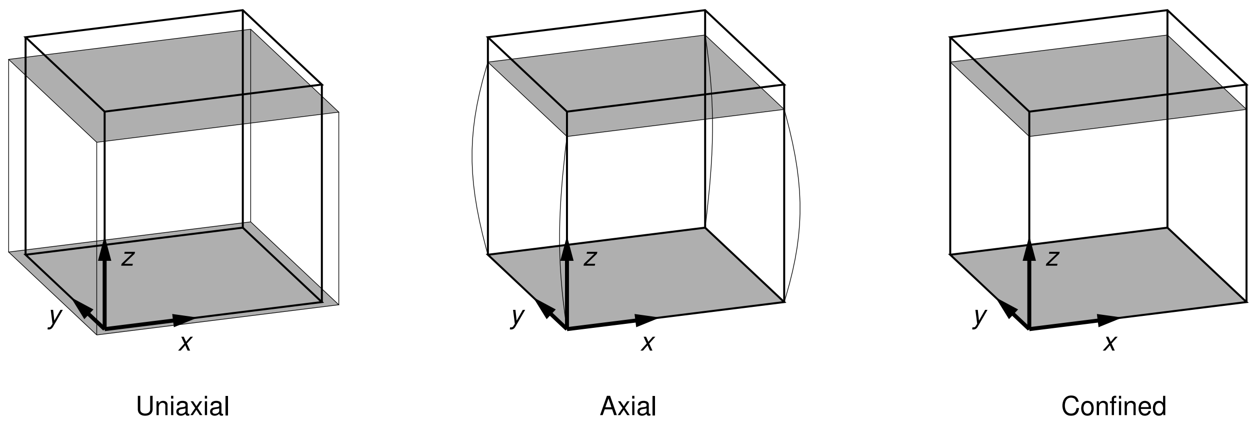


Figure 2.2: Compression tests.

Axial test

An axial test is similar to a uniaxial test, with the additional constraint that nodes on the top and bottom surfaces are also laterally fixed (*i.e.* no movement of these nodes is permitted in the x-y directions). This corresponds to 100% contact friction.

An axial test is shown in Figure 5.

Confined test

A confined test is similar to an axial test, with the addition that nodes on the side surfaces of the image volume are constrained laterally (i.e. no movement of these nodes is permitted in the x-y directions).

A confined test is shown in Figure 5.

Symmetric shear test (symshear)

In a symmetric shear test, the side surfaces are angularly displaced to correspond to a given shear strain. This is shown in Figure 6. The only parameter of relevance to a symmetric shear test is shear_strain.

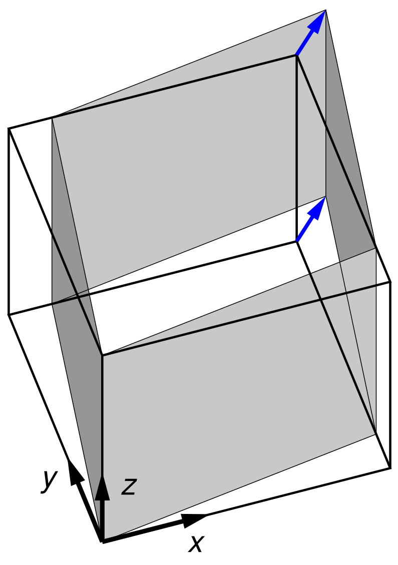


Figure 2.3: symshear test. The side faces (shaded) are displaced as shown.

Directional shear test (dshear)

In a directional shear test, the top surface is displaced laterally, as shown in Figure 7. The direction and degree of displacement are set by the parameter shear_vector, which gives the *x*,*y* shear displacement in the Test Frame. Typically `shear_vector` is unitless, and the actual displacement is the shear vector scaled by the vertical height of the model (*i.e.* the image extent in the z direction in the Test Frame). If however scale_shear_to_height is set to `off`, then `shear_vector` is taken to have absolute units of length.

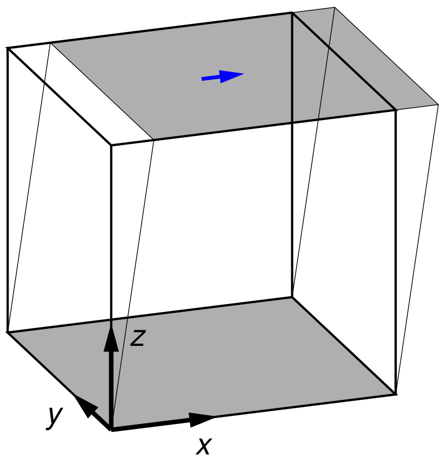


Figure 2.4: dshear test. The upper shaded area represents the rigidly translated boundary surface defined by the shear vector (blue).

Bending test

In a bending test, the top and bottom surfaces are rotated in opposite directions, as shown in Figure 8. The rotation axes are defined by a neutral axis, given by a point in the *x*,*y* plane (shown as `C`) and an angle in the *x*,*y* plane. (The coordinate system shown in the figure is the Test Frame.) The neutral axis, projected onto the top and bottom surfaces, is indicated in blue in Figure 8. The point and angle defining the neutral axis can be set in n88modelgenerator with the parameters central_axis and neutral_axis_angle respectively. The central axis (point `C`) can be specified as a numerical *x*,*y* pair, or as the center of mass or the center of the data bounds; center of mass is the default setting. The default angle of the neutral axis is 90º, parallel to the *y*-axis. The amount of rotation can be specified with the parameter bending_angle. The top and the bottom surfaces are each rotated by half of this value. Positive rotation is defined as in Figure 8.

In a bending test, the top and bottom surfaces are laterally constrained; no x,y motion of the nodes on these surfaces is permitted.

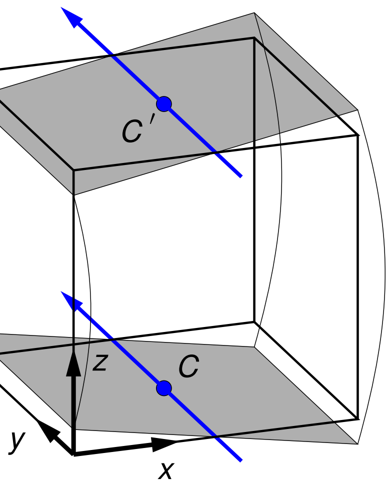


Figure 2.5: Bending test. The shaded areas represent the rigidly rotated boundary surfaces about the neutral axes (in blue). The neutral axes are defined by the central axis (C-C') and an angle in the x-y plane.

Torsion test

In a torsion test, the top surface is rotated about the center axis, as shown in Figure 9. The angle of rotation is given by twist_-angle. In the figure positive rotation is shown. The central axis lies parallel to the *z* axis in the test frame; its position can be specified with the parameter central_axis. The default position of the central axis is passing through the center of mass.

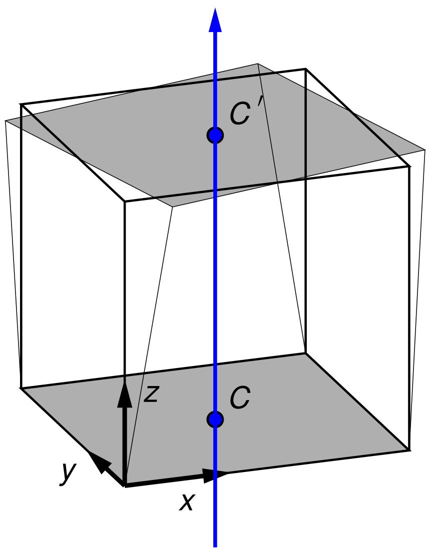


Figure 2.6: torsion test. The upper shaded area represents the rotated boundary surface about the central axis (C-C').

Uneven surfaces

The grey planes in Figure 5 represent the top and bottom boundary surfaces of the image volume. The actual surface to which boundary conditions are applied is by default that part of your object which passes through these boundaries. If your object does not intersect with the top and bottom boundaries of the image volume, then no boundary conditions can be applied using this method.

An alternative is to make use of the parameters top_surface and bottom_surface. The “uneven surface” near a boundary is defined as the surface visible from that boundary (viewed from an infinite distance). Visibility is evaluated using ray tracing. Thus for a porous material such as bone the “uneven surface” consists of nodes on the top visible surface, not including nodes on surfaces down inside the pores.

The `visible` setting can be used for any type of test except symshear. For example, if used with a bending test, the the boundary conditions are no longer exactly tilted planes as shown in figure Figure 8; the displacement of each node on the visible surfaces is still calculated as described from its *x*,*y* coordinates, but the displaced nodes no longer lie all on a plane (because the initial positions are not on a plane.)

Because the visibility test may find some surfaces far from the boundary in question, it should usually be used together with the parameters bottom_surface_maximum_depth and/or top_surface_maximum_depth. These provide a limit, as a distance from the boundary, for the search for the uneven surface.

Material specification

Material specification consists of two parts:

Material Definition creation
One or more material definitions are created. A material definition is a mathematical description of material mechanical properties. It has a definite type (*e.g.* linear isotropic or linear orthotropic) and specific numerical values relevant to that type (*e.g.* a linear isotropic material definition will have particular values of Young’s modulus and Poisson’s ratio).

Material Table generation
The material table maps material IDs, as assigned during segmentation, to material definitions. It is possible to combine different types of materials (*e.g.* isotropic and orthotropic) in the same material table. A single material definition can be assigned to multiple material IDs.

In Numerics88, material definitions are indexed by name. This is not usually evident in `n88modelgenerator`, as for basic usage, the names are generated automatically, and are not needed by the user. However for advanced material specification, this becomes important, as we will see below when material definition files are discussed.

Elastic material properties

Linear elastic materials obey Hooke’s Law,

$$\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \gamma_{yz} \\ \gamma_{zx} \\ \gamma_{xy} \end{bmatrix} = \mathbf{S} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{zx} \\ \sigma_{xy} \end{bmatrix}$$

where $\varepsilon_{\mathrm{xx}}$,$\varepsilon_{\mathrm{yy}}$,$\varepsilon_{\mathrm{zz}}$ are the *engineering normal strains* along the axis directions, γ_{yz},γ_{zx},γ_{xy} are the *engineering shear strains*, and σ_{ij} are the corresponding stresses. **S** is the compliance matrix. The inverse of **S** gives σ in terms of ε, and is the stress-strain matrix **C**, also sometimes called the stiffness matrix.

Isotropic materials

An isotropic material has the same mechanical properties in every direction. Elastic isotropic materials are characterized by only two independent parameters: Young's modulus (E) and Poisson's ratio (ν). The compliance matrix is

$$\mathbf{S} = \frac{1}{E}\begin{bmatrix} 1 & -\nu & -\nu & 0 & 0 & 0 \\ -\nu & 1 & -\nu & 0 & 0 & 0 \\ -\nu & -\nu & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(1-\nu) & 0 & 0 \\ 0 & 0 & 0 & 0 & 2(1-\nu) & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(1-\nu) \end{bmatrix}$$

For n88modelgenerator the isotropic elastic parameters are set with youngs_modulus and poissons_ratio. The default values are 6829 MPa and 0.3, as reported by MacNeil and Boyd (2008).

An isotropic material definition is the default, and will be assumed if no other material type is specified.

Orthotropic materials

Orthotropic elastic materials have two or three mutually orthogonal twofold axes of symmetry. The compliance matrix is

$$\mathbf{S} = \begin{bmatrix} 1/E_x & -\nu_{yx}/E_y & -\nu_{zx}/E_z & 0 & 0 & 0 \\ -\nu_{xy}/E_x & 1/E_y & -\nu_{zy}/E_z & 0 & 0 & 0 \\ -\nu_{xz}/E_x & -\nu_{yz}/E_y & 1/E_z & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{yz} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{zx} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{xy} \end{bmatrix}$$

where

E_i	is the Young's modulus along axis i ,
ν_{ij}	is the Poisson's ratio that corresponds to a contraction in direction j when an extension is applied in direction i ,
G_{ij}	is the shear modulus in direction j on the plane whose normal is in direction i . It is also called the modulus of rigidity.

Note that the ν_{ij} are not all independent. The compliance matrix must be symmetric, hence

$$\begin{aligned} -\nu_{yx}/E_y &= -\nu_{xy}/E_x \ , \\ -\nu_{zy}/E_z &= -\nu_{yz}/E_y \ , \\ -\nu_{xz}/E_x &= -\nu_{zx}/E_z \ . \end{aligned}$$

Therefore only 9 independent parameters are required to fully specify an orthotropic material.

For n88modelgenerator the orthotropic elastic parameters are set with orthotropic_parameters. Whenever this parameter is specified, an orthotropic material definition will be used.

Note

An orthotropic material defined with a compliance matrix as given above necessarily has its axes of symmetry aligned with the coordinate axes. In contrast, an orthotropic material which is rotated relative to the coordinate axes has a more general form of compliance matrix. In Numerics88 software, such a non-aligned orthotropic material must be specified as an anisotropic material. A rotation matrix relates elements of the anisotropic compliance matrix to the orthotropic compliance matrix. If you want the mathematical details, please contact us!

Anisotropic material

The most general form of an elastic material is anisotropic, for which we allow the stress-strain matrix, or the compliance matrix, to have arbitrary values. The stress-strain matrix is symmetric, therefore an anisotropic material requires 21 parameters to define. To define an anisotropic material with `n88modelgenerator`, it is necessary to use a material definitions file. See below.

Plasticity

Elastoplastic material behaviour is an idealisation of a particular kind of nonlinear stress-strain relationship in which we divide the stress-strain relationship into two clearly distinguished regions: (1) an elastic region, which is identical to the linear elastic material behaviour described above, and, (2) a purely plastic region. For a material subject to a uniaxial deformation, this is sketched in Figure 10. In Figure 10A, we see the initial elastic region, which in this sketch is tensile, with slope equal to the Young's modulus. This region continues until the stress reaches the yield strength, *Y*. For further increases in strain beyond this point, the stress ceases to increase, and remains constant at the yield strength. The incremental strain in this region is referred to as the plastic strain. Although we must perform work to produce a plastic strain, the plastic strain is irreversible, as can be seen in Figure 10B. In B, after applying a large plastic strain, the strain is gradually reduced. The plastic strain component is unchanged during the relaxation; instead, it is the elastic component of the strain that is reduced. As the stress depends entirely on the elastic component of the strain, the stress also immediately begins to decrease. Hence, we do not travel back along the "outward" path, but instead return along a shifted version of the linear elastic region: the material exhibits *hysteresis*. Although the initial point and the final point of Figure 10B are both characterised by zero strain, the state is quite different, as the latter state has a large plastic strain. If we continue to reduce the strain, as in Figure 10C, the stress becomes negative - a compressive stress - until, once again, we reach the yield strength limit. Note that the yield strength in tension and the yield strength in compression are not necessarily equal.

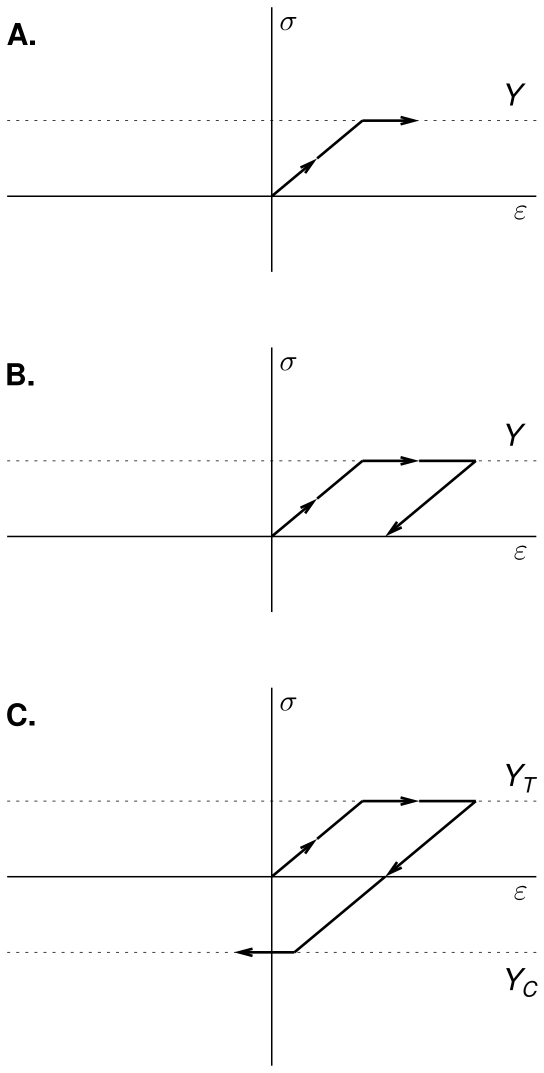


Figure 2.7: Elastoplastic behaviour in one dimension.

In three dimensions, an elastoplastic material is characterised by a yield surface, which is the boundary of the elastic region. The yield surface is defined in stress space (or equivalently in strain space). For isotropic materials, the yield surface is most easily defined in the space of the three principal stresses. Stresses lying inside the yield surface are associated with an elastic state. When the stress reaches the yield surface, the material yields, and further increases in strain result in the stress state moving along the yield surface. Many different shapes of yield surface are possible, and are characteristic of different kinds of materials. Yield surfaces are conveniently defined mathematically by a yield function f, such that the yield surface is the locus of points for which $f = 0$. A complete explanation of elastoplastic behaviour in three dimensions is not given here. We recommend that you consult a good mechanics of materials textbook.

To specify an elastoplastic material, it is necessary both to specify its elastic properties, and its plasticity. Currently Faim only allows plasticity to be defined with isotropic elastic properties. A typical specification of an elastoplastic model using `n88modelgenerator` will look something like this

```
n88modelgenerator --youngs_modulus=6829 --poissons_ratio=0.3 --plasticity=vonmises,50  ↩
    mydata.aim
```

The currently supported plastic yield criteria are described below.

von Mises yield criterion

The von Mises yield criterion states that yielding begins when the distortional strain-energy density attains a certain limit. It is therefore also called the *distortional energy density* criterion. The distortional strain-energy density is the difference between the total strain energy density and the strain energy density arising only from the part of the strain resulting in a volume change. Hence, the distortional strain-energy density is associated with that part of the strain that results in no volume change: or, in other words, the part of the strain that causes a change in shape.

The yield function for a von Mises material, in terms of the three components of the principal stress, is given by

$$f = \frac{1}{6}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]-\frac{1}{3}Y^2$$

The parameter Y is the yield strength in uniaxial tension (or compression).

To specify a von Mises material in `n88modelgenerator`, use the parameter plasticity. For example, `--plasticity=vonmises,68` will define a von Mises material with $Y = 68$. The units of Y are the same as stress, so typically MPa.

Mohr-Coulomb yield criterion

The Mohr-Coulomb yield criterion is a refinement of the Tresca yield condition, which states that yielding begins when the shear stress at a point exceeds some limit. To this, the Mohr-Coulomb criterion adds a dependence on the hydrostatic stress, such that the shear stress limit is dependent on the hydrostatic stress, in particular that the shear stress limit increases with hydrostatic stress. The Mohr-Coulomb yield criterion is characterised by two values: the cohesion c and the angle of internal friction φ. For principal stresses in the order $\sigma_1 > \sigma_2 > \sigma_3$, the Mohr-Coulomb yield function is

$$f = \sigma_1-\sigma_3+(\sigma_1+\sigma_3)\sin\phi-2c\cos\phi$$

Under uniaxial tension, the yield strength is

$$Y_T = \frac{2c\cos}{1+\sin\phi}$$

while under uniaxial compression, the yield strength is

$$Y_C = \frac{2c\cos}{1-\sin\phi}$$

Mohr-Coulomb materials are specified to `n88modelgenerator` using these two yield strengths. See plasticity. For example, `--plasticity=mohrcoulomb,40,80` will define a Mohr-Coulomb material with $Y_T = 40$ and $Y_C = 80$. The units of Y_T and Y_C are the same as stress, so typically MPa.

Material table generation

The parameter material_table allows one of two standard types of material table may be chosen: a simple table, consisting of a single material definition, or a Homminga material table, which relates density to stiffness.

If you require a material table different than either of the standard ones offered, you can use a material definitions file. See below for details.

Homogeneous material table

The simplest material table consists of a single material definition. Thus it corresponds to homogeneous material properties: all elements are assigned the same material properties.

Note that although only a single material definition is created, it is nevertheless still possible for the material table to have multiple entries corresponding to multiple material IDs. In this case every material ID in the table maps of course to the same single material definition. `n88modelgenerator` automates this: it examines the segmented input image, and generates one entry in the material table for every unique material ID (*i.e.* image value) present in the segmented image. Clearly, as a matter of efficiency and simplicity, if you intend to use a image for analysis with homogenous material properties, it is preferable to segment the image object to a single material ID. It is not however, necessary to do so.

Homminga material table

Homminga (2011) introduced a model that attempts to account for varying bone strength with density. In this model, the modulii vary according to the equation

$$E = E_{max}(\rho/\rho_{max})^{1.7}$$

Where ρ is the CT image density. For the orthotropic case, the shear modulii follow the same scaling, and for the anisotropic case, the stress-strain matrix follows this scaling.

To use this type of material table, the data must be segmented such that the material ID of each voxel is proportional to its CT image density. As material IDs are discrete, the CT image density is therefore binned. Hence

$$E = E_{max}(ID/ID_{max})^{1.7}$$

ID_{max} is set with the parameter homminga_maximum_material_id, and the exponent is set with the parameter homminga_-modulus_exponent.

E_{max} will depend on the specified material. For an isotropic material, it will be given by youngs_modulus. However orthotropic or anisotropic materials may also be scaled: the entire stress-strain matrix scales according to the above-stated law.

Warning
In contrast to the homogenous material table, a Homminga material table is not guaranteed *a priori* to have an entry for every material ID present in the input segmented image. If your segmented image has material IDs larger than the specified ID_{max} , `n88modelgenerator` will produce an error.

Material definitions file

The method presented up to this point for defining materials in `n88modelgenerator`, while relatively easy, suffers from some limitations. In particular, only a single material can be specified using the options discussed so far. Furthermore, an anisotropic material can not be specified at all using the command line parameters. `n88modelgenerator` therefore provides an alternate method of defining materials, which is via a material definitions file. A material definitions file can be used to define any material known to `Faim`, any number of materials, and any material table. A material definitions file can be specified with the argument material_definitions.

The material definitions file format is straight-forward, as you can see from this example.

```
MaterialDefinitions:
    CorticalBone:
        Type: LinearIsotropic
        E: 6829
        nu: 0.3
    TrabecularBone:
        Type: LinearIsotropic
        E: 7000
        nu: 0.29
MaterialTable:
    100: TrabecularBone
    127: CorticalBone
```

Here we have a material definitions file containing two materials, both of which are linear elastic materials, but with different numerical values. Besides defining the materials, we have to specify the material table, which maps materials IDs (ie. the values present in the input image) to the materials we have defined.

Note

The indenting in material definitions file is important, as it indicates how objects are grouped. Indenting must be done with spaces, and not with tabs. Technically, the material definitions file is in YAML format. Thus any valid YAML syntax can be used. In particular, it is possible to use curly brackets instead of indenting to indicate nesting, should you so wish.

Here is another example material definitions file, which defines an anisotropic material.

```
MaterialDefinitions:
    ExampleAnisoMat:
        Type: LinearAnisotropic
        StressStrainMatrix: [
 1571.653,   540.033,   513.822,     7.53 ,  -121.22 ,   -57.959,
  540.033,  2029.046,   469.974,    78.591,   -53.69 ,   -50.673,
  513.822,   469.974,  1803.998,    20.377,   -57.014,   -15.761,
    7.53 ,    78.591,    20.377,   734.405,   -23.127,   -36.557,
 -121.22 ,   -53.69 ,   -57.014,   -23.127,   627.396,    13.969,
  -57.959,   -50.673,   -15.761,   -36.557,    13.969,   745.749]

MaterialTable:
    1: ExampleAnisoMat
```

The possible materials, and the values that must be specified for each, are listed in the following table.

Table 2.1: Materials as specified in a material definitions file

Type	Variable	Description
LinearIsotropic	`E:` *value*	Young's modulus
	`nu:` *value*	Poisson's ratio
LinearOrthotropic	`E:` [*value*,*value*,*value*]	Young's modulii as [E_{xx},E_{yy},E_{zz}]
	`nu:` [*value*,*value*,*value*]	Poisson's ratios as [ν_{yz},ν_{zx},ν_{xy}]
	`G:` [*value*,*value*,*value*]	Shear moduli as [G_{yz},G_{zx},G_{xy}]
LinearAnisotropic	`StressStrainMatrix:` [*value1*,*value2*,...,*value36*]	The 36 elements of the stress-strain matrix. Since the stress-strain matrix is symmetric, there are only 21 unique values, but all 36 must be given. They must be specified in the order K_{11} , K_{12} , K_{13}, . . . K_{66} , but since the matrix is symmetric, this is equivalent to K_{11} , K_{21} , K_{31}, . . . K_{66}.
VonMisesIsotropic	`E:` *value*	Young's modulus
	`nu:` *value*	Poisson's ratio
	`Y:` *value*	Yield strength
MohrCoulombIsotropic	`E:` *value*	Young's modulus
	`nu:` *value*	Poisson's ratio
	`c:` *value*	Mohr Coulomb *c* parameter (cohesion).
	`phi:` *value*	Mohr Coulomb φ parameter (friction angle).

Note

Materials are stored in the `n88model` file using exactly the same structure and variable names. See the MaterialDefinitions group of the `n88model` file specification.

Chapter 3

Preparing Finite Element Models with vtkbone

You only need to read this chapter if you are interested in writing scripts to create your own custom model types. For many users, `n88modelgenerator`, as described in the previous chapter, will be sufficient.

Although n88modelgenerator can generate many useful models for FE analysis, at times additional flexibility is required. In order to provide as much flexibility to the user as possible, we provide the option for users to perform custom model generation. This functionality is provided by `vtkbone` toolkit, which is built on VTK . VTK is "*an open-source, freely available software system for 3D computer graphics, image processing and visualization*", produced by Kitware. VTK provides a great deal of functionality to manipulate and visualize data that is useful for finite element model generation and analysis. `vtkbone` is a collection of custom VTK classes that extend VTK to add finite element pre-processing functionality. The `vtkbone` library objects combined with generic VTK objects can be quickly assembled into pipelines to produce nearly infinite customizability for finite element model generation and post-processing analysis.

Basing `vtkbone` on VTK provides the following advantages.

Large existing library of objects and filters
VTK is a large and well established system, with many useful algorithms already packaged as VTK objects.

Built-in visualization
VTK was designed for rendering medical data. With it sophisticated visualizations are readily obtained. The visualization application ParaView is built with VTK and provides excellent complex data visualization. `vtkbone` functionality is easily incorporated into ParaView.

Standardization
The time and effort the user invests in learning `vtkbone` provides familiarity with the widely-used VTK system, and is not limited in application to Numerics88 software.

Extensibility
The advanced user is able to write their own VTK classes where required.

Multiple Language Support
VTK itself consists of C++ classes, but provides wrapping functionality to generate an interface layer to other languages. `vtkbone` uses this wrapping functionality to provide a Python interface.

The best way to learn to use `vtkbone` is to follow the tutorials in Chapter 7.

We recommend that you use Python for assembling programs with `vtkbone`. There are several advantages of using Python, including simplicity of syntax and automatic memory management. In our experience, writing programs using `vtkbone` in Python is far less time consuming, and results in programs that are much easier to debug than writing the same programs in C++ . This is particularly true for users without significant programming experience.

Tip
Many of the tools provided with Faim are implemented as Python scripts. Some use `vtkbone`, and some manipulate the `n88model` file directly through the python netCDF4 module, which is installed automaticall when you install `n88tools`. Examining how these scripts work can be a good way to learn how to write your own custom python scripts for manipulating Faim models.

vtkbone API documentation

The complete Application Programming Interface (API) reference documentation for `vtkbone` is available at http://numerics88.com/-documentation/vtkbone/1.0/ . Class names in this document are linked to the `vtkbone` API documentation, so that if you click on a class name, it should open the documentation for that class. You should refer to the `vtkbone` API reference documentation whenever using a `vtkbone` class, as the descriptions below are introductory, and do not exhaustively cover all the functionality.

API documentation for VTK can be found at http://www.vtk.org/doc/release/6.3/html/ .

Note
If you are using Python instead of C `(and for most purposes, we recommend that you do), then yo u will have to infer the Python interface from the C` interface. This is generally simple: class and method names are the same, as are all positional argument names. Since Python is a weakly-typed language, you do not need to be concerned generally with the declared type of the arguments. A small number of C++ methods in `vtkbone` do not have a Python equivalent, but this is rare.

Array indexing in vtkbone

Arrays in `vtkbone`, as in VTK, C and Python, are zero-indexed. That is, the first element is element 0. This applies also to node numbers and element numbers. (It does not however apply to material IDs, because the material ID is not an array index; it is a key into a table look-up.) Be careful if reading an `n88model` file directly, because node numbers and element numbers are stored 1-indexed (see the file specification). The translation is done automatically if you use the `vtkbone` objects vtkboneN88ModelReader and vtkboneN88ModelWriter .

Typical workflow for vtkbone

Figure 11 shows a typical work flow for creating a finite element model using `vtkbone`. VTK generally consists of two types of objects (or “classes”): objects that contain data, and objects that process data. The latter are called “filters”. Filters can be chained together to create a processing pipeline. In the figure, filters are listed in the boxes with dark black lines and rounded corners; data objects are listed in gray rectangles. The boxes with dark black lines and rounded corners represent actions, and may list one or more VTK or `vtkbone` objects that are suitable for performing the action.

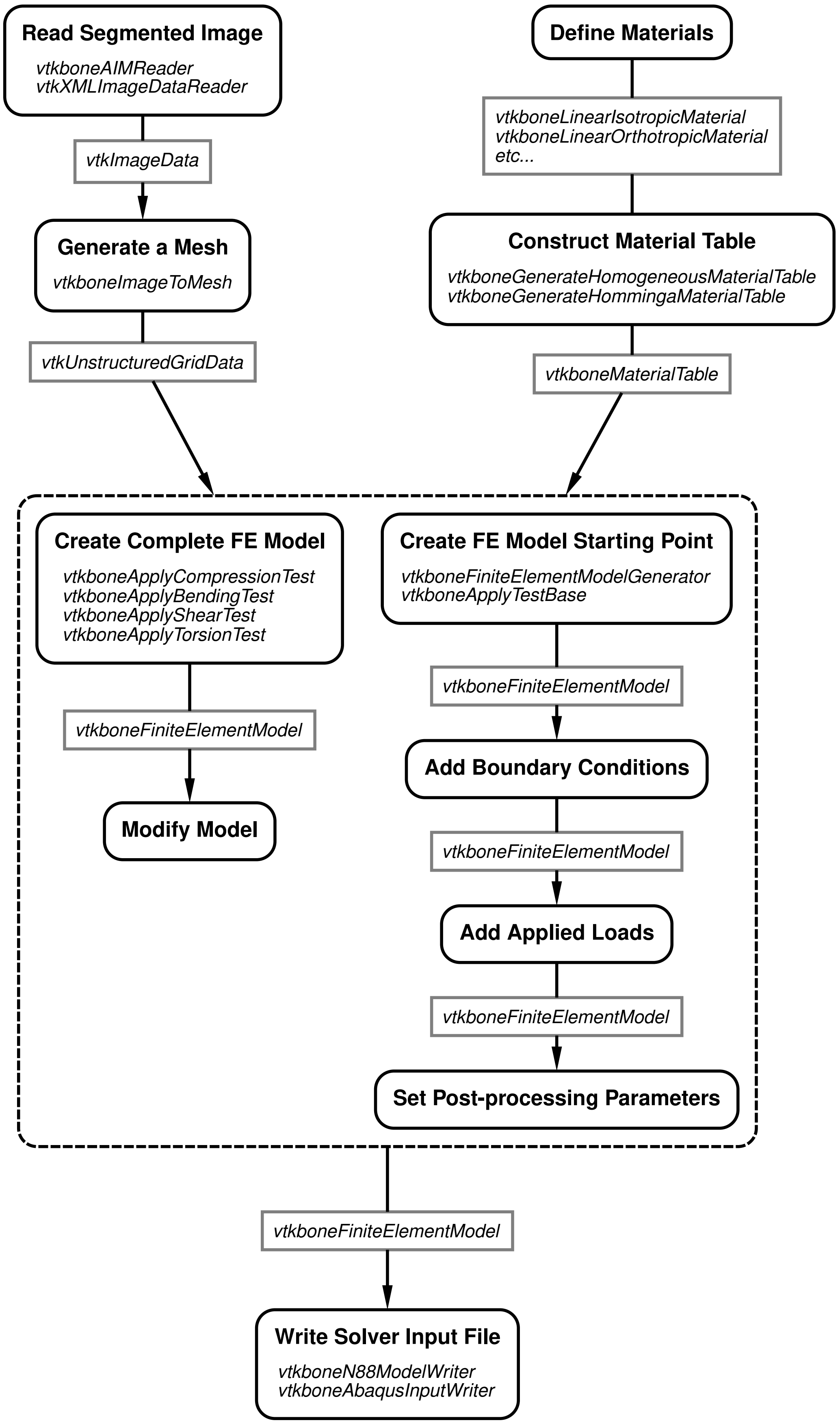


Figure 3.1: Typical work flow for vtkbone.

The typical way to use a VTK filter object is to create it, set parameters, set the input (if relevant), call `Update()`, and then get the output. For example, for a vtkboneAIMReader object, which has an output but no input, we might do this in Python

```
reader = vtkbone.vtkboneAIMReader()
reader.SetFileName ("MYFILE.AIM")
reader.Update()
image = reader.GetOutput()
```

Tip

There is an alternate way to use VTK filter objects, and that is to chain them together in a pipeline. In this case, calling Update on the last item in the pipeline will cause an update of all the items in the pipeline, if required. To connect filters in a processing pipeline, use `SetInputConnection` and `GetOutputPort` instead of `SetInputData` and `GetOutput`. As an example, we can connect a vtkboneAIMReader to a vtkboneImageToMesh like this

```
reader = vtkbone.vtkboneAIMReader()
reader.SetFileName ("MYFILE.AIM")
mesher = vtkbone.vtkboneImageToMesh()
mesher.SetInputConnection (reader.GetOutputPort())
mesher.Update() ❶
```

This automatically calls Update on the reader. Generally, unless you have some application where the pipeline approach is advantageous, we recommend the simpler method of using `SetInputData` and `GetOutput` and explicitly passing the data object between filters.

The vtkboneFiniteElementModel object

The central class that `vtkbone` adds to VTK is a new type of data class, called vtkboneFiniteElementModel . The conceptual structure of vtkboneFiniteElementModel is shown in Figure 12. vtkboneFiniteElementModel is a subclass of the VTK class vtkUnstructuredGrid , which represents a data set as consisting of an assortment of geometric shapes. In VTK terminology, these individual shapes are “Cells”. They map naturally to the concept of Elements in finite element analysis. The vertices of the cells, in VTK terminology, are “Points”. These are equivalent to Nodes in finite element analysis. vtkUnstructuredGrid , like other VTK objects, is capable of storing specific types of additional information, such as one or more scalar or vector values associated with each Cell or Point. This aspect is used for storing, for example, material IDs, which are mapped to the scalar values of the Cells. To vtkUnstructuredGrid , vtkboneFiniteElementModel adds some additional information related to requirements for finite element analysis such as material properties and constraints (*i.e.* displacement boundary conditions and applied loads), as well as sets of Points and/or Cells, which are useful for defining constraints and in post-processing. Sets and constraints are indexed by an assigned name, which is convenient for accessing and modifying them.

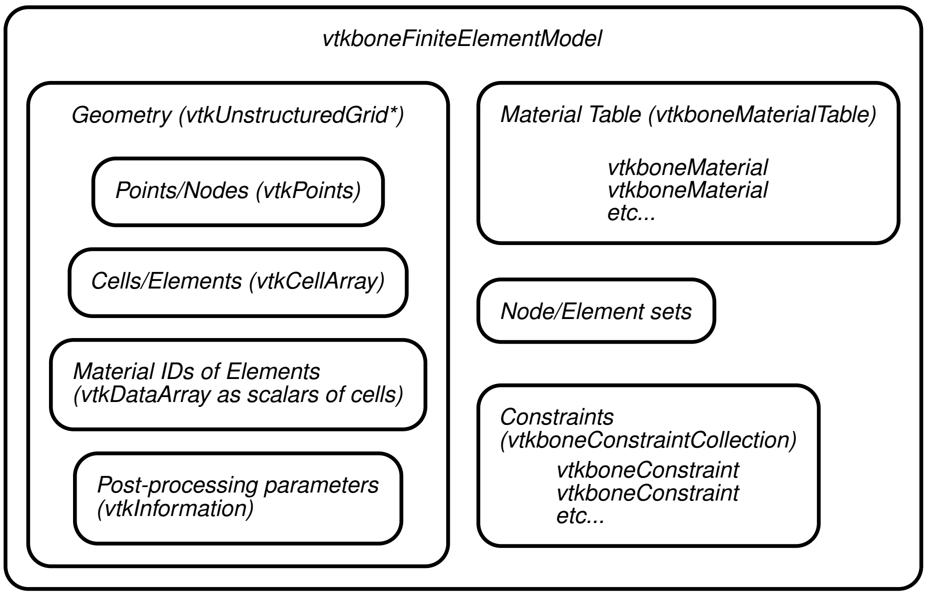

vtkboneFiniteElementModel
Geometry (vtkUnstructuredGrid*)
Points/Nodes (vtkPoints)
Cells/Elements (vtkCellArray)
Material IDs of Elements (vtkDataArray as scalars of cells)
Post-processing parameters (vtkInformation)
Material Table (vtkboneMaterialTable)
vtkboneMaterial
vtkboneMaterial
etc...
Node/Element sets
Constraints (vtkboneConstraintCollection)
vtkboneConstraint
vtkboneConstraint
etc...

Figure 3.2: Structure of vtkboneFiniteElementModel.

Reading a segmented image

We typically read in data as a segmented 3D volumetric image from micro-CT. The image values (*i.e.* the pixel or voxel values) need to correspond to the segmented material IDs. The selection of a file reading object will be appropriate to the input file format. The output of the file reader filter will be a vtkImageData object.

We have already given the example of using a vtkboneAIMReader to read a Scanco AIM file, which was

```
reader = vtkbone.vtkboneAIMReader()
reader.SetFileName ("MYFILE.AIM")
reader.Update()
image = reader.GetOutput()
```

Important

One slightly obscure technical issue which may arise is: are the data of a vtkImageData associated with the Points or the Cells? Either is possible in `VTK`. The scalar image data (scalar because there is one value per location) must be explicitly associated either with the Cells or with the Points. (In fact it's possible to have different scalar data on the Cells and the Points.) Thinking about it as an FE problem, it is natural to associate the image data with Cells, where each image voxel becomes an FE element. Thus, we like to think of each value in the image as being at the center of a Cell in the VTK scheme. VTK however has generally standardized on the convention of image data being on the Points. There are some important consequences. For example, a vtkImageData that has dimensions of (M,N,P) has (M,N,P) Points, but only (M-1,N-1,P-1) Cells. Or conversely, if you have data with dimensions of (R,S,T), and you want to put the data on the Cells, then you actually require a vtkImageData with dimensions of (R+1,S+1,T+1). Also, if the origin is important, one needs to keep in mind that the origin is the location of the zero-indexed Point. In terms of the Cells, this is the "lower-left" corner of the zero-indexed Cell, not the center of that Cell. `vtkbone` objects that require images as input will accept input with data either on the points or on the Cells. However, many `VTK` objects that process images work correctly only with input data on the Points. By contrast, if you want to render the data and color according to the scalar image, the rendering is quite different depending on whether the scalar data is on the Points or the Cells. Generally, you get the expected result in this case by putting the data on the Cells. This discussion is important because it illustrates that there is no one universally correct answer to whether image data belongs on the Points or on the Cells. `vtkbone` image readers, such as vtkboneAIMReader have an option DataOnCells to control the desired behaviour. `VTK` image readers always put image data on the Points, so if you need the data on the Cells, you must to copy the output to a new vtkImageData .

Examples of reading data with vtkbone are given in the tutorials Compressing a cube revisited using vtkbone and Advanced custom model tutorial: a screw pull-out test.

Reading an unsegmented image and segmenting it

If you have an unsegmented image such as a raw micro-CT image that has scalar values still in terms of density, it is possible to process the image with VTK. Segmentation is a complex subject, which we are unable to cover here. For an example of a simple segmentation, where only a density threshold and connectivity are considered, consult the example in the directory `examples/segment_dicom`.

Ensuring connectivity

A well-defined problem for finite element analysis requires that all parts of the object in the image be connected as a single object.

Disconnected parts in the input create an ill-defined problem, with an infinite number of solutions. These arise, for example, when there is noise in the image data. Some solvers cannot solve this kind of problem at all (the global stiffness matrix is singular). `n88solver` will typically find a solution. However, the convergence might be very slow as it attempts to find the non-existent optimum position for the disconnected part.

To avoid this problem, the input image can be processed with the filter ImageConnectivityFilter . This filter has many options and different modes of operation, but in most cases the default mode is sufficient. In the default behaviour:

1. Zero-valued voxels are considered "empty space", and no connection is possible though them.
2. Voxels are considered connected if they share a face. Sharing only a corner or an edge is not sufficient.
3. Only the largest connected object in the input image is passed to the output image. Smaller objects that have no continuous path of connection to the largest connected object are zeroed-out.

Because of the first point, it is clearly necessary to segment the image before applying ImageConnectivityFilter , because empty space must be labelled with the value 0.

```
connectivity_filter = vtkbone.vtkboneImageConnectivityFilter()
connectivity_filter.SetInput (image)
connectivity_filter.Update()
image = connectivity_filter.GetOutput() ❶
```

❶, ❶ Notice that we use the variable name "image" for both the input and the output. This causes no problems in Python, although by doing this we can no longer use this to refer to the input image. If that were necessary, then we should use different names for the input and output.

If your input image is processed and segmented with another software package, it is still a good idea to verify the connectivity of the input image. If your input image is carefully prepared, and you don't want to inadvertently modify it, you can check for connectivity without modifying it like this:

```
connectivity_mapper = vtkbone.vtkboneImageConnectivityMap()
connectivity_mapper.SetInput (image)
connectivity_mapper.Update()
if connectivity_mapper.GetNumberOfRegions() != 1:
    print "WARNING: Input image does not consist of a single connected object."
```

Examples of ensuring connectivity are given in the tutorials Compressing a cube revisited using vtkbone and Advanced custom model tutorial: a screw pull-out test.

Generating a mesh

Once we have a segmented and connected image, we convert the image to a mesh of elements, represented by a vtkUnstructuredGrid object. The base class vtkUnstructuredGrid supports many types of Cells, but currently `vtkbone` supports only `VTK_HEXAHEDRON` and `VTK_VOXEL`. The topology of `VTK_VOXEL` is shown in Figure 13.

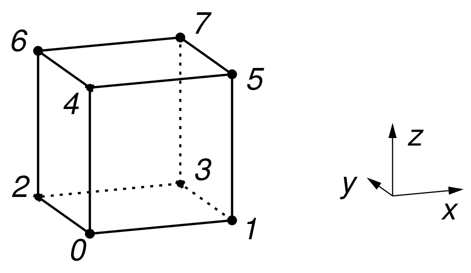


Figure 3.3: Topology of VTK_VOXEL. Local numbering of the nodes (Points) of the element (Cell) is shown (0-indexed).

Generating a mesh in `vtkbone` is straightforward; simply pass the input image to a vtkboneImageToMesh filter. It takes no options; the important choices were made already during the segmentation stage. In Python this looks like this

```
mesher = vtkbone.vtkboneImageToMesh()
mesher.SetInput (image)
mesher.Update()
mesh = mesher.GetOutput()
```

vtkboneImageToMesh creates one Cell (*i.e.* element) of type `VTK_VOXEL` for every voxel in the input image that has non-zero scalar value. The scalar values of the image become the scalar values of the output Cells. It also creates Points at the vertices (corners) of the Cells. There are no duplicate Points: neighbouring Cells will reference the same Point on shared vertices.

Important
Cells and Points in `VTK` are ordered; they can be indexed by consecutive Cell or Point number. This ordering is not inconsequential. In Faim, the solver efficiency is optimal with certain orderings, and in fact there are orderings for which the solver fails with an error message. The ordering output by vtkboneImageToMesh is “x fastest, z slowest”. It is recommended to always preserve this ordering.

Defining materials

Material definitions are generated by creating a instance of a class of the corresponding material type, and then calling the appropriate methods to set the material parameters. Every material must have a unique name. `vtkbone` will assign default unique names when defining a new material object, but the names will be more meaningful if you assign them yourself.

`vtkbone` version 8 supports the following material classes:

- vtkboneLinearIsotropicMaterial
- vktn88LinearOrthotropicMaterial
- vktn88LinearAnisotropicMaterial
- vtkboneVonMisesIsotropicMaterial
- vtkboneMohrCoulombIsotropicMaterial

Plus special material classes that are in fact *material arrays*, which are discussed below.

Here is an example of creating a simple linear isotropic material:

```
linear_material = vtkbone.vtkboneLinearIsotropicMaterial()
linear_material.SetYoungsModulus (800) ❶
linear_material.SetPoissonsRatio (0.33)
linear_material.SetName ("Linear 800")
```

❶ As discussed in A note about units, the units of Young’s modulus depend on the input length units. If the length units are mm and force units in N, then Young’s modulus has units of MPa.

This is the construction of a Mohr-Coulomb elastoplastic material:

```
ep_material = vtkbone.vtkboneMohrCoulombIsotropicMaterial()
ep_material.SetYoungsModulus (800)
ep_material.SetPoissonsRatio (0.33)
ep_material.SetYieldStrengths (20, 40) ❶
ep_material.SetName ("Mohr Coulomb material 1")
```

❶ For Mohr-Coulomb, this pair of numbers is the yield strength in tension and the yield strength in compression. The units of yield strength are the same as stress, so typically MPa.

In addition to the standard material classes, there are material array classes. Simpy put, these define not a single material, but a sequence of similar materials with variable parameters. For a discussion of the circumstances in which this could be useful, see Efficient Handling of Large Numbers of Material Definitions. The material array classes do inherit themselves from vtkboneMaterial (rather than being a collection of vtkboneMaterial objects). They can therefore be used nearly anywhere that a regular material can be; in particular, they can be inserted as entries into a material table. The material array classes are

- vtkboneLinearIsotropicMaterialArray
- vktn88LinearOrthotropicMaterialArray
- vktn88LinearAnisotropicMaterialArray
- vtkboneVonMisesIsotropicMaterialArray
- vtkboneMohrCoulombIsotropicMaterialArray

Constructing a material table

Once you have created your material definitions, you need to combine them into a material table, which maps material IDs to the material definitions.

For example, if we want a homogenous material, and the input image has only the scalar value 127 for bone (and 0 for background), then we can make a material table like this:

```
materialTable = vtkbone.vtkboneMaterialTable()
materialTable.AddMaterial (127, linear_material) ❶
```

❶ We created the material `linear_material` above.

We must assign a material for every segmentation value present in the input. The same material can be assigned to multiple material IDs. For example, suppose the input image has segmentation values 100-103, and we have created two different materials, `materialA` and `materialB`, then we could create a vtkboneMaterialTable like this:

```
materialTable = vtkbone.vtkboneMaterialTable()
materialTable.AddMaterial (100, materialA)
materialTable.AddMaterial (101, materialB)
materialTable.AddMaterial (102, materialB)
materialTable.AddMaterial (103, materialB)
```

There are a couple of helper classes that simplify the creation of material tables for common cases. For a model with a homogenous material, we can use vtkboneGenerateHomogeneousMaterialTable . This class assigns a specified vtkboneMaterial to all the scalar values present in the input mesh. The size of the resulting material table depends on the number of distinct input values. For example,

```
mtGenerator = vtkbone.vtkboneGenerateHomogeneousMaterialTable()
mtGenerator.SetMaterial (material1)
mtGenerator.SetMaterialIdList (mesh.GetCellData().GetScalars())
mtGenerator.Update()
materialTable = mtGenerator.GetOutput()
```

We could alternatively set SetMaterialIdList with the scalars from the image, rather than those of the mesh; the results will be the same.

Another useful helper class is vtkboneGenerateHommingaMaterialTable . Refer to the the section on the Homminga material model in the chapter on preparing models with n88modelgenerator.

Examples of defining materials and creating a material table are given in the tutorials Compressing a cube revisited using vtkbone, Deflection of a cantilevered beam: adding custom boundary conditions and loads and Advanced custom model tutorial: a screw pull-out test.

Creating a finite element model

At this stage, we combine the geometric mesh with the material table to create a vtkboneFiniteElementModel object. The most elementary way to do this is with a vtkboneFiniteElementModelGenerator , which can be used like this

```
modelGenerator = vtkbone.vtkboneFiniteElementModelGenerator()
modelGenerator.SetInput (0, mesh)
modelGenerator.SetInput (1, materialTable)
modelGenerator.Update()
model = modelGenerator.GetOutput()
```

After combining the mesh with the material table, all that is now required to make a complete finite element model is to add boundary conditions and/or applied loads, and to specify node and element sets for the post-processing. For standard tests, there are `vtkbone` filters to generate complete models, and these are described below in Section 3.18.

Creating node and element sets

Before we can create boundary conditions or applied loads, we need to define node and/or element sets that specify all the nodes (or elements) to which we want to apply the boundary condition (displacement or applied load). Node and element sets are also used during post-processing. This will be discussed later in Setting post processing parameters.

Any number of node and element sets may be defined. They must be named, and they are accessed by name. The node and element sets are simply lists of node or element numbers, and are stored as vtkIdTypeArray . There are many ways to create node and element sets. A very simple way is to simply enumerate the node numbers (or element numbers). For example, if we wanted to create a node set of the nodes 8,9,10,11 , this would be the code:

```
nodes = array ([8,9,10,11])
nodes_vtk = numpy_to_vtk (nodes, deep=1, array_type=vtk.VTK_ID_TYPE) ❶
nodes_vtk.SetName ("example_node_set")
model.AddNodeSet (nodes_vtk)
```

❶ In Python, the most flexible way to handle array data is with numpy arrays, however the data must be passed to VTK objects as vtkDataArray . `numpy_to_vtk` does the conversion.

`VTK` offers many ways to select Points and Cells, for example by geometric criteria. As an example of this, refer to the screw_-pullout_tutorial where a node set is selected from nodes located on a particular rough surface, and subject to additional criterion $r_1 < r < r_2$, where r is the radius from a screw axis.

`vtkbone` also offers some utility functions for identifying node and elements sets. These can be found in vtkboneSelectionU-tilities .

Frequently, we require sets corresponding to the faces of the model (*i.e.* the boundaries of the image). In this case, we may use the class vtkboneApplyTestBase . vtkboneApplyTestBase is a subclass of vtkboneFiniteElementModelGenerator , with the extra functionality of creating pre-defined sets. vtkboneApplyTestBase implements the concept of a Test Frame and a Data Frame. Refer to test orientation in the chapter on n88modelgenerator. vtkboneApplyTestBase creates the node and element sets given in the following table. Note that in each case there is both a node and element set, with the same name.

Table 3.1: Node and element sets generated by vtkboneApplyTestBase

Set name	**Consists of**
face_z0	nodes/elements on the bottom surface (z=z_{min}) in the Test Frame.
face_z1	nodes/elements on the top surface (z=z_{max}) in the Test Frame.
face_x0	nodes/elements on the x=x_{min} surface in Test Frame.
face_x1	nodes/elements on the x=x_{max} surface in Test Frame.
face_y0	nodes/elements on the y=y_{min} surface in Test Frame.
face_y1	nodes/elements on the y=y_{max} surface in Test Frame.

The sets “face_z0” and “face_z1” are of particular importance, as the standard tests are applied along the z axis in the Test Frame.

vtkboneApplyTestBase has options `UnevenTopSurface()` and `UnevenBottomSurface()` by which we can choose to have “face_z0” and/or “face_z1” as the set of nodes/elements on an uneven surface, instead of the boundary of the model. This is especially useful when the object in the image does not intersect the top/bottom boundaries of the image. See further discussion on uneven surfaces in the chapter on n88modelgenerator. The two sets “face_z0” and “face_z1” can also be limited to a specific material, as defined by material ID.

vtkboneApplyTestBase is used identically to vtkboneFiniteElementModelGenerator , except that additional optional settings may be set if desired. For example, here we define a model with a test axis in the y direction, and specify that we want the set “face_-z1” to be the uneven surface in the image, where we are limiting the search for the uneven surface to a maximum distance of 0.5 from the image boundary.

```
modelGenerator = vtkbone.vtkboneApplyTestBase()
modelGenerator.SetInput (0, mesh)
modelGenerator.SetInput (1, materialTable)
modelGenerator.SetTestAxis (vtkbone.vtkboneApplyTestBase.TEST_AXIS_Y)
modelGenerator.UnevenTopSurfaceOn()
modelGenerator.UseTopSurfaceMaximumDepthOn()
modelGenerator.SetTopSurfaceMaximumDepth (0.5)
modelGenerator.Update()
model = modelGenerator.GetOutput()
```

An example of using the standard node and element sets from vtkboneApplyTestBase is given in Deflection of a cantilevered beam: adding custom boundary conditions and loads. The tutorial Advanced custom model tutorial: a screw pull-out test demonstrates a sophisticated selection of custom node sets.

Adding boundary conditions

Once we have created the node sets, creating a boundary condition applied to the nodes of a particular node set is straightforward and can be done with the method `ApplyBoundaryCondition()` of vtkboneFiniteElementModel . For example, to fix the bottom nodes and apply a displacement of 0.1 to the top nodes, we could do this

```
model.ApplyBoundaryCondition (
        "face_z0",
        vtkbone.vtkboneConstraint.SENSE_Z, ❶
        0,
        "bottom_fixed") ❷
model.ApplyBoundaryCondition (
        "face_z1",
        vtkbone.vtkboneConstraint.SENSE_Z,
        -0.1, ❸
        "bottom_fixed")
```

❶ `vtkbone.vtkboneConstraint.SENSE_Z` has the value 2 (see vtkboneConstraint). It is possible just to use that value 2 here, but `SENSE_Z` is more informative.

❷ This is the user-defined name assigned to the boundary condition. Every constraint must have a unique name.

❸ Negative if we want compression.

The “sense” is the axis direction along which the displacement is applied. The other axis directions remain free unless you also specify a value for them. It is quite possible, and common, to call `ApplyBoundaryCondition()` three times on the same node set, once for each sense.

ApplyBoundaryCondition() can take different types of arguments, for example arrays of senses, displacements and node numbers. Refer to the API documentation for vtkboneFiniteElementModel . There is also a convenience method FixNodes(), which is a quick way to set all senses to a zero displacement.

Boundary conditions are implemented within vtkboneFiniteElementModel as a specific type of vtkboneConstraint . All the constraints associated with a vtkboneFiniteElementModel are contained in a vtkboneConstraintCollection . It is possible to modify either vtkboneConstraintCollection or a particular vtkboneConstraint manually. For example, we could create a boundary condition on two nodes in the following manner. This is somewhat laborious and usually unnecessary, but it can be adapted to create unusual boundary conditions.

```
node_ids = array([3,5])
node_ids_vtk = numpy_to_vtk (node_ids, deep=1, array_type=vtk.VTK_ID_TYPE)
senses = array ([0,2])     # x-axis, z-axis
senses_vtk = numpy_to_vtk (senses, deep=1, array_type=vtk.VTK_ID_TYPE)
senses_vtk.SetName ("SENSE")
values = array([0.1,0.1])
values_vtk = numpy_to_vtk (values, deep=1, array_type=vtk.VTK_ID_TYPE)
values_vtk.SetName ("VALUE")
constraint = vtkbone.vtkboneConstraint()
constraint.SetName ("a_custom_boundary_condition")
constraint.SetIndices (node_ids)
constraint.SetConstraintType (vtkbone.vtkboneConstraint::DISPLACEMENT)
constraint.SetConstraintAppliedTo (vtkbone.vtkboneConstraint::NODES)
constraint.GetAttributes().AddArray (senses)
constraint.GetAttributes().AddArray (values)
model.GetConstraints().AddItem (constraint)
```

Examples of applying boundary conditions are given in the tutorials Deflection of a cantilevered beam: adding custom boundary conditions and loads and Advanced custom model tutorial: a screw pull-out test.

Adding applied loads

Creating an applied load is similar to creating a displacement boundary condition. They are both implemented as vtkboneConstraint . However, while displacement boundary conditions are applied to nodes, applied loads are applied to elements; in fact they are applied to a particular face of an element (or to the body of an element). Therefore, the ApplyLoad() method of vtkboneFiniteElementModel takes the name of an element set, and has an additional input argument which specifies to which faces of the elements the load is applied. Here is an example of creating an applied load on the top surface of the model:

```
model.ApplyLoad (
        "face_z1", ❶
        vtkbone.vtkboneConstraint.FACE_Z1_DISTRIBUTION,
        vtkbone.vtkboneConstraint.SENSE_Z, ❷
        6900, ❸
        "bottom_fixed")
```

❶ Refers to the element set “face_z1”, not the corresponding node set, which very often also exists with the same name.

❷ In this example, the applied force is perpendicular to the specified element face, but it is not required to be so.

❸ This is the total load applied. The load is evenly distributed between all of the element faces.

To apply forces along non-axis directions, call ApplyLoad() multiple times with different senses.

As with displacement boundary conditions, we can create an applied force manually, if we require more flexibility. It will look something like this:

```
element_ids = array([3,5])
element_ids_vtk = numpy_to_vtk (element_ids, deep=1, array_type=vtk.VTK_ID_TYPE)
distributions = ones ((2,)) * vtkbone.vtkboneConstraint.FACE_Z1_DISTRIBUTION
```

```
distributions_vtk = numpy_to_vtk (distributions, deep=1, array_type=vtk.VTK_ID_TYPE)
distributions_vtk.SetName ("DISTRIBUTION")
senses = array ([0,2])     # x-axis, z-axis
senses_vtk = numpy_to_vtk (senses, deep=1, array_type=vtk.VTK_ID_TYPE)
senses_vtk.SetName ("SENSE")
total_load = 6900
values = total_load * ones(2, float) / 2
values_vtk = numpy_to_vtk (values, deep=1, array_type=vtk.VTK_ID_TYPE)
values_vtk.SetName ("VALUE")
constraint = vtkbone.vtkboneConstraint()
constraint.SetName ("a_custom_applid_load")
constraint.SetIndices (element_ids)
constraint.SetConstraintType (vtkbone.vtkboneConstraint::FORCE)
constraint.SetConstraintAppliedTo (vtkbone.vtkboneConstraint::ELEMENTS)
constraint.GetAttributes().AddArray (distributions)
constraint.GetAttributes().AddArray (senses)
constraint.GetAttributes().AddArray (values)
model.GetConstraints().AddItem (constraint)
```

Tip
You can apply loads to nodes instead of to elements if you desire. You must create a constraint by hand to do this, as there is no convenience method provided for this purpose. This is most sensible when you desire to apply a point force (*i.e.* to a single node). Be careful about applying forces to nodes because applying a constant force to each of a set of nodes on a surface is *not* equivalent to applying a uniform pressure to that surface. By contrast, applying a constant force to a set of element faces is equivalent to a uniform pressure, which is why it is usually more convenient to define loads on element faces.

Important
Applied loads are additive. That is, if you create more than one applied load on a particular element face, the loads will add. Displacement boundary conditions by contrast are unique. If you create more than one displacement boundary condition applying to a particular node and sense, then only one of them will be used by the solver, and the other will be discarded. Which of multiple boundary conditions applying to the same degree of freedom is used is indeterminate, so it is a logical error to create multiple different boundary conditions applying to the same degree of freedom. No warning or error message will be generated in the case of multiple boundary conditions on the same degree of freedom. (It is sometimes convenient to be able to do so in cases where the actual value used turns out not to matter).

An example of adding an applied load is given in the tutorial Deflection of a cantilevered beam: adding custom boundary conditions and loads.

Optional: Adding a convergence set

Adding a *convergence set* is optional, but it allows the solver to use the *convergence set* convergence measure, which is generally the best one for linear models. Best in this context means that the solver can reliably identify when a certain precision has been obtained, and thus stop iterating. Less tailored convergence measures, which don't require the definition of a *convergence set*, must be more conservative, and thus run to more iterations to be certain of obtaining a given precision. See Convergence measure.

Convergence sets are most conveniently defined with the method `ConvergenceSetFromConstraint` of vtkboneFinteElementModel. You simply pass it the most relevant boundary condition or applied force. "Most relevant" simply means the one you are most interested in.

For example, the standard compression tests generate their convergence sets with

```
model.ConvergenceSetFromConstraint("top_displacement")
```

Here *top_displacement* is the name of the boundary condition on the top surface. This results in a convergence set which is equivalent to the total force on the top surface.

In Section 7.6, an applied force is defined on the tip of a cantilever, and the convergence set is generated with

```
model.ConvergenceSetFromConstraint("end_force")
```

This results in a convergence set which is the average displacement of the tip of the cantilever.

However defined, if *convergence set* is used as the convergence measure, then the solver watches that quantity to determine when it has ceased to change meaningfully, and thus, when iterating can be stopped.

Warning
You cannot define a convergence set that consists entirely of fixed nodes. That is, entirely of boundary condition nodes that are set to zero displacement. This is because the solver internally elimates these degrees of freedom, and is hence unable to calculate the corresponding forces during iterations.

Ensuring your model is well-defined

It is possible to create a model that is degenerate, or not well-defined. In other words, a model that has not a single solution, but many solutions (typically an infinite number). As a linear algebra problem, such a problem has a singular global stiffness matrix. For example, consider the standard uniaxial problem where a sample volume is compressed between two hard parallel plates. (See uniaxial test in the chapter on n88modelgenerator). If we specify no contact friction, then although the sample compresses in a predictable way between the two plates, it is free to slide around as a whole (translate) anywhere between the plates. For the particular case of the uniaxial model, n88modelgenerator provides the option to add a pin, which consists of the following additional constraints:

1. fix the *x*,*y* senses of an arbitrary node, and
2. fix one sense of another node (usually from the same element).

The first constraint is sufficient to prevent translation, and the second constraint is required to prevent rotation.

Models with only applied loads and no displacement boundary conditions are always ill-defined.

Practically, `n88solver` will usually solve even ill-defined problems. In fact, for the type of ill-defined problem described here, it often does so faster than the equivalent well-defined problem (*i.e.* one with added "pin" constraints to make it non-singular). Many types of ill-defined problems can cause `n88solver` to converge much more slowly. For example, see the discussion on Ensuring connectivity. Not all solvers however can handle ill-defined problems, so this should be avoided when exporting models to other solvers. Also, if you would like overlay the renderings of two similar ill-defined problems or compare differences in any way, it is usually necessary to first register them to eliminate meaningless differences (such as overall translations or rotations in the example described).

Setting post-processing parameters

If you have followed every step, then you have a model that is completely defined for the solver. In fact you could save it to a file and solve it now. The post-processor n88postfaim however requires a bit more information so that meaningful results can be extracted from the solved model. n88postfaim calculates certain quantities with reference to node or element sets. For example, in a compression test the relevant sets correspond to the top and bottom faces, as we are interested principally in the forces on these faces. These sets already exist ("face_z0" and "face_z1"), as we previously used them to apply boundary conditions. We need to list the relevant node sets to be used by n88postfaim. Of course, if you're doing some custom post-processing that does not involve n88postfaim, then this step is optional and can be skipped. Setting the post-processing node sets involves setting some "information" with a key (this may seem slightly obscure, but it is a standard VTK technique):

```
info = model.GetInformation()
pp_node_sets_key = vtkbone.vtkboneSolverParameters.POST_PROCESSING_NODE_SETS()
pp_node_sets_key.Append (info, "face_z0")
pp_node_sets_key.Append (info, "face_z1")
```

Any number of sets may be specified for post-processing. n88postfaim requires the element sets as well as the node sets, and they must match exactly, meaning that the *n*th post-processing element set must be exactly those elements which contain any of the nodes of the *n*th post-processing node set. (The element set name is not required to be the same as the node set name).

If you've used vtkboneApplyTestBase to get pre-defined node and element sets, then you already have the corresponding element sets, and in fact they have the same names, so

```
info = model.GetInformation()
pp_node_sets_key = vtkbone.vtkboneSolverParameters.POST_PROCESSING_NODE_SETS()
pp_node_sets_key.Append (info, "face_z0")
pp_node_sets_key.Append (info, "face_z1")
pp_elem_sets_key = vtkbone.vtkboneSolverParameters.POST_PROCESSING_ELEMENT_SETS()
pp_element_sets_key.Append (info, "face_z0")
pp_element_sets_key.Append (info, "face_z1")
```

If you've created custom node sets, then you can obtain the corresponding element sets with the method `GetAssociatedElementsFromNodeSet()`, so for example (taken from the screw pull-out tutorial),

```
info = model.GetInformation()
pp_node_sets_key = vtkbone.vtkboneSolverParameters.POST_PROCESSING_NODE_SETS()
pp_elem_sets_key = vtkbone.vtkboneSolverParameters.POST_PROCESSING_ELEMENT_SETS()
for setname in ["bone_top_visible", "screw_top"]:
    pp_node_sets_key.Append (info, setname)
    elementSet = model.GetAssociatedElementsFromNodeSet (setname)
    model.AddElementSet (elementSet)
    pp_elem_sets_key.Append (info, setname)
```

Examples of setting post-processing parameters are given in the tutorials Deflection of a cantilevered beam: adding custom boundary conditions and loads and Advanced custom model tutorial: a screw pull-out test.

Filters for creating standard tests

For each of the standard tests, namely the ones that n88modelgenerator can generate, there is a filter to generate the test, complete with all displacement boundary conditions, applied forces, and relevant post-processing sets. Of course, it is easier to just simply use n88modelgenerator for these cases rather than write a script. However, these filters provide more options than are exposed by n88modelgenerator, and a script will allow you to access these options. Furthermore, sometimes a standard model is nearly, but not quite, what you want. In this case, the fastest way to proceed is to use a standard test generating filter, and then tweak the resulting model.

All the standard test filters are subclasses of vtkboneApplyTestBase (see Creating node and element sets), so that they support variable orientation as defined by the Data Frame and the Test Frame, as well as having the standard sets defined ("face_z0", etc. . .)

The following table lists the standard model filters.

Table 3.2: vtkbone filter classes that generate standard models

vtkbone filter	**n88modelgenerator test types**
vtkboneApplyCompressionTest	uniaxial, axial and confined
vtkboneApplySymmetricShearTest	symshear
vtkboneApplyDirectionalShearTest	dshear
vtkboneApplyBendingTest	bending
vtkboneApplyTorsionTest	torsion

For details on the options supported by these filters, refer to the API documentation.

An example of using a standard test filter is given in the tutorial Compressing a cube revisited using vtkbone.

Modifying a finite element model

Often a standard model type will be very close to the desired test configuration, but some modifications are needed. Every part of vtkboneFiniteElementModel can be modified, or even deleted, after creation. There are in general too many possibilities to enumerate here.

If a model is already written as an `n88model` file, it can be read with vtkboneN88ModelReader , modified, and rewritten.

Updating the history and the log

It is good practice (but not strictly necessary) to add relevant details to the History and Log fields of a model before writing it out. This will assist greatly in the future if it is required to trace back the origins and history of a given `n88model` file.

The history and comments of an `n88model` file can be viewed with the command

```
n88modelinfo --history --comments myfile.n88model
```

You can leave out the `--history` and `--comments` arguments, although then you will get a lot more information about the model, possibly more than you want.

The History field should have one line per executable that modifies the model file. This line should start with a time/date stamp and briefly state the program (and perhaps the user) which modified or created the file. History can be added with the method `AppendHistory()`; the date/time stamp will be automatically added. For example

```
model.AppendHistory("Created with screwpullout.py version 6.0")
```

The Log field is intended to record any other information that would be useful to be able to recover at a later time. Every addition can be any number of lines long. You should record any parameters or settings that are relevant here. As for `AppendHistory()`, `AppendLog()` will add a date/time stamp (although on its own line). It will also ensure that every addition to the Log is separated by black line from other additions to Log, for ease in reading it. For example

```
settingsText = ["Configuration:",
    "input file                        = %s" % input_image_file,
    "output file                       = %s" % output_faim_file,
    "bone material id                  = %s" % bone_material_id,
    "bone material Young's modulus     = %s" % bone_material_modulus,
    "bone material Poisson's ratio     = %s" % bone_material_poissons_ratio,
    "screw material id                 = %s" % screw_material_id,
    "screw material Young's modulus    = %s" % screw_material_modulus,
    "screw material Poisson's ratio    = %s" % screw_material_poissons_ratio,
    "screw displacement                = %s" % screw_displacement,
    "inner ring radius                 = %s" % inner_ring_radius,
    "bone constraint max depth         = %s" % bone_constraint_max_depth]

model.AppendLog ("\n".join(settingsText)) ❶
```

❶ This might look pretty weird if you're not a Python guru. `settingsText` is a Python list of strings (each of one line). `"\n".join(settingsText)` joins them all into one long string, separated by line returns.

Tip
A particularly clever trick if your script uses a configuration file to set values, one which is used by n88modelgenerator, and also used in the above example (which is from the screw pull-out tutorial), is to write the settings into the Comment field in exactly the same format that they appear in the configuration file. Then, if ever the data need to be exactly re-created for some reason, the settings can be copied from the Log and pasted directly into a new configuration file. The script can then be rerun with that configuration file without any further editing.

Examples of adding information to the history and to the log are given in the tutorials Compressing a cube revisited using vtkbone, Deflection of a cantilevered beam: adding custom boundary conditions and loads and Advanced custom model tutorial: a screw pull-out test.

Writing a model file for input to the solver

When your vtkboneFiniteElementModel is the way you like it, writing a file is straightforward:

```
writer = vtkbone.vtkboneN88ModelWriter()
writer.SetInput (model)
writer.SetFileName ("a_snazzy_model.n88model")
writer.Update()
```

Other formats can also be written using the appropriate writer including,

- vtkboneFaimVersion5InputWriter , and
- vtkboneAbaqusInputWriter .

Visualizing intermediate results

When developing a complicated model, it is often a good idea to write out intermediate results that can be visualized. This can be done either by writing out intermediate geometries and node sets using standard VTK file format writers, such as vtkXMLUnstructuredGridWriter and vtkXMLPolyDataWriter , or by writing the model with vtkboneN88ModelWriter as early as possible as you build up your script, before the model is complete. Even incomplete models can be visualized. The tool n88extractsets is handy to extract and visualize node and element sets, as well as boundary conditions and applied loads.

For an example of visualizing intermediate results as the model is built up, see Advanced custom model tutorial: a screw pull-out test.

Error handling

VTK classes do not throw exceptions or halt execution when an error occurs. If catching error conditions is important to you, you need to provide a VTK observer class. For more information, refer to http://www.vtk.org/Wiki/VTK/Tutorials/Callbacks . However, if you don't provide an error observer (and most often, you won't want to be bothered to), you will still be informed about error conditions by a message printed to standard out (i.e. to the console). For scripting purposes, this is generally adequate.

If you do want to trap the error, here is an example in Python.

```
class ErrorObserver:
   def __init__(self):
       self.__ErrorOccurred = False
       self.__ErrorMessage = None
       self.CallDataType = 'string0'
   def __call__(self, obj, event, message):
       self.__ErrorOccurred = True
```

```
        self.__ErrorMessage = message
    def ErrorOccurred(self):
        occ = self.__ErrorOccurred
        self.__ErrorOccurred = False
        return occ
    def ErrorMessage(self):
        return self.__ErrorMessage

errorObserver = ErrorObserver()

reader = vtkbone.vtkboneN88ModelReader()
reader.AddObserver ("ErrorEvent", errorObserver)
reader.SetFileName (filename)
reader.Update()

if errorObserver.ErrorOccurred():
    print "ERROR reading file: ", errorObserver.ErrorMessage()
    sys.exit (-1)
```

vtkbone provides a very simple error observer class, vtkboneErrorWarningObserver . Its use however is limited to C++ code; use the above example for Python.

Chapter 4

Solving Linear Problems

Obtaining solutions to linear problems using n88solver_slt

For a model with only linear elastic materials, the solver can be run as follows

```
n88solver_slt myfile.n88model
```

In special cases, you may want to use `n88solver_sla` instead of `n88solver_slt`: See Efficient Handling of Large Numbers of Material Definitions. Everything in this section applies equally well to that solver.

The solution as expressed as displacements - from the original position - at node. The displacements are written into the input file; no additional output file is created. If the `n88model` file contains an existing solution, it will be overwritten. Furthermore, if there is an existing solution, it will be used as a starting point for the solver for further iterations. This behaviour is not always desired and can be suppressed; see restart for details.

Tip
To check whether an `n88model` file has already been solved, the following command is useful

```
n88modelinfo --history --solutions myfile.n88model
```

See Section 9.12 for more details.

The complete list of arguments to n88solver is given in the Command Reference chapter.

Convergence

n88solver_slt is a pre-conditioned conjugate gradient solver which improves the solution through an iterative process. Therefore it is necessary to define a convergence criterion that defines when the solution is good enough, and the iterating can stop.

Convergence measure

n88solver_slt provides the options to select from among different *convergence measures*. See convergence_measure.

The traditional convergence measure is the maximum change over all degrees of freedom. We call this method *maximum du*. Mathmatically,for the i^{th} iteration it is defined as

$$e_i = \frac{max_j |x_{i,j} - x_{i-1,j}|}{max_j |x_{i-1,j}|}$$

where $x_{i,j}$ is the displacement of the j^{th} degree of freedom at the i^{th} iteration. The maximum is taken over all degrees of freedom.

The difficulty with this convergence measure is that it is not clear what numerical value of tolerance is optimal, as it is not obvious how it relates to quantities that a user would be directly interesting in. Although the convergence measure is unitless, there is in fact no consistent relationship between e_i and the relative precision of quantities such as displacement and force. Therefore the tolerance must be chosen conservatively based on experience.

In version 8, we therefore introduce a new convergence measure, which we call a *convergence set*. Essentially, this is a parameter, c, equivalent directly to a quantity of interest to the user. This parameter depends on the model. For example for a compression test with fixed strain or displacement, it would be equivalent to the reaction force on the top surface (more precisely the top boundary condition). On the other hand, if you define a compression test with a given force, in that case an appropriate parameter c would be the average displacement of the top surface. The solver continues iterations until the relative change in c from iteration to iteration falls below a specified threshold:

$$e_i = \frac{|c_i - c_{i-1}|}{|c_{i-1}|}$$

The choice of tolerance is now straight-forward: if you want to obtain a certain relative precision in your calculated reaction force for example, let us say one part in 10^4, then you allow a bit of a safety margin and chose for example a tolerance of 10^{-5}.

Clearly the difficulty is now in defining the quantity c. Fortunately, the standard faim model generator tools, including `n88modelgenerator` and `vtkbone` will define a suitable one for you. For the standard tests, it is the complement of the most important moving boundary condition, or most important applied force, as appropriate. By the *complement*, we mean that c is calculated as a force in the case of a boundary condition; conversely it is calculated as an average displacement in the case of an applied force. The definition of c therefore consists of defining a *convergence set*, which is some collection of degrees of freedom, together with some specification of what is to be calculated over this collection of degrees of freedom. It is exactly analogus to a constraint, which is interally how boundary conditions and applied forces are stored in `n88model` files; a *convergence set* is stored in a similar manner in an `n88model` file. See n88model File Format. Clearly, in the case that no convergence set is defined in the `n88model` file, the `convergence set` method for determining convergence cannot be used. In this case, the solver will fall back to the traditional *maximum du* method.

Regardless of the convergence measure chosen, the convergence measure does not decay smoothly, but can be jumpy or noisy. Therefore, a convergence window is introduced, so that iterations are not terminated prematurely by a randomly low convergence measure value. To be considered converged, the convergence measure e_i must remain below the threshold for at least the specified number of consecutive iterations. For the *maximum du* method, we have found by experience that a convergence window of 3 is typically sufficient. For the *convergence set* method, because it looks at only a part of the whole model, we have found that the convergence window must be increased as the number of degrees of freedom increases. Based on empirical analysis of many models, we suggest the following formula for the convergence window

$$w = 0.16\sqrt{n}$$

where n is the number of nodes in the model. This formula is in fact what the solver will use if you don't explicitly chose another value with the parameter convergence_window.

Maximum iterations

In addition to the convergence criterion described above, a *maximum number of iterations* can be set. This is useful for stopping the iterating if the thresholds have been set too low (*i.e.* too strictly). Sometimes we may want to stop and perform a more sophisticated analysis of the quality of the solution before deciding if we want to proceed with further iterations.

Note that no matter how the solver terminated, we can re-launch it, possibly with different convergence criteria. By default, the solver will use an existing solution as the starting point and continue to refine it from where it left off. Note however, that not all the numerical parameters of the conjugate gradient method are stored in the `n88model` file. Therefore, stopping and re-starting the solver does not result in precisely than same progression of iterations as compared with simply letting the solver run uninterupted. Some additional iterations are required to reconstruct the conjugate gradient information.

If you want to make a close investigation of the convergence of your model as the solver iterates, you can make use of the iterations_file option to output all iteration data to a file. It can be informative to plot these data on a log-log graph (convergence measure e_i versus iteration number i).

Evaluating solution quality

For a linear problem, the solver is solving a system equivalent to

$$\mathbf{Kx} = \mathbf{f}$$

where **x** are the displacements, **f** are the forces (including all the internal forces on each node), and **K** is a global stiffness matrix. The solver never actually constructs **K**; the memory requirements would be prohibitive, as **K** is a matrix of size N^2, where N is the number of degrees of freedom. The residuals are defined as

$$\mathbf{r} = \mathbf{K}\mathbf{x} - \mathbf{f}$$

For the exact solution, the residual vector is identically zero. As we are obtaining a numerical solution rather than an exact solution, we cannot in practice obtain exactly zero-valued residuals. The remaining value of the residuals is a good measure of the accuracy of the solution, with smaller residuals indicating a closer match to the unobtainable perfect solution.

To answer the question, “What is a good value for the residuals?”, observe that the residuals have units of force. We therefore need to compare with a characteristic force in the system.

Numerics88 provides a tool, <n88evaluate,n88evaluate>, to evaluate a solution. It is run like this

```
n88evaluate myfile.n88model
```

The output related to the residuals looks like this

```
Analysis of forces (residuals):
    max err           : 3.00E-07
    rms err           : 3.15E-08
    max err/max force : 3.51E-06
    rms err/max force : 3.68E-07
```

The second two numbers are the maximum and RMS residuals, scaled to the maximum nodal force in the solution. These values are a measure of the relative error. Note that this error is only the mathematical error of the solution to the stated system of equations. There are naturally other sources of error, such as that due to the measurement and discretisation of the physical object, and the error in determining the material properties of the object. When the solver is working normally, these other sources of error will be much larger than the remaining mathematical error in the solution obtained by the solver.

`n88evaluate` also performs a check that the boundary conditions are indeed satisfied:

```
Analysis of solution displacements at boundary conditions:
    max err           : 0.00E+00
    rms err           : 0.00E+00
```

This is a trivial check: anything other zero or very small values indicates a problem with solver.

Chapter 5

Solving Nonlinear Problems

Obtaining solutions to nonlinear problems with n88solver_spt

If you have defined plasticity for any materials used in your model, then you must use the solver n88solver_spt, which is a solver suitable for small-strain elastoplastic models. This solver is invoked exactly as is `n88solver_slt`. It recognizes a couple of additional options related to the plastic convergence. To solve an elastoplastic model, the solver first obtains a linear elastic solution, and then performs a plastic iteration to update the plastic strain. This is repeated until the plastic convergence criterion is met. Thus linear solutions, consisting of many linear iterations, alternate with single plastic iteration steps.

Note
It is perfectly possible to run `n88solver_spt` on a model with only linear elastic material definitions. `n88solver_spt` takes no longer to run on a linear model than does `n88solver_slt`. However it does use more memory. Conversely, it is also possible to run `n88solver_slt` on a model containing elastoplastic material definitions. In this case, the plasticity is simply ignored, and the linear solution will be obtained.

Convergence

For elastoplastic problems, the default convergence measure remains the traditional `dumax` method, instead of the new `convergence set` method. See Convergence measure. The reason for this is that, not infrequently the addition of plasticity has only a small effect on quantities like reaction force. In these cases, observing a quantity such as the total reaction force to determine convergence does not work well for the plastic iterations. Furthermore, when solving an elastoplastic problem, we are more likely to be interested in quantities pertaining to the entire volume, such as the number and location of yielded elements, rather than only quantities that are calculated over just a boundary condition, such as reaction force. Recall that the `dumax` convergence measure is calculated over all degrees of freedom, while the `convergence set` convergence measure is typically calculated over a chosen boundary condition.

Tip

As was the case for linear files, you can generate a file with all the iteration data using the option iterations_file. For elastoplastic solutions, this file can be quite large. Here is a command to extract just the last linear iteration of every plastic iteration step, which often contains all the information we are looking for (*i.e.* the full plastic evolution, as well as the linear tolerance for each plastic iteration, and the number of linear iterations required at each plastic step).

```
awk '$2!=previous {print line; previous=$2}
     $2==previous {line = $0; previous=$2}' iterations.txt
```

This command can be run in Linux and macOS, as well as in a Bash shell in Windows 10. In case you don't have `awk`, here is a Python script that does the same thing

```
lines = open("iterations.txt").readlines()
output = [p for (l,p) in zip(lines,[lines[0]] + lines[:-1]) if l.split()[1] != p.split() ↩
    [1]]
for o in output: print o,
```

Obtaining accurate nonlinear solutions by progressively applying loads

In contrast to a linear elastic model, there is in general no single unique solution for a given end-state of a system with elastoplastic characteristics. As discussed in the section plasticity in the chapter *Preparing Finite Element Models with n88modelgenerator*, elastoplastic models exhibit irreversibility and hysteresis, and thus have a path dependence. In other words, a dependence not only on the final state, but on the history in obtaining the final state. For a real object, the history is the time-dependence of the state, presumably starting from some initial neutral state. Within the solver, it is not necessary (or possible) to account for a continuous time dependence of the state: nevertheless even if we solve for a single end state of an elastoplastic model, the solver necessarily traces a path in a mathematical space from some starting point to the final solution. Just as for the real physical situation, this path in mathematical space can affect the final solution. Therefore, the most strictly correct approach to solving nonlinear elastoplastic problems is to incrementally apply loads (or strains), starting with a solution at or near the elastic limit (*i.e.* near the onset of nonlinear behaviour), and obtaining a complete solution at each load increment, until the final state is obtained. This is obviously more complicated than a single all-at-once solution, and also more time-consuming. The question is, does this make any practical difference? Frequently, for loads applied monotonically in a single direction, the answer is no. Conversly, if your physical situation involves increasing and decreasing a load, or changing the direction of an applied load, then it is important to model this load history. A tutorial demonstrating the incremental application of a load to an elastoplastic problem is A cantilevered beam with elastoplastic material properties .

Evaluating nonlinear solution quality

Evaluating the correctness of an elastoplastic solution is more subtle than evaluating the correctness of a linear elastic model, for the simple reason that, as mentioned in the previous section, there is no single unique solution to an elastoplastic problem.

There are nevertheless some measures we can use. Internal forces must still balance, and we can examine the residuals, as in Evaluating solution quality in the section on linear models.

When examining the yield strain, there must be no unyielded elements for which a positive yield function is calculated. Here is the check of that in n88evaluate:

```
Analysis of yield function F:
    Unyielded elements with F>0:
        count              : 0
        max F              : -
        rms F              : -
        max F/max stress   : -
        rms F/max stress   : -
```

Actually in rare cases, a small number of unyielded elements might have very small positive values of yield function, but in this case, the values should be very small indeed.

Secondly, one might expect all the yielded elements in the solution (*i.e.* those elements with a nonzero plastic strain) to lie on the yield surface (F=0). In fact, this is not necessarily the case. Even in an elastoplastic model carefully solved with incremental applied test strain, it may happen that some elements reach the yield stress (*i.e.* the yield surface) for some value of applied test strain, but then actually experience a substantially reduced stress at a higher applied test strain, due to the mechanical failure or yield of some other part of the model. Thus it is perfectly possible to have an end-state solution in which some elements are observed to have non-zero plastic strains but are in a stress state much less than the yield stress (*i.e.* well inside the yield surface). More common though is for yield elements to have a very small remnant positive yield function, which is somewhat analogous to the residual in the linear case.

Values related to the yield function calculated for all yielded elements are reported by n88evaluate, as shown in this example:

```
Analysis of yield function F:
    Yielded elements:
        count                : 2058
        min F                : -1.85E+01
        max F                : 1.08E-04
        rms F                : 7.77E+00
        min F/max stress     : -2.12E-01
        max F/max stress     : 1.23E-06
        rms F/max stress     : 8.88E-02
```

In light of the above discussion, the important value is `max F/max stress`: it can be used as a measure of the relative error of the plastic component of the solution.

Chapter 6

Post-Processing and Analysis

Calculating additional solution fields with n88derivedfields

The fundamental solution from n88solver are the displacements on each node. However, this is often not the only value of interest. Subsequently running n88derivedfields on the `n88model` file will generate additional fields and add them to the active solution in the file.

Tip
To check which solution fields are present in a `n88model` file, run

```
n88modelinfo --solutions your_model.n88model
```

The following are the additional fields that will be added to the `n88model` file by n88derivedfields.

ReactionForce

The reaction force at each node, in the 3 coordinate directions (f_x,f_y,f_z). For a linear problem the reaction force is given by

$$\mathbf{f} = \mathbf{K}\mathbf{x}$$

This is of course the same equation that the solver has solved, except that now we use it with the solution values for $\mathbf{x}$ (the displacements) to determine forces. If the solution is accurate, then the forces will be nearly all zero, except on degrees of freedom where a boundary condition (displacement or applied force) applies. Those therefore are the interesting values.

Strain

The strain at each element, given by $\varepsilon_{\mathrm{xx}}$, $\varepsilon_{\mathrm{yy}}$, $\varepsilon_{\mathrm{zz}}$, γ_{yz}, γ_{zx}, γ_{xy}, where $\varepsilon_{\mathrm{ii}}$ is the *engineering normal strain* along the axis direction *i*, and the γ_{ij} are the *engineering shear strains*.

Note that the field `Strain` is always the total strain, so that for elasto-plastic models, the elastic strain can be obtained by subtracting `PlasticStrain` from `Strain`.

PlasticStrain

The plastic strain at each element. The plastic strain is the irreversible strain that arises from further deformation once the elastic limits as defined by the yield surface as been reached. `PlasticStrain` has the same 6 components as `Strain`.

Stress

The stress at each element, given by σ_{xx}, σ_{yy}, σ_{zz}, σ_{yz}, σ_{zx}, σ_{xy} .

Note that the stress can be obtained directly from the strain (and vice versa) using the material properties. See Elastic material properties.

VonMisesStress

The von Mises stress is a scalar value that is frequently used as a yield criterion. It is also used as a heuristic measure of the “magnitude” of the stress at a point, for example for the purpose of coloring a rendering according to stress concentration. It is defined on each element by

$$\sigma_v^2 = \frac{1}{2}\left((\sigma_{xx}-\sigma_{yy})^2 + (\sigma_{yy}-\sigma_{zz})^2 + (\sigma_{zz}-\sigma_{xx})^2\right) + 3\left(\sigma_{yz}^2 + \sigma_{zx}^2 + \sigma_{xy}^2\right)$$

It can also be expressed more concisely as a norm of the devatoric stresses. For details refer to any Mechanics of Solids textbook.

StrainEnergyDensity

The strain energy density is given by

$$U = \frac{1}{2}\left(\sigma_{xx}\varepsilon_{xx} + \sigma_{yy}\varepsilon_{yy} + \sigma_{zz}\varepsilon_{zz} + \sigma_{yz}\gamma_{yz} + \sigma_{zx}\gamma_{zx} + \sigma_{xy}\gamma_{xy}\right)$$

This expression continues to be valid even for nonlinear elastoplastic models, provided that the strain values are limited to the elastic strain component.

In a finite element context, the strain energy density is a scalar value defined on each element.

Exporting solution fields from the model file

If n88postfaim, which is described in the next section, provides the values which are of interest to you, you will not need the numerical data of the solution fields. In other cases, where you want do some custom post-processing on the solution, it will be necessary to obtain the solution fields as array data. There are several options for obtaining the field data from an `n88model` file:

1. Use n88extractfields to export fields to a text file. This is convenient because text files are easy to understand and easy to import. The trade off is that text files are inefficient in terms of disk space required, and relatively slow to write and read.
2. Use the `vtkbone` object vtkboneN88ModelReader . This requires writing some code in C++ or Python.
3. Import the data into third party software that can read NetCDF4 or HDF5.

Obtaining standard post-processing values with n88postfaim

`n88postfaim` is a tool performs a number of standard analyses on a solved `n88model` file. It produces a text file output reporting summarized results in a table format.

Running n88postfaim

`n88postfaim` requires that n88derivedfields has been run on the solved `n88model` file because it makes use of the derived fields. If any field is required for a particular table, but is not present in the `n88model` file, `n88postfaim` will simply silently skip that table.

In the usual case, running `n88postfaim` is as simple as,

```
n88postfaim -o analysis.txt radius_slice82_bending.n88model
```

This will generate an output file `analysis.txt`. The output is a report of values that are commonly of interest in finite element calculations.

The sections below will discuss a few important options that affect the output of `n88postfaim`. For a complete list of arguments supported by `n88postfaim`, see the Command Reference chapter.

Note

The model `radius_slice82_bending.n88model`, which is used in examples below, can be generated from the data file `radius_slice82.aim`, with the following command:

```
n88modelgenerator --test=bending radius_slice82.aim
```

This data file is provided for the radius compression tutorial, but here we apply a bending test so that angular analysis quantities such as torques are defined. This model also has been segmented to have more than one material ID. In particular, ID 127 is used to identify cortical bone and ID 100 is used to identify cancellous bone.
This applies to all tables except Plastic Strain, for which the flag `--plasticity=vonmises,40` was added to the `n88modelgenerator` arguments.

Specifying post-processing node and element sets

Some of the quantities that `n88postfaim` reports are calculated with respect to defined node and/or element sets. For example, for a compression test, the forces on the top and bottom surfaces are of interest. If we define node and element sets corresponding to these surfaces, then `n88postfaim` will, amongst other things, calculate these forces for us. Post-processing node and element sets must be defined during the model generation stage. If you used n88modelgenerator, some relevant node and element sets have automatically been defined. For custom models generated with `vtkbone` see Creating node and element sets.

The available sets in an `n88model` file can be discovered with n88modelinfo. For example, the command

```
n88modelinfo --sets --element_sets radius_slice82_bending.n88model
```

gives the following output:

```
NodeSets:
----------------------------------------------------------------------

  Name : face_z0
  Part : Part1
  NumberOfNodes : 40032

  Name : face_z1
  Part : Part1
  NumberOfNodes : 25991

  Name : face_x0
  Part : Part1
  NumberOfNodes : 15

  Name : face_x1
  Part : Part1
  NumberOfNodes : 14

  Name : face_y0
  Part : Part1
  NumberOfNodes : 27

  Name : face_y1
  Part : Part1
  NumberOfNodes : 17
----------------------------------------------------------------------

ElementSets:
----------------------------------------------------------------------

  Name : face_z0
  Part : Part1
  NumberOfElements : 28999
  Name : face_z1
  Part : Part1
  NumberOfElements : 21210

  Name : face_x0
  Part : Part1
  NumberOfElements : 8

  Name : face_x1
  Part : Part1
  NumberOfElements : 6

  Name : face_y0
  Part : Part1
  NumberOfElements : 12

  Name : face_y1
  Part : Part1
  NumberOfElements : 8
----------------------------------------------------------------------
```

Given that the sets of interest have been generated and are present in the `n88model` file, we must tell `n88postfaim` which to actually use. Much of the time this is also done at the model generation stage. For models generated with `vtkbone`, see Setting post-processing parameters. n88modelgenerator also writes a list of sets to use into the `n88model` file, but note that this list often does not encompass all of the available sets. For example, for any type of compression test, n88modelgenerator will only list the top and bottom surface sets to be used for post-processing, although it generates node and element sets for all faces. In a confined test the forces on the side faces are sometimes of interest, so this may be a case where the list of post-processing sets as generated by n88modelgenerator is insufficient. `n88postfaim` has command line options that allow us to override the list of post-processing sets from the `n88model` file. Here an example:

```
n88postfaim --node_sets face_y0,face_y1 --element_sets face_y0,face_y1 -o analysis.txt  ↩
    radius_slice82_bending.n88model
```

Note that for each node set, `n88postfaim` requires the corresponding element set. For example, for a set consisting of all the nodes on a surface, we also require the set of all elements on the surface. `n88modelgenerator` (and `vtkbone` objects which generate sets automatically) will generate sets such that the corresponding node and element sets have the same names. If this is the case, that we have matching node and element sets, then a simpler but equivalent version of the above example command is

```
n88postfaim --sets face_y0,face_y1 -o analysis.txt radius_slice82_bending.n88model
```

Specifying a rotation center

Certain quantities, such as rotations and torques, are calculated relative to a reference point, or center. This reference point can be specified in a number of ways:

1. For bending and torsion tests, n88modelgenerator will write a default rotation center into the `n88model` file, which will be located at the center of mass of the model.
2. n88modelgenerator supports an argument central_axis that allows the reference point to be specified, as as numerical coordinates or as the center of mass or the center of bounds. The reference value will be written to the `n88model` file. If specified, it overrides the above default.
3. `n88postfaim` supports an argument rotation_center that can be used to specify the reference point. If specified, it overrides any value in the `n88model` file.

If the rotation point is not specified in one of these ways, then the corresponding analysis values and tables will not be calculated or reported. This simplifies the analysis output for models for which these values are typically not of interest (*e.g.* an axial compression test).

Description of output tables

Below are listed the tables provided in the output of `n88postfaim`.

Note that not all values or tables are generated for every model. Angular values are generated only if a rotation center is defined (see the above section), while a break-down of values per material is only performed in the case that more than one material is defined.

Important
`n88postfaim` knows nothing of the Test Frame coordinate system (see Test Orientation). All coordinate directions in the analysis file are in the original Data Frame coordinate system. An exception is that the names of the sets, as assigned by `n88modelgenerator` and listed in Table 3.1, are obtained from their orientation in the Test Frame.

Important
The table numbering is not fixed. Tables are simply numbered sequentially at the time they are generated. You cannot rely on a certain table number consistently identifying a given table.

Model Input

This table lists general parameters of the model input.

```
Table 1: Model Input
----------------------------------------------------------------------------
Filename:                                     radius_slice82_bending.n88model
Element dim X:                                                          0.082
Element dim Y:                                                          0.082
Element dim Z:                                                          0.082
Number of elements:                                                   2667590
Number of nodes:                                                      3816642
Number of nodes per element:                                                8
Dimension of problem:                                                       3
```

Materials

The material definitions as assigned to each material ID are listed. In addition, a very brief summary of the material definition is provided, in particular the material type is shown, and a rough indication of the stiffness is given by the parameter E_{ii_max}. For an isotropic material, E_{ii_max} is the Youngs modulus E, while for an orthotropic material it is the maximum of E_{xx}, E_{yy}, and E_{zz} . In addition, the total number of elements in the model having each material ID are shown, giving a measure of the distribution of the materials.

```
Table 2: Materials
----------------------------------------------------------------------------
Number of materials:                                                        2
----------------------------------------------------------------------------
   m      ID   Name                   Type                  E_ii_max   Elements
   1     100 NewMaterial1           LinearIsotropic         6829.0    1351375
   2     127 NewMaterial1           LinearIsotropic         6829.0    1316215
```

Note that in this example, it happens that although we have two material IDs (defined during segmentation), they are both assigned to the same material definition.

The output will be somewhat different for material arrays, since material arrays correspond to a range of material IDs. Here is an example:

```
Table 2: Materials
----------------------------------------------------------------------------
Number of materials:                                                       1
----------------------------------------------------------------------------
   m      ID    Name                   Type                   E_ii_max   Elements
   1    1..127 NewMaterial1_homminga LinearIsotropic                -       7087
```

Also, for any of the tables described below for which sub-tables for each material ID are generated, it is to be noted that all material IDs corresponding to a material array are grouped into a single subtable. This prevents the amount of output from becoming excessive.

If you require more details about the materials defined, we recommend that you use the n88modelinfo command. For example

```
n88modelinfo --materials radius_slice82_bending.n88model
```

Post-processing sets

The sets used by `n88postfaim` are reported. See Specifying post-processing node and element sets .

```
Table 3: Post-processing Sets
----------------------------------------------------------------------------
Number of sets:                                                            2
----------------------------------------------------------------------------
     n    Node set name              Nodes    Element set name         Elements
     1    face_z1                    25991    face_z1                     21210
     2    face_z0                    40032    face_z0                     28999
```

Strain

Statistics of the six strain components for each element, namely the three engineering normal strains ε_{xx}, ε_{yy}, ε_{zz} and the three engineering shear strains γ_{yz}, γ_{zx}, γ_{xy}

For models with elastoplastic material definitions, the strain given here is the total strain (*i.e.* the sum of the elastic and plastic strains).

The strains are summarized in terms of statistical quantities, namely average, standard deviation, minimum and maximum, and skewness and kurtosis. The median strain, 5th, 25th, 75th and 95th percentile strains are reported. Finally, the fraction of strains that are below zero (*i.e.* compressive strain) is reported in addition to the median and average strain of the negative (compressive) and positive (tensile) strain.

The summary of strains is provided for all elements in the model as well as being summarized for each specific material ID in the case of more than one defined material. In this example model, this provides a means of considering differences in the summary of strains in the cortex (*e.g.* material ID 127) separately from trabecular (*e.g.* material ID 100) bone.

Strain is dimensionless.

```
Table 4: Strain
----------------------------------------------------------------------------
m:                                                                       ALL
Material ID:                                                             ALL
............................................................................
           epsilon_xx epsilon_yy epsilon_zz   gamma_yz   gamma_zx   gamma_xy
average    -3.190E-04 -1.595E-04  5.405E-04 -7.457E-06 -2.048E-03 -3.663E-05
std_dev     2.099E-03  1.544E-03  6.843E-03  2.937E-03  4.153E-03  1.403E-03
minimum    -2.150E-02 -1.771E-02 -6.982E-02 -5.306E-02 -7.585E-02 -3.298E-02
maximum     1.734E-02  2.012E-02  7.162E-02  4.388E-02  4.232E-02  2.821E-02
skewness   -7.522E-01 -1.510E-01  4.932E-01 -8.113E-01 -9.770E-01  6.881E-02
kurtosis    1.184E+00  2.076E+00  3.916E-01  7.286E+00  3.599E+00  7.669E+00
median     -3.340E-05 -8.509E-06 -1.603E-05  1.328E-04 -9.438E-04 -3.450E-05
```

```
perc05     -4.750E-03 -2.959E-03 -9.953E-03 -5.143E-03 -9.573E-03 -2.163E-03
perc25     -1.070E-03 -8.355E-04 -3.705E-03 -9.735E-04 -4.461E-03 -6.944E-04
perc75      7.472E-04  5.336E-04  3.638E-03  1.404E-03  3.828E-04  6.016E-04
perc95      2.837E-03  2.399E-03  1.409E-02  4.025E-03  3.254E-03  2.158E-03
----------------------------------------------------------------------------
m:                                                                         1
Material ID:                                                             100
............................................................................
           epsilon_xx epsilon_yy epsilon_zz   gamma_yz   gamma_zx   gamma_xy
average    -3.326E-04 -2.304E-04  9.468E-04 -2.711E-04  8.815E-05 -1.733E-05
std_dev     1.403E-03  1.296E-03  4.307E-03  2.824E-03  2.967E-03  1.433E-03
minimum    -2.057E-02 -1.771E-02 -4.567E-02 -5.306E-02 -5.665E-02 -3.298E-02
maximum     1.734E-02  2.012E-02  6.647E-02  4.388E-02  4.232E-02  2.821E-02
skewness   -9.487E-01 -5.547E-01  8.212E-01 -8.143E-01 -8.987E-01 -5.569E-02
kurtosis    5.294E+00  4.647E+00  4.572E+00  1.121E+01  9.849E+00  1.051E+01
median     -9.529E-05 -5.413E-05  1.652E-04 -1.758E-05  7.115E-05 -7.972E-06
----------------------------------------------------------------------------
m:                                                                         2
Material ID:                                                             127
............................................................................
           epsilon_xx epsilon_yy epsilon_zz   gamma_yz   gamma_zx   gamma_xy
average    -3.049E-04 -8.671E-05  1.232E-04  2.632E-04 -4.240E-03 -5.645E-05
std_dev     2.629E-03  1.760E-03  8.690E-03  3.025E-03  4.054E-03  1.372E-03
minimum    -2.150E-02 -1.667E-02 -6.982E-02 -3.880E-02 -7.585E-02 -1.501E-02
maximum     1.322E-02  1.588E-02  7.162E-02  3.375E-02  2.053E-02  2.617E-02
skewness   -6.398E-01 -3.604E-02  4.942E-01 -8.592E-01 -1.007E+00  2.105E-01
kurtosis   -2.316E-01  7.413E-01 -7.675E-01  4.422E+00  3.701E+00  4.171E+00
median      1.376E-04  9.347E-05 -2.057E-03  6.242E-04 -4.044E-03 -9.920E-05
```

Skewness is a measure of the asymmetry of the distribution of element stresses. *Kurtosis* is a measure of the “peakedness” of the distribution of element stresses.

Plastic Strain

For models with elastoplastic material definitions, a table of plastic strain statistics is produced. To obtain the elastic strain, subtract the plastic strain from the total strain, given in the previous table.

The presentation of the plastic strain the same format as for the total strain.

Plastic strain is dimensionless.

```
============================================================================
Table 5: Plastic Strain
----------------------------------------------------------------------------
m:                                                                       ALL
Material ID:                                                             ALL
............................................................................
           epsilon_xx epsilon_yy epsilon_zz   gamma_yz   gamma_zx   gamma_xy
average    -3.774E-04 -1.827E-04  5.602E-04 -2.491E-05 -1.051E-03 -4.255E-05
std_dev     2.441E-03  1.858E-03  4.103E-03  2.424E-03  3.285E-03  9.990E-04
minimum    -6.403E-02 -6.146E-02 -9.844E-02 -1.862E-01 -1.647E-01 -1.062E-01
maximum     4.919E-02  4.925E-02  1.223E-01  1.418E-01  1.750E-01  7.206E-02
skewness   -1.856E+00 -7.680E-01  1.454E+00 -3.772E+00 -3.946E+00  2.007E+00
kurtosis    1.172E+01  1.926E+01  1.147E+01  2.736E+02  8.944E+01  2.992E+02
median      0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
perc05     -5.234E-03 -3.476E-03 -5.073E-03 -2.307E-03 -6.641E-03 -1.150E-03
perc25      0.000E+00  0.000E+00  0.000E+00  0.000E+00 -9.717E-04 -5.828E-06
perc75      0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
perc95      2.724E-03  2.380E-03  8.666E-03  2.226E-03  5.648E-04  9.484E-04
----------------------------------------------------------------------------
m:                                                                         1
```

```
Material ID:                                                          100
.........................................................................
           epsilon_xx epsilon_yy epsilon_zz   gamma_yz   gamma_zx   gamma_xy
average    -2.516E-04 -2.011E-04  4.528E-04 -1.325E-04 -3.686E-05  2.363E-06
std_dev     1.569E-03  1.441E-03  2.876E-03  2.513E-03  2.424E-03  9.711E-04
minimum    -6.084E-02 -6.146E-02 -9.844E-02 -1.862E-01 -1.647E-01 -1.062E-01
maximum     4.919E-02  4.925E-02  1.223E-01  1.418E-01  1.750E-01  6.961E-02
skewness   -4.158E+00 -3.443E+00  3.959E+00 -5.739E+00 -3.362E+00  5.373E-02
kurtosis    5.475E+01  5.797E+01  5.475E+01  4.191E+02  3.503E+02  4.686E+02
median      0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
-------------------------------------------------------------------------
m:                                                                      2
Material ID:                                                          127
.........................................................................
           epsilon_xx epsilon_yy epsilon_zz   gamma_yz   gamma_zx   gamma_xy
average    -5.066E-04 -1.638E-04  6.704E-04  8.559E-05 -2.093E-03 -8.867E-05
std_dev     3.085E-03  2.205E-03  5.060E-03  2.324E-03  3.700E-03  1.025E-03
minimum    -6.403E-02 -4.663E-02 -7.185E-02 -1.076E-01 -1.294E-01 -2.535E-02
maximum     3.604E-02  4.230E-02  1.107E-01  8.670E-02  3.620E-02  7.206E-02
skewness   -1.209E+00  4.159E-02  7.811E-01 -1.199E+00 -4.140E+00  3.735E+00
kurtosis    4.603E+00  8.276E+00  3.481E+00  6.679E+01  4.224E+01  1.604E+02
median      0.000E+00  0.000E+00  0.000E+00  0.000E+00 -5.584E-04  0.000E+00
=========================================================================
```

Stress

Statistics of the six stress components for each element, including the normal stresses (σ_{xx}, σ_{yy}, σ_{zz}) and shear stresses (σ_{yz}, σ_{zx}, σ_{xy}).

The presentation of the stress follows the same format as described for the Strain table.

Units depend on inputs, but typically displacements are expressed in millimeters (mm), forces in newtons (N), and stresses in MPa. See Note about units.

```
Table 6: Stress
-------------------------------------------------------------------------
m:                                                                    ALL
Material ID:                                                          ALL
.........................................................................
             sigma_xx   sigma_yy   sigma_zz   sigma_yz   sigma_zx   sigma_xy
average    -8.027E-01 -5.936E-01  3.083E+00 -1.959E-02 -5.378E+00 -9.621E-02
std_dev     1.315E+01  1.070E+01  5.073E+01  7.714E+00  1.091E+01  3.686E+00
minimum    -2.380E+02 -2.004E+02 -5.796E+02 -1.394E+02 -1.992E+02 -8.662E+01
maximum     1.682E+02  1.632E+02  5.517E+02  1.153E+02  1.111E+02  7.410E+01
skewness   -5.570E-01  4.960E-01  4.539E-01 -8.113E-01 -9.770E-01  6.881E-02
kurtosis    5.054E+00  4.068E+00  4.404E-01  7.286E+00  3.599E+00  7.669E+00
median     -4.492E-01 -3.217E-01 -2.718E-01  3.489E-01 -2.479E+00 -9.062E-02
perc05     -2.244E+01 -1.716E+01 -7.487E+01 -1.351E+01 -2.514E+01 -5.681E+00
perc25     -7.064E+00 -5.724E+00 -2.868E+01 -2.557E+00 -1.172E+01 -1.824E+00
perc75      5.727E+00  2.874E+00  2.650E+01  3.687E+00  1.005E+00  1.580E+00
perc95      1.979E+01  1.944E+01  1.020E+02  1.057E+01  8.546E+00  5.668E+00
-------------------------------------------------------------------------
m:                                                                      1
Material ID:                                                          100
.........................................................................
             sigma_xx   sigma_yy   sigma_zz   sigma_yz   sigma_zx   sigma_xy
average     6.726E-01  3.019E-01  6.486E+00 -7.120E-01  2.315E-01 -4.551E-02
std_dev     1.009E+01  7.009E+00  3.126E+01  7.418E+00  7.793E+00  3.764E+00
minimum    -1.424E+02 -1.625E+02 -3.346E+02 -1.394E+02 -1.488E+02 -8.662E+01
maximum     1.682E+02  1.632E+02  5.062E+02  1.153E+02  1.111E+02  7.410E+01
skewness    3.128E-03  4.413E-01  7.910E-01 -8.143E-01 -8.987E-01 -5.569E-02
```

```
kurtosis     8.270E+00  1.406E+01  4.799E+00  1.121E+01  9.849E+00  1.051E+01
median       8.653E-02 -4.944E-03  8.636E-01 -4.619E-02  1.869E-01 -2.094E-02
----------------------------------------------------------------------------
m:                                                                         2
Material ID:                                                             127
............................................................................
             sigma_xx   sigma_yy   sigma_zz   sigma_yz   sigma_zx   sigma_xy
average     -2.317E+00 -1.513E+00 -4.100E-01  6.914E-01 -1.114E+01 -1.483E-01
std_dev      1.554E+01  1.341E+01  6.472E+01  7.944E+00  1.065E+01  3.604E+00
minimum     -2.380E+02 -2.004E+02 -5.796E+02 -1.019E+02 -1.992E+02 -3.943E+01
maximum      1.506E+02  1.427E+02  5.517E+02  8.865E+01  5.392E+01  6.873E+01
skewness    -5.163E-01  5.951E-01  4.757E-01 -8.592E-01 -1.007E+00  2.105E-01
kurtosis     3.035E+00  1.604E+00 -7.415E-01  4.422E+00  3.701E+00  4.171E+00
median      -3.882E+00 -2.612E+00 -1.698E+01  1.640E+00 -1.062E+01 -2.606E-01
```

Strain Energy Density

Statistics on the strain energy density are reported. See StrainEnergyDensity in Section 9.5 for a definition of the strain energy density.

For models with elastoplastic material definitions, the strain energy density is the elastic strain energy density. (Plastic strain energy density is not well defined: the work done producing a given a plastic strain is mostly converted into heat energy and cannot be retreived again as mechanical work.)

The presentation of the strain energy density follows the same format as described for the Strain table.

```
Table 7: Strain Energy Density
----------------------------------------------------------------------------
m:                                                                       ALL
Material ID:                                                             ALL
............................................................................
average      2.091E-01
std_dev      3.039E-01
minimum      5.704E-15
maximum      2.186E+01
skewness     4.357E+00
kurtosis     9.588E+01
median       8.209E-02
perc05       4.649E-04
perc25       1.149E-02
perc75       2.918E-01
perc95       8.012E-01
----------------------------------------------------------------------------
m:                                                                         1
Material ID:                                                             100
............................................................................
average      9.484E-02
std_dev      2.108E-01
minimum      5.704E-15
maximum      1.662E+01
skewness     7.458E+00
kurtosis     1.533E+02
median       1.993E-02
----------------------------------------------------------------------------
m:                                                                         2
Material ID:                                                             127
............................................................................
average      3.264E-01
std_dev      3.382E-01
minimum      1.353E-12
maximum      2.186E+01
```

```
skewness    3.914E+00
kurtosis    9.946E+01
median      2.203E-01
```

Von Mises Stress

Statistics on the von Mises stress are reported. See VonMisesStress in Section 9.5 for a definition of the von Mises stress.

The presentation of the von Mises stress follows the same format as for the Strain table.

```
Table 8: Von Mises Stress
----------------------------------------------------------------------------
m:                                                                       ALL
Material ID:                                                             ALL
............................................................................
average     3.920E+01
std_dev     3.147E+01
minimum     9.139E-06
maximum     4.915E+02
skewness    8.934E-01
kurtosis    5.365E-01
median      3.204E+01
perc05      2.624E+00
perc25      1.251E+01
perc75      5.944E+01
perc95      9.817E+01
----------------------------------------------------------------------------
m:                                                                         1
Material ID:                                                             100
............................................................................
average     2.455E+01
std_dev     2.461E+01
minimum     9.139E-06
maximum     4.237E+02
skewness    1.832E+00
kurtosis    4.876E+00
median      1.643E+01
----------------------------------------------------------------------------
m:                                                                         2
Material ID:                                                             127
............................................................................
average     5.423E+01
std_dev     3.065E+01
minimum     1.460E-04
maximum     4.915E+02
skewness    4.575E-01
kurtosis    1.077E-01
median      5.081E+01
```

Nodal Displacements

The three components of displacements ($\mathtt{u_x}$, $\mathtt{u_y}$, $\mathtt{u_z}$) are reported. A sub-table is generated for each post-processing node set. Statistics of the displacements are reported over all the nodes of each set.

Units are self-consistent, but are typically millimeters (mm). See A note about units.

```
Table 9: Nodal Displacements
----------------------------------------------------------------------------
Node set:                                                                  1
Name:                                                                face_z1
```

```
..........................................................................
                 ux          uy          uz
average     0.000E+00  0.000E+00  8.493E-03
std_dev     0.000E+00  0.000E+00  3.727E-02
minimum     0.000E+00  0.000E+00 -6.689E-02
maximum     0.000E+00  0.000E+00  7.695E-02
median      0.000E+00  0.000E+00  7.534E-03
--------------------------------------------------------------------------
Node set:                                                                2
Name:                                                              face_z0
..........................................................................
                 ux          uy          uz
average     0.000E+00  0.000E+00  8.176E-03
std_dev     0.000E+00  0.000E+00  5.033E-02
minimum     0.000E+00  0.000E+00 -8.768E-02
maximum     0.000E+00  0.000E+00  1.392E-01
median      0.000E+00  0.000E+00  1.250E-02
```

Nodal Forces

The three components of force (F_x, F_y, F_z) are reported. A sub-table is generated for each post-processing element set. The forces are provided giving statistical values over all elements in the set.

Units depend on inputs, but are typically Newtons (N). See A note about units.

```
Table 10: Nodal Forces
--------------------------------------------------------------------------
Node set:                                                                1
Name:                                                              face_z1
..........................................................................
                 Fx          Fy          Fz
total      -8.767E+02 -3.222E+00  5.025E+02
average    -3.373E-02 -1.240E-04  1.933E-02
std_dev     7.261E-02  3.936E-02  3.336E-01
minimum    -8.420E-01 -3.484E-01 -2.614E+00
maximum     4.068E-01  6.302E-01  1.399E+00
median     -2.464E-02 -4.476E-04  4.233E-03
--------------------------------------------------------------------------
Node set:                                                                2
Name:                                                              face_z0
..........................................................................
                 Fx          Fy          Fz
total       8.773E+02  3.162E+00 -5.032E+02
average     2.191E-02  7.898E-05 -1.257E-02
std_dev     7.203E-02  5.302E-02  2.423E-01
minimum    -3.655E-01 -3.909E-01 -1.399E+00
maximum     4.889E-01  3.679E-01  1.196E+00
median      8.519E-04 -2.016E-03  3.913E-03
```

Nodal Twist

Similar to nodal displacements, statistics on the angular displacements for each node set are provided.

The angular displacements are defined as the projected angles between the vector to the initial location of the node and the vector to the displaced location of the node. The vectors are projected onto a plane perpendicular to the specified axis. This is shown in Figure 14, which defines `ROTx`. `p` is the initial position of the node, and `p'` is the displaced position of the node, as calculated by FE. These two vectors are projected onto the *y*-*z* plane, and the angle between them in this plane is defined as `ROTx`. `ROTy` and `ROTz` are similarly defined. Angular displacements are relative to the center of rotation; this is shown as p_0 in Figure 14. See specifying a rotation center.

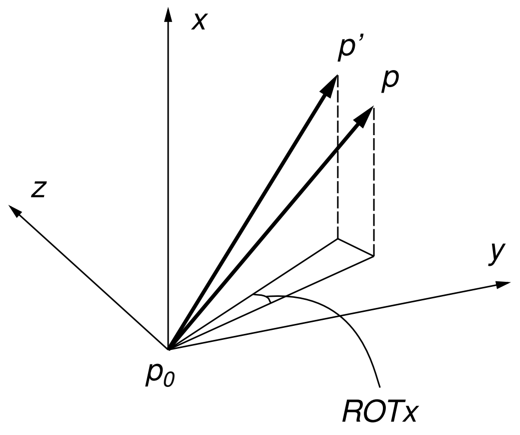


Figure 6.1: Definition of projected angle ROTx.

Note
`ROTx`, `ROTy`, `ROTz` do not form a set of Euler angles.

Nodes that are within an exclusion radius (default value 10^{-6}) of the rotation center are excluded from the calculation, as the angular displacement of a node at the rotation center (initial or final position) is not defined.

Units are radians (rad).

```
Table 11: Nodal Twist
-----------------------------------------------------------------------------
Twist measured relative to:                            66.049 54.985 4.510
Exclusion radius:                                                 1.0E-06
-----------------------------------------------------------------------------
Node set:                                                               1
Name:                                                             face_z1
.............................................................................
                 ROTx        ROTy        ROTz
n               25991       25991       25991
average     5.978E-04 -3.252E-03  0.000E+00
std_dev     3.424E-03  2.180E-03  0.000E+00
minimum    -8.422E-03 -6.893E-03  0.000E+00
maximum     7.567E-03 -6.411E-07  0.000E+00
median      6.324E-04 -3.274E-03  0.000E+00
-----------------------------------------------------------------------------
Node set:                                                               2
Name:                                                             face_z0
.............................................................................
                 ROTx        ROTy        ROTz
n               40032       40032       40032
average    -7.531E-04  4.147E-03  0.000E+00
std_dev     4.239E-03  2.363E-03  0.000E+00
minimum    -1.014E-02  6.411E-07  0.000E+00
maximum     9.126E-03  8.099E-03  0.000E+00
median     -3.388E-04  4.688E-03  0.000E+00
```

Nodal Torques

Similar to nodal twist, statistics on the the nodal torques for each node set are reported.

As with the nodal twist results, torques are calculated relative to a reference point. See specifying a rotation center.

Units depend on inputs, but are typically in newton-millimeters (Nmm). See Note about units.

```
Table 12: Nodal Torques
----------------------------------------------------------------------------
Torque measured relative to:                             66.049 54.985 4.510
----------------------------------------------------------------------------
Node set:                                                                  1
Name:                                                                face_z1
............................................................................
                   Tx          Ty          Tz
total        1.094E+04 -3.683E+04 -1.796E+03
average      4.210E-01 -1.417E+00 -6.909E-02
std_dev      2.312E+00  1.847E+00  7.455E-01
minimum     -5.420E+00 -2.341E+01 -9.929E+00
maximum      3.204E+01  1.070E-01  5.532E+00
median       2.183E-02 -6.439E-01 -2.549E-03
----------------------------------------------------------------------------
Node set:                                                                  2
Name:                                                                face_z0
............................................................................
                   Tx          Ty          Tz
total       -1.094E+04  3.682E+04  1.796E+03
average     -2.733E-01  9.198E-01  4.486E-02
std_dev      1.487E+00  1.466E+00  5.923E-01
minimum     -1.111E+01 -3.944E+00 -3.920E+00
maximum      7.102E+00  1.176E+01  5.743E+00
median      -4.530E-03  3.083E-01 -2.374E-03
```

Load Sharing

A calculation of the fraction of the load carried by each material ID is provided, based on the nodal forces in each associated node set.

The portion of total load on the node set is reported for each material in terms of nodal forces (F_x, F_y, F_z). Nodal torques (T_x, T_y, T_z) are also reported if a center of rotation is defined. See specifying a rotation center. The total forces and torques are also reported, and it should be noted that are the same as reported in Nodal Forces and Nodal Torques

The method used to determine the loads carried by each material requires identifying the nodes belonging to each material. Since material definitions are based on elements, some nodes are shared by more than one material. In these cases, the forces and torques associated with the node are proportionally assigned to each material definition.

```
Table 13: Load Sharing
----------------------------------------------------------------------------
Torque measured relative to:                          66.0487 54.9845 4.5100
----------------------------------------------------------------------------
Node set:                                                                  1
Name:                                                                face_z1
............................................................................
                  material          Fx          Fy          Fz
                       100 -2.2735E+02  2.2343E+01  1.5989E+02 ❶
                       127 -6.4936E+02 -2.5565E+01  3.4260E+02
                ----------  ----------  ----------  ----------
                     total -8.7671E+02 -3.2224E+00  5.0249E+02 ❷

                  material          Tx          Ty          Tz
                       100  1.3237E+03 -4.6310E+03 -5.3746E+02
                       127  9.6174E+03 -3.2197E+04 -1.2583E+03
                ----------  ----------  ----------  ----------
                     total  1.0941E+04 -3.6828E+04 -1.7958E+03
----------------------------------------------------------------------------
```

```
Node set:                                                                  2
Name:                                                                face_z0
............................................................................
                  material          Fx          Fy          Fz
                       100 -8.0150E+01  1.3524E+02 -2.2235E+02
                       127  9.5741E+02 -1.3208E+02 -2.8086E+02
                ----------  ----------  ----------  ----------
                     total  8.7726E+02  3.1616E+00 -5.0321E+02

                  material          Tx          Ty          Tz
                       100 -4.4656E+03  1.5580E+04  1.3600E+02
                       127 -6.4737E+03  2.1242E+04  1.6599E+03
                ----------  ----------  ----------  ----------
                     total -1.0939E+04  3.6823E+04  1.7959E+03
```

1 Represents the total force attributed to material definition 127 (cortical bone in this model).

2 This result is the same as the total `F_z` in Nodal Forces.

Tabulating results from analysis files

The analysis file generated by n88postfaim is intended to be human-readable. If you run several similar models, it is common to want to tabulate certain numerical results in spreadsheet format. It is possible, but tiresome, to open the analysis file for each solved model individually and manually search for the desired numbers. To make this process more efficient, we provide the tool n88tabulate. See Section 9.16. This tool extracts certain specified values from any number of analysis files and collates them into a tabular format suitable for importing into a spreadsheet.

Chapter 7

Tutorials

This chapter presents a number of tutorials to help you learn the Faim finite element tools.

A zip file containing the data files used for the tutorials, as well as the tutorial scripts, can be downloaded from http://numerics88.com/-downloads/ .

The first series of tutorials introduces the standard work flow for Faim, where standard models as generated by n88modelgenerator are desired. These tutorials are

1. An introductory tutorial: compressing a solid cube
2. Compression test of a radius bone slice
3. Bending test of a radius bone with an uneven surface

These are intended to be followed in order, as each one builds on the previous.

Following these introductory tutorials is a series dealing with more advanced topics

There is a tutorial that introduces models with nonlinear elasto-plastic material properties.

1. Bending of a radius bone with elasto-plastic material properties.

Then there are a series of tutorials which present the building of custom models using `vtkbone`. This series is intended only for those who find n88modelgenerator insufficiently flexible for their needs. The tutorials in this series are

1. Compressing a cube revisited using vtkbone
2. Deflection of a cantilevered beam; adding custom boundary conditions and loads
3. A cantilevered beam with elastoplastic material properties
4. Advanced custom model tutorial: a screw pull-out test

Finally, some additional examples are provided with the distribution. These are not described in the manual, but do demonstrate addition concepts or functionality.

Introductory tutorial: Compressing a solid cube

We start with a very simple example, where we compress a uniform homogenous cube. This tutorial will demonstrate:

- How to use the standard test generator `n88modelgenerator` to generate a finite element model suitable for input to the solver.

- How to solve the model.
- How to use ParaView to visualize the model and the solution.
- How to identify key values in the analysis file.

The data file is `cube6x6x6.vti`. It can be found in the `data` folder of the the tutorial zip file available for download from http://numerics88.com/downloads/ . We recommend that you copy it to a temporary working directory for this tutorial.

You can examine this data file, which we will be using as input, with ParaView. To do this, open ParaView and select the menu item File → Open, and navigate to the location of `cube6x6x6.vti`. You will notice that after selecting the file and clicking OK, nothing is displayed, although the file name now appears in the *Pipeline Browser*. This is typical for ParaView, and allows options relevant to the source to be modified before the data is actually loaded. In this case, there are no options we are concerned with, so we can go ahead and click Apply (on the Properties tab of the Pipeline browser) to actually load the data. At first, only a wire-frame cube will be displayed, which shows the extents of the image data. To actually inspect the data, we are going to change the drop-down list on the toolbar that currently displays *Outline* to *Points*. This results in a display of a number of points in space, as shown in Figure 15.

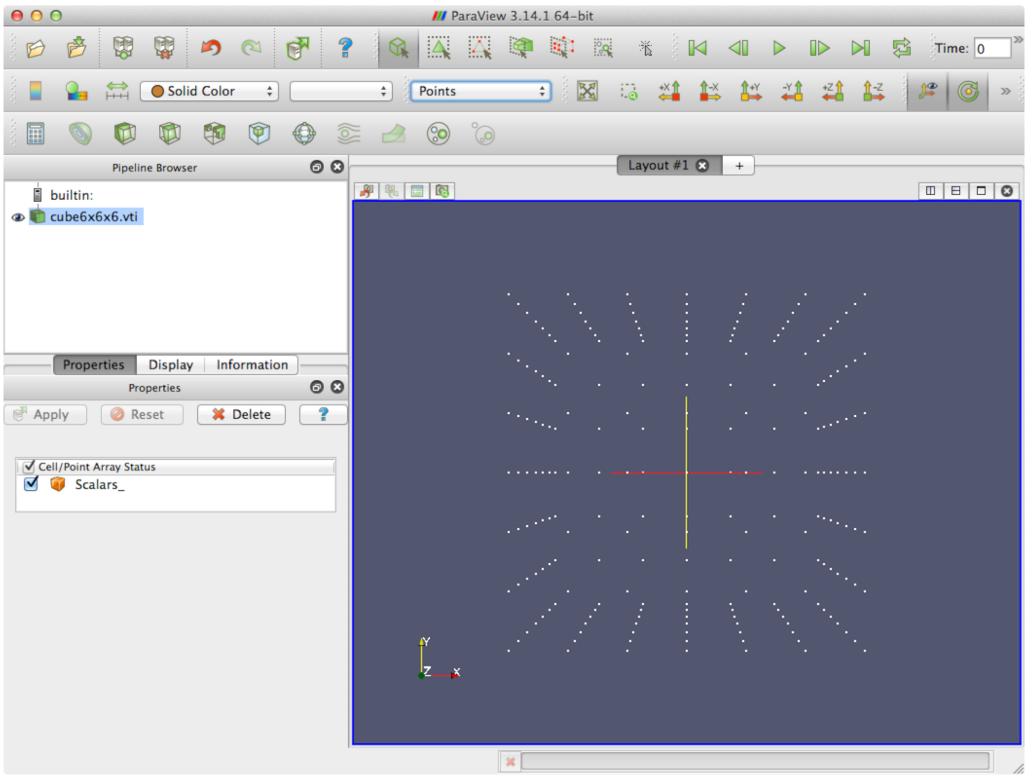


Figure 7.1: Points view of 6x6x6 cube.

If you're alert, you'll notice that in fact there are 7×7×7 points. This is due to the fact that the actual data for this data file is associated with the *Cells*, to use VTK terminology, rather than the *Points*. The points shown are therefore in this case the corners of the cells. To make this clear, change the view again from *Points* to *Surface with Edges*. This will now look like Figure 16. (Click and drag in the image window of ParaView to rotate the object - experiment with both the right and left mouse buttons, and also while holding down any of the Shift, Control and Alt keys). We are going to create a finite element model where every *Cell*, or small constituent cube from Figure 16 will become one element in the finite element model.

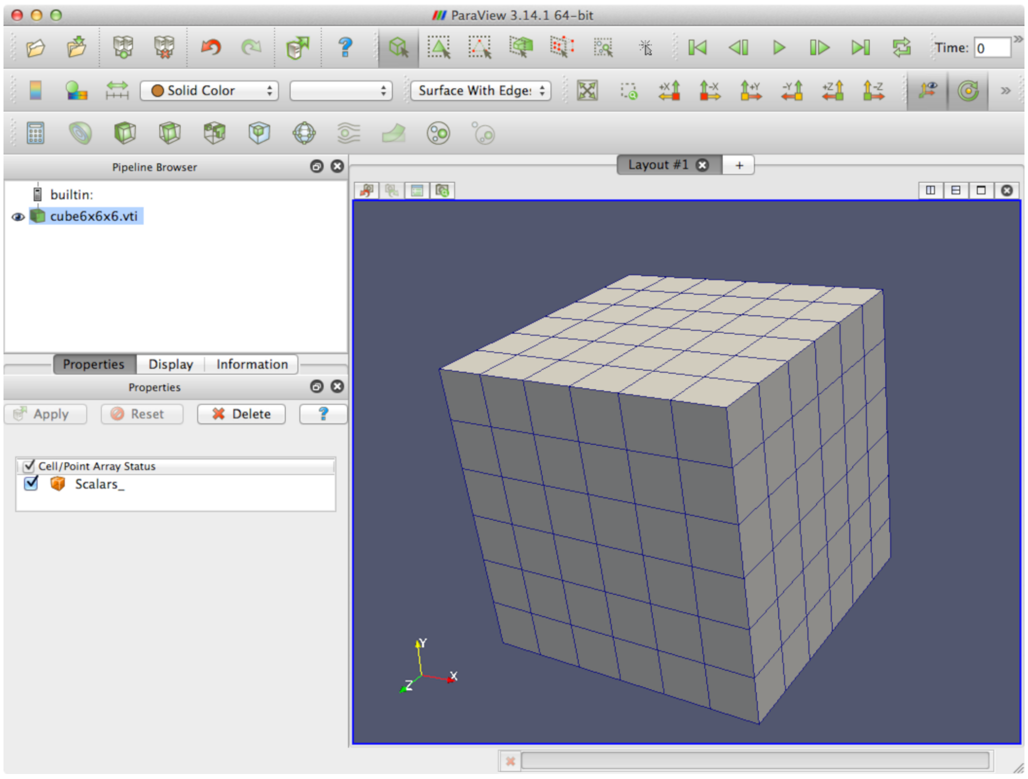


Figure 7.2: Surface with edges view of 6x6x6 cube.

For a simulated test, we are going to apply a compression test using `n88modelgenerator` to this data file. There are a number of different standard compression tests, as described in Standard Tests. Here we are going to use the axial variation. In an axial compression test, the sides are unconstrained and the top and bottom surfaces constrained laterally, as if they experience a high contact friction with the imaginary surfaces applying the compression.

Generating the model

The first step is to open a Terminal (on Windows a Command Prompt or PowerShell). Make sure both that the Faim is on the Path, as described in Section 1.4.2, and also that you have activated the Anaconda python environment for `n88tools`, as described in Section 1.4.4.

Important
If you close the terminal part way through this tutorial, and then pick it up again later by opening a new terminal, you will have to re-set the environment variables and re-activate the conda environment.

Assuming that you have copied the data file `cube6x6x6.vti` to your current working directory, the command to generate the model is

```
n88modelgenerator --test=axial cube6x6x6.vti
```

Since we haven't specified otherwise, `n88modelgenerator` will select all default parameters, including default material properties (homogeneous material with isotropic Young's modulus of 6829 MPa and Poisson's ratio 0.3), and a displacement, applied to the top surface in the z direction, numerically equivalent to an apparent level strain of -0.01 (the minus indicates compressive strain). Refer to the section on n88modelgenerator for details on setting parameters differently if you wish to do so.

Here is the output when we run it:

```
n88modelgenerator Version 8.0
Copyright (c) 2010-2016, Numerics88 Solutions Ltd.
Licensed to Numerics88 Solutions Ltd.; lic. no. 91

input_file   = cube6x6x6.vti
output_file  = cube6x6x6_axial.n88model
connectivity_filter          = on
test                         = axial
test_axis                    = z
normal_strain                = -0.01
top_surface                  = intersection
bottom_surface               = intersection
material_table               = homogeneous
youngs_modulus               = 6829
poissons_ratio               = 0.3

   0.00 Reading input data.
   0.02 Read 343 points.
   0.02 Image bounds:
        0.0000 6.0000 0.0000 6.0000 0.0000 6.0000
   0.02 Applying connectivity filter.
   0.02 Masked out 0 unconnected voxels.
   0.02 Converting to hexahedral mesh.
   0.02 Generated 216 hexahedrons.
   0.02 Constructing material table.
   0.02 Material table has 1 entry.
   0.02 Constructing finite element model.
   0.02 Model bounds:
        0.0000 6.0000 0.0000 6.0000 0.0000 6.0000
   0.02 Generated the following constraints:
          bottom_fixed : 147 nodes
          top_fixed : 98 nodes
          top_displacement : 49 nodes
   0.02 Writing Numerics88 Model file cube6x6x6_axial.n88model .
   0.03 Done.
```

We now have a file `cube6x6x6_axial.n88model` that can be used directly as input to the solver.

Solving the model

Having now defined the problem, we can solve it, and do some post-processing, all in one step with faim.

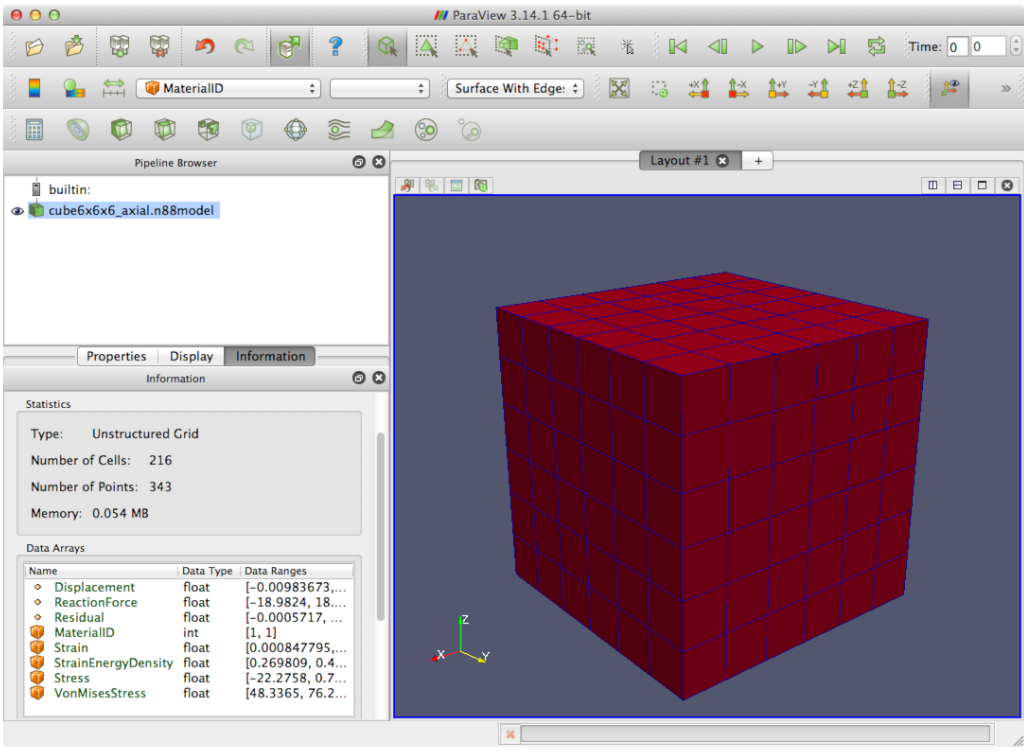
```
faim cube6x6x6_axial.n88model
```

The output is:

```
Model has 216 elements.
Model contains only linear material definitions.

Choosing n88solver_slt.
Running solver: n88solver_slt cube6x6x6_axial.n88model
n88solver_slt version 8.0
Copyright (c) 2010-2016, Numerics88 Solutions Ltd.
Licensed to Numerics88 Solutions Ltd.; lic. no. 91
Problem:
  active solution       = (none)
  active problem        = Problem1
  number of elements    = 216
  number of nodes       = 343
Solver engine:
  engine                  = mt
  precision               = double
  threads                 = 1
Convergence parameters:
  convergence measure     = set
  convergence tolerance = 1e-06
  convergence window      = 16
  maximum iterations      = 30000

    time (s)      iter        conv
         0.0        30     5.4E-07

Convergence measure tolerance reached.
Number of linear iterations = 30
Peak data allocation : 75.8 kiB

Running field calculator: n88derivedfields cube6x6x6_axial.n88model
n88derivedfields version 8.0
Copyright (c) 2010-2016, Numerics88 Solutions Ltd.
Licensed to Numerics88 Solutions Ltd.; lic. no. 91
Problem:
  active solution         = Solution1
  active problem          = Problem1
  number of elements      = 216
  number of nodes         = 343
Solver engine:
  precision               = single
Peak data allocation: 19.8 kiB

Running analysis tool: n88postfaim --output_file cube6x6x6_axial_analysis.txt  ↩
    cube6x6x6_axial.n88model
```

Visualizing the results with ParaView

First ensure that ParaView is set up with the plugins to read Numerics88 files, as described in Installing and using the Numerics88 plugins for ParaView. Assuming that the plugins are loaded correctly, `cube6x6x6_axial.n88model` can be opened directly with ParaView. When we first open this file, it looks very similar to the input data. However, if we go to the *Information* tab in the Pipeline Browser, we can see that there are now several Data Arrays, *Displacement*, *ReactionForce*, etc... as shown in Figure 17. Notice that the icon next the the array name indicates whether the data is on *Points* or *Cells*, which is equivalent in finite element terminology to *Nodes* and *Elements*, respectively.



Information

Statistics

Type: Unstructured Grid

Number of Cells: 216

Number of Points: 343

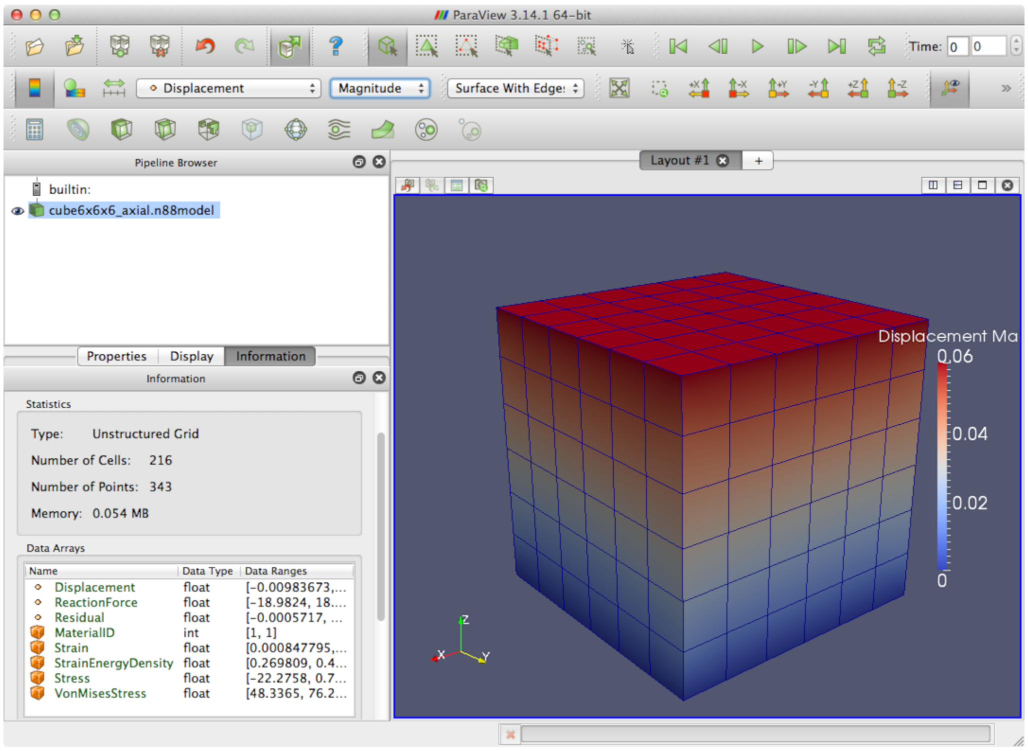
Memory: 0.054 MB

Data Arrays

Name	Data Type	Data Ranges
Displacement	float	[-0.00983673,...
ReactionForce	float	[-18.9824, 18....
Residual	float	[-0.0005717, ...
MaterialID	int	[1, 1]
Strain	float	[0.000847795,...
StrainEnergyDensity	float	[0.269809, 0.4...
Stress	float	[-22.2758, 0.7...
VonMisesStress	float	[48.3365, 76.2...

Figure 7.3: Solved 6x6x6 cube with Data Arrays.

There are many ways to visualize the data. As a simple example, choose *Displacement* from the drop-down menu on the toolbar that currently shows *_MaterialID*. Also click the Toggle Color Legend Visibility button on the toolbar (on the very left side). ParaView should now look like Figure 18. Notice that a new drop-down box appears that shows *Magnitude*. This occurs because the Displacements are a vector quantity. Experiment with changing this to *Z*, *X* and *Y*.



Information

Statistics

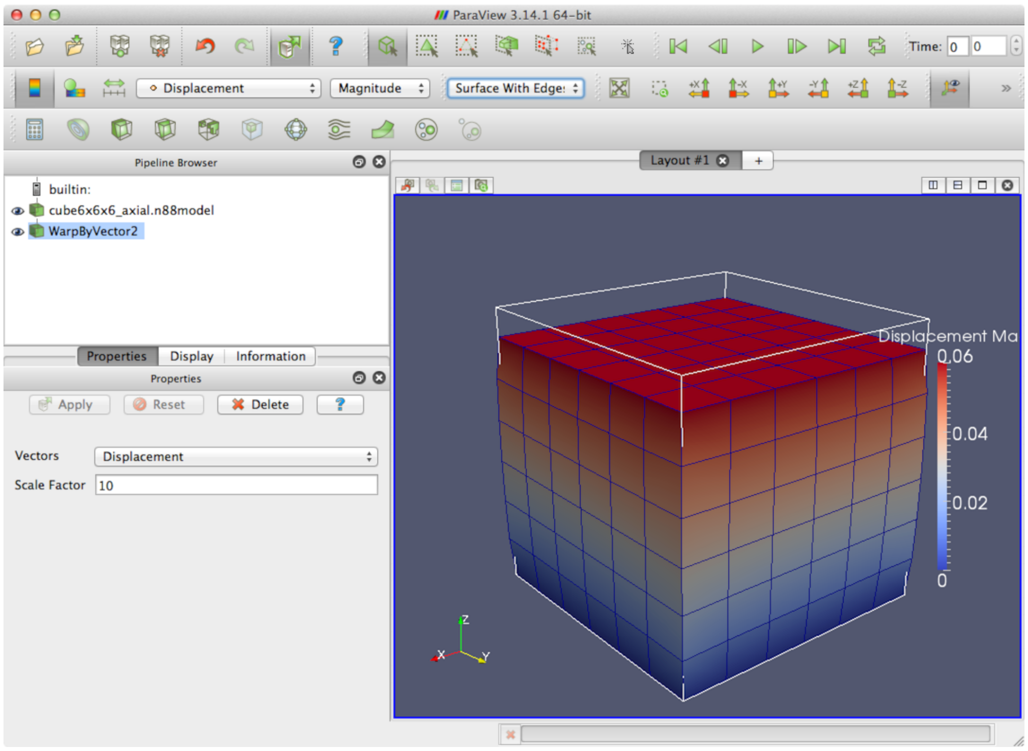
Type: Unstructured Grid
Number of Cells: 216
Number of Points: 343
Memory: 0.054 MB

Data Arrays

Name	Data Type	Data Ranges
Displacement	float	[-0.00983673,...
ReactionForce	float	[-18.9824, 18....
Residual	float	[-0.0005717, ...
MaterialID	int	[1, 1]
Strain	float	[0.000847795,...
StrainEnergyDensity	float	[0.269809, 0.4...
Stress	float	[-22.2758, 0.7...
VonMisesStress	float	[48.3365, 76.2...

Figure 7.4: Solved 6x6x6 cube colored by Displacement.

Although we now have the cube colored by Displacement, the object is shown in its undeformed unloaded shape. To visualize the deformations, we can use the *Warp By Vector* tool. There is an icon for this on the bottom Toolbar. Because we have imposed a small strain, -0.01, it will be hard to see. The *Warp By Vector* tool however allows us to apply a Scale Factor. We will set this to 10, so that the displacements are amplified by a factor of 10. The results are shown in Figure 19, where the compression and outward bulging of the sides are clearly seen. In this figure, we have, in addition to applying the Warp By Vector tool, re-enabled the display of the original `cube6x6x6_axial.n88model`, which was automatically disabled by ParaView when we connected a filter object to it. We then set its display type to *Outline*, resulting in the white box outline in Figure 19, which indicates the original undeformed box shape.



Vectors: Displacement

Scale Factor: 10

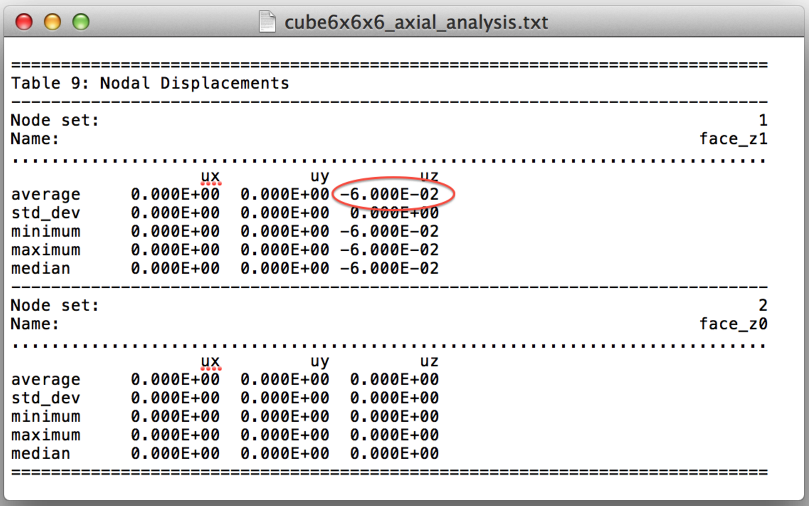
Figure 7.5: Solved 6x6x6 cube shown with exaggerated displacement using the Warp By Vector tool.

Obtaining numerical values from the analysis file

A typical result we want to obtain with a compression test is the object apparent stiffness. Numerically the stiffness is the net external force divided by the displacement. We can find the displacement and force on the top surface from the analysis file, `cube6x6x6_axial_analysis.txt`. This file is a text file, and can be opened with any text editor. Refer to the section on post-processing with n88postfaim for the complete explanation of the values available.

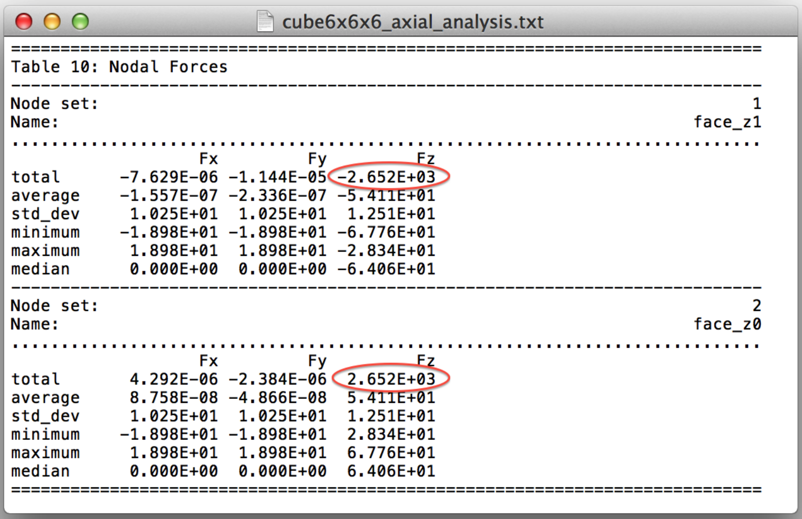
The displacement is obtained from table Nodal Displacements. The displacements in this table are listed according to node set.

`n88modelgenerator` has defined some standard node sets (for a complete list see Creating node and element sets in the chapter on Preparing Models with `vtkbone`.) Here the node sets that are relevant are the two surfaces to which the boundary conditions are applied, namely the top and bottom surfaces, *face_z1* and *face_z0*, respectively. The analysis file has been generated using these two node sets. If we examine the Nodal Displacements table of `cube6x6x6x_axial_analysis.txt`, as shown in Figure 20, we see that the top node set has a uniform displacement in the *z* direction of -0.06 mm. The relevant number is circled in red. Notice also that the minimum and maximum are the same so all nodes of this set are equally displaced, as we expect, since this is in fact a boundary condition. The other node set is the nodes of the bottom surface, and it has constant displacement of 0.



```
================================================================================
Table 9: Nodal Displacements
--------------------------------------------------------------------------------
Node set:                                                                      1
Name:                                                                    face_z1
................................................................................
                     ux          uy          uz
average      0.000E+00   0.000E+00  -6.000E-02
std_dev      0.000E+00   0.000E+00   0.000E+00
minimum      0.000E+00   0.000E+00  -6.000E-02
maximum      0.000E+00   0.000E+00  -6.000E-02
median       0.000E+00   0.000E+00  -6.000E-02
--------------------------------------------------------------------------------
Node set:                                                                      2
Name:                                                                    face_z0
................................................................................
                     ux          uy          uz
average      0.000E+00   0.000E+00   0.000E+00
std_dev      0.000E+00   0.000E+00   0.000E+00
minimum      0.000E+00   0.000E+00   0.000E+00
maximum      0.000E+00   0.000E+00   0.000E+00
median       0.000E+00   0.000E+00   0.000E+00
================================================================================
```

Figure 7.6: uz components in Nodal Displacements table of the analysis file.



```
================================================================================
Table 10: Nodal Forces
--------------------------------------------------------------------------------
Node set:                                                                      1
Name:                                                                    face_z1
................................................................................
                    Fx          Fy          Fz
total       -7.629E-06  -1.144E-05  -2.652E+03
average     -1.557E-07  -2.336E-07  -5.411E+01
std_dev      1.025E+01   1.025E+01   1.251E+01
minimum     -1.898E+01  -1.898E+01  -6.776E+01
maximum      1.898E+01   1.898E+01  -2.834E+01
median       0.000E+00   0.000E+00  -6.406E+01
--------------------------------------------------------------------------------
Node set:                                                                      2
Name:                                                                    face_z0
................................................................................
                    Fx          Fy          Fz
total        4.292E-06  -2.384E-06   2.652E+03
average      8.758E-08  -4.866E-08   5.411E+01
std_dev      1.025E+01   1.025E+01   1.251E+01
minimum     -1.898E+01  -1.898E+01   2.834E+01
maximum      1.898E+01   1.898E+01   6.776E+01
median       0.000E+00   0.000E+00   6.406E+01
================================================================================
```

Figure 7.7: Fz components in Nodal Forces table of the analysis file.

Similarly to the table for displacements, table Nodal Forces shows forces, summed over the defined node sets. Here the relevant value is -2651 N, as shown in Figure 21. The apparent stiffness of the cube is therefore

$$\frac{-2651\,N}{-0.06\,mm} = 4.42 \times 10^5 N/mm$$

Is this value reasonable? We can estimate what we should get. Completely ignoring lateral expansion and Poisson's ratio, we can do a quick estimate that the stiffness of a homogeneous cube should be approximately,

$$k = \frac{EA}{h} = \frac{[6829\, N/mm^2][6\, mm]^2}{[6mm]} = 4.10 \times 10^5 N/mm$$

This is close to what we obtained from the finite element model. The difference arises from the fact that the finite element model takes account of the complicated lateral expansion (bulging of the sides) that occurs in an axial test, while our simple back-of-the-envelope calculation assumes uniaxial conditions (*i.e.*, no lateral constraint on the top and bottom boundary surfaces).

This concludes the cube tutorial. You have learned how to generate standard models from image data using `n88modelgenerator`, how to solve the models, how to visualize the models using ParaView, and how to do some elementary post-processing analysis.

Tutorial: Compression test of a radius bone slice

In the previous tutorial, we saw how to generate a finite element model from an image file using n88modelgenerator, how to solve it, how to visualize the results, and how obtain some relevant numerical results. In this tutorial, we are going to generate and solve a similar compression test. Instead of a small contrived image, we will be using a real data file obtained from a microCT scan of a distal radius bone. We will also provide more detail about the steps along the way, and be introduced to some of the tools that aid in examining and verifying models.

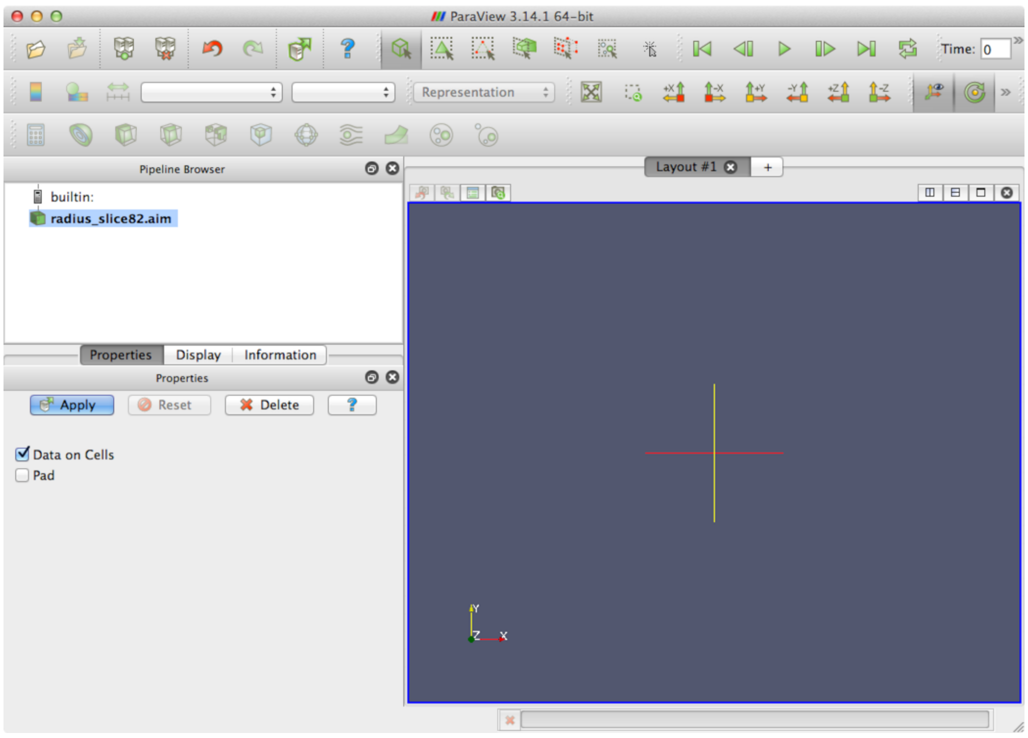
In detail, this tutorial will demonstrate:

- How to use n88modelinfo to obtain information about `n88model` files, and in particular to trace back exactly how they were generated and processed.
- How to examine the residuals to evaluate the accuracy of the solution.
- How to quantify the load sharing between the two types of bone, cortical bone and trabecular bone.
- How to compress data files using n88copymodel for efficient storage.

The data file is `radius_slice82.aim`, and it obtained with the tutorial data available from http://numerics88.com/downloads/- . This is a large image file of 325×437×110 voxels in size. It was obtained with a scan resolution of 82 micrometers. The tutorial will be demonstrated using this data file. However, a reduced-resolution file, `radius_slice164.aim`, is also provided. The resolution has been reduced to an effective 164 micrometers, resulting in a much smaller data file with dimensions 163×219×55. If you are working on a computer with limited memory, or are just impatient, then you can follow along using the smaller file.

Before proceeding, ensure that the Numerics88 plugins for ParaView are loaded as described in Section 1.4.5.

In the previous tutorial you might recall that the data file was a VTK image data file, and that it explicitly had the data on the *Cells* rather than on the *Points*. Most image file formats make no such distinction, but ParaView always uses one or the other, as it affects how the data are rendered. In fact if you experiment you will determine that certain filters will work in one case and not the other, or that other filters will work differently depending on whether the data are on the Points or the Cells. As an example, the *Contour* filter requires data on the Points, while the *Threshold* filter generally only gives the results you expect with the data on the Cells. You will see when opening an AIM file that in the Properties tab we have a couple of options, which are *Data on Cells* and *Pad*. This is shown in Figure 22. For this tutorial we want to select *Data on Cells*, which is the default.

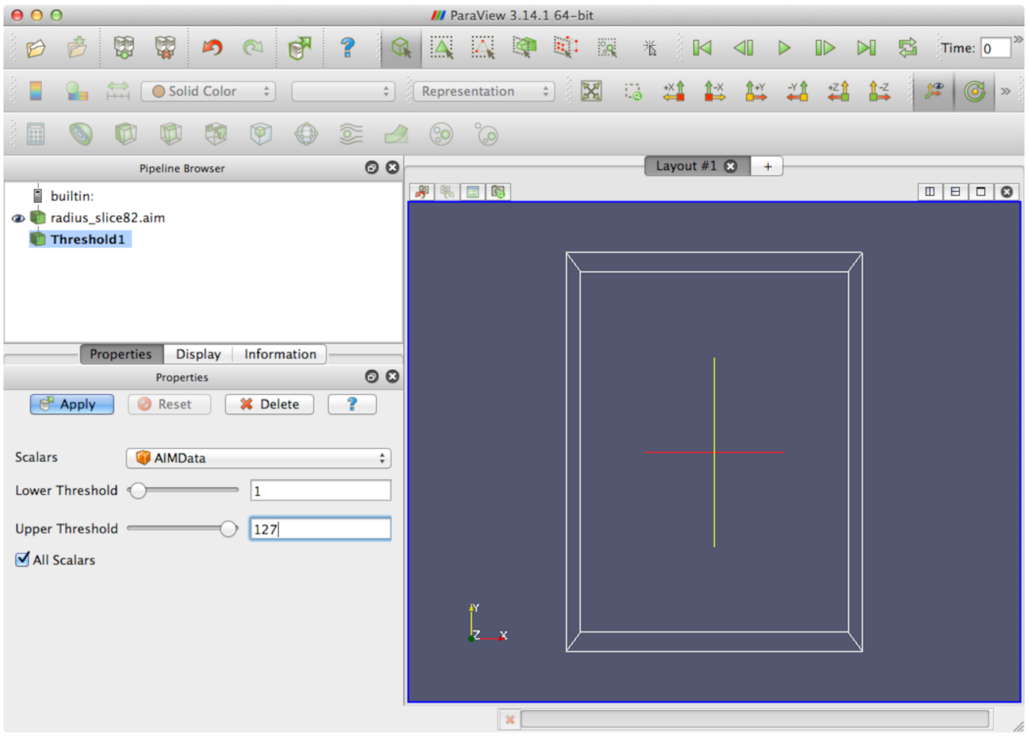


Properties

- [✓] Data on Cells
- [ ] Pad

Figure 7.8: Options when opening an AIM file.

Once you've opened the file `radius_slice82.aim` (or `radius_slice164.aim`) and clicked Apply, locate the icon for the Threshold filter on the toolbar. Change the Lower Threshold to 1 before clicking Apply, as shown in Figure 23; Scalars should be set to *AIMData*.



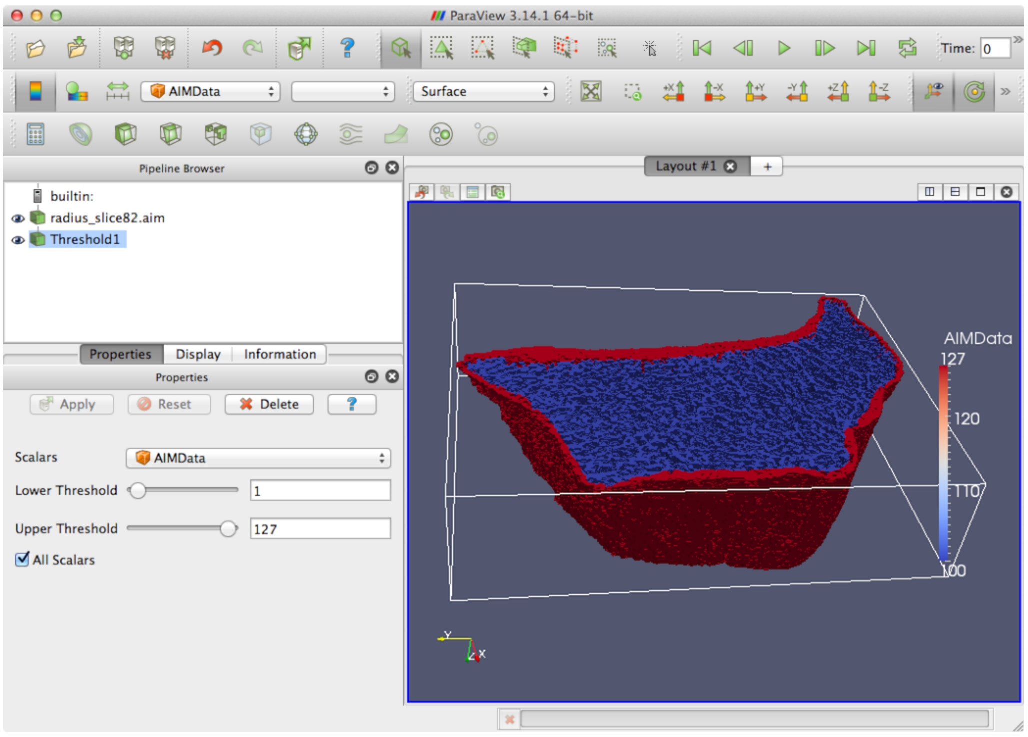
Properties

Scalars	AIMData
Lower Threshold	1
Upper Threshold	127

- [✓] All Scalars

Figure 7.9: The threshold filter.

Now change the *Representation* drop-down box to *Surface* and the *Color by* drop-down box to *AIMData*. Also turn on the legend by clicking the Toggle Color Legend Visibility button. After rotating the image (click and drag in the image window) to get a good viewing angle, this should look something like Figure 24. You can see that this data file has been segmented such that the cortical bone has material ID 127 and the trabecular bone has material ID 100.



Scalars AIMData
Lower Threshold 1
Upper Threshold 127
☑ All Scalars

Figure 7.10: Input image for the radius slice tutorial.

Generating the model

As before, we recommend copying the data file `radius_slice82.aim` into a temporary working directory. The command to generate the model is

```
n88modelgenerator --test=uniaxial radius_slice82.aim
```

The resulting model file will be named `radius_slice82_uniaxial.n88model`.

Note
Don't forget that before running `n88modelgenerator`, make sure that Faim is on the Path, as described in Section 1.4.2, and also that you have activated the Anaconda python environment for `n88tools`, as described in Section 1.4.4.

Before we solve it, we are going to examine this model file using n88modelinfo. You will find that n88modelinfo is a very useful tool for getting information about the models, and for tracing back how they were created and solved. n88modelinfo can be run like this,

```
n88modelinfo radius_slice82_uniaxial.n88model
```

n88modelinfo can generate quite a bit of output. We will shortly see how to reduce this to just the information that we are interested in. For now though, let's look at the complete output. Comments follow below the example output.

```
History:
-----------------------------------------------------------------
```

```
2016-Sep-15 14:49:17 Model created by n88modelgenerator version 8.0
----------------------------------------------------------------------

Log:
----------------------------------------------------------------------
2016-Sep-15 14:49:17
n88modelgenerator Version 8.0
Copyright (c) 2010-2016, Numerics88 Solutions Ltd.
Licensed to Numerics88 Solutions Ltd.; lic. no. 91

input_file   = radius_slice82.aim
output_file  = radius_slice82_uniaxial.n88model
connectivity_filter           = on
test                          = uniaxial
test_axis                     = z
normal_strain                 = -0.01
pin                           = off
top_surface                   = intersection
bottom_surface                = intersection
material_table                = homogeneous
youngs_modulus                = 6829
poissons_ratio                = 0.3

   0.02 Reading input data.
   0.05 Read 15849468 points.
   0.05 Image bounds:
        49.6920 76.3420 38.7040 74.5380 0.0000 9.0200
   0.05 Applying connectivity filter.
   0.66 Masked out 0 unconnected voxels.
   0.66 Converting to hexahedral mesh.
   1.56 Generated 2667590 hexahedrons.
   1.56 Constructing material table.
   1.86 Material table has 2 entries.
   1.86 Constructing finite element model.
   5.17 Model bounds:
        50.1020 76.0960 39.1140 74.2100 0.0000 9.0200
   5.17 Generated the following constraints:
          bottom_fixed : 40032 nodes
          top_displacement : 25991 nodes

----------------------------------------------------------------------

Active Settings:
----------------------------------------------------------------------
  Active Solution : None
  Active Problem : Problem1
  Active Part : Part1
----------------------------------------------------------------------

Materials:
----------------------------------------------------------------------

  Name : NewMaterial1
  Type : LinearIsotropic
  E : 6829.0
  nu : 0.3
----------------------------------------------------------------------

Parts:
----------------------------------------------------------------------

  Name : Part1
  NumberOfNodes : 3816642
  Hexahedrons :
    NumberOfNodesPerElement : 8
    NumberOfElements : 2667590
----------------------------------------------------------------------

Constraints:
----------------------------------------------------------------------

  Name : bottom_fixed
  Part : Part1
  Type : NodeAxisDisplacement
  NumberOfValues : 40032

  Name : top_displacement
  Part : Part1
  Type : NodeAxisDisplacement
  NumberOfValues : 25991

  Name : convergence_set
  Part : Part1
  Type : NodeAxisForce
  NumberOfValues : 25991
----------------------------------------------------------------------

NodeSets:
----------------------------------------------------------------------

  Name : face_z0
  Part : Part1
  NumberOfNodes : 40032

  Name : face_z1
  Part : Part1
  NumberOfNodes : 25991

  Name : face_x0
  Part : Part1
  NumberOfNodes : 15

  Name : face_x1
  Part : Part1
  NumberOfNodes : 14

  Name : face_y0
  Part : Part1
  NumberOfNodes : 27

  Name : face_y1
  Part : Part1
  NumberOfNodes : 17
----------------------------------------------------------------------

ElementSets:
----------------------------------------------------------------------

  Name : face_z0
  Part : Part1
  NumberOfElements : 28999

  Name : face_z1
  Part : Part1
```

```
    NumberOfElements : 21210

    Name : face_x0
    Part : Part1
    NumberOfElements : 8

    Name : face_x1
    Part : Part1
    NumberOfElements : 6

    Name : face_y0
    Part : Part1
    NumberOfElements : 12

    Name : face_y1
    Part : Part1
    NumberOfElements : 8
----------------------------------------------------------------------

Problems:
----------------------------------------------------------------------

    Name : Problem1
    Part : Part1
    Constraints : bottom_fixed,top_displacement
    ConvergenceSet : convergence_set
    PostProcessingNodeSets : face_z1,face_z0
    PostProcessingElementSets : face_z1,face_z0
----------------------------------------------------------------------

Solutions:
----------------------------------------------------------------------
----------------------------------------------------------------------
```

Some things to note about the output of n88modelinfo:

- The *History* is a useful field to see what programs were run to generate or modify the file, and when.
- The *Log* field is similar to the History, except that it gives far more detailed information. Of particular note is that n88modelgenerator reports its complete configuration, including all parameters values relevant to the particular test type, even ones which haven't been explicitly set, but are default values.
- This file hasn't been solved yet, so there is nothing in *Solutions*.
- The sets defined for post-processing are *face_z1* and *face_z0*, which are the top and bottom surfaces, respectively. We will need this information later to interpret the results in the analysis file.

Now, as mentioned, that is a lot of output. Often we are interested in just part of the output. In this case, we can specify the bits we want. For example, to get just the History and the Log, we could do this,

```
n88modelinfo --history --log radius_slice82_uniaxial.n88model
```

Tip

To discover what the valid arguments to n88modelinfo are, you can either refer to the manual (See Section 9.12), or you can run `n88modelinfo --help`.

Tip
If you want the output of n88modelinfo to be saved in a file, then run it like this

```
n88modelinfo radius_slice82_uniaxial.n88model > info.txt
```

This will direct the output of n88modelinfo to the file `info.txt`.

Solving the model

From the previous tutorial, we know that we can use faim to solve the model and perform so post-processing on it. faim itself actually just calls three other programs to carry out the actual work. Usually it's easiest to call faim, but in this tutorial we are going to call the individual processing programs ourselves, so we can understand what faim is doing.

The first step carried out by faim is to solve the model with n88solver_slt, which we can do with

```
n88solver_slt radius_slice82_uniaxial.n88model ❶
```

❶ The specification `slt` for the solver means that this is the solver for *small strain*, *linear* problems_, using a *material table*.

Tip
This model will take some time to solve. If you have licensed the GPU solvers, and have suitable hardware, then you probably would like to jump right into using the GPU hardware. To do this, specify the engine and device. For example, for a system with two compute-capable NVidia cards, including the one being used for the display, the command would be:

```
n88solver_slt --engine=nv --device=0,1 radius_slice82_uniaxial.n88model
```

If you have a system where the compute GPUs are distinct from the video card used for the display, such as is typical for nVidia Tesla hardware, then the correct device option for two compute-capable NVidia cards is more likely to be `--device=1,2` .

We can see how this has modified the `n88model` file by running n88modelinfo again. To avoid the lengthy complete output, here we use arguments that show only the sections that have in fact changed

```
n88modelinfo --history --log --solutions radius_slice82_uniaxial.n88model
```

The output is:

```
History:
----------------------------------------------------------------------
2016-Sep-15 14:49:17 Model created by n88modelgenerator version 8.0
2016-Sep-15 15:22:54 Solved by n88solver_slt 8.0
----------------------------------------------------------------------

Log:
----------------------------------------------------------------------
2016-Sep-15 14:49:17
n88modelgenerator Version 8.0
Copyright (c) 2010-2016, Numerics88 Solutions Ltd.
Licensed to Numerics88 Solutions Ltd.; lic. no. 91

input_file   = radius_slice82.aim
output_file  = radius_slice82_uniaxial.n88model
connectivity_filter            = on
test                           = uniaxial
test_axis                      = z
normal_strain                  = -0.01
pin                            = off
top_surface                    = intersection
```

```
bottom_surface                = intersection
material_table                = homogeneous
youngs_modulus                = 6829
poissons_ratio                = 0.3

   0.02 Reading input data.
   0.05 Read 15849468 points.
   0.05 Image bounds:
        49.6920 76.3420 38.7040 74.5380 0.0000 9.0200
   0.05 Applying connectivity filter.
   0.66 Masked out 0 unconnected voxels.
   0.66 Converting to hexahedral mesh.
   1.56 Generated 2667590 hexahedrons.
   1.56 Constructing material table.
   1.86 Material table has 2 entries.
   1.86 Constructing finite element model.
   5.17 Model bounds:
        50.1020 76.0960 39.1140 74.2100 0.0000 9.0200
   5.17 Generated the following constraints:
          bottom_fixed : 40032 nodes
          top_displacement : 25991 nodes

2016-Sep-15 15:22:54
n88solver_slt version 8.0
Copyright (c) 2010-2015, Numerics88 Solutions Ltd.
Licensed to Numerics88 Solutions Ltd.; lic. no. 91
Problem:
  active solution       = (none)
  active problem        = Problem1
  number of elements    = 2667590
  number of nodes       = 3816642
Solver engine:
  engine                = nv
  precision             = double
  devices               = 0
Convergence parameters:
  convergence measure   = set
  convergence tolerance = 1e-06
  convergence window    = 312
  maximum iterations    = 30000
Convergence measure tolerance reached.
Number of linear iterations = 2761
Peak data allocation (system, device): 872 MiB, 692 MiB
----------------------------------------------------------------------

Solutions:
----------------------------------------------------------------------

  Name : Solution1
  Problem : Problem1
  Variables defined on nodes:
    Displacement
----------------------------------------------------------------------
```

Note things are worth noting here. In the *Log* section, we now have a record of the complete configuration of the solver (in this case, it happens to be default values). And in the *Solutions* section, we now have a solution (“Solution1”) with a field defined on the nodes, namely *Displacements*.

Evaluating the accuracy of the solution

Faim includes a tool that can be used to evaluate the accuracy of the obtained solutions. This is discussed in the section Evaluating solution quality. It can be run like this:

```
n88evaluate radius_slice82_uniaxial.n88model
```

Warning
The `n88evaluate` tool in its current implementation requires far more memory than the solver itself does. For this example, it will use almost 60GB of memory, while the solver needed less than 2GB. Therefore, currently, **you should not attempt to run this part of the tutorial on a machine with less than 64GB of RAM** .

The output is,

```
Analysis of solution displacements at boundary conditions:
    max err           : 0.00E+00
    rms err           : 0.00E+00

Analysis of forces (residuals):
    max err           : 1.28E-05
    rms err           : 9.35E-07
    max err/max force : 9.26E-06
    rms err/max force : 6.79E-07
```

The meaning of these results is discussed the section Evaluating solution quality; briefly we can take the number `rms err/ max force` as a measure of the relative error. Here it is 7×10^{-7}, which is acceptably small.

Obtaining additional solution fields with n88derivedfields

So far our solution consists only of displacements. Many other values are of interest, for example strains and stresses. These are calculated with n88derivedfields. It can be run very simply as,

```
n88derivedfields radius_slice82_uniaxial.n88model
```

Now let's have a look at what's in the model file, using again n88modelinfo,

```
n88modelinfo --history --solutions radius_slice82_uniaxial.n88model
```

The output is:

```
History:
----------------------------------------------------------------------
2016-Sep-15 14:49:17 Model created by n88modelgenerator version 8.0
2016-Sep-15 15:22:54 Solved by n88solver_slt 8.0
2016-Sep-15 15:27:58 Processed by n88derivedfields 8.0
----------------------------------------------------------------------

Solutions:
----------------------------------------------------------------------

  Name : Solution1
  Problem : Problem1
  Variables defined on nodes:
    Displacement
    ReactionForce
  Variables defined on elements:
    Strain
    Stress
    StrainEnergyDensity
    VonMisesStress
----------------------------------------------------------------------
```

We have a number of new solution fields (or variables). Some are defined on the nodes and some defined on the elements. For details on these fields, see Section 9.5.

Important
Even if you are not interested in the numerical values of the fields added by n88derivedfields, they are required by n88postfaim. Running the latter requires first running the former.

Using n88postfaim to generate the analysis file

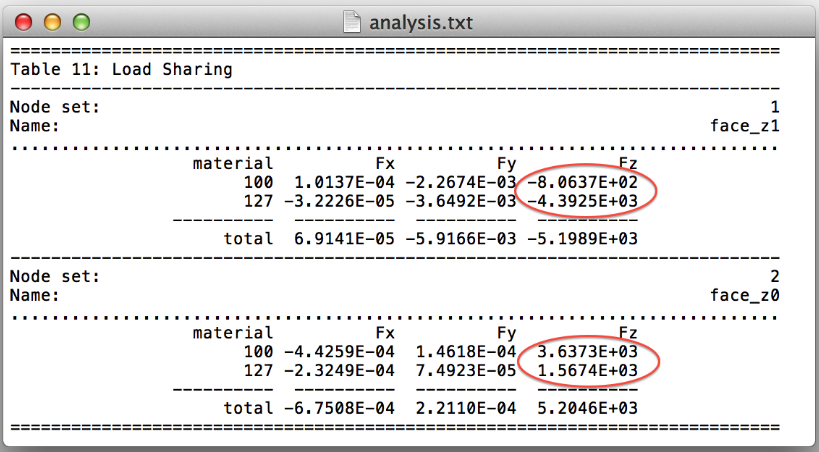
The final step performed by faim is to call n88postfaim, which does post-processing analysis. In the previous tutorial we saw that an analysis file was generated, which is a text file with a number of tables summarizing the numerical results. It is n88postfaim that generates this text file. To run it on an `n88model` file that contains all the solution fields is once again straightforward in most cases,

```
n88postfaim -o analysis.txt radius_slice82_uniaxial.n88model
```

Note that unlike the previous commands, for n88postfaim we actually have to specify an output file with `-o analysis.txt`. (If we don't, then the output will just be printed to the terminal.) The faim command, which combines `n88solver_slt`, `n88derivedfields`, and `n88postfaim`, would have automatically generated the filename `radius_slice82_uniaxial_analysis.txt` in this case, but that is getting a little bit lengthy, so we'll just use `analysis.txt` here.

Determining load sharing distribution with n88postfaim

We already saw some of the values in the analysis file in the previous tutorial. For this tutorial, we are going to have a look at table Load Sharing, as shown in Figure 25. We see that this table breaks up the total load on each node set according to material ID. In this case, we have material ID 127 being cortical bone, and material ID 100 being trabecular bone. Recall that the material properties are not different; it is merely a different labelling. Here we will see the reason for doing this. Recall also that the sets defined for post-processing are the top and the bottom surfaces. (If you're not sure of this then the command `n88modelinfo --problems radius_slice82_uniaxial.n88model` will show you.) Because of the alignment in the CT scanner, in this case the top surface is proximal, and the bottom surface is distal. Referring to the values circled in red in Figure 25, we conclude that on the proximal surface of this radius bone slice, the proportion of the load carried by the trabecular bone is (-806) / (-5199) = 15.5%, while on the distal surface of the slice the proportion of the load carried by the trabecular bone is (3637) / (5199) = 70.0%.



```
==============================================================================
Table 11: Load Sharing
------------------------------------------------------------------------------
Node set:                                                                    1
Name:                                                                  face_z1
..............................................................................
                   material          Fx          Fy          Fz
                        100  1.0137E-04 -2.2674E-03 -8.0637E+02
                        127 -3.2226E-05 -3.6492E-03 -4.3925E+03
                ----------- ----------- ----------- -----------
                      total  6.9141E-05 -5.9166E-03 -5.1989E+03
------------------------------------------------------------------------------
Node set:                                                                    2
Name:                                                                  face_z0
..............................................................................
                   material          Fx          Fy          Fz
                        100 -4.4259E-04  1.4618E-04  3.6373E+03
                        127 -2.3249E-04  7.4923E-05  1.5674E+03
                ----------- ----------- ----------- -----------
                      total -6.7508E-04  2.2110E-04  5.2046E+03
==============================================================================
```

Figure 7.11: Load Sharing table in analysis file.

Enabling compression for large model files

The `n88model` file format supports compression internally and transparently. An `n88model` which contains compressed data can be read with every N88 tool just like any other `n88model`, without the need for the user to explicitly de-compress the data. Compression is not used by default, because it does have an increased calculation overhead for reading and writing (particularly for writing). However, once we are finished with processing the model, we typically want to keep the data around for archival purposes. It is recommended to compress the `n88model` files for archiving. This can be done with the n88compress tool, as follows,

```
n88compress radius_slice82_uniaxial.n88model
```

For this data file, enabling compression reduces its size from 438 MB to 226 MB, a reduction of 47%.

This ends the tutorial on a compression test on a radius bone slice. We were introduced to n88modelinfo, we solved a realistic model, we looked at using the residuals to evaluate the quality of the solution, we saw how to do load distribution calculations, and finally we learned how to enable compression to more efficiently store large `n88model` files.

Tutorial: Bending test of a radius bone with an uneven surface

In the previous two tutorials, we had input images where the object in the image intersected the top and bottom bounds of the image, thus forming nice flat surfaces to which we could apply boundary conditions. This won't always be the case. In this tutorial we'll look at an object with a very uneven surface.

In detail, this tutorial will demonstrate:

- How to use the uneven surface parameters of n88modelgenerator.
- How to use n88extractsets to examine our boundary conditions.

The data file is `radius82.aim`. As for the previous tutorial, there is also a reduced resolution version, `radius164.aim`. This data is particularly large, with the unreduced version having a size of 400×350×1100, or 154 million voxels; the resulting finite element model will have 14 million elements.

The input image is shown in Figure 26.

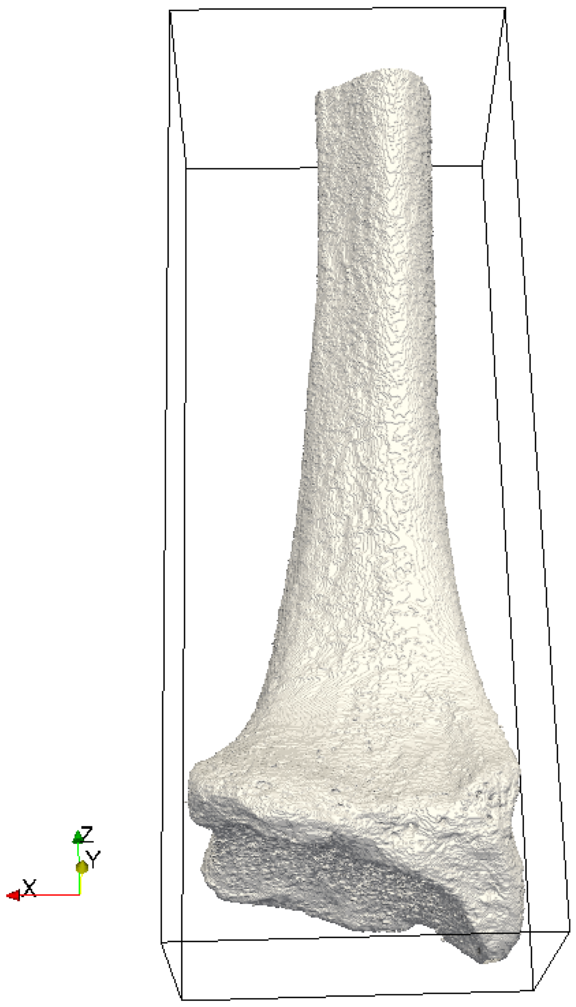


Figure 7.12: Radius bone image for bending test.

Tip

In this tutorial, we are no longer going to go into detail on how to load and render data in ParaView, as we did in the previous two tutorials. If you're curious about how we generated that image of the radius bone from the image file, these are the steps:

1. Open the `radius82.aim`, and before clicking Apply, deselect Data on Cells
2. Add a Contour filter. The default contour value (63.5) is fine.
3. In View Options, add a Headlight with value 0.06.

Generating the model with n88modelgenerator

We are going to apply a bending test, as described in Bending test. In order to identify the rough head of the bone as a boundary surface, we use the option bottom_surface=visible. As it implies, it will select nodes that are visible from a certain point of view. In this case, visible means "looking up from below" (effectively from an infinite distance, as parallel rays are used). Note that the distal head of the bone is in the "bottom" of the image, that is at smaller values of *z*. With this option, you can imagine that we might "see" parts of the object that are far away if they are not obscured by the foreground part of the image. We don't want these distant parts of the object to form part of our boundary set, so when we use the bottom_surface=visible option, we nearly always want to set a depth limit as well using bottom_surface_maximum_depth. In this case a suitable limit is 15 (units are the same as the image units, which are millimeters in this case). In general there may be a bit of experimentation to get the best depth limit.

Since we have several parameters that we want to specify, it will be more convenient to create a configuration file for n88modelgenerator than to specify them individually on the command line, as we have done previously. To do this, open a text editor, and create the following file. Save it to your working directory as `radius_bending_test.conf`.

```
# File: radius_bending_test.conf
#
# A configuration file for the radius bending tutorial.

input_file                    = radius82.aim
test                          = bending
bottom_surface                = visible
bottom_surface_maximum_depth  = 15
```

Lines starting with # are comment lines: any line starting with # is ignored.

We can now run n88modelgenerator by specifying only the configuration file to use:

```
n88modelgenerator --config radius_bending_test.conf
```

Tip
Some text editors automatically add a `.txt` file extension. You can either subsequently rename the file, or just accept the `.txt` ending and everywhere in this tutorial use the actual complete file name. Even more confusing can be that many operating systems by default hide the file extension in the file browser, so that you may save a file as `radius_bending_test.conf`, and the file browser in your operating system shows it with this name, but its complete name is actually `radius_bending_test.conf.txt`. The complete name must be specified to all Numerics88 tools.

Using n88extractsets to obtain and visualize boundary conditions

Because this is a non-trivial boundary set, we really want to visualize it to make sure it is reasonable and that it corresponds to what we expect. The best way to do this is with the tool n88extractsets. This is the command to use:

```
n88extractsets --constraints radius82_bending.n88model
```

Here “--constraints” means both boundary conditions and applied loads. (We can leave off this option, but then we will get even more output files which in the present case we are not interested in.)

The output looks like this:

```
Reading N88 Model file : radius82_bending.n88model
Writing constraint : radius82_bending_constraint_bottom_fixed.vtp
Writing constraint : radius82_bending_constraint_top_fixed.vtp
Writing constraint : radius82_bending_constraint_top_displacement.vtp
Writing constraint : radius82_bending_constraint_bottom_displacement.vtp
```

We see that four files are generated, one for each constraint. These are VTK “PolyData” files, which consist of a set of “Vertices” (points), one for each node in the boundary condition set. n88modelgenerator has separated the “fixed” constraints, which are degrees of freedom that are fixed at zero, and the “displacement” constraints, which are degrees of freedom that are fixed at some non-zero value. This distinction is sometimes useful, although the solver does not require it. In this case the nodes belonging to the constraint or boundary condition have *x* and *y* fixed at zero, and *z* at non-zero values. Thus the “fixed” and “displacement” sets will consist of the same set of nodes, but with different senses and values. We are going to open the file `radius82_bending_constraint_bottom_displacement.vtp` displacement and render it together with the contoured input image. This is shown in Figure 27. Each individual node belonging to the boundary condition is shown as a blue dot.

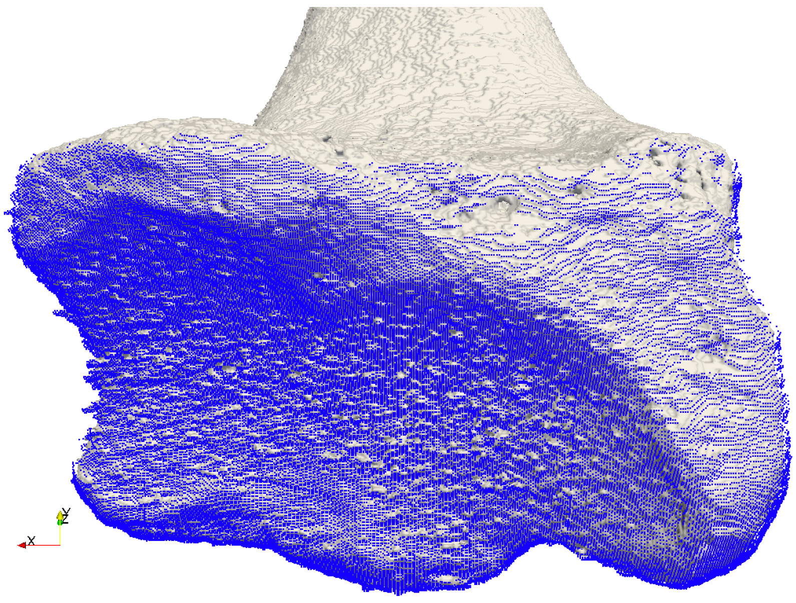


Figure 7.13: Set of nodes on bottom boundary condition for radius bone bending test.

Tip

Generating this image is quite straightforward. We start with the contoured input image data, as above, then we also open the file `radius82_bending_constraint_bottom_displacement.vtp`, and simply render it as “Solid Color”, setting the color to blue.

This looks good so we can go ahead and solve this model with faim. Expect this to take a while - go grab a coffee.

```
faim radius82_bending.n88model
```

Tip

Just as in the previous model, if you have licensed the GPU solvers, and have suitable GPU hardware, then you are going to want to use it. faim can take all the arguments that n88solver can so for example:

```
faim --engine=nv --device=0,1 radius82_bending.n88model
```

where as before the device list will depend on the number of GPUs in your system and their configuration .

As this is a very large file, once solved we should enable compression as in the previous tutorial. Compression can take a rather long time on a file this large. Remember that it is never necessary to uncompress an n88model file before reading it.

```
n88compress radius82_bending.n88model
```

A comparison of the original input image with the solved model is shown in Figure 28. Here we have used a Warp By Vector filter with a Scale Factor of 15 to make the distortion more evident to the eye.

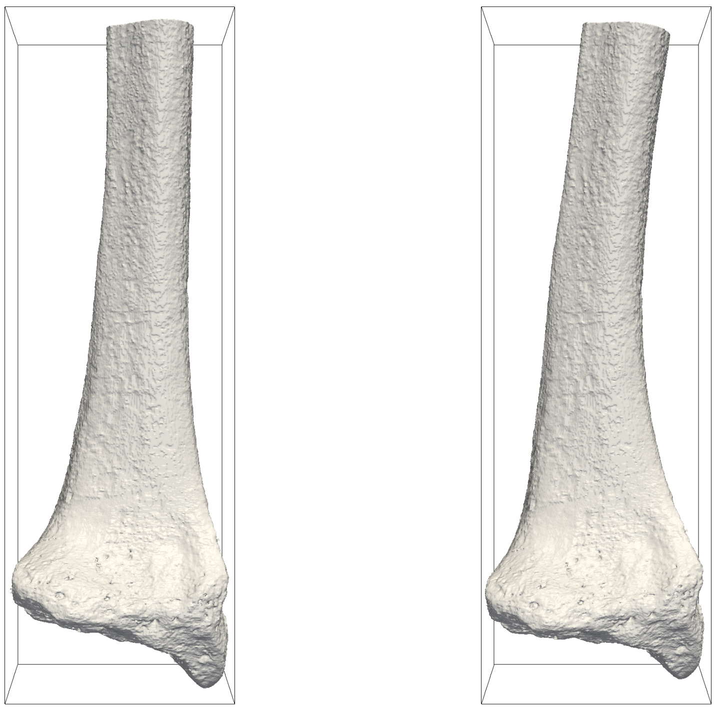


Figure 7.14: Comparison of original input and solved model of bending radius bone, with 15 times displacement amplification.

Tip
Generating an attractive rendering of the solved model (or any `n88model` file) with ParaView takes a few additional steps. We saw that with an input image, we could use the Contour filter to get a nice surface with curvature that reflects the light in ways that give us visual clues about the shape of the object. An `n88model` file by contrast consists of a collection of cubic voxels, each of which has flat surfaces (however small they may be), all oriented the same. A direct rendering of it therefore lacks the visual lighting cues that we expect. With a few additional steps, we can convert it to a smooth surface with curvature. For Figure 28 we applied the following steps (to the result of the Warp By Vector filter):

1. Apply an Extract Surface filter. This converts the data from an Unstructured Grid (in this case a bunch of Hexahedrons) to a surface consisting of Polygons.
2. Apply a Smooth filter with Number of Iterations set to 300.

Another useful way to render this data is coloured by von Mises stress. See VonMisesStress. This is shown in Figure 29.

Tip
You will want to manually set the scale of the coloring for von Mises stress, as the uneven contact surface has locally very high stresses, which however are uninteresting (and even unphysical, as the microscopic contact surface irregularities would yield). You can adjust the range by selecting Color Map Editor from the View menu, then click on the Rescale to Custom Range button to the left of the color map plot.

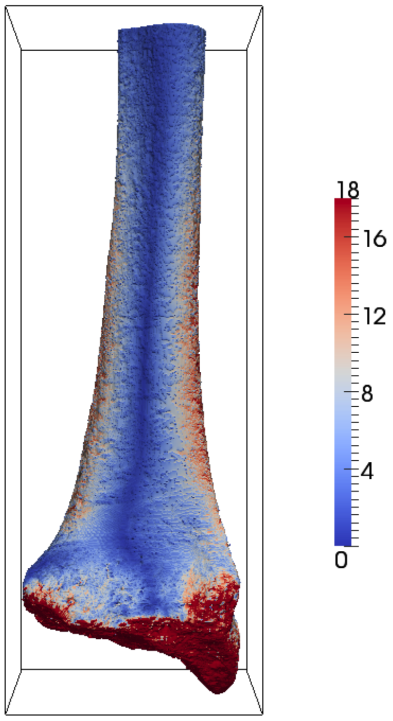
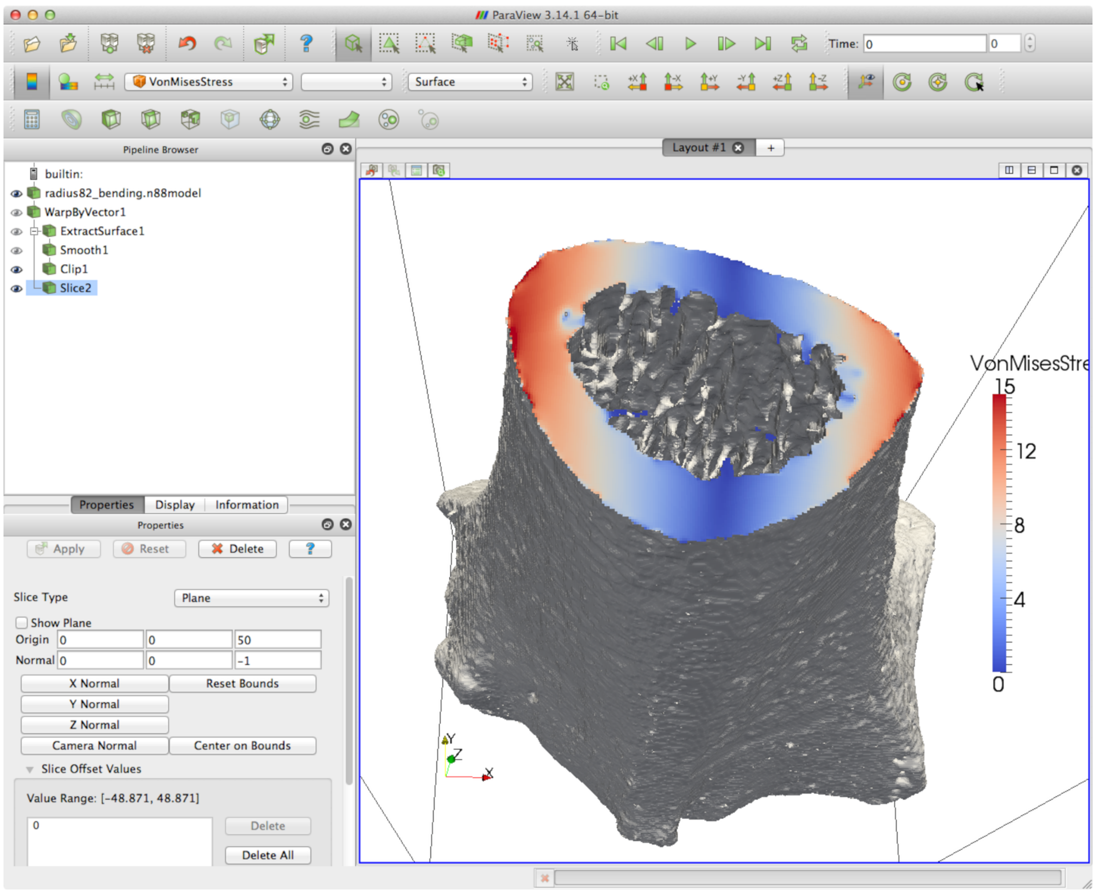


Figure 7.15: Radius in bending test with coloring by von Mises stress

Showing the von Mises stress as in Figure 29 is informative, but only indicates the stress on the visible surfaces. Often we will want to look at the stresses within the volume. One way to do this is with a Slice filter. This is shown in Figure 30. Without going into a great deal of detail, you can see the filters used in this rendering in the Pipeline Browser.

Tip

The Slice filter should be used on volume data, and not on surface data. Notice that in Figure 29 we've applied the Slice filter to the output of WarpByVector1, and not to ExtractSurface1 or anything derived from it.



VonMisesStress
Surface

builtin:
radius82_bending.n88model
WarpByVector1
ExtractSurface1
Smooth1
Clip1
Slice2

Slice Type: Plane
Show Plane
Origin: 0 0 50
Normal: 0 0 -1
Slice Offset Values
Value Range: [-48.871, 48.871]
0

Figure 7.16: von Mises stress on a slice of the radius in bending test

Numerical results

The interesting quantity in the analysis file `radius82_bending_analysis.txt` (see the section on post-processing with n88postfaim) is the torque around the bending axis, which in this case is in the *y* direction. Refer to Figure 8. This quantity is given as the `total` of `Ty` in the following table from `radius82_bending_analysis.txt`. By default, this is calculated around the center of mass of the object, although you can re-run n88postfaim and specify an argument for the argument rotation_-center if you want the torques calculated around an axis passing through a different point. Because the head of the bone is "down" in the sense of smaller *z*, `face_z0` is the head of the bone, and `face_z1` is the cut face of the shaft. In any case, we can see that the torques balance. The numerical value of the *y* compenent of the torque is 1997 N·mm (see A note about units), or 1.997 N·m.

```
========================================================================
Table 11: Nodal Torques
-----------------------------------------------------------------------
Torque measured relative to:                        60.502 94.130 48.216
-----------------------------------------------------------------------
Node set:                                                              1
Name:                                                            face_z1
........................................................................
                  Tx          Ty          Tz
total       -1.213E+02 -1.997E+03 -1.928E+01
average     -1.099E-02 -1.810E-01 -1.747E-03
std_dev      1.134E-01  1.252E-01  2.173E-02
minimum     -6.034E-01 -5.249E-01 -9.884E-02
maximum      3.538E-01  4.623E-01  6.071E-02
median      -8.431E-03 -1.915E-01  4.481E-05
```

```
--------------------------------------------------------------------------
Node set:                                                                2
Name:                                                              face_z0
...........................................................................
                   Tx          Ty          Tz
total       1.215E+02  1.996E+03  1.927E+01
average     1.601E-03  2.630E-02  2.538E-04
std_dev     1.591E+00  5.163E+00  9.762E-01
minimum    -3.176E+01 -2.068E+01 -2.480E+01
maximum     2.722E+01  8.554E+01  2.405E+01
median     -2.631E-02 -7.920E-01 -1.935E-02
===========================================================================
```

Tutorial: Radius bending with elasto-plastic material properties

In this tutorial, we are going to repeat the radius bending test of the previous tutorial, but this time we will use nonlinear elasto-plastic material properties. We recommend that you first read the section on Plasticity.

Creating the model

Because nonlinear models take substantially longer to solve than linear models, for this tutorial we are going to use the reduced-resolution image file `radius164.aim`. However, if you have the processing power and the time to obtain solutions, and you want to use the original resolution file `radius82.aim`, you can of course do so.

Creating a model with elasto-plastic material properties with `n88modelgenerator` is straight-forward: one simply has to set the plasticity option. For example, the following configuration file is similar to the one in the last tutorial, but we have added `plasticity =vonmises,10`. This means that we want a *von Mises* yield criterion (see von Mises yield criterion) with a yield strength of 10 MPa. There is no scientific justification for choosing this numerical value for the yield strength: it was chosen simply because it produces interesting results for this tutorial.

```
# File: radius_bending_elastoplastic.conf
#
# A configuration file for the tutorial: radius bending with
# elasto-plastic material properties.

input_file       = radius164.aim
output_file      = radius_bending_elastoplastic.n88model
test                          = bending
bottom_surface                = visible
bottom_surface_maximum_depth  = 15
plasticity                    = vonmises,10
```

As before, we generate the model with

```
n88modelgenerator --config radius_bending_elastoplastic.conf
```

We can verify that the resulting model file has elasto-plastic material definitions using the handy n88modelinfo command,

```
n88modelinfo --materials radius_bending_elastoplastic.n88model
```

The output is

```
Materials:
---------------------------------------------------------------------

  Name : NewMaterial1
  Type : VonMisesIsotropic
  E : 6829.0
  nu : 0.3
  Y : 10.0
----------------------------------------------------------------------
```

Solving the model

We can solver the model with faim,

```
faim radius_bending_elastoplastic.n88model
```

Tip
As before, if you have licensed the GPU solvers, and have suitable GPU hardware, then you are going to want to use the engine and device options to obtain faster solutions.

Let us look into the file to see what fields are present for a solved elasto-plastic model. The command to list the solutions is, as before,

```
n88modelinfo --solutions radius_bending_elastoplastic.n88model
```

this gives an output of

```
Solutions:
----------------------------------------------------------------------

  Name : Solution1
  Problem : Problem1
  Variables defined on nodes:
    Displacement
    ReactionForce
  Variables defined on elements:
    PlasticStrain
    Strain
    Stress
    StrainEnergyDensity
    VonMisesStress
  Variables defined on gauss points:
    PlasticStrain
----------------------------------------------------------------------
```

Everything here is as before for linear solutions, with the addition of a new field `PlasticStrain`. `PlasticStrain` is the irreversible strain that arises from exceeding the elastic limits as defined by the yield surface. See PlasticStrain in the section Calculating additional solution fields with n88derivedfields. You may also note that *variables defined on gauss points* is a new category. In essence, this is a higher accuracy version of *variables defined on elements*, and it is required for accurately processing elastoplastic models.

Rendering yielded elements

We can use ParaView to open the solved model file `radius_bending_elastoplastic.n88model`. In Figure 33 we've rendered the surface of the model such that unyielded elements are shown in grey, while yielded elements are shown in red. For elasto-plastic materials, there is a clear distinction between elements that remain within the elastic limits and therefore have zero plastic strain, and those which have exceeded the elastic limits and have non-zero plastic strain. (where non-zero means that at least one of the 6 components *xx*, *yy*, *zz*, *yz*, *zx* and *xy* of the plastic strain is non-zero). In order to generate the rendering of Figure 33 we set the *Coloring* to the *Magnitude* of *PlasticStrain*. You can find these in drop-down boxes in the toolbar in ParaView, as shown in Figure 31. Next we will manually set a tiny range for the color scale, thus ensuring that practically every element that is yielded is shown in fully saturated red. If we set a symmetric scale around zero, then unyielded elements, which have a *PlasticStrain* magnitude of zero, will be drawn in a neutral gray. To set the color scale, click Rescale to Custom Data Range, which is just to the left of the drop-down box for *PlasticStrain*, as shown in Figure 32. For this rendering I used a range of -0.00001 to 0.00001 . Note that in Paraview, the *Magnitude* of the *PlasticStrain* is simply the square root of the sum of the squares of the 6 components of plastic strain. This quantity has no physical interpretation, but it is useful for distinguishing yielded and unyielded elements, as here.

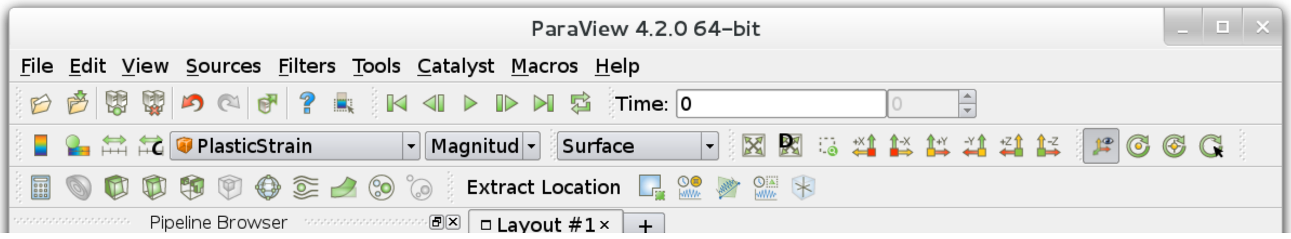


Figure 7.17: Setting the color display to the Magnitude of PlasticStrain.

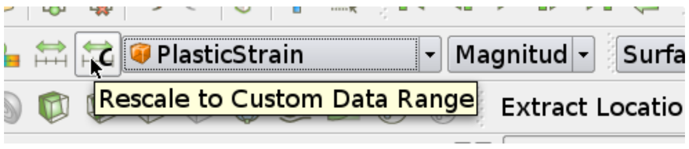


Figure 7.18: The Rescale to Custom Data Range button.

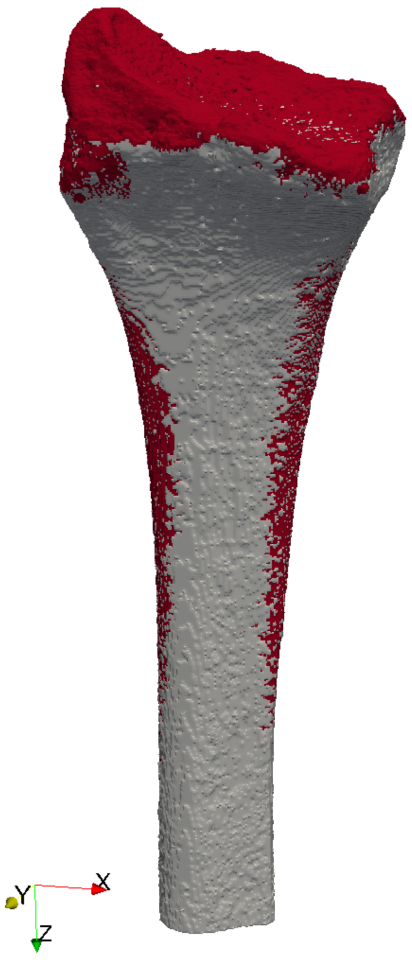


Figure 7.19: Bending radius test with elasto-plastic material properties. Yielded elements are shown in red.

What we observe in Figure 33 rendering is that there are essentially three regions of plastic deformation in this bone subject to a bending force. They are,

- The uneven head of the bone. This region yields fundamentally because the deformation is applied here, and the surface is rough. Rough surfaces yield easily in localised spots: crudely speaking, you don't have to push very hard on a pointy little protusion to bend it. This yielding is uninteresting, and if you were to slice the model here, you would find that the yielding is superficial, that is, not very deep.
- On the inside surface of the bend, the bone yields in compression.
- On the outside surface of the bend, the bone yields in tension.

You can't actually tell from Figure 33 what is yielding in compression and what in tension, but with a little bit of more manipulation, we can generate an image that does show this. Since we know *a priori* that the tension and compression on the sides of the bone shaft will be predominantly in the *z* direction, we can change the component of *YieldStrain* from *Magnitude* to *ZZ*. (You may need to manually re-adjust the color scale, as ParaView will automatically rescale to the data range when you change the variable for the color.) Elements yielded in compression now show as blue, as in Figure 34. We have in addition used a *Slice* filter, as in the previous tutorial. This allows us to see that the yielded region is rather thick.

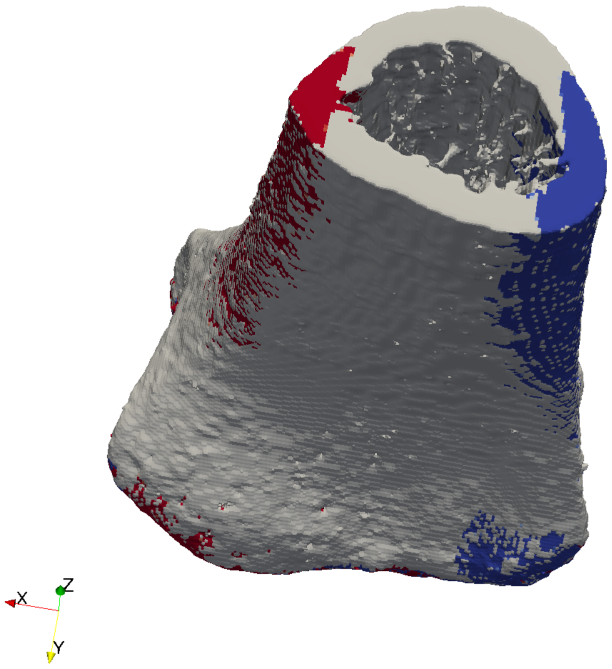


Figure 7.20: A slice through the radius. Yielded elements are shown in red for elements yielded in tension, and in blue for elements yielded in compression.

Numerical results

In comparison with the linear case, the *y* component of the torque has dropped about 1.5%, from 1.997 N·m to 1.968 N·m; hence a decrease in stiffness of 1.5%. In conclusion, this amount of plasticity has not significantly affected the results.

```
==========================================================================
Table 12: Nodal Torques
--------------------------------------------------------------------------
Torque measured relative to:                          60.546 94.150 48.216
--------------------------------------------------------------------------
Node set:                                                                1
Name:                                                              face_z1
..........................................................................
                  Tx         Ty         Tz
total      -1.066E+02 -1.967E+03 -3.557E+01
average    -3.555E-02 -6.560E-01 -1.186E-02
std_dev     4.106E-01  4.849E-01  7.938E-02
minimum    -1.796E+00 -1.831E+00 -2.889E-01
maximum     1.024E+00  1.301E+00  1.671E-01
median     -3.379E-02 -6.803E-01 -2.385E-03
--------------------------------------------------------------------------
Node set:                                                                2
Name:                                                              face_z0
..........................................................................
                  Tx         Ty         Tz
total       1.072E+02  1.968E+03  3.570E+01
average     5.497E-03  1.009E-01  1.831E-03
std_dev     2.888E+00  5.542E+00  1.195E+00
```

```
minimum    -2.380E+01 -2.593E+01 -9.494E+00
maximum     2.158E+01  4.561E+01  1.482E+01
median     -1.126E-01 -1.084E+00  1.470E-02
============================================================================
```

A more careful calculation: incrementally applying the load

There are always more subtle considerations for nonlinear calculations than for linear calculations. One aspect of elasto-plastic calculations is that they exhibit hysteresis, or irreversible changes to strain. In this way, the solutions depend in fact, not only on the current applied state, but in principle on the whole time-dependent history.

Whether this is significant or not in practice is something that can be investigated experimentally - or rather computationally in our case. In the present case, we already know that there is only a 1.5% difference in numerical results between the linear model and the elastoplastic model. So this more careful method of applying the load in the nonlinear case is very unlikely to result in significant differences in the result. This tutorial is therefore more of a demonstration of principle, and an introduction to the possibility of modifying already-solved `n88model` files.

To apply the bending in increments, we will take advantage of the fact that n88modegenerator can accept an existing `n88model` file as input. In this case, it will preserve the grid, *i.e.* the points and elements of the model, but generate new boundary conditions and/or material definitions. Crucially, it also preserves an existing solution, which is then automatically used as the starting value when the solver is subsequently called.

We are first going to make a configuration file containing all the parameters of n88modegenerator that are the same for each increment of bending.

```
# File: common.conf
#
# A configuration file for the tutorial: radius bending with
# elast-plastic material properties.
#
# This file contains all the parameters that don't change on
# each increment of bending.

test = bending
bottom_surface = visible
bottom_surface_maximum_depth = 15
plasticity = vonmises,10
```

Now we are going to call n88modegenerator and faim multiple times, in steps of 0.1°, from bending angle 0.6° up to bending angle 1.0°. 0.6° is chosen as a the starting angle because it happens to be just after the onset of nonlinear behaviour. In general, it takes a bit of experimentation to find the minimum applied test condition for which some elements start to exceed the linear region.

Here are the commands. You may want to put these into a script file.

```
n88modelgenerator --conf=common.conf --bending_angle=0.6 radius164.aim  ↩
    incremental_bending_0.6.n88model
n88solver_spt incremental_bending_0.6.n88model
n88modelgenerator --conf=common.conf --bending_angle=0.7 incremental_bending_0.6.n88model  ↩
    incremental_bending_0.7.n88model
n88solver_spt incremental_bending_0.7.n88model
n88modelgenerator --conf=common.conf --bending_angle=0.8 incremental_bending_0.7.n88model  ↩
    incremental_bending_0.8.n88model
n88solver_spt incremental_bending_0.8.n88model
n88modelgenerator --conf=common.conf --bending_angle=0.9 incremental_bending_0.8.n88model  ↩
    incremental_bending_0.9.n88model
n88solver_spt incremental_bending_0.9.n88model
n88modelgenerator --conf=common.conf --bending_angle=1.0 incremental_bending_0.9.n88model  ↩
    incremental_bending_1.0.n88model
n88solver_spt incremental_bending_1.0.n88model
```

Once we have run all of these commands, we can verify that the final data file, `incremental_bending_1.0.n88model`, does indeed show the history of being processed multiple times:

```
n88modelinfo --history incremental_bending_1.0.n88model
```

This gives an output of:

```
History:
----------------------------------------------------------------------
2016-Sep-27 12:53:47 Model created by n88modelgenerator version 8.0
2016-Sep-27 13:09:03 Solved by n88solver_spt 8.0
2016-Sep-27 13:09:07 Model modified by n88modelgenerator version 8.0
2016-Sep-27 13:21:12 Solved by n88solver_spt 8.0
2016-Sep-27 13:21:16 Model modified by n88modelgenerator version 8.0
2016-Sep-27 13:33:43 Solved by n88solver_spt 8.0
2016-Sep-27 13:33:47 Model modified by n88modelgenerator version 8.0
2016-Sep-27 13:46:27 Solved by n88solver_spt 8.0
2016-Sep-27 13:46:31 Model modified by n88modelgenerator version 8.0
2016-Sep-27 14:03:09 Solved by n88solver_spt 8.0
----------------------------------------------------------------------
```

As usual, the details can be recovered with the `--log` options of n88modelinfo, but the output is lengthy, so we will not show it here.

To perform the post-processing on the final result, we call,

```
n88derivedfields incremental_bending_1.0.n88model
n88postfaim incremental_bending_1.0.n88model
```

Numerically, the results have changed little in this case, as expected. We now have a *y*-component of torque of 1.972 N·m, which compares with 1.997 N·m in the linear case, and 1.968 N·m for the “all at once” elastoplastic case.

```
============================================================================
Table 12: Nodal Torques
----------------------------------------------------------------------------
Torque measured relative to:                            60.546 94.150 48.216
----------------------------------------------------------------------------
Node set:                                                                  1
Name:                                                                face_z1
............................................................................
                   Tx          Ty          Tz
total      -1.116E+02 -1.972E+03 -4.279E+01
average    -3.723E-02 -6.579E-01 -1.427E-02
std_dev     4.146E-01  4.921E-01  7.945E-02
minimum    -1.818E+00 -1.874E+00 -2.931E-01
maximum     9.960E-01  1.297E+00  1.614E-01
median     -4.138E-02 -6.728E-01 -3.365E-03
----------------------------------------------------------------------------
Node set:                                                                  2
Name:                                                                face_z0
............................................................................
                   Tx          Ty          Tz
total       1.116E+02  1.972E+03  4.286E+01
average     5.721E-03  1.011E-01  2.197E-03
std_dev     3.191E+00  6.173E+00  1.345E+00
minimum    -2.732E+01 -2.842E+01 -1.075E+01
maximum     2.276E+01  4.839E+01  1.579E+01
median     -1.405E-01 -1.222E+00  2.123E-02
============================================================================
```

This tutorial is the final tutorial in the series presenting the Faim standard workflow, with models generated by n88modelgenerator. Those interested in generating custom models will want to continue on to the tutorials presenting `vtkbone`. If you intend for the moment to use only n88modelgenerator for generating your models, then you can stop here.

Tutorial: Compressing a cube revisited using vtkbone

In the preceding tutorials, we used n88modelgenerator to quickly generate finite element models from segmented 3D images. n88modelgenerator has many parameters that can be used to tune the models in produces, but inevitably, the variety of models that can be produced using the parameter-setting approach is limited. A far more flexible approach is scripting. Numerics88 contains a collection of objects suitable for constructing and manipulating finite element objects. These can be scripted with Python. Python is one of the easiest languages to learn, and yet retains a great deal of expressive power. This collection of objects is built on top of VTK and is referred to as `vtkbone`. It is documented in Chapter 3.

In this tutorial, we are going to revisit the first tutorial, Introductory tutorial: Compressing a solid cube. In fact we're going to do it all over again, only this time, we will generate the model by writing a little script with `vtkbone`, instead of using n88modelgenerator. It will be more work, but we will have a working model-generation script that could be further tweaked to do things that would not be possible with n88modelgenerator.

Getting familiar with Python, VTK and Numpy

It is not necessary to know Python in order to write and modify scripts using `vtkbone`, as very often you can make obvious modifications to existing scripts. However, having a basic familiarity can make you more comfortable with the following scripting. As Python is very widely used, there are any number of excellent introductory books. A suggested place to start is the on-line tutorial at http://docs.python.org/tutorial/ .

One feature of Python which we will use that is not a part of the standard Python distribution (but is distributed with Numerics88 software) is Numpy, which efficiently handles numerical arrays in Python. Again, prior knowledge of Numpy is not required, but will help. Documentation for Numpy can be found at http://docs.scipy.org/doc/ . We recommend https://docs.scipy.org/doc/-numpy-dev/user/quickstart.html as an introduction.

Finally, there is VTK . VTK is quite complex and rather more difficult to learn than either Python or Numpy, but fortunately it is not necessary to know very much VTK. We will be using a mixture of custom `vtkbone` objects and standard VTK objects. When one of these comes up in the following tutorials, you may want to have a glance at the corresponding API documentation for that object. This is explained in Section 3.1.

Preliminaries: first lines of Python

First create a working directory. Using your favourite text editor, create a file `apply_compression.py`.

Tip
You can also use an editor or an integrated development environment specifically intended for python, such as IDLE, but this is not necessary. A plain old text editor will work fine. On Windows, Notepad can be used. On OS X, you can use TextEdit, which you will find in the Utilities folder within Applications. If using TextEdit, be sure to select Format → Make Plain Text.

Note
If you want to cheat and not actually type this tutorial script line-by-line as we go, you can find the finished version in the directory `tutorials/cube_with_vtk`, once you unpack the archive of tutorial data that can be downloaded from http://numerics88.com/downloads .

Start by adding these lines, which import all the Python modules that we will be using:

```
from __future__ import division
import argparse
import os
import sys
import vtk
import vtkbone
```

Once you save this, you already have a script that you can run! In fact, you should run it, with just these lines in it - even though it does nothing yet, because it will verify that Python can successfully locate VTK and `vtkbone`. The script can be run like this (make sure you've saved `apply_compression.py`),

```
$ python apply_compression.py
```

Note
The dollar sign (`$`) at the beginning of the line is the prompt: don't type that. On Windows the prompt will be something like `C:\>` . On all systems the prompt might contain additional information, such as the current directory.

You should get as output . . . nothing whatsoever. If you get an error like "ImportError: No module named vtk", then it is likely that the n88tools is not installed, or that the anaconda python environment is not activated. Refer to Section 1.4.4.

We recommend also having a version number in your script. Increment it whenever you change the script (not every time you add a line, but if you modify the finished script later so that the resulting model is somewhat different, then increment the version number.) We'll see soon how we can ensure that the script version number gets written into the log of the `n88model` file. Although we're not accountants, we highly recommend having an audit trail that will allow you to know exactly how a given model was generated. (Obviously, you should archive copies of every version of your script, not just the most recent one. You should also floss daily, which we're sure that you do.) For now, just add a version number to the script with this line. We are on version 3, since this tutorial has been in the manual for quite some time, and it has been tweaked a couple of times.

```
script_version = 3
```

Now, we're going to want to specify the input image file on the command line, because this will allow us to use the script on any input file, not just one hard-coded by name into the script. We're also going to want to inform the user that an input file name is required if they don't supply one. ("The user" is most likely you yourself, but don't assume that next week you'll remember how you intended to use the script you write this week.) The python module `argparse` is really handy for this. The following lines will do the desired thing:

```
parser = argparse.ArgumentParser (
    description="""Apply a compression test.
This script does essentially the same as the command
"n88modelgenerator --test=uniaxial"
but uses vtkbone for this purpose.
""")

parser.add_argument ("input_file",
   help="An input image file of the segmented data; must be in VTK XML format (.vti).")

args = parser.parse_args()
```

So now when we run it as before, this time we do get some output:

```
$ python apply_compression.py
usage: apply_compression.py [-h] input_file
apply_compression.py: error: too few arguments
```

Progress!

Let's see what happens if we run it with the `-h` flag. Note that `argparse` has automatically added a `-h` flag, the purpose of which is to get help about the command.

```
$ python apply_compression.py -h
usage: apply_compression.py [-h] input_file

Apply a compression test. This script does essentially the same as the command
"n88modelgenerator --test=uniaxial" but uses vtkbone for this purpose.

positional arguments:
  input_file  An input image file of the segmented data; must be in VTK XML
              format (.vti).

optional arguments:
  -h, --help  show this help message and exit
```

Reading the input file

The input file is `cube6x6x6.vti` and as usual you can find it in the `data` folder of your distribution. We've seen it before in the first tutorial. Copy it to your working directory.

As the data is in VTK's `.vti` format (properly referred to as "VTK XML Image Data file format"), we'll need a vtkXMLImageDataReader object to read it. That will look like this:

```
print "Reading", args.input_file
reader = vtk.vtkXMLImageDataReader()
reader.SetFileName(args.input_file)
reader.Update()
image = reader.GetOutput()
```

vtkXMLImageDataReader is a type of VTK "filter" (specifically a "source"). What we've done is very typical for VTK filters and we'll see this sequence of steps for employing a VTK filter over and over again. It is,

1. Create the filter object.
2. Set any inputs. (Here there are none, because a source doesn't have any.)
3. Set any parameter values. In this case we set the parameter value `FileName()`.
4. Call `Update()`. (Otherwise nothing happens and we wonder why.)
5. Get any output.

In fact, this isn't the only way to use VTK filter objects, but it is the simplest and it is the procedure we will nearly always employ in our scripts.

Let's provide some feedback at this point so we have some indication that the data was correctly read. While we're at it, let's do some error checking to stop things right here if that data wasn't able to be read,

```
if not image:
    print "No image data read."
    sys.exit(1)

print "Read image with dimensions", image.GetDimensions()
```

Now running it should result in,

```
$ python apply_compression.py cube6x6x6.vti
Reading cube6x6x6.vti
Read image with point dimensions (7, 7, 7) ❶
```

❶ Wait a minute! Why are the reported dimensions (7, 7, 7) when they are really 6×6×6? It is because these are the reported Point (or Node) dimensions, rather than the Cell (or Element) dimensions. If you're confused, review the discussion on this point in Introductory tutorial: Compressing a solid cube.

Ensuring connectivity

We could assume that the input image is properly segmented and just proceed with generating a mesh. since this is an introductory tutorial perhaps we should. However, it happens not infrequently for whatever reason that a finite element model is attempted on an image which does not consist of a single connected object. This can cause all sorts of trouble. Consider this: if there are disconnected floating bits in the model, where is the proper place for the solver to put them in the solution? Sometimes the solution of such models will be very slow, other times the model will solve OK, but some of the post-processing numbers may appear strange if you don't realize that they are calculated over the entire model, including bits which are subject to no constraints.

So to avoid potential grief, this is a good place to drop in a vtkboneImageConnectivityFilter . It will strip away (actually zero-out) any parts of the input image that aren't in some way connected to the largest object in the image. It is a safe and prudent step in the generation of a well-defined finite element model.

```
print "Applying connectivity filter."
connectivity_filter = vtkbone.vtkboneImageConnectivityFilter()
connectivity_filter.SetExtractionModeToLargestRegion()
connectivity_filter.SetInputData(image)
connectivity_filter.Update();
image = connectivity_filter.GetOutput()
```

Tip

Is it legitimate to assign the output to the variable *image* when that was also the name of the input? The answer is yes. It's quite kosher in Python to clobber a variable name by assigning it to something else. Python is more clever than you might think about this. It will in fact keep the data associated with the original input variable around as long required, even though we have no means to refer to it or access it now. (And technically speaking, here it will be required, at least as long as connectivity_filter exists, because connectivity_filter will still use the original input data. As long as connectivity_filter is around, we might decide to use it again without changing the input, so Python won't get rid of it.)

Generating a mesh

The filter object for generating an FE mesh from an input image is vtkboneImageToMesh . The FE mesh represents the geometry of the model, and consists of elements and nodes (concretely, it will be an object of type vtkUnstructuredGrid). Note that in VTK terminology, elements will be called Cells, and nodes will be called Points. Most of the time we don't need to set any parameters to vtkboneImageToMesh except the input.

```
# Generate a finite element mesh from the input image

geometry_generator = vtkbone.vtkboneImageToMesh()
geometry_generator.SetInputData(image)
geometry_generator.Update()
geometry = geometry_generator.GetOutput()

print "Generated %d elements and %d nodes." % \
      (geometry.GetNumberOfCells(), geometry.GetNumberOfPoints())
```

Now our output is beginning to get interesting,

```
$ python apply_compression.py cube6x6x6.vti
Reading cube6x6x6.vti
Read image with point dimensions (7, 7, 7)
Applying connectivity filter.
Generated 216 elements and 343 nodes.
```

Quick check: $6^3 = 216$ and $7^3 = 343$, so we're good.

Tip

It is possible to write out the geometry to a file in VTK's XML Unstructured Grid format using vtkXMLUnstructuredGridWriter . You will then be able to open it in ParaView. It should be very similar to Figure 16. (In contrast though to rendering the input image, if there were any zero-valued voxels, there would be no need to threshold to remove the corresponding cells, as they are already absent from the meshed geometry.) The lines of code to save the geometry to a file are as follows:

```
writer = vtk.vtkXMLUnstructuredGridWriter()
geometry_file = "geometry.vtu"
print "Writing geometry to", geometry_file
writer.SetFileName(geometry_file)
writer.SetInputData(geometry)
writer.Write()
```

Defining materials and creating a material table

Now we need to define some material properties. We can do this by creating an instance of some specific derived class of vtkboneMaterial . The one of these is vtkboneLinearIsotropicMaterial . Let's make one of them,

```
print "Creating a linear isotropic material."
material = vtkbone.vtkboneLinearIsotropicMaterial()
material.SetName("linear_iso_material") ❶
material.SetYoungsModulus(6829) ❷
material.SetPoissonsRatio(0.3) ❸
```

❶ We can give it any name we want. If we need to access it later, we can look it up by name.

❷, ❸ These are default values, so we actually didn't really need these lines, but it doesn't hurt be explicit, and now it is clear how to set different values should you want to do so.

The other thing we must do is to make a material table, which associates the values in the input image (segmentation IDs or material IDs) with defined materials. Our image file `cube6x6x6.vti` has the uniform value of 1 on every voxel, so we need to make a material table that associates 1 with our material defined above. But perhaps we might want to run this script someday on an input file that uses different values (127 is very common for historical reasons). We could write here some fancy scripting that would examine the input data and produce a list of all the different values in the image, then map all those values to our material (since we're only using one material here). This sounds a bit complicated, but fortunately, there is a `vtkbone` object, vtkboneGenerateHomogeneousMaterialTable , that does exactly this for us:

```
mt_generator = vtkbone.vtkboneGenerateHomogeneousMaterialTable()
mt_generator.SetMaterial(material)
mt_generator.SetMaterialIdList(image.GetCellData().GetScalars()) ❶
mt_generator.Update()
material_table = mt_generator.GetOutput()
print "Generated material table with %d entries." % material_table.GetNumberOfMaterials()
```

❶ Unfortunately, it is not as simple as just setting “image” as the argument to `SetMaterialIdList`. We have to be quite explicit about specifying the scalar data on the cells, in this manner.

Applying a compression test

To apply boundary conditions appropriate to a compression test, we can make use of the object vtkboneApplyCompressionTest , which will do practically all the work for us. vtkboneApplyCompressionTest requires as inputs both the mesh and the material table that we defined above.

```
# Apply a compression test (uniaxial)

print "Applying a uniaxial compression test."
generator = vtkbone.vtkboneApplyCompressionTest()
generator.SetInputData(0, geometry) ❶
generator.SetInputData(1, material_table) ❷
generator.Update()
model = generator.GetOutput()
```

❶ Input 0 to vtkboneApplyCompressionTest must be the mesh geometry, as a vtkUnstructuredGrid object.

❷ Input 1 to vtkboneApplyCompressionTest must be the material table, as a vtkboneMaterialTable object.

Writing an n88model file

The output of vtkboneApplyCompressionTest is a vtkboneFiniteElementModel object, which is a complete representation of the problem we want to solve with finite element analysis. It remains to write out this model in `n88model` file format.

```
# Write an n88model file

output_file = os.path.splitext(args.input_file)[0] + "_custom.n88model" ❶
# Remove directory, so file ends up in current directory.
output_file = os.path.split(output_file)[1]

print "Writing n88model file:", output_file
writer = vtkbone.vtkboneN88ModelWriter()
writer.SetInputData(model)
writer.SetFileName(output_file)
writer.Update()
```

❶ This is some fancy Python to derive the output file name from the input file name.

That's it. If everything works correctly, the output should look like this:

```
$ python apply_compression.py cube6x6x6.vti
Reading cube6x6x6.vti
Read image with point dimensions (7, 7, 7)
Applying connectivity filter.
Generated 216 elements and 343 nodes.
Creating a linear isotropic material.
Generated material table with 1 entries.
Applying a uniaxial compression test.
Writing n88model file: cube6x6x6_custom.n88model
```

Modifying the file history and log

We promised at the beginning to record the script version number in the file, and some far we haven't done this. First we'll have a look at what is currently in the history field.

```
$ n88modelinfo --history cube6x6x6_custom.n88model
History:
----------------------------------------------------------------------
2012-Sep-24 08:18:01 Model created by vtkboneApplyCompressionTest version 1.0 .
----------------------------------------------------------------------
```

This is useful information so instead of replacing it, we can just add to it. To do this, add the following line to the script, just before writing out the file:

```
model.AppendHistory("Created by apply_compression.py version %s ." % script_version)
```

Now run the script again, and this time when we run n88modelinfo, we get:

```
$ n88modelinfo --history cube6x6x6_custom.n88model
History:
----------------------------------------------------------------------
2012-Sep-24 08:22:14 Model created by vtkboneApplyCompressionTest version 6.0 .
2012-Sep-24 08:22:14 Created by apply_compression.py version 2 .
----------------------------------------------------------------------
```

Good, now we'll always know that the `cube6x6x6_custom.n88model` file was created with version 2 of the script (which called vtkboneApplyCompressionTest from `vtkbone` version 6.0).

We can also have a look at the log, which gives more detailed information:

```
$ n88modelinfo --log cube6x6x6_custom.n88model
Log:
----------------------------------------------------------------------
2012-Sep-24 08:22:14
vtkboneApplyCompressionTest settings:

TopConstraintSpecificMaterial: -1
BottomConstraintSpecificMaterial: -1
UnevenTopSurface: 0
UnevenBottomSurface: 0
TestAxis: 2
AppliedStrain: -0.01
AppliedDisplacement: 0
TopSurfaceContactFriction: 0
BottomSurfaceContactFriction: 0
ConfineSides: 0
Pin: 0
PinCellClosestToXYCenter: 1
PinCellId: 0

----------------------------------------------------------------------
```

There is already quite a lot of information here, provided automatically by vtkboneApplyCompressionTest . In particular we have all the parameters of vtkboneApplyCompressionTest , which were all set to default values because we didn't change any of them. We could, if we wanted, add even more information to the log, using the method `model.AppendLog`, just as we used `model.AppendHistory`. In this case, there is nothing lacking that we can't query. For example, although no material information appears in the log, we can determine it with n88modelinfo,

```
$ n88modelinfo --materials cube6x6x6_custom.n88model
Materials:
----------------------------------------------------------------------

  Name : linear_iso_material
  Type : LinearIsotropic
  E : 6829.0
  nu : 0.3
----------------------------------------------------------------------
```

You can now proceed if you want to solve and analyze the model exactly as in An introductory tutorial: compressing a solid cube.

This completes the tutorial on building the 6×6×6 cube compression model using `vtkbone`. We've seen that it takes considerably more work to write a script than to call n88modelgenerator, so whenever it suffices, it is preferable to use n88modelgenerator.

However, although in this case we've done nothing that n88modelgenerator couldn't have done, we hope that you can imagine that now that we have a script, that we could potentially modify it in any number of ways beyond what would be possible with n88modelgenerator. In subsequent tutorials, we'll explore these possibilities.

Tutorial: Deflection of a cantilevered beam; adding custom boundary conditions and loads

In this tutorial, we are going to use `vtkbone` to create a model that is different than anything that could create with n88modelgenerator. The test will be the deflection of a uniform beam fixed at one end, in other words a cantilever. We have chosen this model because there is a simple analytic solution to which we can compare the result.

One aspect that will be new to this tutorial will be an applied force as part of the problem definition. Generally though, it is preferable to define models with fixed position boundary conditions and solve for the forces, rather than to specify forces and solve for a displacement. The reason for this will be discussed in the subsequent tutorial.

The completed script, `create_cantilever.py`, can be found in the `cantilever` subdirectory in the examples.

Importing the required python modules

As in the previous tutorial, we start the python script by importing the python modules that we will need. This time we will also need the `numpy` module, as we are going to do some array manipulation.

```
from __future__ import division
import argparse
import numpy
from numpy.core import * ❶
import vtk
import vtkbone
from vtk.util.numpy_support import vtk_to_numpy, numpy_to_vtk ❷
```

❶ This just saves some typing later. For example we'll be able to use the function `array` instead of the longer `numpy.array`.

❷ These are the functions that allow us to convert numpy arrays to and from VTK data arrays.

As before, we'll also set a script version number:

```
script_version = 3
```

Setting command line options

As before, we use the `argparse` module, which makes it quite simple to define a couple of arguments for running the script, one of which, the applied force, will have a numerical value.

```
parser = argparse.ArgumentParser (
    description="""Generate a model for a cantilever with an
applied force to the end of the beam.""")

parser.add_argument ("applied_force", type=float,
   help="The applied force to the end of the beam.")

parser.add_argument ("output_file",
    help="Name for output n88model file.")

args = parser.parse_args()
```

Generating the image data

The beam is going to have a very simple geometry, one which we generate algorithmically without too much trouble. This is also going to serve as a brief introduction to numpy arrays. Because the analytic solution for the cantilever is essentially a 2D problem, we are going to use just a beam width of just a single element. To scale up to a realistic width, if desired, one can just scale all the forces. We are going to create a beam of 200×1×20 elements, with a cubic element of side length 0.5mm. Thus the beam has dimensions of length 100mm, height 10mm, and width 0.5mm (but again, everything scales linearly with the width, so the obtained solution can be used for arbitrary widths).

Here is how we create a 3-dimensional array data of size 200×1×20:

```
dims = array ((20, 1, 200)) ❶
cellmap = ones (dims) ❷
```

❶ The order of the dimensions is *z*,*y*,*x*, because numpy indices always are ordered with the "fastest-changing" index last, which must be *x*. On the other hand, VTK will generally want arguments specified as *x*,*y*,*z*. We will have to be careful about which order to use when.

❷ `ones` is a numpy function that creates an array (in this case a 3-dimensional array) filled with 1s.

We to convert this from a `numpy` array, which is natural to Python, to to a VTK data array:

```
cellmap_vtk = numpy_to_vtk(ravel(cellmap), deep=1, array_type=vtk.VTK_INT)
```

There are a couple of subtle points here. The first is that VTK is actually going to want the flattened data, meaning as one long 1-dimensional array, rather than as a 3-dimensional array. (It will keep track of the dimensionality separately, as we will see below.) Hence the use of `ravel` function, which is a numpy function that returns the input array as a one-dimensional array (without copying the underlying data if possible). The other aspect to note is that we specify `deep=1`, which specifies that the VTK array should create its own copy of the underlying data, instead of just referring to the numpy data. This is less memory efficient, but there are potential pitfalls with sharing the data, so we'll go with the more robust method of making a copy.

Now that we have the data, we're going to create a vtkImageData object which adds information such as the dimensions and the spacing.

```
image = vtk.vtkImageData()
image.SetDimensions(dims[::-1] + 1) ❶
image.SetSpacing(0.5, 0.5, 0.5)
image.GetCellData().SetScalars(cellmap_vtk)
```

❶ This is a little bit tricky. First, `dims[::-1]` simply means "dims reversed", which we need because, as discussed above, dims is ordered *z*,*y*,*x*, but VTK requires *x*,*y*,*z*. Secondly we're adding 1 (to every dimension) because vtkImageData dimensions are always in terms of the number of Points, rather than the number of Cells. The end result is (201, 2, 21).

We've set the spacing to 0.5 . In this tutorial, we are going to use units of millimetres. Units are not specified in the `n88model` file. Instead we will just have to ensure that all our units are consistent. See A note about units.

We can at this point write out the vtkImageData as a `.vti` file, and open it with ParaView to ensure that we have obtained the desired result. It should ressemble Figure 35. As a beam, it looks absurdly thin, but to emphasise once again, we are solving essentially a 2D problem; the numerical results obtained can be scaled to any beam width.

```
# Optional: write out image data to examine it

print ("Writing geometry file: beam_image.vti")
writer = vtk.vtkXMLImageDataWriter()
writer.SetInputData(image)
writer.SetFileName("beam_image.vti")
writer.Update()
```

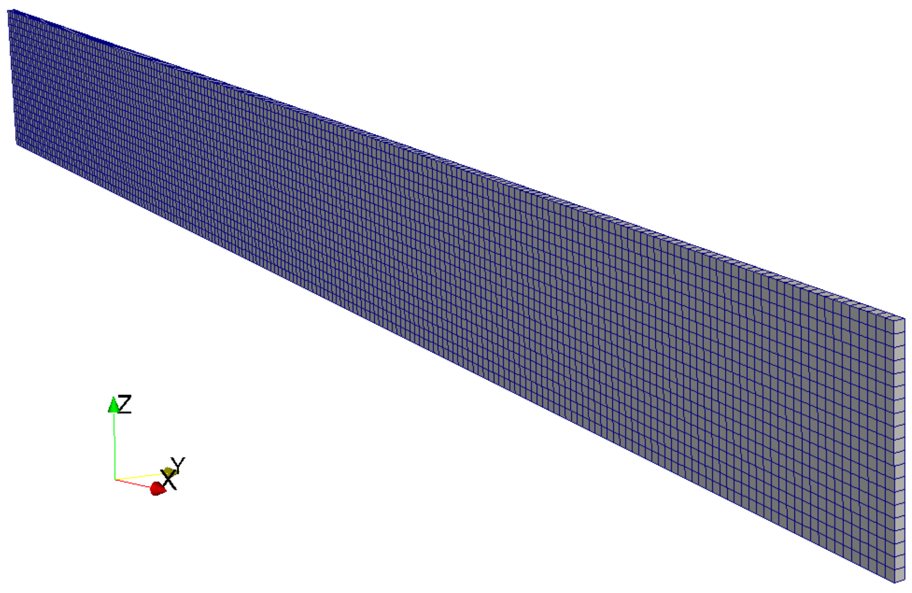


Figure 7.21: Generated beam image.

Generating a base model without boundary conditions

Now that we have an image, as in the previous tutorial, we convert it to a geometric mesh:

```
# Generate a geometrical mesh from the input image

mesh_generator = vtkbone.vtkboneImageToMesh()
mesh_generator.SetInputData(image)
mesh_generator.Update()
mesh = mesh_generator.GetOutput()
```

We also define a material (steel) and a material table.

```
# Create a material

material = vtkbone.vtkboneLinearIsotropicMaterial()
material.SetName("steel")
material.SetYoungsModulus(2.0E5) ❶
material.SetPoissonsRatio(0.3)

material_table = vtkbone.vtkboneMaterialTable()
material_table.AddMaterial (1, material) ❷
```

❶ 200GPa is a typical value for the Young's modulus of steel. We will use units of MPa. We have already declared that our length units are mm, hence all units will be consistent provided that we use Newtons for forces.

❷ The value 1 comes from the fact that we filled our image with 1s. All the elements will now be mapped to the material *steel*.

In contrast to the previous tutorial, we won't be using one of the standard test generation filters. Rather we will use the base test generation filter vtkboneApplyTestBase , which creates a vtkboneFiniteElementModel object without any boundary conditions.

```
# Create a model without boundary conditions.

generator = vtkbone.vtkboneApplyTestBase()
generator.SetInputData(0, mesh)
generator.SetInputData(1, material_table)
generator.Update()
model = generator.GetOutput()
```

Before we add displacement boundary conditions and applied loads, let's save the model so we can examine the results as we build up our script. Of course the model isn't complete yet, but that doesn't prevent us from saving and examining it.

```
# Write an n88model file

print "Writing n88model file:", args.output_file
writer = vtkbone.vtkboneN88ModelWriter()
writer.SetInputData(model)
writer.SetFileName(args.output_file)
writer.Update()
```

Important
In everything that follows, it is intended that you add new lines to the script **before** the code (shown just above) that saves the model to a file. Otherwise of course the saved file won't include our additions and changes.

To run the script will require both a numerical value for the applied force and an output file name. For now use these values:

```
python create_cantilever.py -10 cantilever.n88model
```

We are choosing to use a negative applied force, because it is more natural to think of a downward force applied to a cantilever.

Adding fixed boundary conditions

We want to fix one end of our beam, to weld it to the (virtual) wall. Usually the step requiring the most work in defining boundary condition is identifying the set of nodes that constitute the boundary surface we are interested in. In this case, vtkboneApplyTestBase has done the work for us, because although it doesn't define any boundary conditions, it does define node (and element) sets on all the faces. (To be more precise, it defines node and element sets consisting of any nodes/elements located at the *x*,*y* and *z* extents of the model.) This is discussed in Creating node and element sets. The names of these sets are listed there, but if you've run the script up to this point, you can also use n88modelinfo to query the set names:

```
$ n88modelinfo --node_sets cantilever.n88model
NodeSets:
----------------------------------------------------------------------

  Name : face_z0
  Part : Part1
  NumberOfNodes : 402

  Name : face_z1
  Part : Part1
  NumberOfNodes : 402

  Name : face_x0
  Part : Part1
  NumberOfNodes : 42

  Name : face_x1
  Part : Part1
  NumberOfNodes : 42

  Name : face_y0
  Part : Part1
  NumberOfNodes : 4221

  Name : face_y1
  Part : Part1
  NumberOfNodes : 4221
----------------------------------------------------------------------
```

There are also corresponding element sets, which can be listed with the `--element_sets` option to n88modelinfo.

Node set *face_x0* is the one to which we are interested in applying a fixed boundary condition. If you refer to the the API documentation for vtkboneFiniteElementModel, you will see that there are a number of methods for defining boundary conditions. One possibility is to use the method `FixNodes`, which will fix the specified node set in all senses (directions). Only one line of code would be required:

```
model.FixNodes ("face_x0", "fixed_beam_base") ❶
```

❶ *face_x0* is the name of an existing node set; *fixed_beam_base* is the name we are assigning to the new constraint.

However, as we are trying to obtain a result as close as possible to the analytic 2D solution, it is actually better to not to limit the freedom of motion in the *y* direction on the boundary condition. This way, no *y* direction forces will arise. Were there to be any forces in the *y* direction, this would cause some essentially 3D effect on the *x*-*z* plane by the mechanism of Poisson's ratio. So instead of using `FixNodes`, we will use the following slightly more verbose code

```
# Create the fixed boundary conditions at the base of the beam.
# To obtain a more truely 2D result, no constraint is applied to
# displacements in the _y_ direction.

model.ApplyBoundaryCondition(
    "face_x0",
    vtkbone.vtkboneConstraint.SENSE_X,
    0,
    "fixed_beam_base_x")
model.ApplyBoundaryCondition(
    "face_x0",
    vtkbone.vtkboneConstraint.SENSE_Z,
    0,
    "fixed_beam_base_z")
```

If you now run the script, you can then use n88modelinfo to verify that the boundary condition has indeed been generated:

```
$ n88modelinfo --constraints cantilever.n88model
Constraints:
----------------------------------------------------------------------

  Name : fixed_beam_base_x
  Part : Part1
  Type : NodeAxisDisplacement
  NumberOfValues : 42

  Name : fixed_beam_base_z
  Part : Part1
  Type : NodeAxisDisplacement
  NumberOfValues : 42
----------------------------------------------------------------------
```

Adding an applied load to tip of the beam

At the free end of the beam, we are going to apply a load. Creating an applied load is very similar to creating a displacement boundary condition. vtkboneFiniteElementModel provides a number of methods for this purpose. There are some important differences,

1. Applied loads are applied to element sets; displacement boundary conditions are applied to node sets.
2. Applied loads require the additional specification of a particular face of the elements to which to apply the load, or else the specification that it is a body force. We are going to apply the load to the outward faces of the end elements (*i.e.* those facing in the *x* direction).

Here is the code to create an applied load constraint, named *end_force* to the pre-defined element set *face_x1*. corresponding to the end face of the beam.

```
# Apply a force to the far end of the beam

model.ApplyLoad(
  "face_x1", ❶
  vtkbone.vtkboneConstraint.FACE_X1_DISTRIBUTION, ❷
  vtkbone.vtkboneConstraint.SENSE_Z, ❸
  args.applied_force, ❹
  "end_force") ❺
```

❶ This node set was created by vtkboneApplyTestBase . Here *face_x1* means elements on the *x1* face of the entire model.

❷ This specifies the *x1* faces of the elements.

❸ This specifies the direction of the applied force. (The value of `vtkbone.vtkboneConstraint.SENSE_Z` is 2, but the named constant conveys the intent more clearly than the numerical value.)

❹ The applied force will be equally divided among the element faces in the set. Units, as discusssed above, are Newtons.

❺ The name of the newly-created constraint.

Adding a convergence set

As discussed in Convergence measure there are different possibilites for the convergence measure, which is used by the solver to determine when the solution has iterated enough to obtain an acceptable solution. Generally, the best convergence measure to use for linear problems is *convergence set*. This convergence measure can only be used if we define a *convergence set* within the model file. A *convergence set* is something that we choose, and we generally want to choose the quantity that we are most interested in calculating. For example, for a cantilever, this quantity could be the displacement of the tip of the cantilever. You might imagine that this would be difficult to specify. But in most cases, this quantity of interest is the complement of some boundary condition or applied force. In this case, the displacement is the complement of the force applied to the tip. There is a method to generate a convergence set from a boundary condition or from an applied force, and it is very simple to use:

```
# Create a convergence set: the displacement of the tip

model.ConvergenceSetFromConstraint("end_force")
```

This method notices that the constraint named *end_force*, which we created previously, is an applied force, and that it is applied to the faces of certain elements. It then constructs the compliment, which is the displacement, averaged over all nodes located on those element faces. It is this average displacement of the tip that the solver will watch to determine when its value ceases to change meaningfully. At that point the solver is finished.

Note
In this case we have passed an applied force to `ConvergenceSetFromConstraint`, and so the complement is naturally the average displacement of the corresponding nodes. If instead you pass a boundary condition to `ConvergenceSetFromConstraint`, then the resulting *convergence set* will be the total force on the nodes belonging to the specified boundary condition.

Note
The fact the we define a convergence set in the model file does not limit us to choosing the *convergence set* convergence measure. Although the solver will default to using the *convergence set* convergence measure if it finds a *convergence set* defined in the n88model file, we can always run the solver while specifying a different convergence measure, using the option convergence_measure. Similarly, we can skip altogether defining a convergence set, and the solver will default to a convergence measure that doesn't require it. The only drawback is that the other convergence measures are necessarily more conservative, and so the solver will usually run for more iterations than would be strictly necessary for the desired precision.

Specifying sets for post-processing

There is one more step required, and that is to identify the sets to be used for post-processing calculations by n88postfaim. We are interested in values on the sets *face_x0* and *face_x1*. The magic lines of code are:

```
# Set the node sets and element sets that will be used for post-processing

info = model.GetInformation()
pp_node_sets_key = vtkbone.vtkboneSolverParameters.POST_PROCESSING_NODE_SETS()
pp_elem_sets_key = vtkbone.vtkboneSolverParameters.POST_PROCESSING_ELEMENT_SETS()
pp_node_sets_key.Append(info, "face_x0")
pp_elem_sets_key.Append(info, "face_x0")
pp_node_sets_key.Append(info, "face_x1")
pp_elem_sets_key.Append(info, "face_x1")
```

After running the script, we can verify that these post-processing sets are in fact specified in the `n88model` file:

```
$ n88modelinfo --problems cantilever.n88model
Problems:
----------------------------------------------------------------------

  Name : Problem1
  Part : Part1
  Constraints : fixed_beam_base_x,fixed_beam_base_z,end_force
  ConvergenceSet : convergence_set
  PostProcessingNodeSets : face_x0,face_x1
  PostProcessingElementSets : face_x0,face_x1
----------------------------------------------------------------------
```

Tip
It is possible to skip this step, and instead to specify later the node and element sets to be used by n88postfaim on the command line of n88postfaim with the argument

```
--sets=face_x0,face_x1
```

Documenting the model in the file log

As discussed previously, it is good practice to document the model creation in both the file History and the file Log. Here we add these lines (again they must come before the code that saves the model):

```
# Update history and log

model.AppendHistory("Created by create_cantilever.py version %s ." % script_version)

model.AppendLog(
"""create_cantilever.py
Cantilever beam model with applied force on far face of %s .
Using vtkbone version %s .
""" % (args.applied_force, vtkbone.vtkboneVersion.GetVTKBONEVersion()))
```

If we run the script to generate the `n88model` file, we can at any later time get a brief description of the model and determine what versions were used (including what version of `vtkbone`).

```
$ n88modelinfo --history --log cantilever.n88model
History:
----------------------------------------------------------------------
2016-Sep-22 17:33:32 Created by create_cantilever.py version 3 .
----------------------------------------------------------------------

Log:
----------------------------------------------------------------------
2016-Sep-22 17:33:32
create_cantilever.py
Cantilever beam model with applied force on far face edge of -10.0 .
Using vtkbone version 1.0 .
----------------------------------------------------------------------
```

Solving the problem and comparing with theory

The model is quickly solved with faim:

```
$ faim cantilever.n88model
```

If we open the solved file `cantilever.n88model` in ParaView, we can observe the beam deflection as shown in Figure 36. Here the deflection is amplified by 10 so as to be more evident. The figure is colored by the *xx* component of strain, with red being tensile and blue being compressive. This is easily done in ParaView, simply by selecting the relevant quantities from the drop-down boxes in the toolbar, as in Figure 37.

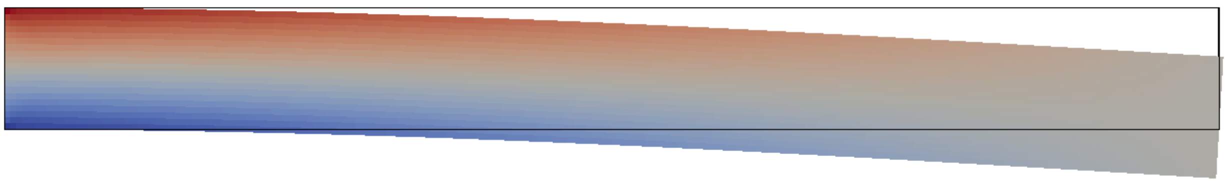


Figure 7.22: Deflection of loaded cantilever beam. Displacement amplified by 10. Coloration by xx component of strain.

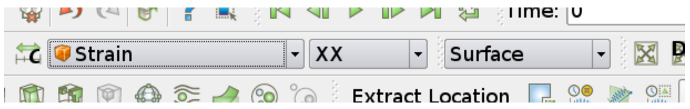


Figure 7.23: XX component of strain selected in ParaView toolbar.

Now let's compare quantitatively with the analytical result for deflection of a cantilever beam as found in any Mechanics of Solids textbook or on wikipedia at https://en.wikipedia.org/wiki/Deflection_%28engineering%29). We have that the deflection

δ of the end of a cantilever beam is

$$\delta = \frac{FL^3}{3EI}$$

where

F	= force acting on the tip of the beam
L	= length of the beam (span)
E	= modulus of elasticity
I	= area moment of inertia

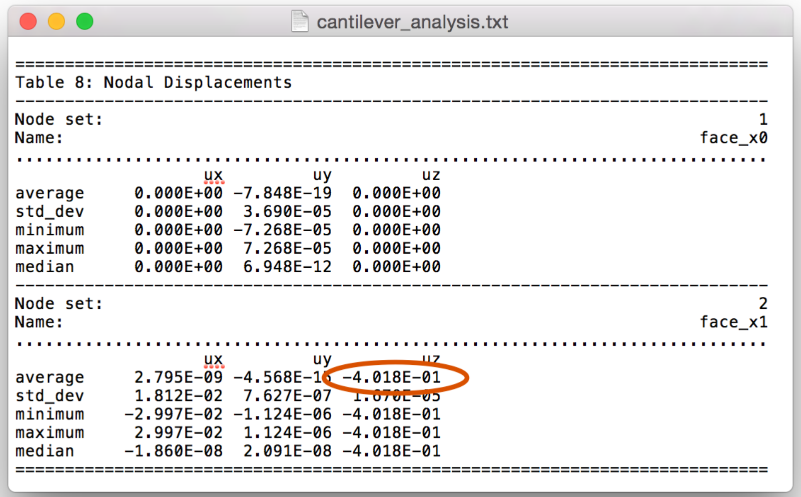
For a beam with a rectangular cross-section $b \times h$, the area moment of inertia is

$$I = \frac{bh^3}{12}$$

so that we have

$$\delta = \frac{4FL^3}{Ebh^3} = \frac{4\,(10\,\mathrm{N})(100\,\mathrm{mm})^3}{(2\times 10^5\,\mathrm{MPa})(0.5\,\mathrm{mm})(10\,\mathrm{mm})^3} = 0.4\,\mathrm{mm}$$

You can observe this deflection in ParaView, and we can get a precise number by looking in the `beam_analysis.txt` file, in the table *Nodal Displacements*. In this case the result, 0.4018, is very close to 0.4 .



```
==============================================================================
Table 8: Nodal Displacements
------------------------------------------------------------------------------
Node set:                                                                    1
Name:                                                                  face_x0
..............................................................................
                  ux         uy         uz
average    0.000E+00 -7.848E-19  0.000E+00
std_dev    0.000E+00  3.690E-05  0.000E+00
minimum    0.000E+00 -7.268E-05  0.000E+00
maximum    0.000E+00  7.268E-05  0.000E+00
median     0.000E+00  6.948E-12  0.000E+00
------------------------------------------------------------------------------
Node set:                                                                    2
Name:                                                                  face_x1
..............................................................................
                  ux         uy         uz
average    2.795E-09 -4.568E-16 -4.018E-01
std_dev    1.812E-02  7.627E-07  1.670E-05
minimum   -2.997E-02 -1.124E-06 -4.018E-01
maximum    2.997E-02  1.124E-06 -4.018E-01
median    -1.860E-08  2.091E-08 -4.018E-01
==============================================================================
```

Figure 7.24: Amount of deflection of the end face of the cantilever beam, as found in the analysis file.

This concludes the cantilever beam tutorial. We learned how to create custom models using `vtkbone` that are beyond the standard types of models that n88modelgenerator can generate. We were also introduced to a new type of constraint, which was the applied load.

Tutorial: A cantilevered beam with elastoplastic material properties

This tutorial uses the same model as the previous one, but now we will solve it using nonlinear elastoplastic material properties.

Analytic solution

The cantilever problem has a known analytic solution even in the case of nonlinear elastoplastic material properties. This solution is due to Timoshenko and Gere (1997).

Before building and solving some models, we will consider the analytic solution, because it will indicate what range of test loads are both interesting and reasonable, which is a non-trivial question for nonlinear problems.

The applied load at which the cantilever begins to yield, F_y, is

$$F_y = \frac{\sigma_y b h^2}{6L}$$

where σ_y is the material yield strength (*i.e.* the value of uniaxial stress at which the material starts to yield), and all other symbols are as in the previous section.

For our current model, for which we will use σ_y = 120 MPa, this evaluates to

$$F_y = \frac{(120\,\mathrm{MPa})(0.5\,\mathrm{mm})(10\,\mathrm{mm})^2}{6\,(100\,\mathrm{mm})} = 10\,\mathrm{N}$$

You will notice that this value is corresponds (not entirely coincidently) with the applied force used for the linear case in the previous section, for which we had calculated a deflection of 0.4 mm.

In the yielding region, the beam deflection is

$$\frac{\delta}{\delta_y} = \left(\frac{F_y}{F}\right)^2 \left(5 - \left(3 + \frac{F}{F_y}\right)\sqrt{3 - \frac{2F}{F_y}}\right)$$

This expression is only valid for $1 \leq F\ /\ F_y \leq 3/2$; the cantilever will not withstand any force larger than this. For the current model this range corresponds to between 10 N and 15 N.

Changes to the generation script

The model generation script is named `create_cantilever_ep.py`. It differs from the script in the previous tutorial, `create_cantilever.py`, only in the definition of the material. This becomes

```
# Create a material

material = vtkbone.vtkboneVonMisesIsotropicMaterial()
material.SetName("steel")
material.SetYoungsModulus(2.0E5)  # units are MPa
material.SetPoissonsRatio(0.3)
material.SetYieldStrength(120)   # units are MPa
```

For a *von Mises* elastoplastic material, we have exactly one new parameter as compared with a linear material, and that is the yield strength, here set to 120 MPa. The exact parameters required depend on the material. For example a *Mohr Coulomb* material would have two additional parameters, which are set with the method `SetYieldStrengths(Y_tension,Y_compression)`. As always, for exact usage refer to the `vtkbone` API documentation (vtkboneVonMisesIsotropicMaterial and vtkboneMohrCoulombIsotropicMaterial).

Generating the model and verifying the material

As in the linear case, we generate the model with

```
python create_cantilever_ep.py -14.5 cantilever_ep_145.n88model
```

And we can quickly verify that this model uses a *von Mises* material with

```
n88modelinfo --material cantilever_ep.n88model
```

The output is

```
Materials:
----------------------------------------------------------------------

  Name : steel
  Type : VonMisesIsotropic
  E : 200000.0
  nu : 0.3
  Y : 120.0
----------------------------------------------------------------------
```

Solving the model

The cantilever is, for various reasons, a particularly difficult model for a finite element solver. When combined with nonlinear material properties, in order to get the most accurate results, it is necessary to tighten the convergence tolerance. Thus for the following results, we ran the solver as follows,

```
faim --convergence_tolerance=1E-9 cantilever_ep_145.n88model ❶
```

Tip
Although this is a small model, elastoplastic models take considerably longer to run than linear models, so if you have a system with a suitable GPU, make use of the option `--engine=nv`. On the other hand, such a small model is solved fastest all on one GPU, even in a system with multiple available GPUs.

Plastic strain distribution

A solution with applied force of 14.5 is shown in Figure 39. In comparison with the linear case of Figure 36, we see that the strain is much more concentrated near the fixed end of the beam.

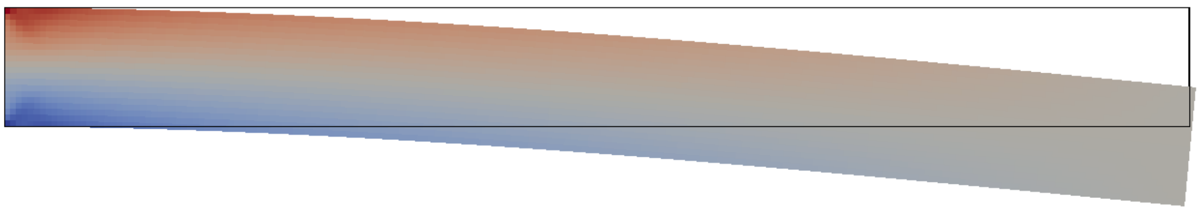


Figure 7.25: Deflection of loaded elastoplastic cantilever beam. Displacement amplified by 10. Coloration by xx component of total strain.

Comparison of finite element and analytic results

By generating and solving models for various loads in the plastic range, we can generate table Table 7.1. To do this, first we create a number of sequence of models

```
python create_cantilever_ep.py -10.0 cantilever_ep_100.n88model
python create_cantilever_ep.py -10.5 cantilever_ep_105.n88model
python create_cantilever_ep.py -11.0 cantilever_ep_110.n88model
python create_cantilever_ep.py -11.5 cantilever_ep_115.n88model
python create_cantilever_ep.py -12.0 cantilever_ep_120.n88model
python create_cantilever_ep.py -12.5 cantilever_ep_125.n88model
python create_cantilever_ep.py -13.0 cantilever_ep_130.n88model
python create_cantilever_ep.py -13.5 cantilever_ep_135.n88model
python create_cantilever_ep.py -14.0 cantilever_ep_140.n88model
python create_cantilever_ep.py -14.5 cantilever_ep_145.n88model
python create_cantilever_ep.py -15.0 cantilever_ep_150.n88model
```

You probably want to put all these commands in a script or batch file.

And then we solve them all

```
faim --convergence_tolerance=1E-9 cantilever_ep_100.n88model
faim --convergence_tolerance=1E-9 cantilever_ep_105.n88model
faim --convergence_tolerance=1E-9 cantilever_ep_110.n88model
faim --convergence_tolerance=1E-9 cantilever_ep_115.n88model
faim --convergence_tolerance=1E-9 cantilever_ep_120.n88model
faim --convergence_tolerance=1E-9 cantilever_ep_125.n88model
faim --convergence_tolerance=1E-9 cantilever_ep_130.n88model
faim --convergence_tolerance=1E-9 cantilever_ep_135.n88model
faim --convergence_tolerance=1E-9 cantilever_ep_140.n88model
faim --convergence_tolerance=1E-9 cantilever_ep_145.n88model
faim --convergence_tolerance=1E-9 cantilever_ep_150.n88model
```

As we can see from the number of elements exceeding the plastic limit (the last column of the table), FAIM does indeed show plastic onset at 10 N load. The data are visualized in table Figure 40. Agreement is very good until the onset of beam failure approaches. Then there begins to be a some divergence between FAIM and the analytic results. Better agreement can be obtained with a smaller element size, but fundamentally near the singularity of failure, there are very rapid changes in plastic strain through the cross-section, and these cannot be well modelled by numerical discretisation. However, away from this singularity, numerical results are good.

Tip

When running several models at different parameter points, it can become tedious to open each analysis file and search out the relevant quantity. We can use the n88tabulate tool to save some effort. In the present case, after we have solved all the models, the following command will generate the 4th column of the table (displacement as calculated by FAIM):

```
n88tabulate -V dz_avg_ns2 *_analysis.txt
```

The variable name for the desired quantity (here `dz_avg_ns2`) can either be found in the n88tabulate section of the manual, or by referring to the on-line help from running n88tabulate with the `-h` flag.

Table 7.1: Elastoplastic cantilever results

load	tip displacement			yielded
	linear	analytic elastoplastic	faim elastoplastic	
10.0	0.40	0.4000	0.4020	2
10.5	0.42	0.4201	0.4222	4
11.0	0.44	0.4406	0.4427	28
11.5	0.46	0.4621	0.4641	50
12.0	0.48	0.4852	0.4869	84
12.5	0.50	0.5107	0.5120	124
13.0	0.52	0.5397	0.5404	174
13.5	0.54	0.5745	0.5738	228
14.0	0.56	0.6188	0.6149	294
14.5	0.58	0.6835	0.6700	368
15.0	0.60	0.8889	0.7560	454

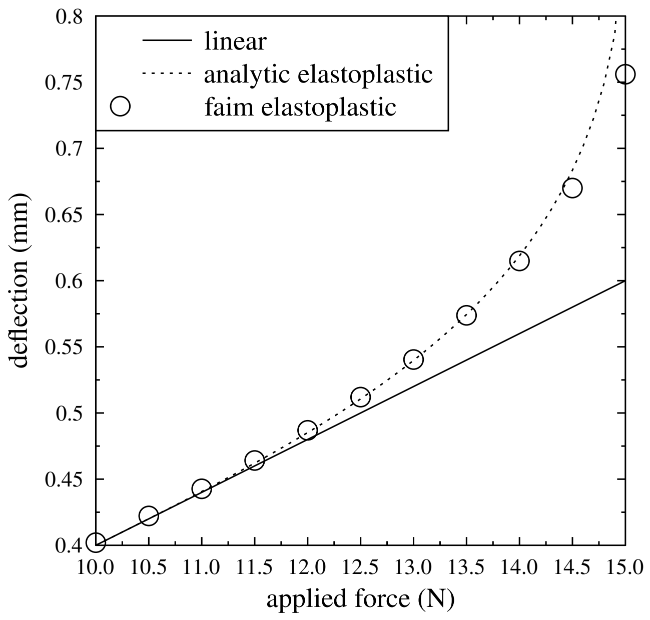


Figure 7.26: Comparison of FAIM and analytic results for elastoplastic cantilever.

Tip
If you want, you can experiment with increasing the number of elements in the model (reducing the element size) to see how this affects the result.

Incremental loading and hysteresis

Up to this point, we have solved a sequence of nonlinear models at different loads without giving a lot of thought about how these loads are applied. In fact we have solved each load point "from scratch". From a theoretical point of view, it would be better to start from the greatest load for which the model stays in the linear range, and then incrementally add small amounts of load, obtaining a sequence of slowly changing nonlinear solutions, each of which is used as the starting point for the solver for the subsequent load. This is discussed in Obtaining accurate nonlinear solutions by progressively applying loads. The question is, does this actually matter? Here we will investigate this and discover that the answer is "it depends".

The first thing we need is a script to take an existing solved n88model file, and modify the applied force. You can find this script, named `modify_force.py`, in the `cantilever` subdirectory of the examples. Since you are getting by now pretty good at scripts, here are all the preliminaries, up to reading in an existing n88 model file:

```
from __future__ import division
import argparse
import vtk
import vtkbone

script_version = 1

parser = argparse.ArgumentParser (
    description="""Take an existing cantilever model file, and modify the applied force
while leaving any existing solution unmodified. It can thus be used as the starting
value for a solution with the new applied force.""")

parser.add_argument ("input_file",
   help="An existing cantilever model file.")

parser.add_argument ("applied_force", type=float,
   help="The new applied force.")

parser.add_argument ("output_file",
    help="Name for output file.")

args = parser.parse_args()

# Read existing model (including possible solution)

print "Reading n88model file:", args.input_file
reader = vtkbone.vtkboneN88ModelReader()
reader.SetFileName (args.input_file)
reader.Update()
model = reader.GetOutput()
```

Now, we could modify the numerical values of the force constraint, but from a programming view, it is easier to just delete it and re-create it.

```
# Delete the old applied force.

model.GetConstraints().RemoveItem("end_force")

# Apply the new force to the far end of the beam.

model.ApplyLoad(
  "face_x1",
  vtkbone.vtkboneConstraint.FACE_X1_DISTRIBUTION,
  vtkbone.vtkboneConstraint.SENSE_Z,
  args.applied_force,
  "end_force")
```

That’s the meat of it. Now we just finish up with the usual entires to the history and the log, and write out the modified file.

```
# Update history and log

model.AppendHistory("Modified modify_force.py version %s ." % script_version)

model.AppendLog(
"""modify_force.py
Changed applied force on far face edge to %s .
Using VTKBONE version %s .
""" % (args.applied_force, vtkbone.vtkboneVersion.GetVTKBONEVersion()))

# Write an n88model file

print "Writing n88model file:", args.output_file
writer = vtkbone.vtkboneN88ModelWriter()
writer.SetInputData(model)
writer.SetFileName(args.output_file)
writer.Update()
```

Tip

Had we created the model with n88modegenerator, it would have been even easier to change the load in the model file: n88modegenerator can take as an input an existing model file, and it will preserve any existing solutions while modifying the material properties or constraints according to the command line arguments in the usual fashion.

Now to run this, we first create and solve a nonlinear model as we did above, with an applied force that we know, from the previous analysis, is just at the limit of linear behaviour.

```
python create_cantilever_ep.py -10 cantilever_ep.n88model
faim --convergence_tolerance=1e-9 cantilever_ep.n88model
```

As previously, we can extract from the analysis file just the numerical value for the deflection, like this

```
n88tabulate -V dz_avg_ns2 cantilever_ep_analysis.txt
```

which returns `-4.020E-01`.

Now we use our `modify_force.py` script to increase to applied force to -10.5 .

```
python modify_force.py cantilever_ep.n88model -10.5 from_100_to_105.n88model
```

And we solve it and extract the new deflection.

```
faim --convergence_tolerance=1E-9 from_100_to_105.n88model
```

What we want to see, is that faim starts with the following two status lines:

```
Model contains elastoplastic material definitions.
Model contains existing solution.
```

And further on, once the solver `solver_sp` itself has been launched, we want to verify that we see the following status output:

```
Using existing solution as starting value.
```

Then, rinse and repeat until the desired final load is reached:

```
python modify_force.py from_100_to_105.n88model -11 from_105_to_110.n88model
faim --convergence_tolerance=1E-9 from_105_to_110.n88model
n88tabulate -V dz_avg_ns2 from_105_to_110_analysis.txt
python modify_force.py from_105_to_110.n88model -11.5 from_110_to_115.n88model
faim --convergence_tolerance=1E-9 from_110_to_115.n88model
n88tabulate -V dz_avg_ns2 from_110_to_115_analysis.txt
```

and so on . . .

We can thus add another column to Table 7.1, and compare the “all-at-once” nonlinear solutions with the incremental solutions. Table 7.2 shows just these two columns. The results are practically indistinguishable. So can we therefore conclude that carefully applying an incremental load is pointless extra work? Not quite. We are not at the end of the story yet. Let us take our solution at a load of 14.5, and from there *decrement* the applied load back down to the linear region. Programmatically, this looks much like before:

```
python modify_force.py from_140_to_145.n88model -14 from_145_to_140.n88model
faim --convergence_tolerance=1E-9 from_145_to_140.n88model
python modify_force.py from_145_to_140.n88model -13.5 from_140_to_135.n88model
faim --convergence_tolerance=1E-9 from_140_to_135.n88model
```

and so on . . .

We can tabulate all the deflections at once,

```
n88tabulate -V filename,dz_avg_ns2 *_analysis.txt
```

These additional load decreasing points are tabulated in Table 7.3. These are plotted together with the increasing load points up to 14.5 in Figure 41. Now we see that that there is in fact a difference. Indeed we recognize the classic hysteresis curve. (Note that compared with Figure 40, we have swapped the axes, just so that it looks more conventional.)

Table 7.2: Elastoplastic cantilever incremental results

load	FAIM EP	FAIM incr
10.0	0.4020	0.4020
10.5	0.4222	0.4222
11.0	0.4427	0.4427
11.5	0.4641	0.4641
12.0	0.4869	0.4870
12.5	0.5120	0.5120
13.0	0.5404	0.5405
13.5	0.5738	0.5738
14.0	0.6149	0.6150
14.5	0.6700	0.6700
15.0	0.7560	0.7560
15.5	0.9611	0.9611

Table 7.3: Elastoplastic cantilever results for decreasing loads

load	FAIM decr
14.0	0.6499
13.5	0.6299
13.0	0.6098
12.5	0.5897
12.0	0.5696
11.5	0.5495
11.0	0.5294
10.5	0.5093
10.0	0.4892
0.0	0.0874

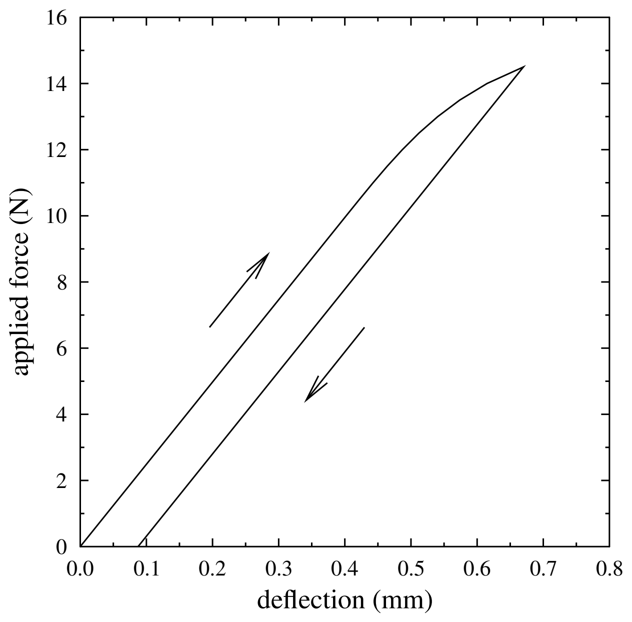


Figure 7.27: Hysteresis exhibited by elastoplastic cantilever.

This concludes the tutorial on a cantilever with elastoplastic material properties. We learned how to use elastoplastic materials in `VTKBONE` scripts, and also how to apply loads incremental steps to nonlinear models by modifying an existing `n88model` file. By carefully applying incremental loading to the cantilever, we determined that results were essentailly unaffected as compared with an “all at once” solution for the initial deflection of the beam, but that a residual deflection remains during the subsequent unloading of the beam. This residual deflection, which is the hysteresis, can only be observed by applying the load incrementally.

Advanced custom model: A screw pull-out test

In the preceding tutorials we were introduced to using `vtkbone` to create original models that cannot be generated using n88modelgenerator . We mentioned that frequently the most challenging part of creating such models is identifying the sets of nodes and/or elements corresponding to the boundary conditions that we desire. In that tutorial, however, we didn’t actually need to identify any such sets ourselves, as we found that the standard node and element sets as provided by vtkboneApplyTestBase were suitable for our purposes. In this tutorial, by contrast, we will use some sophisticated criteria for identifying the desired sets for boundary conditions. This includes,

- Identifying and characterizing features in the input image. Namely, we will determine the geometric location of a screw axis.
- Identifying nodes by spatial location (distance from the screw, as well as depth from the top surface).
- We will further reduce the selection of nodes based on visibility from a certain viewing angle, which is a useful technique for locating nodes on an uneven surface.

In the course of this example, we will generate the files `screwpullout.py` and `screwpullout.conf`. You can find the completed versions of these files in the `examples/screwpullout` directory of the distribution.

The model: a screw pull-out test

This example is a finite element model of an important mechanical test for orthopaedic biomechanics. This tutorial is based on the work of Stadelmann et al (2012). Physical tests were done in which a volume of bone substitute was constrained with a ring and the screw was pulled out. Here we construct a finite element model corresponding to this physical test.

The geometry of the model is in the file `sawbone.aim` in the `data` directory of the distribution. It consists of a volume of bone substitute into which a screw has been embedded. This is shown in Figure 42. The data have been segmented such that bone substitute is labelled with ID 127 (shown in beige), and the screw with ID 90 (shown in blue). The mechanical test is to find the force required to pull out the screw.

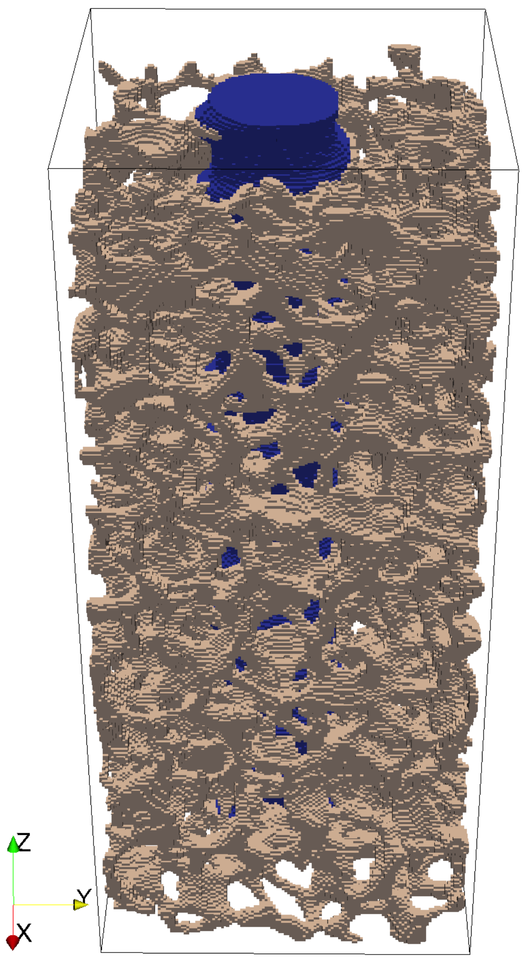


Figure 7.28: Screw model segmented image

Important
The script will look for the data file `sawbone.aim` in whatever directory it is run from. On your distribution, the example script and the data file are in different directories, `tutorials/screw_pull_out` and `data` respectively. We recommend that you copy the files from both these directories to a temporary working directory for this tutorial.

Preliminaries: first lines of Python

Using your favourite text editor, create a file `screwpullout.py`.

By now you should be pretty familiar with importing the necessary Python modules:

```
from __future__ import division
import os
import sys
import time
import vtk
import vtkbone
```

As before, we'll also set a script version number:

```
script_version = 8 ❶
```

❶, ❶ A version of this script has been used as a tutorial in previous versions of Faim. In Faim 8.0 we are on the 8th iteration of this script.

Since generating a model from a large micro-CT scan can take a lot of time, it is convenient to print status messages as the script proceeds, and to have these messages time stamped, so that we can see what steps potentially should be optimized (or where the script fails). The following function will take one or more strings and print them out one per line, with a time stamp on the first, and indenting the subsequent lines.

```
def message(msg, *additionalLines):
    """Print message with time stamp.

    The first argument is printed with the a time stamp.
    Subsequent arguments are printed one to a line without a timestamp.
    """
    print "%8.2f %s" % (time.time()-start_time, msg)
    for line in additionalLines:
        print " " * 9 + line
start_time = time.time()
```

Using a configuration file to store parameters

This model is going to be quite complicated. To keep things orderly, we will put all our parameters in a configuration file. The configuration file is a record of exactly which parameters were used to generate a particular model. We're going to write the configuration file itself in Python code, so that we don't have to write a file parser to read it. Here is what the configuration file (`screwpullout.conf`) looks like:

```
# -------------------------------------------------------------------------
#  Configuration file screwpullout.conf
#
#  This configuration file is in the format of python source code.
#  If you stick with simple assignments, then it looks like a typical
#  configuration file, and can probably be read with other file parsers,
#  if you wish to do so.

# Input image file.
input_image_file = "sawbone.aim"

# Output n88model file.
# - take the input file name and change the extension to .n88model
n88model_file = os.path.splitext(input_image_file)[0] + ".n88model"

# Bone material
```

```
bone_material_id = 127
bone_material_modulus = 6829.0    # 6829.0 MPa for bone
bone_material_poissons_ratio = 0.3

# Screw material
screw_material_id = 90
screw_material_modulus = 69000.0   # 69 GPa for Aluminum
screw_material_poissons_ratio = 0.3

# Displacement (in physical length units of the model) applied to the screw
# surface.
screw_displacement = 0.01

# Ring radii for finding nodes of bone material to which we will apply the
# constrained ring.
inner_ring_radius = 4.5
outer_ring_radius = 7.0

# Max depth for finding nodes of bone material to which we will apply the
# constrained ring. The max is measured from the highest node of constrained
# bone found.
bone_constraint_max_depth = 1.5
```

Now we add to our script the following:

1. A bit of code to get the configuration file name from the command line.
2. One line to execute the configuration file as Python code.
3. Some lines to print out all the values that we expected to read in. This is very good practice so when you run it, you can verify that everything is as you expect.

All that looks like this:

```
if len(sys.argv) != 2:
  print "Usage: python screwpullout.py example.conf"
  sys.exit(1)
config_file = sys.argv[1]

# Read in configuration file.
message("Reading configuration file " + config_file)
# Here we are actually executing it as python code.
execfile(config_file)

# Print out values that we read in. This also has the effect of causing
# this script to die if configuration values are missing (which is a good thing).
settings_text = ["Configuration:"]
settings_text.append( "input file                     = %s" % input_image_file)
settings_text.append( "output file                    = %s" % n88model_file)
settings_text.append( "bone material id               = %s" % bone_material_id)
settings_text.append( "bone material Young’s modulus  = %s" % bone_material_modulus)
settings_text.append( "bone material Poisson’s ratio  = %s" % bone_material_poissons_ratio)
settings_text.append( "screw material id              = %s" % screw_material_id)
settings_text.append( "screw material Young’s modulus = %s" % screw_material_modulus)
settings_text.append( "screw material Poisson’s ratio = %s" % screw_material_poissons_ratio ↩
    )
settings_text.append( "screw displacement             = %s" % screw_displacement)
settings_text.append( "inner ring radius              = %s" % inner_ring_radius)
settings_text.append( "bone constraint max depth      = %s" % bone_constraint_max_depth)
message(*settings_text) ❶
```

1 This is slightly advanced python, where the asterisk means that we pass the list of *N* items (strings in this case) not as a single list argument, but as *N* individual arguments. It just happens that given the way we wrote our `message` function, this is the best thing to do here.

Now when we run our script, we also have to specify the name of the configuration file:

```
$ python screwpullout.py screwpullout.conf
```

Reading the segmented image file

We will use a vtkboneAIMReader to read the data file, which is in the Scanco AIM file format. This file contains a segmented image. As well, we want to add some additional lines to report our progress, and print some values as a sanity check.

```
message("Reading input data.")
reader = vtkbone.vtkboneAIMReader()
reader.SetFileName(input_image_file)
reader.DataOnCellsOn() ❶
reader.Update()
image = reader.GetOutput()
message("Read %d points from image file." % image.GetNumberOfPoints())
image_bounds = image.GetBounds() ❷
message("Image bounds:", (" %.4f"*6) % image_bounds)
```

1 As discussed in several previous tutorials, we can either have the image data on the Cells or the Points. `vtkbone` is generally agnostic on this point, but it is good to be clear.

2 This is a standard VTK method for many types of VTK objects, returning an array of six values: x_{min}, x_{max}, y_{min}, y_{max}, z_{min}, z_{max}.

The output so far, when we run the Python script, will look something like this:

```
$ python screwpullout.py screwpullout.conf
    0.00 Reading configuration file screwpullout.conf
    0.00 Configuration:
         input file                     = sawbone.aim
         output file                    = sawbone.n88model
         bone material id               = 127
         bone material Young's modulus  = 6829.0
         bone material Poisson's ratio  = 0.3
         screw material id              = 90
         screw material Young's modulus = 69000.0
         screw material Poisson's ratio = 0.3
         screw displacement             = 0.01
         inner ring radius              = 4.5
         bone constraint max depth      = 1.5
    0.00 Reading input data.
    0.07 Read 5775920 points from AIM file.
    0.07 Image bounds:
          11.9700 27.4740 11.7420 27.1320 0.1140 35.3400
```

Converting the image data to elements

As in the tutorial Compressing a cube revisited using vtkbone, we need to convert the input CT image data to a vtkUnstructuredGrid object representing the geometry. Again, we will use a vtkboneImageToMesh filter for this purpose.

```
message("Converting to hexahedral cells.")
mesher = vtkbone.vtkboneImageToMesh()
mesher.SetInputData(image)
mesher.Update()
mesh = mesher.GetOutput()
message("Generated %d hexahedrons" % mesh.GetNumberOfCells())
```

Defining material properties

Once again, we repeat the steps of the tutorial Compressing a cube revisited using vtkbone, and we generate a material table and two materials: bone and screw.

```
message ("Creating material table.")
material_table = vtkbone.vtkboneMaterialTable()

# Create an isotropic material for bone and add it to the table.
bone_material = vtkbone.vtkboneLinearIsotropicMaterial()
bone_material.SetName("bone")
bone_material.SetYoungsModulus(bone_material_modulus)
bone_material.SetPoissonsRatio(bone_material_poissons_ratio)
material_table.AddMaterial(bone_material_id, bone_material)

# Create an isotropic material for the screw and add it to the table.
screw_material = vtkbone.vtkboneLinearIsotropicMaterial()
screw_material.SetName("screw")
screw_material.SetYoungsModulus(screw_material_modulus)
screw_material.SetPoissonsRatio(screw_material_poissons_ratio)
material_table.AddMaterial(screw_material_id, screw_material)
```

Creating a vtkboneFiniteElementModel object

In the tutorial, Deflection of a cantilevered beam; adding custom boundary conditions and loads, we used vtkboneApplyTestBase to combine the geometry with the model table into a vtkboneFiniteElementModel object. vtkboneApplyTestBase didn't create any displacement boundary conditions or applied loads for us, but it did define some standard sets that we subsequently used to define our displacement boundary conditions and applied load. This time, those standard sets won't we very useful for us. So instead of vtkboneApplyTestBase , we'll use an even more elementary model-creating filter called vtkboneFiniteElementModel-Generator , which creates a vtkboneFiniteElementModel object without any pre-defined sets.

Tip
Actually, it is not quite true that we couldn't use need any standard sets. The standard set “face_z1” would be the top surface of the screw, which is one of the sets that we need. However, for the purposes of demonstration, we'll show how to find that node set manually.

```
message("Constructing a finite element model object.")
generator = vtkbone.vtkboneFiniteElementModelGenerator()
generator.SetInputData(0, mesh)
generator.SetInputData(1, material_table)
generator.Update()
model = generator.GetOutput()
model.ComputeBounds() ❶
bounds = model.GetBounds()
message("Model bounds:", (" %.4f"*6) % bounds)
```

❶ Unlike vtkImageData objects, vtkUnstructuredGrid objects, from which vtkboneFiniteElementModel objects are derived, don't know their bounds unless you explicitly request them to be computed.

Writing an n88model file

Now that we have a vtkboneFiniteElementModel object, we can save it. Of course, the model isn't finished yet, but just as in the previous tutorial, we can still save it and examine it as we go.

```
message("Writing file %s" % n88model_file)
writer = vtkbone.vtkboneN88ModelWriter()
writer.SetInputData(model)
writer.SetFileName(n88model_file)
writer.Update()
```

Important
Once again, in everything that follows it is intended that you add new lines to the script **before** the code (show just above) that saves the model to a file. Otherwise of course the saved `n88model` file won't reflect our additions and changes.

Adding history and log fields

By now you'll be familiar with adding History and Log fields to help us later trace back the details of the creation of this model. Let's add all this information (before the code to save the file!):

```
model.AppendHistory("Created by screwpullout.py version %s ." % script_version)

model.AppendLog(
"""screwpullout.py
Model of screw being pulled out of bone substitute material.
Using VTKBONE version %s .
Configuration file : %s
""" % (vtkbone.vtkboneVersion.GetVTKBONEVersion(), config_file)
+ "\n".join(settings_text)) ❶
```

❶ This looks a little bit complicated. `"\n".join(settings_text))` converts the Python list of strings to a single long string, inserting a line return ("\n") between each list item. We then just add it to the other string.

Now run the script. As a reminder, this is done with

```
$ python screwpullout.py screwpullout.conf
```

As shown in previous tutorials, we can retrieve the History and Log fields from the `n88model` file at any time with n88modelinfo:

```
$ n88modelinfo --history --log sawbone.n88model
History:
----------------------------------------------------------------------
2016-Sep-27 16:12:21 Created by screwpullout.py version 8 .
----------------------------------------------------------------------

Log:
----------------------------------------------------------------------
2016-Sep-27 16:12:21
screwpullout.py
Model of screw being pulled out of bone substitute material.
Using vtkbone version 1.0 .
Configuration file : screwpullout.conf
Configuration:
input file                        = sawbone.aim
output file                       = sawbone.n88model
```

```
bone material id                = 127
bone material Young’s modulus  = 6829.0
bone material Poisson’s ratio  = 0.3
screw material id               = 90
screw material Young’s modulus = 69000.0
screw material Poisson’s ratio = 0.3
screw displacement              = 0.01
inner ring radius               = 4.5
bone constraint max depth       = 1.5
----------------------------------------------------------------------
```

Determining the screw orientation

In order to properly apply the desired constraints, we will need to know where the screw is. We can do this algorithmically, by calculating the principal axes of inertia of the screw using vtkboneTensorOfInertia . We are going to assume that the principal axis closest to the *z* axis is the screw axis. This won’t be exactly true. Consider for example if the screw is cut off unevenly, then the principal axis of inertia won’t be exactly the same as the screw axis, but for our purposes, it is good enough.

```
message("Determining screw geometry.")

moi = vtkbone.vtkboneTensorOfInertia()
moi.SetInputData(image)
moi.SetSpecificValue(screw_material_id) ❶
moi.Update()
message("Number of cells belonging to screw: %d" % moi.GetCount())
message("Volume of screw: %.2f" % moi.GetVolume())
screwCenterOfMass = (moi.GetCenterOfMassX(),
                     moi.GetCenterOfMassY(),
                     moi.GetCenterOfMassZ())
message("Center of mass of screw: %.5f, %.5f, %.5f" % screwCenterOfMass)
screwAxis = moi.GetPrincipalAxisClosestToZ()
message("Axis of screw: %.5f, %.5f, %.5f" % screwAxis)
screwDistanceToBoundary = (bounds[5] - screwCenterOfMass[2]) / screwAxis[2]
screwCenterAtBoundary = (
    screwCenterOfMass[0] + screwDistanceToBoundary * screwAxis[0],
    screwCenterOfMass[1] + screwDistanceToBoundary * screwAxis[1],
    bounds[5]) ❷
message("Distance from screw center of mass to top boundary: %.3f" %  ↩
    screwDistanceToBoundary)
message("Screw center at top boundary: %.3f, %.3f, %.3f" % screwCenterAtBoundary)
```

❶ This is how we limit the inertia tensor to be calculated only over the screw elements.

❷ This is a simple geometric calculation: given the center of mass of the screw and the direction of the screw axis, find the intersection with the upper bound of the model.

Now we run it, and this part of the script generates output like this:

```
    1.55 Determining screw geometry.
    1.67 Number of cells belonging to screw: 449618
    1.67 Volume of screw: 666.13
    1.67 Center of mass of screw: 20.20622, 19.02016, 18.21310
    1.67 Axis of screw: -0.00733, -0.00243, 0.99997
    1.67 Distance from screw center of mass to boundary: 16.785
    1.67 Screw center at boundary: 20.083, 18.979, 34.998
```

Comparing by eye with the rendering in ParaView, we can determine that these values are about right, so we give ourselves a gold star in advanced math and carry on.

Adding a boundary condition: applying a displacement to the screw end

We want to add a boundary condition to the screw where it intersects the boundary of the model. All these nodes lie on a plane, so they are easily found with the function `AddNodesOnPlane` provided in vtkboneNodeSetsByGeometry . Note that these nodes get associated with the FE model object, and we have to assign a name, in this case “screw_top”, so that we can refer later to this set.

```
message("Adding the screw_top boundary condition.")

vtkbone.vtkboneNodeSetsByGeometry.AddNodesOnPlane(
    2, ❶
    bounds[5], ❷
    "screw_top", ❸
    model,
    screw_material_id) ❹
message("Found %d nodes belonging to screw_top" %
     model.GetNodeSet("screw_top").GetNumberOfTuples())
```

❶ The value 2 specified the z-axis (VTK and python being zero-indexed).

❷ This is z_{max}.

❸ The name of the node set we are creating.

❹ This argument is optional, and specifies that we only want nodes associated with material ID “screw_material_id”. This is not actually necessary for the given data, since no elements of other material IDs intersect the z_{max} surface.

We want to be able to inspect this result, and ensure that we have in fact selected the nodes on the top of the screw. To do this, run the script to update the model file. Now, as in the tutorial Bending test of a radius bone with an uneven surface, we are going to use the tool n88extractsets to extract and visualize the node set.

```
$ n88extractsets sawbone.n88model
Reading N88 Model file : sawbone.n88model
Writing node set : sawbone_node_set_screw_top.vtp
```

The file `sawbone_node_set_screw_top.vtp` can be opened an visualized with ParaView. The nodes are shown in Figure 43, exactly on the end of the screw. This is what we want.

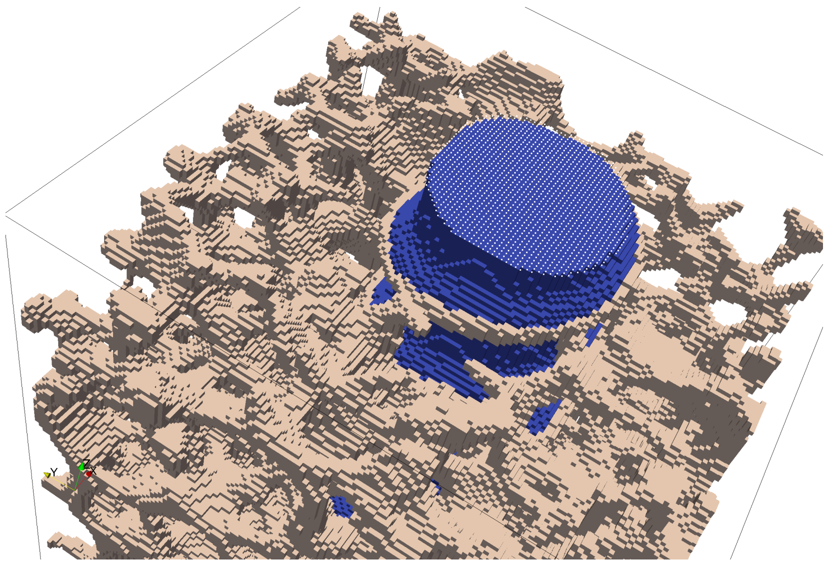


Figure 7.29: Screw top nodes, shown as white dots on the surface of the screw

Tip

An alternative to using n88extractsets is to add lines to extract and save the node set directly to the script. We no longer recommend this, as it makes the script longer, more complex, and slower to run. However, for the record, this is how it would be done,

```
writer = vtk.vtkXMLUnstructuredGridWriter()
writer.SetInputData(model.DataSetFromNodeSet("screw_top"))
writer.SetFileName("screw_top_nodes.vtu")
writer.Update()
```

Having verified that we have found the set of nodes that we want, we can use the method `ApplyBoundaryCondition` of the vtkboneFiniteElementModel object to create a boundary condition. Note that we also give this the name "screw_top_-displacement".

```
model.ApplyBoundaryCondition(
    "screw_top", ❶
    2, ❷
    screw_displacement, ❸
    "screw_top_displacement")
```

❶ The name of the set to which is apply the boundary condition.

❷ Once again the value 2 means the z direction

❸ This variable is the numerical value of the displacement.

Fixing the nodes in a ring on the bone surface

This boundary condition is much more difficult, because we want to find nodes lying approximately in a ring on a rough surface. The approach we will take is to successively whittle down candidate nodes by applying a sequence of criteria, until we have finally just the nodes we want. These are the criteria:

1. Elements (cells) lie between a specified inner radius and outer radius, as measured from the screw axis.
2. Nodes lie within a maximum specified depth from the highest node satisfying the first criterion.
3. Nodes are visible from above.

Tip

These selection criterion could in principle be applied in a different order. The reason for doing the selection by visibility last, is that it is computationally expensive, so we want to whittle down the candidate nodes/elements as much as possible before applying a visibility test.

Step 1: Selecting cells within a hollow cylinder

VTK uses the concept of implicit functions which can be used to select points and cells within or without a certain geometry. Here we are going to use two vtkCylinder objects, and combine them with a difference operation with a vtkImplicitBoolean . This will result in a hollow cylinder. VTK has a filter object, vtkExtractGeometry , that will select points and cells based on a specified implicit function.

One complication is that set of Points in the output of vtkExtractGeometry are different than the original Points, and so the Point IDs will be different. However, we need to know the original Point IDs in order to be able to apply boundary conditions to the FE model. The solution to this is to use a concept in VTK called "Pedigree ID". These can be accessed with the method `GetPedigreeIds` from the PointData.

Note

Not every VTK data set will have Pedigree IDs. They must be added to the data set before we start chopping out subsets. However, by default vtkboneFiniteElementModelGenerator creates vtkboneFiniteElementModel objects with Pedigree IDs.

```
message("Adding the fixed_bone_surface boundary condition.")

inner_cylinder = vtk.vtkCylinder() ❶
inner_cylinder.SetRadius(inner_ring_radius)
inner_cylinder.SetCenter(screwCenterAtBoundary[0], 0, screwCenterAtBoundary[1]) ❷

outer_cylinder = vtk.vtkCylinder()
outer_cylinder.SetRadius(outer_ring_radius)
outer_cylinder.SetCenter(screwCenterAtBoundary[0], 0, screwCenterAtBoundary[1]) ❸

rotate_Y_to_Z = vtk.vtkTransform() ❹
rotate_Y_to_Z.RotateX(90)

cylinder_difference = vtk.vtkImplicitBoolean()
cylinder_difference.AddFunction(outer_cylinder)
cylinder_difference.AddFunction(inner_cylinder)
cylinder_difference.SetOperationTypeToDifference()
cylinder_difference.SetTransform(rotate_Y_to_Z)

cylinder_extractor = vtk.vtkExtractGeometry()
cylinder_extractor.SetImplicitFunction(cylinder_difference)
cylinder_extractor.SetInputData(model)
cylinder_extractor.Update()
geometry_in_ring = cylinder_extractor.GetOutput() ❺

message("Found %d elements between inner and outer radii." % geometry_in_ring. ↩
    GetNumberOfCells())
```

❶ Important: vtkCylinder is by default oriented with a y axis of rotation. We will rotate to z axis of rotation later.

❷, ❸ Note that the center is swapped $y \leftrightarrow z$ because of the transform that will be applied.

❹ This is the transform we need to bring $y \rightarrow z$. Note that the transformation will be applied to input points, not to the cylinder geometry.

❺ The output will be another vtkUnstructuredGrid, which consists of a subset of the input geometry (including a subset of both Cells and Points).

Now, this is a good place to see what we have so far for a selection. There are two possibilites: we could write out `geometry_in_ring` with a vtkXMLUnstructuredGridWriter filter, or we could add the element IDs as a set to the model. Let's do the latter:

```
elements_in_ring = vtk.vtkIdTypeArray() ❶
elements_in_ring.DeepCopy(geometry_in_ring.GetCellData().GetPedigreeIds())
elements_in_ring.SetName("in_ring")
model.AddElementSet(elements_in_ring)
```

❶ To keep things clear, we're going to make a copy of the data array that is the PedigreeIds. This will allow us to modify it, by for example re-naming it, without affecting the original. There are two steps to this: creating a new empty vtkIdTypeArray and then using its `DeepCopy` method on the data array we want to copy.

Again, run the script to update the `n88model` file. We can now extract this element set from it as follows:

```
$ n88extractsets --element_sets sawbone.n88model
Reading N88 Model file : sawbone.n88model
Writing element set : sawbone_element_set_in_ring.vtp
```

Figure 44 shows this selection (*i.e.* the file `sawbone_element_set_in_ring.vtp`), together with the screw elements, shown for context. (We used a Threshold filter in ParaView to show just the screw cells from `sawbone.n88model`.) Figure 45 is another view of the same data. This view is more suited to inspecting the ring geometry of our selection. To construct this view, first hit the +z button on the toolbar in order to view exactly along the *z* axis. Then from View Settings under the Edit menu, select Use Parallel Projection. Finally, change the Representation of both data sets to Surface With Edges in order to show individual Cells.

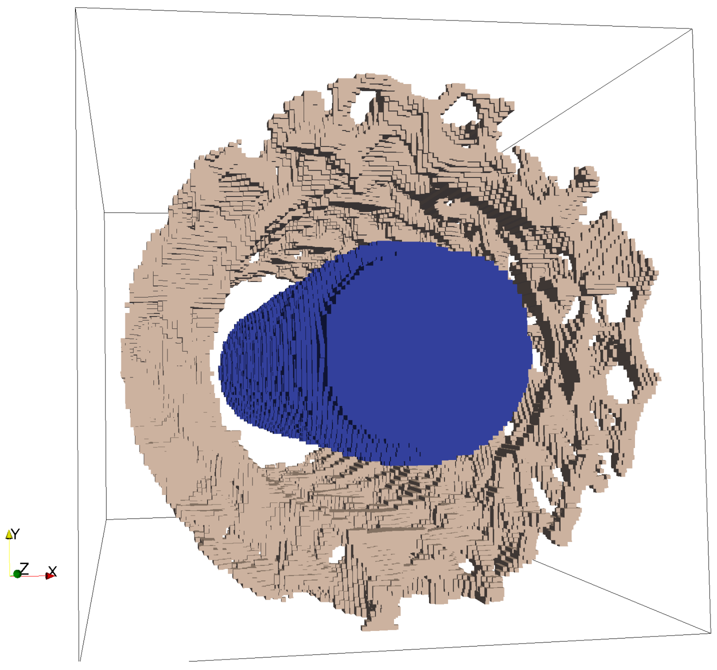


Figure 7.30: Geometry as selected by hollow cylinder filter

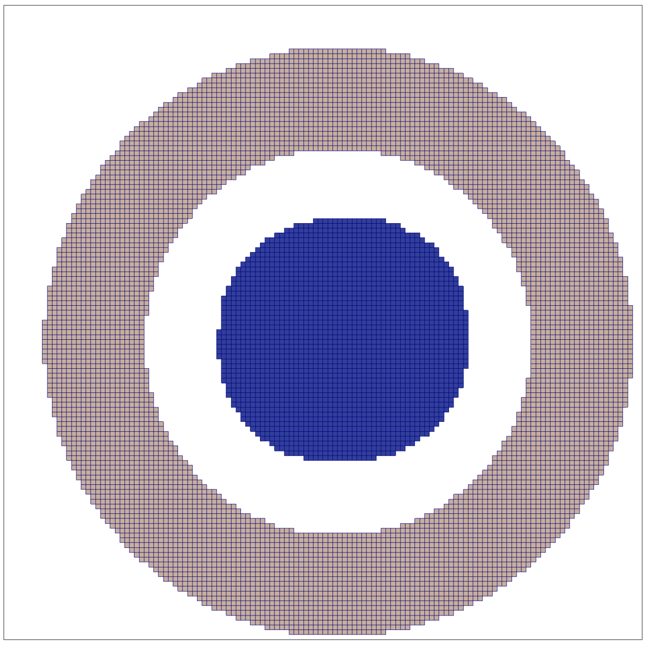


Figure 7.31: Geometry as selected by hollow cylinder filter, seen in flat projection

Step 2: Eliminating nodes below a certain depth

To select elements based on depth, as measured from the highest node in our set, we apply a similar approach as we did to select elements within the correct radii. We use a VTK implicit function, in this case a vtkBox , to specify the geometrical volume to which we want to limit our element set.

```
message("Filtering node set by depth.")

geometry_in_ring_bounds = geometry_in_ring.GetBounds() ❶
message("Bounds of ring geometry: ", (" %.4f"*6) % geometry_in_ring_bounds)
box_bounds = (geometry_in_ring_bounds[0],
              geometry_in_ring_bounds[1],
              geometry_in_ring_bounds[2],
              geometry_in_ring_bounds[3],
              geometry_in_ring_bounds[5] - bone_constraint_max_depth,
              geometry_in_ring_bounds[5])
message("Limiting selection to box bounds: ", (" %.4f"*6) % box_bounds)

box = vtk.vtkBox()
box.SetBounds(box_bounds)

filter = vtk.vtkExtractGeometry()
filter.SetImplicitFunction(box)
filter.ExtractInsideOn()
filter.ExtractBoundaryCellsOn()
filter.SetInputData(geometry_in_ring)
filter.Update()
geometry_depth_filtered_ring = filter.GetOutput()

message("Found %d elements in bounding box." % geometry_depth_filtered_ring. ↩
    GetNumberOfCells())
```

❶ Note that the z_{max} bound of `geometry_in_ring` will be at the highest bit of bone in the ring.

Now just as before, we can create a corresponding element set for the purposes of inspection:

```
elements_depth_filtered_ring = vtk.vtkIdTypeArray()
elements_depth_filtered_ring.DeepCopy(geometry_depth_filtered_ring.GetCellData(). ↩
    GetPedigreeIds())
elements_depth_filtered_ring.SetName("depth_filtered_ring")
model.AddElementSet(elements_depth_filtered_ring)
```

Run the script, and use n88extractsets to extract the element sets, and it will create a new file, `sawbone_element_set_-depth_filtered_ring.vtp`.

Figure 46 shows the remaining elements after filtering by depth.

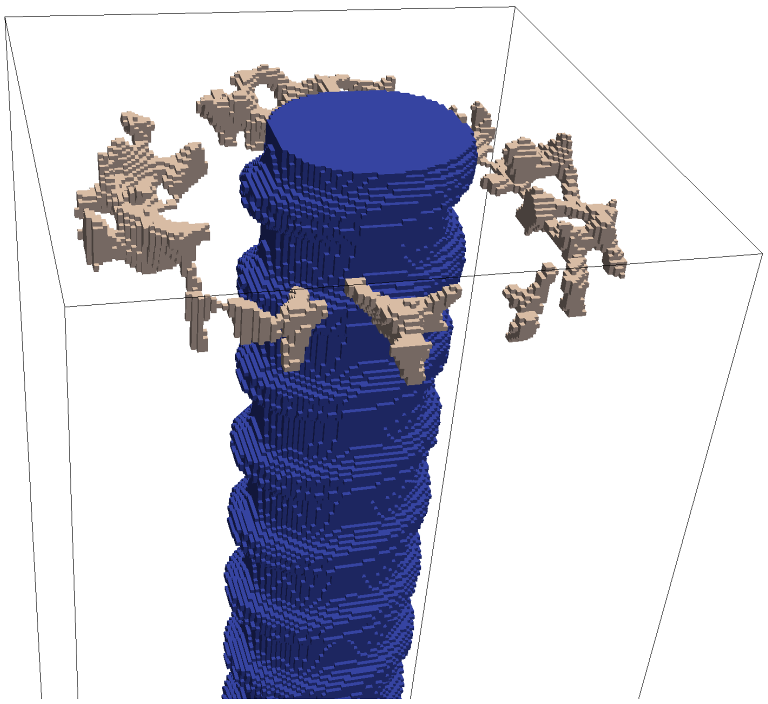


Figure 7.32: Ring geometry after filtering by depth

Step 3: Selecting only the nodes visible from above

We can use the function `FindNodesOnVisibleSurface` from vtkboneNodeSetsByGeometry for this purpose. We need to pass it a normal vector for the viewing direction, as well as an empty vtkIdTypeArray for storing the result.

```
message("Finding visible nodes.")

visibleNodesIds = vtk.vtkIdTypeArray() ❶
normalVector = (0,0,1) ❷
vtkbone.vtkboneNodeSetsByGeometry.FindNodesOnVisibleSurface(
  visibleNodesIds,
  geometry_depth_filtered_ring,
  normalVector,
  bone_material_id) ❸
visibleNodesIds.SetName("ring_top_visible")
model.AddNodeSet(visibleNodesIds)

message("Found %d visible nodes." % visibleNodesIds.GetNumberOfTuples())
```

1. This will store the result as a list of Point IDs.
2. This is the negative of the viewing direction.
3. `FindNodesOnVisibleSurface` automatically returns the Pedigree Ids, provided that they exist on in input object (they do).

Again, run the script to update the `n88model` file. This time we want to extract the node sets

```
$ n88extractsets --node_sets sawbone.n88model
Reading N88 Model file : sawbone.n88model
Writing node set : sawbone_node_set_screw_top.vtp
Writing node set : sawbone_node_set_ring_top_visible.vtp
```

The resulting ring-shaped cloud of points (file `sawbone_node_set_ring_top_visible.vtp`) is shown in Figure 47. These are the nodes to which we will apply our fixed boundary condition.

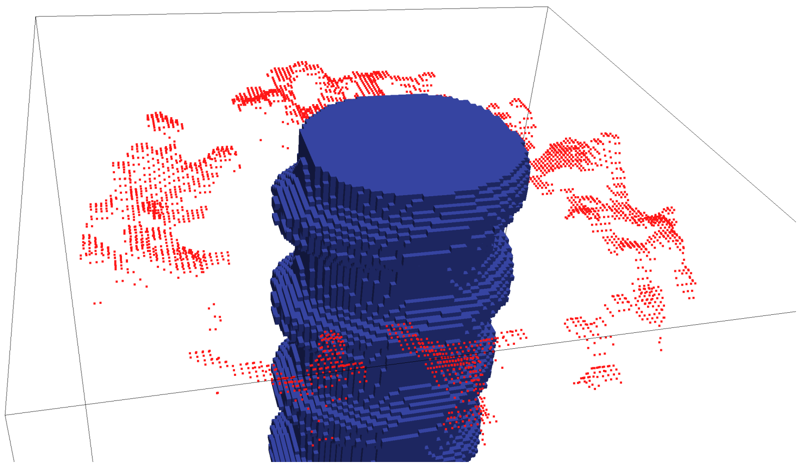


Figure 7.33: Bone nodes after filtering by visibility from above

Defining the boundary condition on the bone

Now that we have a named node set for this constraint, it is easy to create the desired boundary condition, which we will name “fixed_bone_surface”:

```
model.FixNodes("ring_top_visible", "fixed_bone_surface")
```

Adding a convergence set

As we did in Section 7.6, we will add a *convergence set*. See Convergence measure for discussion.

```
# Create a convergence set: the force on the screw

model.ConvergenceSetFromConstraint("screw_top_displacement")
```

This method notices that the constraint named *screw_top_displacement*, which we created previously, is a boundary condition. It then constructs the compliment, which is the force summed over all nodes subject to the boundary conditions. It is this force that the solver will watch to determine when its value ceases to change meaningfully. At that point the solver is finished.

Specifying sets for post-processing

Just as we saw in the tutorial Deflection of a cantilevered beam; adding custom boundary conditions and loads, there remains one more step to complete the `n88model` file, and that is to identify the sets to be used for post-processing calculations by n88postfaim. We are interested in values calculated on the sets “ring_top_visible” and “screw_top”. However, when we have generated our own custom sets, as we have here, we must be careful about providing both node sets and the corresponding element sets to n88postfaim. If you review how we created the sets for generating boundary conditions, you will observe that we only generated the node sets. Fortunately, there is a method `GetAssociatedElementsFromNodeSet` of vtkboneFiniteElementModel that will identify the corresponding element set given a node set.

```
info = model.GetInformation()
pp_node_sets_key = vtkbone.vtkboneSolverParameters.POST_PROCESSING_NODE_SETS()
pp_elem_sets_key = vtkbone.vtkboneSolverParameters.POST_PROCESSING_ELEMENT_SETS()
for setname in ["ring_top_visible", "screw_top"]:
    pp_node_sets_key.Append(info, setname)
    elementSet = model.GetAssociatedElementsFromNodeSet(setname)
    model.AddElementSet(elementSet)
    pp_elem_sets_key.Append(info, setname)
```

After running the script, we can verify that these post-processing sets are in fact specified in the `n88model` file,

```
$ n88modelinfo --problems sawbone.n88model
Problems:
-----------------------------------------------------------------------

  Name : Problem1
  Part : Part1
  Constraints : screw_top_displacement,fixed_bone_surface
  ConvergenceSet : convergence_set
  PostProcessingNodeSets : ring_top_visible,screw_top
  PostProcessingElementSets : ring_top_visible,screw_top
-----------------------------------------------------------------------
```

Tip
As before, it is possible to skip this step, and instead to specify the node and element sets to be used by n88postfaim on the command line of n88postfaim with the arguments

```
--node_sets=ring_top_visible,screw_top --element_sets=ring_top_visible,screw_top
```

We now have a complete `n88model` file. If you want, you can proceed to solve it using faim, as in previous tutorials. We leave it as an exercise to identify, from the analysis file, the net forces between the screw top and the constrained ring of bone.

This concludes the screw pull-out tutorial. In this tutorial we learned how to generate node sets based on complex criteria, to which we can then apply boundary conditions. This is the final tutorial in the series on learning `vtkbone`.

Additional examples

In addition to the tutorials, there are additional examples included in the `other_examples` directory. Currently these consist of

segment_dicom
An example of reading a raw image file and performing a simple segmentation based on a density threshold and connectivity.

Chapter 8

Special Topics

Efficient Handling of Large Numbers of Material Definitions

In typical usage of Faim, the number of defined materials is small. In fact, often we define just a single material as “bone”. We can, and do, take advantage of the expectation of relatively few defined materials in the following three ways:

1. The solver can pre-calculate important values for each material. In particular, the standard solver pre-calculates a 24×24 *local stiffness matrix* for each material. This saves quite a bit of time on each iteration, and the storage is insignificant, provided that the number of material definitions is substantially less than the number of elements.
2. In the n88model file format, each individual material definition is stored as a kind of object, with a name, a named type, and named characteristics and values. This allows great flexibility in defining material types. The net impact on the file size is insignificant so long as the number of material definitions is substantially less than the number of elements.
3. When generating tables of post-processing results with n88postfaim, results can be tabulated in subtables broken down by material ID. This is useful, but only so long as the number of defined materials stays within a range easily scanned by humans.

Although these are important advantages, there are occasions when the assumption of few material definitions is not so good. Here are two such cases:

A A Homminga material table is used, which generates a sequence of varying material properties according to image density. In this case, we are typically talking about a material table of the order of one hundred material IDs. The assumptions *1* (solver pre-calculated values) and *2* (efficient file storage of material definitions) still hold, but the output of n88postfaim, if broken down by material, becomes cumbersome and excessive.

B Some researchers have proposed models in which the bone anisotropy is continuously variable. To model this with FE software requires that each element have its own stiffness matrix. Therefore the number of required material definitions is equal to the number of elements. In this case, following assumptions *1* and *2* results in a large inefficiencies: the solver uses greatly more memory, and the model file is many times larger than it would be for geometric data only.

To address these issues, version 8 of Faim introduces the concept of *material arrays*, in contrast to the existing *material tables*. This is an expansion of the capabilities of Faim, and is really only relevant for the two cases listed above. For all other cases, one could say for normal usage, the previous concept of material tables is preferable, and it remains the default.

For the file format, a simple extension of the `n88model` standard is adopted, wherein a material definition object within the file (in practice a *group* in netCDF terminology), may optionally, instead of having named attributes, have arrays of any length with the same names (where arrays in netCDF are called *variables*). The length of the array indicates then that *M* materials are being defined at once, and that they should get sequential material IDs. Here are how the two above cases can be handled:

A
: Homminga material table: You could have in your model file a single material array of length 127 for example. It has material ID 1, which implies the definition of materials 1..127. The material ID for each of your elements is in this range. This is in fact the method of operation of `n88modelgenerator` if you select a Homminga material table, and likewise for the vtkbone class vtkboneGenerateHommingaMaterialTable .

B
: Continuously variable anisotropy: You could have in your model file a single material array of length equal to the number of elements N. It has material ID 1, implying the definition of materials 1..N . Consequently, you must have labelled your elements with sequential material IDs 1..N .

These are the typical cases, but more exotic combinations are allowed. You don't need to necessarily start an array at material ID 1, and you may define multiple material arrays. You can also mix traditional single material definitions with material arrays, and there is no requirement that all the definitions in your file are of the same type. For example, you could have one material array of isotropic materials, and another of orthotropic materials. The only rule is that be no overlap of material IDs, but otherwise in principle anything is allowed.

Let us look at the consequences for the solver. For linear models, there are two solvers. The traditional and commonly used solver `n88solver_slt`, which uses material tables internally, and the new solver `n88solver_sla`, which uses material arrays internally, and is efficient ***only*** when the number of material definitions is equal to or comparable to the number of materials. Firstly, the solvers are entirely independent of the `n88model` file. This is an important point: **all solvers can read all model files**. `n88solver_slt` always converts all material definitions in the model file, regardless of whether defined individually or in arrays, into a material table with entries for each material ID. This material table includes pre-calculated local stiffness matrices, and the number of entries is equal to the summed lengths of all defined material arrays, plus the number of individually defined materials. Conversely, `n88solver_sla` always generates an internal material array of the same length as the number of elements. Even if you only define one, or few, materials, these few materials will repeat over and over so that there is one entry per element. The critical efficiency of `n88solver_sla` as compared with `n88solver_slt` is that only the minimal number of material parameters is stored in the material array, and storage of pre-calculated values is avoied. As a consequence `n88solver_sla` is almost always slower than `n88solver_slt`; the trade-off is that `n88solver_slt` uses really huge amounts of memory when the number of defined materials becomes comparable to the number of elements.

Note

The script `faim` will always use the solver `n88solver_slt` except in the single case where exactly one material array is defined, and it has length equal to the number of elements. In this case, `faim` will chose to use the `n88solver_sla` solver. You can of course always run the solver of your choice manually.

Finally, when it comes to post-processing with n88postfaim, where sub-tables for each material ID are generated, all material IDs corresponding to a material array are grouped into a single subtable. This prevents the amount of output from becoming excessive.

Direct Mechanics

Microstructural organization plays an important role in macroscopic mechanical behaviour. For example, bone microarchitectural organization, as shown here in a human proximal femur, can exhibit patterns that are related to the macrostructural mechanical behaviour, and those patterns vary depending on the mechanical requirements at each location within the bone. A useful approach to characterizing the microstructural patterns (also referred to as "fabric") is to determine the anisotropic properties of sub-volumes of bone. In some regions of the femur, for example, the bone microarchitecture will be highly aligned with the bone axis, but in other parts the alignment may be predominantly in a transverse orientation. The anisotropic properties typically need to be defined at several locations due to spatial variation.

Anisotropy can be defined in terms of either the fabric or mechanical behaviour. Methods for characterizing the fabric are based on techniques such as mean intercept length or star volume analysis, and a good resource is the paper by Odgaard (1997a).

Essentially, fabric methods focus on the distribution of tissue microarchitecture. Alternatively, the mechanical elastic behaviour can be determined, and has been shown by Odgaard et al. (1997b) that the anisotropic fabric and mechanical properties are similar. This observation makes sense, and reinforces the concept that underlying bone micro-architecture is an important factor in determining mechanical behaviour. Here we focus on the determination of bone anisotropic elastic behaviour using a so-called *direct mechanics* assessment as proposed by van Rietbergen et al. (1996). In summary, six elastic finite element tests are performed on a cubic subvolume, and those results are used to define a 6×6 stiffness matrix that relates stress to strain as per Hooke's Law,

$$\sigma = \mathbf{C}\varepsilon \ .$$

The most general anisotropic material requires 21 independent coefficients to fully characterize, but it is usually most convenient to assume there are planes of elastic symmetry, in which case there exists an orientation of a coordinate system where only 9 independent elastic coefficients are needed. See the section Linear Orthotropic Material. In this case,

$$\mathbf{C} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ & C_{22} & C_{23} & 0 & 0 & 0 \\ & & C_{33} & 0 & 0 & 0 \\ & & & C_{44} & 0 & 0 \\ & sym. & & & C_{55} & 0 \\ & & & & & C_{66} \end{bmatrix} .$$

Finite element models of real measurement data of biological materials do not exhibit perfect orthotropic symmetry, therefore the process of reducing the 6×6 matrix from 21 independent coefficients to 9 involves finding an optimal coordinate system such that some of the coefficients are close to zero. It is reasonable to assume that bone mechanical behaviour can be reduced to a case of orthotropy; however, caution should be exercised as it is up to the user to determine whether this simplification is appropriate.

The basis of the direct mechanics approach is the application of six finite element tests to an appropriate bone subvolume:

1. uniaxial normal strain in the x-direction (ε_{xx})
2. uniaxial normal strain in the y-direction (ε_{yy})
3. uniaxial normal strain in the z-direction (ε_{zz})
4. uniaxial shear strain in the x-direction (γ_{yz})
5. uniaxial shear strain in the y-direction (γ_{zx})
6. uniaxial shear strain in the z-direction (γ_{xy})

These tests are applied under the conditions of unit engineering strain. Each test is evaluated for the six resulting stresses (σ_{xx}, σ_{yy}, σ_{xx}, σ_{yz}, σ_{zx}, σ_{xy}), thus providing directly the values of the 6×6 stiffness matrix. The stresses are calculated as a volume average, which can be shown to be equivalent to the surface stresses on the faces of the cube.

Finding the optimal rotation of the coordinate system to represent orthotropic behaviour involves first decomposing the stiffness matrix into symmetric and asymmetric components. The asymmetric component is discarded, as conservation laws require that the stiffness matrix be symmetric. (The asymmetric component thus consists entirely of measurement error.) An optimal rotation is then found that minimizes the coefficients that would be zero for a true orthotropic material expressed in the coordinate system of its planes of symmetry.

The primary outputs from the direct mechanics approach are the stiffness and compliance matrices ($\mathbf{S} = \mathbf{C}^{-1}$) in the original coordinate system, as well as in the coordinate system of optimal orthotropy. The 3×3 rotation matrix **R** that describes the transformation from the specimen coordinate system to the optimal coordinate system is given; the rows are the principal axes in the original coordinate system. Finally, from the compliance matrix, the standard orthotropic elastic constants E_i,ν_{ij},G_{ii} are extracted. See Linear Orthotropic Material for the definitions.

The use of the n88directmechanics tool is described in detail in Section 9.6.

An example run of the *direct mechanics* analysis is shown below.

```
$ n88directmechanics test25a.aim
n88directmechanics version 6.0
Copyright (c) 2012, Numerics88 Solutions Ltd.
```

```
input_file                   = test25a.aim
material_table               = homogeneous
youngs_modulus               = 6829.0
poissons_ratio               = 0.3
connectivity_filter          = on

    0.00 Reading image file test25a.aim
    0.00 Read 17576 points from image file.
    0.00 Applying connectivity filter.
    0.00 Masked out 0 unconnected voxels.
    0.00 Converting to hexahedral cells.
    0.01 Generated 7087 hexahedrons
    0.01 Creating material table.
    0.01 Creating three uniaxial models.
    0.03 Writing n88 model file: test25a_strain_xx.n88model
    0.14 Writing n88 model file: test25a_strain_yy.n88model
    0.25 Writing n88 model file: test25a_strain_zz.n88model
    0.34 Creating three symshear models.
    0.35 Writing n88 model file: test25a_strain_yz.n88model
    0.46 Writing n88 model file: test25a_strain_zx.n88model
    0.57 Writing n88 model file: test25a_strain_xy.n88model
    0.66 Calling solver on test25a_strain_xx.n88model
    2.20 Calling solver on test25a_strain_yy.n88model
    3.76 Calling solver on test25a_strain_zz.n88model
    5.23 Calling solver on test25a_strain_yz.n88model
    6.59 Calling solver on test25a_strain_zx.n88model
    7.87 Calling solver on test25a_strain_xy.n88model
    9.05 Reading n88 model file: test25a_strain_xx.n88model
    9.07 Reading n88 model file: test25a_strain_yy.n88model
    9.08 Reading n88 model file: test25a_strain_zz.n88model
    9.09 Reading n88 model file: test25a_strain_yz.n88model
    9.10 Reading n88 model file: test25a_strain_zx.n88model
    9.11 Reading n88 model file: test25a_strain_xy.n88model

    Volume fraction = 0.45357

    Apparent stiffness matrix in specimen coordinate system

[[ 1571.653   540.033   513.822     7.53   -121.22    -57.959]
 [  540.033  2029.046   469.974    78.591   -53.69    -50.673]
 [  513.822   469.974  1803.998    20.377   -57.014   -15.761]
 [    7.53     78.591    20.377   734.405   -23.127   -36.557]
 [ -121.22    -53.69    -57.014   -23.127   627.396    13.969]
 [  -57.959   -50.673   -15.761   -36.557    13.969   745.749]]

    Apparent compliance matrix in specimen coordinate system

[[  7.570e-04  -1.586e-04  -1.704e-04   1.977e-05   1.170e-04   4.323e-05]
 [ -1.586e-04   5.610e-04  -1.000e-04  -5.441e-05   5.808e-06   2.090e-05]
 [ -1.704e-04  -1.000e-04   6.294e-04  -4.883e-06   1.569e-05  -7.273e-06]
 [  1.977e-05  -5.441e-05  -4.883e-06   1.372e-03   4.787e-05   6.410e-05]
 [  1.170e-04   5.808e-06   1.569e-05   4.787e-05   1.621e-03  -1.819e-05]
 [  4.323e-05   2.090e-05  -7.273e-06   6.410e-05  -1.819e-05   1.349e-03]]

    Material parameters in specimen coordinate system
    -------------------------------------------
    Exx =  1320.98
    Eyy =  1782.54
    Ezz =  1588.79
    Gyz =   728.81
    Gzx =   617.06
    Gxy =   741.27
    -------------------------------------------
    nu_yx =  0.28270
    nu_zx =  0.27081
    nu_xy =  0.20950
    nu_zy =  0.15888
    nu_xz =  0.22516
    nu_yz =  0.17825
    -------------------------------------------

    Optimum rotation matrix R:

[[ 0.32957 -0.83991 -0.4312 ]
 [ 0.30346  0.52671 -0.79403]
 [ 0.89404  0.13084  0.42846]]

    Apparent stiffness matrix in best orthotropic coordinate system

[[ 2197.117   466.121   496.104    30.725    39.277     6.441]
 [  466.121  1852.499   506.856    32.259    14.028    -0.103]
 [  496.104   506.856  1464.576    -5.755   -28.362    14.264]
 [   30.725    32.259    -5.755   650.075   -35.665   -15.051]
 [   39.277    14.028   -28.362   -35.665   697.661     8.234]
 [    6.441    -0.103    14.264   -15.051     8.234   705.066]]

    Apparent compliance matrix in best orthotropic coordinate system

[[  5.068e-04  -8.804e-05  -1.419e-04  -2.273e-05  -3.367e-05  -1.863e-06]
 [ -8.804e-05   6.126e-04  -1.826e-04  -2.865e-05  -1.630e-05   4.167e-06]
 [ -1.419e-04  -1.826e-04   7.952e-04   2.496e-05   4.544e-05  -1.482e-05]
 [ -2.273e-05  -2.865e-05   2.496e-05   1.546e-03   8.154e-05   3.175e-05]
 [ -3.367e-05  -1.630e-05   4.544e-05   8.154e-05   1.442e-03  -1.571e-05]
 [ -1.863e-06   4.167e-06  -1.482e-05   3.175e-05  -1.571e-05   1.419e-03]]

    Material parameters in best orthotropic coordinate system

    -------------------------------------------
    Exx =  1973.20
    Eyy =  1632.50
    Ezz =  1257.55
    Gyz =   646.74
    Gzx =   693.58
    Gxy =   704.48
    -------------------------------------------
    nu_yx =  0.14372
    nu_zx =  0.17848
    nu_xy =  0.17371
    nu_zy =  0.22968
    nu_xz =  0.28004
    nu_yz =  0.29816
    -------------------------------------------

    9.47 Done.
```

Pistoia Failure Load Estimate

The failure load for a linear elastic model is based on the work by Dr. Walter Pistoia (Pistoia 2001a and 2001b). Numerics88 provides a tool, n88pistoia that can be used to carry out these calculations. In general, **it is more accurate and preferable to solve an elastoplastic model in order to obtain failure loads**. However, we include the Pistoia tool, mostly for those who wish to compare current data to older results on which a Pistoia analysis was done.

The basic principal is that failure load is defined as the load at which a pre-defined volume of tissue (percentage critical volume) exceeds a pre-defined Energy Equivalent Strain (critical EES). Typical values are 2.0% and 0.007, respectively. It should be noted that the so-called Pistoia criterion is not a standard failure criteria used in classical mechanics of materials; however, it has been extensively validated with experimental testing of cadaver bones, and it is the most widely used and accepted criterion for image-based linear FE modelling.

The *first* sub-table contains the failure load information (the sub-table is denoted by a series of horizontal dots). The calculation of the failure load requires post-processing the EES for each element of the solved linear FE model. After ordering the EES in a histogram, the actual strain at the critical volume threshold (e.g., 2%) is determined and reported in the table as `EES at vol_crit`. As this is a linear FE model, a scale-factor for this EES can be determined relative to the critical EES, and this is captured in a defined factor. A table of factors is provided at the bottom of the Pistoia Failure Load Estimate table, and the factor associated with the defined critical volume and critical EES is reported specifically in this first sub-table (other values of critical volume and critical EES could be applied if necessary using the alternative table factors). Knowing the total reaction force of the solved model (usually `RFz`) and the actual EES value at the critical volume, a linear factor can be applied to estimate the failure load: `failure load =RFz × factor`.

Note
Although a similar process can be applied to determine the torsional failure load (and is reported as torsional failure load) there have not been any experimental validations of this technique published to date. It is not recommended to use the reported torsional failure load until experimental validation is completed. Nevertheless, it is provided here for the users' convenience.

The *second* sub-table contains a summary of the axial and torsional stiffness values, and these are identical to the previous corresponding tables. For example, `RFz` from node set 1 has already been reported in Nodel Forces as total `F_z_`. They are reported again in this table for convenience.

Important
All failure loads are calculated assuming that axial compression or torsion was applied along the `z`-axis in the Data Frame.

The *third* sub-table contains a summary of the histogram results for the analysis of EES. All materials defined in the model are pooled for this histogram (i.e., cortical bone and trabecular bone), and it is the basis for determining the EES at the critical volume used for the failure load calculation. It is important to note that the user has the option to pre-define a material that is to be excluded from the failure load analysis, and that excluded material is reported at the top of the table (`Excluded material id`). This is useful, for example, if the FE model contains platens that should not be included in the failure load analysis (i.e., the failure load of the platens are not of interest).

The *fourth* sub-table contains a summary of the number of elements that exceed critical EES, and is broken down by material definition. This information allows the user to determine, for example, whether failure was based on cortical bone versus trabecular bone.

The *fifth* sub-table contains factors that could be used (by user hand calculation) to determine the estimated failure load for different critical volumes or critical EES.

```
Table 1: Pistoia Failure Load Estimate
-----------------------------------------------------------
Pistoia Criterion for Energy-Equivalent-Strain (EES)
  (*) Results valid for linear, isotropic model only.
  (*) Warning: Torsion failure load not validated. Caution!
-----------------------------------------------------------
Number of elements in analysis:                      349829
Excluded material id:                                  none
...........................................................
Critical volume (%):                                 2.0000
Critical EES:                                        0.0070
EES at vol_crit:                                     0.0131
Factor (from table):                             0.5332E+00
```

```
Failure load (RFz * factor) [N]:                   -0.3248E+04 ❶
Torsional failure load (Tz * factor) [Nmm]:         0.9764E-03
-----------------------------------------------------------
Axial and Torsional Stiffness:
...........................................................
RFz (node set 1) [N]:                              -0.6091E+04
Uz (node set 1) [mm]:                              -0.9020E-01
Axial stiffness [N/mm]:                             0.6753E+05 ❷
Tz (node set 1) [Nmm]:                              0.1831E-02
Rotz (node set 1) [rad]:                           -0.1787E-03
Torsional stiffness [Nmm/rad]:                     -0.1025E+02 ❸
-----------------------------------------------------------
Distribution of energy-equivalent-strain: EES = sqrt(2U/E).
...........................................................
                            EES
            average  0.6135E-02
            std_dev  0.3210E-02
            minimum  0.1332E-07
            maximum  0.3725E-01
           skewness  0.4787E+00
           kurtosis  0.9386E+00
             median  0.6089E-02
-----------------------------------------------------------
Distribution of failed materials.
...........................................................
           material       # els          %
                127        1454     20.7803
                100        5543     79.2197 ❹
         ----------  ----------  ----------
              total        6997    100.0000
-----------------------------------------------------------
Factor table:
         crit_vol |    crit_ees
      %     # vox |      0.0050      0.0060      0.0070      0.0080      0.0090
 ------  -------- |  ----------  ----------  ----------  ----------  ----------
   1.00    349829 |  0.3400E+00  0.4080E+00  0.4759E+00  0.5439E+00  0.6119E+00
   2.00    699658 |  0.3809E+00  0.4570E+00  0.5332E+00  0.6094E+00  0.6855E+00
   3.00   1049487 |  0.4071E+00  0.4886E+00  0.5700E+00  0.6514E+00  0.7329E+00
   4.00   1399316 |  0.4274E+00  0.5129E+00  0.5984E+00  0.6838E+00  0.7693E+00
   5.00   1749145 |  0.4444E+00  0.5333E+00  0.6222E+00  0.7111E+00  0.8000E+00
   6.00   2098974 |  0.4582E+00  0.5498E+00  0.6414E+00  0.7331E+00  0.8247E+00
   7.00   2448803 |  0.4703E+00  0.5644E+00  0.6585E+00  0.7525E+00  0.8466E+00
```

❶ Estimated failure load of the bone in uniaxial compression, given the critical volume of 2% and critical EES of 0.0070.

❷ Calculated based on the total Fz (also termed RFz) of node set 1 divided by the average displacement Uz of the surface defined by node set 1.

❸ Calculated based on the total Tz of node set 1 divided by the average displacement Uz of the surface defined by node set 1.

❹ Indicates that approximately 79% of the failed voxels comprising the 2% critical volume were in the trabecular tissue, while only 21% were in the cortical tissue.

Chapter 9

Command Reference

Table 9.1: List of Faim command-line programs

Module	Description
faim	Convenience utility that calls n88solver, n88derivedfields and n88postfaim in sequence.
n88coarsen	Reduce the size of finite element models so that an approximate solution can be obtained quicker and with less memory.
n88copymodel	Copy, convert or compress a finite element model file.
n88compress	Compress a finite element model file in-place.
n88derivedfields	Calculate additional field values (forces, stress, strain, etc) that are not generated by n88solver.
n88directmechanics	Perform *direct mechanics* calculations.
88evaluate	Calculate some values that indicate the correctness of the solution.
n88extractfields	Extracts specified solution fields as tabular text data.
n88extractsets	Extract node sets, element sets and constraint sets and write them to VTK PolyData (`.vtp`) files.
n88interpolatesolution	Copies and interpolates a solution from a solved reduced-resolution n88model file, produced using n88coarsen, into the original n88model file.
n88modelgenerator	Generate a finite element model from a segmented 3D image.
n88modelinfo	Print summary information for a Numerics88 FE model file.
n88pistoia	Estimate failure loads from a linear model.
n88postfaim	Generate tables of standard post-processing quantities.
n88solver (_sl and _sp)	Solvers suitable for small-strain models with linear elastic material definitions (_el) or with non-linear elastoplastic material definitions (_ep).
n88tabulate	Tabulate values from n88postfaim output files for importing into a spreadsheet.

faim

A convenience utility that calls n88solver, n88derivedfields and n88postfaim in sequence on the specified model file.

The analysis file produced by n88postfaim will be named after the input file, with "_analysis.txt" replacing the extension of the input file.

The most appropriate solver for your input model will be used.

- If your model contains elastoplastic material definitions, `n88solver_spt` will be used.

- If your model contains exactly one material array with length equal to the number of elements, `n88solver_sla` will be used.
- In all other cases, `n88solver_slt` will be used.

The analysis file produced by n88postfaim will be named after the input file, with "_analysis.txt" replacing the extension of the input file.

The command line arguments of faim are listed below. As they are passed through to the programs doing the work, they are grouped by program that they are passed to. In each case the options are identical to those of the program doing the work.

Arguments passed to n88solver

```
convergence_measure
convergence_tolerance
convergence_window
device
engine
iterations_file
license_check
maximum_iterations
maximum_plastic_iterations
plastic_convergence_window
precision
quiet
restart
threads
```

For details, refer to n88solver.

Arguments passed to n88derivedfields

```
device
engine
quiet
threads
```

For details, refer to n88derivedfields.

Arguments passed to n88postfaim

```
element_sets
node_sets
quiet
rotation_center
```

For details, refer to n88postfaim.

Arguments passed to n88coarsen

```
material_averaging
```

For details, refer to n88coarsen.

Table 9.2: faim arguments not passed to any program

Option	Description
-h, --help	Show help and exit.
--use_coarsen	Generate a coarsened model if possible to calculate an initial estimate of the solution. For certain models, this may speed-up finding the final solution.
--no_post	Do not run the postprocessor.

n88coarsen

Description

This tool is used to reduce the size of finite element models so that an approximate solution can be obtained quickly and with less memory. It operates either directly on FE models, or on segmented image data.

Usage

```
n88coarsen [-h] [--material_averaging {linear,homminga_density}]
                  input_file output_file
```

When operating on `n88model` files, it will increase the size of elements by a factor of 2 in each dimension (thus a factor of 8 in volume), resulting in fewer larger elements. The output model is coarser: the coarsening is always done by adding volume to make larger elements, never by removing material, so that as compared with the input model, the output model always has greater or equal volume. Material properties are averaged over all the input elements corresponding to each output element. Empty space is treated as having identically zero stiffness, wherever empty space in the input is encompassed within an output element. All essential features of the model, including boundary conditions, applied forces, and post-processing sets, are translated to the new coarser mesh.

When the input is an image, the resolution is reduced by exactly 1/2 in each linear dimension. Each 2x2x2 cube in the input becomes a single voxel in the output, with value equal to the maximum in the corresponding input 2x2x2. This operation does not average input values, since it does not make any sense to average segmentation values, which are just labels. Instead, it takes the maximum value over all the input voxels corresponding to an output voxel. This is a somewhat arbitrary choice. For this reason it is preferable to use `n88coarsen` directly on `n88model` files, where material averaging is possible.

SUPPORTED INPUT FORMATS

- Numerics88 model file (.n88model)
- DICOM (a directory)
- Scanco AIM (.aim)
- MetaImage (.mha or .mhd)
- VTK XML ImageData (.vti)

SUPPORTED OUTPUT FORMATS

- Numerics88 model file (.n88model). If the input is an n88model file.
- VTK XML ImageData (.vti). If the input is an image.

Table 9.3: n88coarsen optional arguments

Option	**Description**
-h, --help	Show help and exit.
--material_averaging	Determine how the material averaging is done. If `linear`, then stress-strain matrices will be linearly averaged. If `homminga_density`, then the stress- strain matrices are first scaled to a density using the Homminga formula (i.e. raised to the power 1/1.7), then averaged, then converted back the stiffness by raising to the power 1.7. `homminga_density` nearly always gives more accurate approximations than `linear`.

n88copymodel

Description

Copy, convert or compress a finite element model file.

Usage

```
n88copymodel [-h] [--compress] input [input2] output
```

File formats are automatically identified by their extensions. Ambiguous input file extensions are resolved by examining the file.

Two input files are allowed if the first is a FAIM version 5 input file (`.inp`), and the second is a FAIM version 5 output file (`.dat`). This will create a complete, solved `n88model` file. Either `.inp` or `.dat` can also be converted individually, but in the case of `.dat` files, the resulting `n88model` file will be incomplete, as the `.dat` file alone does not contain either material definitions or constraints; however, it can be rendered and processed by `n88postfaim`, but not re-solved.

SUPPORTED INPUT FORMATS

- Numerics88 model file (.n88model)
- Abaqus input file (.inp)
- Faim version 5 input file (.inp)
- Faim version 5 output file (.dat)

SUPPORTED OUTPUT FORMATS

- Numerics88 model file (.n88model)
- Abaqus input file (.inp)
- VTK XML Unstructured Grid file (.vtu)

Tip

VTK XML Unstructured Grid files can be read be and rendered by ParaView, even without the Numerics88 plugins. They include the complete geometry, plus any solution fields, but lack any constraint or material information.

Table 9.4: n88copymodel optional arguments

Option	Description
-h, --help	Show help and exit.
--compress, -c	Use compression when writing the output file if the file format supports it. Compressed `n88model` files do not need to be uncompressed in order to use them: they can be used in all cases exactly like uncompressed files. Compressed files may be slower to read, and are particularly slower to write.

Note

If you compress an `n88model` file, and then run either `n88solver` or `n88derivedfields` on it, it will end up in a mixed state, where the original data is compressed, but the new data added by `n88solver` or `n88derivedfields` is uncompressed. There is nothing wrong with this as the file is still completely valid and useable. However, usually if compression is important, one wants the entire file data compressed. Therefore, we recommend not compressing the file until you have completed all the normal processing steps on it. It is of course possible to convert a partially compressed `n88model` file to a fully compressed `n88model` file by running `n88copymodel` or `n88compress` on it again.

See also the section Converting Faim version 5 file formats.

n88compress

```
n88compress FILENAME
```

is an alias for

```
n88copymodel --compress FILENAME FILENAME
```

Refer to the documentation for n88copymodel.

n88derivedfields

Description

Calculates additional field values (forces, stress, strain, etc) that are not generated by n88solver. Fields are written into the n88model file.

For discussion of use, see the section on using n88derivedfields in the Post-processing chapter.

Usage

```
n88derivedfields [options] input_file
```

Arguments

Table 9.5: n88derivedfields arguments

Argument	Description
--help [-h]	Print help and exit.
--version [-v]	Print version information.
--quiet [-q]	Suppress output to terminal (except for error messages).
--precision arg (=single)	Set the floating point precision used. Values: single, mixed, double.

n88directmechanics

Description

Perform direct mechanics calculations. See Section 8.2 in the Special Topics chapter.

Usage

```
n88directmechanics [-h] [-c FILE] [--generate] [--solve] [--analyze]
                   [--material_table {homogeneous,homminga}]
                   [--youngs_modulus YOUNGS_MODULUS]
                   [--poissons_ratio POISSONS_RATIO]
                   [--orthotropic_parameters ORTHOTROPIC_PARAMETERS]
                   [--homminga_maximum_material_id HOMMINGA_MAXIMUM_MATERIAL_ID]
                   [--homminga_modulus_exponent HOMMINGA_MODULUS_EXPONENT]
                   [--connectivity_filter {on,off}]
                   input_file
```

Table 9.6: n88directmechanics input arguments

Option	**Description**
input_file	An image file with segmented data. Note that the file name of the original image file should be used even when the only action is `--solve` and/or `--analyze`; the n88model file names will be derived from the image file name. Supported input formats: - DICOM (a directory) - Scanco AIM (.aim) - MetaImage (.mha or .mhd) - VTK XML ImageData (.vti)

Table 9.7: n88directmechanics action arguments

Option	**Description**
--generate	Generate models. (Generates 6 n88model files.)
--solve	Solve models. (n88model files are updated with solutions.)
--analyze	Perform direct mechanics analysis on solved files.

Multiple action arguments may be specified. If no action argument is specified, it is equivalent to specifying them all.

n88directmechanics material specification arguments

```
material_table
youngs_modulus
poissons_ratio
orthotropic_parameters
homminga_maximum_material_id
homminga_modulus_exponent
```

These arguments are identical to the equivalent arguments of n88modelgenerator. See Material specification parameters.

Table 9.8: n88directmechanics optional arguments

Option	**Description**
-h, --help	Show help and exit.
-c FILE, --config FILE	Specify a configuration file. The configuration file may specify any arguments that take a value, one per line, in the format name=value (leave the double dash "--" off of the argument name). This format is identical to n88modelgenerator. See Section 2.1.

n88directmechanics additional parameters

```
connectivity_filter
spacing
```

These arguments are identical to the equivalent arguments of n88modelgenerator. See Input image parameters.

Tip
There are no options passed to the solver. If this is required, run `n88directmechanics` with the `--generate` action, then manually run n88solver on each of the resulting `n88model` files, using the desired solver options, then run `n88directmechanics` again with the `--analyze` action.

n88evaluate

Description

A tool to evaluate the quality of solutions.

For discussion of use, see the section on using evaluating solution quality and the section section on using evaluating nonlinear solution quality.

Usage

```
n88evaluate [options] input_file
```

Arguments

Table 9.9: n88evaluate arguments

Argument	Description
--help [-h]	Print help and exit.
--sparse [-s]	Use sparse matrices for calculation. This is the default, but requires that scipy be installed.
--dense [-d]	Use dense matrices for calculation. This does not require scipy to be installed, but as the memory requirements scale as the square of the number of degrees of freedom in the problem, this is feasible only for very small problems.

n88extractfields

Description

Extracts specified solution fields as tabular text data.

Usage

```
n88extractfields [-h] [--output_file OUTPUT_FILE] fields input_file
```

Table 9.10: n88extractfields positional arguments

Option	Description
fields	A comma-delimited list of names of solution fields to extract. May be the name of either a solution node value (*e.g.* “Displacement”) or a solution element value (*e.g.* “Stress”; see also Calculating additional solution fields with n88derivedfields) Additionally, “NodeNumber”, “ElementNumber”, “MaterialID”, “NodeCoordinates”, “ElementCoordinates” or “Topology” can be specified. Element coordinates are the centers of the elements. Topology gives for each element the 8 node numbers of the nodes constituting the element. The order is as in the `n88model` file, refer to the file specification. All fields must be the same length, which practically means that they must either be all node values or all element values.
input	The model file.

Table 9.11: n88extractfields optional arguments

Option	Description
-h, --help	Show help and exit.
--output_file OUTPUT_FILE, -o OUTPUT_FILE	Output file. If not specified, output will go to STDOUT.

Examples

This will extract the displacement values as an N×3 array, where N is the number of nodes:

```
$ n88extractfields Displacement mymodel.n88model
-0.00136573     -0.00136573     0.0
-0.000770869    -0.00142601     0.0
-0.000218384    -0.00141035     0.0
0.000218384     -0.00141035     0.0
0.000770869     -0.00142601     0.0
0.00136573      -0.00136573     0.0
-0.00142601     -0.000770869    0.0
...
```

This example will extract both element number and corresponding stress. As the stress is 6-valued, this makes a total of 7 values per row of output:

```
$ n88extractfields ElementNumber,Stress mymodel.n88model
1       -0.752387       -0.752387       -69.0185        0.965844        0.965844        ↩
   -0.00933552
2       -4.98979        -1.50565        -73.2319        0.629349        0.690826        ↩
   1.61737
3       -6.35569        -0.494144       -74.5778        0.486541        -4.27155e-16    ↩
   -5.6954e-16
4       -4.98979        -1.50565        -73.2319        0.629349        -0.690826       ↩
   -1.61737
5       -0.752385       -0.752386       -69.0185        0.965844        -0.965844       ↩
   0.00933552
6       -1.50565        -4.98979        -73.2319        0.690826        0.629349        ↩
   1.61737
7       -1.50565        -4.98979        -73.2319        0.690826        -0.62934
...
```

n88extractsets

Description

Extract node sets, element sets and constraint sets and write them to VTK PolyData (.vtp) files which can be opened with ParaView. This is mostly useful for visualizing sets, boundary conditions and applied forces. For nodes sets and constraints, these files will consist of a collection of vertices.

Usage

```
n88extractsets [-h] [--constraints] [--node_sets] [--element_sets] input
```

Table 9.12: n88extractsets arguments

Option	Description
-h, --help	show this help message and exit
--constraints, -C	Extract constraints.
--node_sets, -N	Extract node sets.
--element_sets, -E	Extract element sets.

If no arguments are specified, all types of sets will be extracted.

Warning
This utility will generate file names based on the names of the sets, and will overwrite existing files with the same names without warning.

n88interpolatesolution

Description

Copies and interpolates a solution from a solved reduced-resolution n88model file, produced using n88coarsen, into the original n88model file. This may help to obtain faster solutions.

Usage

```
n88interpolatesolution [-h] full_model reduced_model
```

Warning
For linear models only.

n88modelgenerator

Description

Generates a finite element model from a segmented 3D image.

Refer to the chapter on using n88modelgenerator.

Usage

```
n88modelgenerator [options] input_file [output_file]
```

Supported input image file formats

n88modelgenerator currently supports the following input formats:

- DICOM (automatically selected when a directory is given as the input),
- Scanco `.aim` files,
- ITK MetaImage files (`.mha`) or (`.mhd`),
- VTK XML Image Data files (`.vti`),
- existing Numerics88 Model file (`.n88model`)

Note
There are some limitations when reading DICOM files. In particular, encapsulated format cannot be read. It is sometimes not possible to determine the *z*-spacing from DICOM files. In this case use the option spacing.

Note
If an n88model file is provided as an input file, the mesh (i.e. the points and elements) will be taken from the input, as well as any possible solution fields. A new material table and new constraints will be generated. This is useful for incremental loading tests of nonlinear models, as it allows the boundary conditions to be updated while preserving an existing solution.

Supported output file formats

The standard output format of `n88modelgenerator` is an `n88model` file (see Appendix B). If you specify an output file with extension `.n88model`, the `n88model` file format will be used. This is the default output type, and if no output file is specified, an output file will be generated from the stem of the input file, with the extension `.n88model` appended.

`n88modelgenerator` also supports the output of Abaqus input files. An Abaqus input file will be generated whenever an output file with extension `.inp` is specified.

Input and output parameters

Input and output parameters specify the files that are used for input and output.

Table 9.13: n88modelgenerator Input and Output Parameters

Argument	**Description**
input_file	Specify the name of the input file. Note that it is not necessary to explicitly use "--input_file" on the command line, as the first positional argument (i.e. the first argument not starting with a dash), is taken to be the input file.
output_file	Specify the name of the output file. If not specified, a default output file name will be used, which is of the form `[input]_[test_type].n88model` . Note that it is not necessary to explicitly use "--output_file" on the command line even if you want to specify the output file name, as the second positional argument, (i.e. the second argument not starting with a dash), if present, is taken to be the output file. However the type of output file is determined by the extension of output_file, therefore if output different than the default type (`n88model`) is desired, the output file must be explicitly specified.

Input image parameters

Table 9.14: n88modelgenerator Input Image Parameters

Argument	Description
spacing	Force the spacing of the input image. This is sometimes required for DICOM files, for which the *z*-spacing sometimes cannot be determined. Values should be given as a comma-delimited list of *x*,*y*,*z* values. *e.g.* `0.5,0.5,0.5`.
connectivity_filter	Enable/disable connectivity filtering which extracts only the largest connected object in the input image. See Ensuring connectivity in the chapter about `vtkbone` for a discussion of this issue. Valid values are `on`, `off` and `warn`. The default is `on`.

Test configuration parameters

Test configuration parameters define the mechanical test that will be applied to the object in the image.

Table 9.15: n88modelgenerator Test Configuration Parameters

Argument	Description
test	Specify test type. Valid values are `uniaxial`, `axial`, `confined`, `bending`, `torsion`, `symshear` and `dshear`. See Standard Tests.
test_axis	Specify the test axis. See Test Orientation. Valid values are *x*, *y*, and *z*. The default is *z*.
normal_strain	For a compression type test, specifies an apparent level strain. Negative values correspond to compression. Strain is the default if neither strain nor displacement are specified. Default -0.01, corresponding to 1% compressive strain.
shear_strain	For a symshear test, this sets the apparent engineering shear strain applied to the model. Unitless. Default 0.01.
strain	Shortened equivalent of either normal_strain or shear_strain, depending on the test type.
displacement	Specify an applied displacement (with units of length) for a compression type test. Negative values correspond to compression. This parameter is exclusive with `normal_strain`: one or the other may be used, but not both.
pin	Fully define the constraints for a uniaxial model by adding an arbitrary pinned point to prevent lateral translation, and a second partially pinned point to prevent lateral rotation. If this option is off, the system of equations for a uniaxial test is singular. Faim can solve it regardless, and will in fact typically solve it faster. This option is ignored for test types other than uniaxial. Valid values are `off`, `center`, `corner` and `on`. The value `corner` adds a pin at the element with the minimum *z*,*y*,*x* coordinates in the Test Frame (*i.e.* select by minimum *z*, then by minimum *y*, then by minimum *x*). `center` adds a pin at the element closest to the center *x*,*y* position in the Test Frame. (The *z* coordinate is not considered, unless two elements are equally close to the *x*,*y* center, in which case the one with smallest *z* is selected.) The value `on` is equivalent to `center`. Default is `off`.

Table 9.15: (continued)

Argument	Description
central_axis	The x,y coordinates (in the Test Frame) of the central axis, which is parallel to the z axis (in the Test Frame). Example: `0,0` . Alternatively, you can specify `center_of_mass` or `center_of_bounds`. The default is `center_of_mass`. The central axis is used in bending and torsion tests.
bending_angle	The degree of tilt between the top and bottom surfaces in a bending test. Units are degrees. The default is 1º.
neutral_axis_angle	The angle of the neutral axis in the x,y plane (in the Test Frame) in a bending test. 0º is parallel to the x-axis. Units are degrees. Default is 90º, parallel to the y-axis.
shear_vector	The amount of shear displacement of the top surface as a vector in the x,y plane (in the Test Frame) for a dshear test. Units are length units if scale_shear_to_height is off, otherwise a unitless ratio. Default is 0.01,0 .
scale_shear_to_height	If `on`, shear_vector will be scaled by the height of the model extent (in the z direction in the Test Frame) to determine the shear displacement applied for a dshear test. Valid values are `on` and `off`. Default is `on`.
twist_angle	Amount of rotation of the top surface in a torsion test. Units are degrees. Default is 1º.

Surface detection parameters

Surface detection parameters modify how the top and bottom surfaces of the object image are identified. For most test types, the principle boundary conditions are applied to these two surfaces. If not specified, by default these surfaces are identified as all nodes (or elements) at the top or bottom extent of the input.

Table 9.16: n88modelgenerator Surface Detection Parameters

Argument	Description
top_surface	Specify method of selecting top surface. Valid values are `intersection` and `visible`. See Uneven surfaces.
bottom_surface	Specify method of selecting bottom surface. Valid values are `intersection` and `visible`. See Uneven surfaces.
top_surface_maximum_depth	Specify the maximum depth for identifying the top surface. Only applies if `top_surface` = `visible`. If unspecified, depth is unlimited. Depth is measured from the top boundary of the volume.
bottom_surface_maximum_depth	Specify the maximum depth for identifying the bottom surface. Only applies if `bottom_surface` = `visible`. If unspecified, depth is unlimited. Depth is measured (upwards) from the bottom boundary of the volume.
top_constraint_material_id	Apply boundary conditions at the top surface only to cells and nodes of the specified material ID.
bottom_constraint_material_id	Apply boundary conditions at the bottom surface only to cells and nodes of the specified material ID.

Material specification parameters

Material specification parameters are used to specify material definitions, and to select a material table that maps material IDs to material definitions.

Table 9.17: n88modelgenerator Material Specification Parameters

Argument	**Description**
poissons_ratio	Specify isotropic Poisson's ratio. The default is 0.3 .
youngs_modulus	Specify isotropic Young's modulus. The default is 6829.
orthotropic_parameters	Specify orthotropic parameters as E_x,E_y,E_z,ν_{yz},ν_{zx},ν_{xy},G_{yz},G_{zx},G_{xy} . If not set, isotropic parameters will be assumed. **Important**: There are two common conventions for ordering the mixed index quantities ν_{ij} and G_{ij}. Numerics88 software uses the ordering *YZ*, *ZX*, *XY*. It is important to observe this when specifying orthotropic properties in `n88modelgenerator`, as these are input in the form of an ordered list.
plasticity	Specify an elastoplastic yield criterion. Specify as several values separated by commas. The first value is an elastoplastic yield criterion name; subsequent values are numeric arguments appropriate to the method. Supported methods: `VonMises,Y` : `Y` is the yield strength. Refer to von Mises yield criterion. `MohrCoulomb,YT,YC` : `YT` is the yield strength in tension and `YC` is the yield strength in compression. Refer to Mohr-Coulomb yield criterion.
material_table	Specify method for generating material table. Valid values are `homogeneous` and `homminga`. `homogeneous` assigns the same material to all material IDs. `homminga` generates a table of materials according to Homminga et al. Refer to Homminga material table for details.
homminga_maximum_material_-id	Specify the maximum material ID used in Homminga density to modulus conversion. The default is 127.
homminga_modulus_exponent	Specify exponent used in Homminga density to modulus conversion. The default is 1.7 .
material_definitions	Specify a material definitions file for advanced material specification. If specified, all other material specification arguments will be ignored. Refer to the section material definitions file in the chapter on Preparing Finite Element Models With n88modelgenerator.

Solver parameters

Solver parameters affect the execution of the solver. They are independent of the model creation, and are specific to the solver used. If given as arguments to `n88modelgenerator`, they will be stored in the `n88model` file. However for most purposes, it is better to leave these out of the `n88model` file and either use the defaults as selected by the solver, or else to specify them as command line arguments directly to the solver. See n88solver.

Table 9.18: n88modelgenerator Solver Parameters

Argument	Description
convergence_tolerance	Specify convergence tolerance for conjugate gradient iterations. If not specified a default value will be used. See Generating the displacements with n88solver.
maximum_iterations	Specify the maximum number of conjugate gradient iterations. If not specified a default value will be used. The default is 30000. See Generating the displacements with n88solver.
plastic_convergence_tolerance	Specify convergence tolerance for plastic iterations. If not specified a default value will be used.
maximum_plastic_iterations	Specify the maximum number of plastic iterations. If not specified a default value will be used. The default is 100.

n88modelinfo

Description

Print summary information for a Numerics88 finite element model file.

Usage

```
n88modelinfo [-h] [--active] [--history] [--log] [--materials]
             [--parts] [--node_sets] [--element_sets] [--sets]
             [--constraints] [--problems] [--solutions]
             input_file
```

Table 9.19: n88modelinfo positional arguments

Option	Description
input_file	The .n88model file to read.

Table 9.20: n88modelinfo action arguments:

Option	Description
--active	List active solution, problem and part.
--history	Show history.
--log	Show log.
--materials	List defined materials.
--parts	Show parts.
--node_sets	Show nodesets.
--element_sets	Show elementsets.
--sets	Show both node and element sets. (Equivalent to --node_sets and --element_sets.)
--constraints	Show constraints.
--problems	Show problems.
--solutions	Show solutions.

Multiple action arguments may be specified. If no action argument is specified, it is equivalent to specifying them all.

Table 9.21: n88modelinfo optional arguments

Option	Description
-h, --help	Show help and exit.

n88pistoia

Description

Calculate Pistoia yield critera. This is a method if estimating yield strength from linear solutions. In general, it would be preferable to use a non-linear elastoplastic model to calculate yield strengths. This utility is provided mostly for comparing with older results.

For discussion of use, see the section on the Pistoia failure load estimate in the special topics chapter.

Note that `n88pistoia` is implemented in python (in `tools/pistoia.py`), so you can copy it and modify it should you wish to modify the analysis.

Usage

```
n88pistoia [options] input_file
```

Arguments

Table 9.22: n88pistoia arguments

Argument	Description
--help [-h]	Print help and exit.
--output_file [-o] arg	Specify an output file. If no output file is specified, output will go to STDOUT.
--constraint [-n] arg	Specify the constraint (i.e. boundary condition or applied load) to use for analysis. This is the surface to which forces are applied. The default ("top_displacement") will work for models generated with n88modelgenerator.
--rotation_center [-c] arg	Specify the spatial center used for calculation of angular quantities. The argument must be given as a triplet of coordinates. If not specified, the value will be read from the input file. If not available, no angular quantities will be calculated.
--include [-i] arg	Only elements with the specified material IDs will be included in the calculation. Multiple IDs can be specified in a comma-delimited list (e.g. 100,101,105).
--exclude [-e] arg	All elements with the specified material IDs will be excluded from the calculation. Multiple IDs can be specified in a comma-delimited list (e.g. 100,101,105).

n88postfaim

Description

Generate tables of standard post-processing quantities.

For discussion of use, see the section on using n88postfaim in the post-processing chapter.

Note that `n88postfaim` is implemented in python (in `tools/postfaim.py`), so you can copy it and modify it should you wish to modify the analysis.

Usage

```
n88postfaim [options] input_file
```

Arguments

Table 9.23: n88postfaim arguments

Argument	Description
--help [-h]	Print help and exit.
--output_file [-o] arg	Specify an output file. If no output file is specified, output will go to STDOUT.
--node_sets [-N] arg	Specify the node sets to use for analysis. The argument should be a list of node set names, separated by commas. If not specified, the value will be read from the input file.
--element_sets [-E] arg	Specify the element sets to use for analysis. The argument should be a list of element set names, separated by commas. Each node set must be matched by the corresponding set of elements. If not specified, the value will be read from the input file.
--sets [-s] arg	A convenience option that sets both node_sets and elements_sets. This is only useful if corresponding node and element sets are identically named.
--rotation_center [-c] arg	Specify the spatial center used for calculation of angular quantities. The argument must be given as a triplet of coordinates. If not specified, the value will be read from the input file. If not available, no angular quantities will be calculated.

n88solver (_slt, _sla and _spt)

Description

`n88solver_slt` and `n88solver_sla` are solvers suitable for small-strain models with linear elastic material definitions. `n88solver_spt` can solve nonlinear models containing elastoplastic material definitions.

`n88solver_slt` and `n88solver_spt` use material tables internally: they are most efficient when the number of defined materials is substantially less than the number of elements in the model. This is the usual case. `n88solver_sla` is a special-purpose solver that uses a material array internally: it is more efficient when the number of defined materials is comparable to the number of elements. See Efficient Handling of Large Numbers of Material Definitions.

See the chapters on Solving Linear Problems and Solving Nonlinear Problems for discussion of use.

Usage

```
n88solver_slt [options] input_file
n88solver_sla [options] input_file
n88solver_spt [options] input_file
```

Arguments

Table 9.24: n88solver arguments

Argument	Description
--help [-h]	Print help and exit.
--version [-v]	Print version information and exit.
--quiet [-q]	Suppress output to terminal (except for error messages).
--license-check [-l]	Print licensing information.
--engine [-g] arg (=mt)	Set the solver engine. Valid values are `mt` for the multi-threaded CPU engine and `nv` for the nVidia GPU engine. Note that a license from Numerics88 Solutions is required to use the GPU engine.
--threads [-t] arg	Set the number of threads for the mt engine. If not specified, the number of threads will be set to one per CPU core on the system, or one thread per 2048 elements, whichever is less.
--device [-d] arg (=0)	Set the nVidia CUDA device to use (applies only to nv solver). Multiple devices may be specified in a comma delimited list.
--precision arg (=double)	Set the floating point precision used. Values: `single`, `mixed`, `double`.
--restart [-r]	Do not use the existing solution as initial value.
--convergence_measure [-m] arg (=auto)	Set the convergence measure. See convergence measure in the section on solving linear models. For linear models, if `auto` is selected, `set` will be used if a convergence set is defined in the model; otherwise the fallback is `dumax`. For elastoplastic models, the default is always `dumax`, even when a convergence set is defined. Values: `set`, `dumax`, `durms`, `auto`.
--convergence_tolerance [-e] arg (=1E-6)	Set the convergence tolerance.
-convergence_window [-w] arg	Set the linear convergence window. Convergence is not considered reached until the convergence measure remains below the threshold for at least this number of consecutive iterations.
-plastic_convergence_window [-W] arg	Set the plastic convergence window. Plastic convergence is not considered reached until the convergence measure remains below the threshold for at least this number of consecutive iterations.
--maximum_iterations [-n] arg (=30000)	Set maximum number of linear iterations. Note that for elastoplastic models the count of linear iterations is reset on each plastic iteration. [-N] arg
--maximum_plastic_iterations arg (=1000)	Set maximum number of plastic iterations.
--iterations_file [-i] arg	Specify a file to output all iteration data.

The `convergence_tolerance`, `maximum_iterations`, and `maximum_plastic_iterations` may also be set in the input file. If present in both the input file as well as specified on the command line as options to `n88solver`, the options on the command line to `n88solver` take precedence.

n88tabulate

Description

Extract and tabulate values from n88postfaim output files. The result is suitable for importing into a spreadsheet.

Usage

```
n88tabulate [-h] [--variables VARIABLES] [--from FROM] [--header]
                  [--delimiter DELIMITER] [--output_file OUTPUT_FILE]
                  [input_files [input_files ...]]
```

Table 9.25: n88tabulate positional arguments

Option	Description
input_files	`n88postfaim` output files to process. Any number may be specified, and wildcard expansion of `*` and `?` is performed on systems where the shell does not do this.

Table 9.26: n88tabulate optional arguments

Option	Description
-h, --help	show this help message and exit
--variables VARIABLES, -V VARIABLES	A list of the variables to extract from the input files. Separate variable names with commas. See below for a list of valid variable names. If not specified all possible variables will be selected (this makes for a very large table).
--from FROM, -f FROM	Obtain the list of variables from the first line of a text file. The variable names may be separated by any kind of delimiter (white space or commas). Note that an output file (from n88tabulate, generated with the `--header` option) can be used as a `--from` argument, in which case the same selection of variables will be used.
--header, -H	Print a header line first. May be used even if no input files are specified.
--delimiter DELIMITER, -d DELIMITER	Delimiter character to separate columns. Default is a tab ("\t").
--output_file OUTPUT_FILE, -o OUTPUT_FILE	Output file. If not specified, output will go to STDOUT.

For any variables not found in the analysis file, a dash ("-") will be inserted into the output table.

Examples

In the following example, every possible variable will be extracted from every file ending in "_analysis.txt" in the directory. This will result in a very large number of values. The output will be written to the file `summary.txt`.

```
n88tabulate -H -o summary.txt *_analysis.txt
```

In the following example, we request the total forces along the z direction on the first two node sets for two different analysis files.

```
$ n88tabulate -H -V "filename,fz_ns1,fz_ns2" test25a_analysis.txt test42a_analysis.txt
filename  fz_ns1  fz_ns2
test25a_uniaxial.n88model -0.1019E+02 0.1019E+02
test42a_uniaxial.n88model -0.4641E+02 0.4641E+02
```

The following example is exactly the same, but the output goes to a file.

```
n88tabulate -H -V "filename,fz_ns1,fz_ns2" -o summary.txt test25a_analysis.txt  ↩
    test42a_analysis.txt
```

Now suppose we want the same selection of variables on a different analysis file, we could do the following. Notice that we are getting the list of variables from the existing file `summary.txt`.

```
$ n88tabulate -H --from summary.txt test99a_analysis.txt
filename    fz_ns1  fz_ns2
test99a_uniaxial.n88model   -0.6442E+02     0.6442E+02
```

In the following example, we are interested in the strain energy density, and request some statistical values. We also use a comma as the delimiter.

```
$ n88tabulate -H -d ',' -V "sed_avg,sed_stddev,sed_skew,sed_kurt" analysis.txt
sed_avg,sed_stddev,sed_skew,sed_kurt
0.2990E+00,0.1127E+00,-0.1512E+01,0.8999E+00
```

Variables

In the variable list, certain variables can take one or more numeric indices. This is denoted with `%`. For example, for `id_mat%m`, actual variable names are `id_mat1` for the first defined material, `id_mat2` for the second defined material, and so on. Similarly for `dx_avg_ns%n`, actual variables names are `dx_avg_ns1` for the first node set, `dx_avg_ns2` for the second node set, and so on.

Table 9.27: Variables corresponding to values in table “Model Input”

variable name	**value in analysis file table**
filename	Filename
num_els	Number of elements
num_nodes	Number of nodes

Refer to Section 6.3.2.1.

Table 9.28: Variables corresponding to values in table “Materials”

variable name	**value in analysis file table**
mats_mats	Number of materials
id_mat%m	The material ID of the mth defined material
count_mat%m	Number of elements for the mth defined material

Refer to Section 6.3.2.2.

Table 9.29: Variables corresponding to values in table “Post-processing Sets”

variable name	**value in analysis file table**
num_pp_sets	The number of sets used in post-processing.

Refer to Section 6.3.2.3.

Table 9.30: Variables corresponding to values in table “Strain Energy Density”

variable name	**value in analysis file table**
sed_avg	average (all materials)
sed_stddev	std_dev (all materials)
sed_skew	skewness (all materials)
sed_kurt	kurtosis (all materials)
sed_min	minimum (all materials)
sed_max	maximum (all materials)
sed_median	median (all materials)
sed_avg_mat%m	average over the m^{th} defined material
sed_stddev_mat%m	sed_dev over the m^{th} defined material
sed_skew_mat%m	skewness over the m^{th} defined material
sed_kurt_mat%m	kurtosis over the m^{th} defined material
sed_min_mat%m	minimum over the m^{th} defined material
sed_max_mat%m	maximum over the m^{th} defined material
sed_median_mat%m	median over the m^{th} defined material

Refer to Section 6.3.2.7.

Table 9.31: Variables corresponding to values in table “Von Mises Stress”

variable name	**value in analysis file table**
svm_avg	average (all materials)
svm_stddev	std_dev (all materials)
svm_skew	skewness (all materials)
svm_kurt	kurtosis (all materials)
svm_min	minimum (all materials)
svm_max	maximum (all materials)
svm_median	median (all materials)
svm_avg_mat%m	average over the m^{th} defined material
svm_stddev_mat%m	svm_dev over the m^{th} defined material
svm_skew_mat%m	skewness over the m^{th} defined material
svm_kurt_mat%m	kurtosis over the m^{th} defined material
svm_min_mat%m	minimum over the m^{th} defined material
svm_max_mat%m	maximum over the m^{th} defined material
svm_median_mat%m	median over the m^{th} defined material

Refer to Section 6.3.2.8.

Table 9.32: Variables corresponding to values in table “Nodal Displacements”

variable name	**value in analysis file table**
dx_avg_ns%n	The average displacement in the x direction over all nodes in the n^{th} node set.
dx_stddev_ns%n	The standard deviation of the displacement in the x direction over all nodes in the n^{th} node set.

Table 9.32: (continued)

variable name	value in analysis file table
dx_min_ns%n	The minimum displacement in the x direction over all nodes in the nth node set.
dx_max_ns%n	The maximum displacement in the x direction over all nodes in the nth node set.
dx_median_ns%n	The median displacement in the x direction over all nodes in the nth node set.
dy_avg_ns%n	The average displacement in the y direction over all nodes in the nth node set.
dy_stddev_ns%n	The standard deviation of the displacement in the y direction over all nodes in the nth node set.
dy_min_ns%n	The minimum displacement in the y direction over all nodes in the nth node set.
dy_max_ns%n	The maximum displacement in the y direction over all nodes in the nth node set.
dy_median_ns%n	The median displacement in the y direction over all nodes in the nth node set.
dz_avg_ns%n	The average displacement in the z direction over all nodes in the nth node set.
dz_stddev_ns%n	The standard deviation of the displacement in the z direction over all nodes in the nth node set.
dz_min_ns%n	The minimum displacement in the z direction over all nodes in the nth node set.
dz_max_ns%n	The maximum displacement in the z direction over all nodes in the nth node set.
dz_median_ns%n	The median displacement in the z direction over all nodes in the nth node set.

Refer to Section 6.3.2.9.

Table 9.33: Variables corresponding to values in table “Nodal Forces”

variable name	value in analysis file table
fx_ns%n	The total force in the x direction over all nodes in the nth node set.
fx_stddev_ns%n	The standard deviation of the force in the x direction over all nodes in the nth node set.
fx_min_ns%n	The minimum force in the x direction over all nodes in the nth node set.
fx_max_ns%n	The maximum force in the x direction over all nodes in the nth node set.
fx_median_ns%n	The median force in the x direction over all nodes in the nth node set.
fy_ns%n	The total force in the y direction over all nodes in the nth node set.
fy_stddev_ns%n	The standard deviation of the force in the y direction over all nodes in the nth node set.
fy_min_ns%n	The minimum force in the y direction over all nodes in the nth node set.
fy_max_ns%n	The maximum force in the y direction over all nodes in the nth node set.
fy_median_ns%n	The median force in the y direction over all nodes in the nth node set.
fz_ns%n	The total force in the z direction over all nodes in the nth node set.
fz_stddev_ns%n	The standard deviation of the force in the z direction over all nodes in the nth node set.
fz_min_ns%n	The minimum force in the z direction over all nodes in the nth node set.
fz_max_ns%n	The maximum force in the z direction over all nodes in the nth node set.
fz_median_ns%n	The median force in the z direction over all nodes in the nth node set.

Refer to Section 6.3.2.10.

Table 9.34: Variables corresponding to values in table “Load Sharing”

variable name	value in analysis file table
fx_ns%n_mat%m	The force in the x direction over nodes in the nth node set, summed over nodes belonging to the mth defined material.

Table 9.34: (continued)

variable name	**value in analysis file table**
fy_ns%n_mat%m	The force in the y direction over nodes in the nth node set, summed over nodes belonging to the mth defined material.
fz_ns%n_mat%m	The force in the z direction over nodes in the nth node set, summed over nodes belonging to the mth defined material.

Refer to Section 6.3.2.13.

Table 9.35: Variables corresponding to values in table “Pistoia Failure Load Estimate”

variable name	**value in analysis file table**
pis_stiffx	The stiffness in the x direction.
pis_stiffy	The stiffness in the y direction.
pis_stiffz	The stiffness in the z direction.
pis_fx_fail	The estimated failure load in the x direction.
pis_fy_fail	The estimated failure load in the y direction.
pis_fz_fail	The estimated failure load in the z direction.

Note

The Pistoia Failure Load Estimate table is no longer generated by n88postfaim, but may be generated by the tool n88pistoia if desired. The corresponding variables are by default not included, unless a variable list which includes them is specified.

Refer to Section 8.3 and Section 9.13.

Chapter 10

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Appendix A

Upgrading from previous versions

Upgrading from Faim version 7

Changing from `vtkn88` to `vtkbone`

In version 8, the closed-source `vtkn88` is replaced with the open-source `vtkbone`. Therefore, in all your python scripts, you will have to search for `vtkn88` and replace it with `vtkbone`. (Similarly for the capitalized versions: `VTKN88` → `VTKBONE`.)

Upgrading from Faim version 6

Updating version 6 `vtkn88` scripts to work with version 7

`vtkn88` is now based on VTK version 6. Many of the example scripts in `vtkn88` version 6 and earlier used the VTK method `SetInput`, which has been deprecated and replaced with `SetInputData`. Simply replacing `SetInput` with `SetInputData` is sufficient to fix these scripts.

For example, here is a simple operation, in Python, that writes a n88model file. This is the version 6 version:

```
writer = vtkn88.vtkn88N88ModelWriter()
writer.SetInput(model)
writer.SetFileName(output_file)
writer.Update()
```

For version 7, it needs to be updated to:

```
writer = vtkn88.vtkn88N88ModelWriter()
writer.SetInputData(model)
writer.SetFileName(output_file)
writer.Update()
```

Upgrading from Faim version 5

Converting Faim version 5 file formats

Faim version 5 used two file formats: `.inp` files for input files to faim, and `.dat` files for output. These can be upgraded to version 6 style `n88model` files with the n88copymodel tool. You may want to upgrade old archived files. Besides being much more space efficient, the new file format is also more robust. It is also standards-compliant, and is more easily read with third party software. (See n88model File Format.)

To convert a version 5 style file, use n88copymodel like this,

```
n88copymodel olddata.inp newdata.n88model
```

You can also specify that compression be used in writing the `n88model` file, like this

```
n88copymodel --compress olddata.inp newdata.n88model
```

Compressed `n88model` files take less disk space, but are slower to read and particularly to write. They are otherwise identical to uncompressed `n88model` files. You never need to uncompress them before using them.

Version 5 `.dat` output files are somewhat more problematic to convert to version 6 `n88model` files, because the `.dat` files do not contain the complete model information. In particular, they lack any information about material parameters or about boundary conditions or applied loads. Nevertheless, if you have only a `.dat` file, it is still possible to convert it to a `n88model` file, but the resulting model will be incomplete. It can be opened and visualized with ParaView, and it is possible to read the solution fields out of it, but it cannot be re-solved, nor can it be processed with n88postfaim.

A `.dat` file can be converted with

```
n88copymodel olddata.dat newdata.n88model
```

As before, you may optionally specify `--compress`.

If you have both the original `.inp` and the `.dat` file, they can be converted to a single `n88model` file by specifying both as input arguments,

```
n88copymodel olddata.inp olddata.dat newdata.n88model ❶
```

❶ The order is important: the `.inp` should be specified first.

This will create a `n88model` file that can used either as a complete input file to `n88solver`, should you wish to solve it again, and that also contains the complete solution fields.

Updating 5 `vtkn88` scripts to work with 6

Here we outline the steps required to update a version 5.x `vtkn88` script to work in 6.0 . We do not document all the changes and additions to `vtkn88` in 6.0, instead we only concentrate on those changes that must be made to get old scripts to work correctly in 6.0

1. `vtkn88Material` instances should be assigned a name.

   All materials are now required to have a unique name. In fact, if you don't explicitly set a name, `vtkn88` will assign a unique name for you, but it will be an uninformative name such as "NewMaterial1". Names can be assigned like this:

   ```
   bone_material = vtkn88.vtkn88LinearIsotropicMaterial()
   bone_material.SetName("bone")
   ```

2. Method `SetModelSourceDescription` of `vtkn88FiniteElementModel` is deprecated.

   Having this method present will not prevent the scripts from running, but will generate a warning message. The functionality is now encompassed by the Log field of `vtkn88FiniteElementModel`, which allows a much greater amount of information to be recorded.

3. Method `NodeIdsFromSelection` of `vtkn88FiniteElementModel` is deprecated.

   Use the method `GetNodeSet` instead.

4. Method `CreateDisplacementConstraint` of `vtkn88FiniteElementModel` is renamed to `ApplyBoundaryCondition`.

5. Method `CreateFixedConstraint` of `vtkn88FiniteElementModel` is renamed to `FixNodes`.

6. Method `CreateForceConstraint` of `vtkn88FiniteElementModel` is renamed to `ApplyLoad`.
7. Method `DataSetFromSelection` of `vtkn88FiniteElementModel` is deprecated.

   Use either `DataSetFromNodeSet` or `DataSetFromElementSet`.
8. Method `PolyDataFromSelection` of `vtkn88FiniteElementModel` is deprecated.

   You can duplicate this functionality as follows. Instead of

   ```
   visible_bone_vertices = model.PolyDataFromSelection("bone_top")
   ```

   the following code can be used instead:

   ```
   reduceToPolyData = vtk.vtkGeometryFilter()
   reduceToPolyData.SetInput(model.DataSetFromNodeSet("bone_top"))
   reduceToPolyData.MergingOff()
   reduceToPolyData.Update()
   visible_bone_vertices = reduceToPolyData.GetOutput()
   ```

   Note that this functionality is rarely required, as its main use was to write node sets as VTK PolyData files (which are slightly more efficient than VTK Unstructured Grid files). We now recommend not performing this within scripts at all, but instead to use n88extractsets to extract the node sets from `.n88model` files.
9. The names of node sets (and element sets) must be set on the data array of Point IDs.

   Instead of this

   ```
   model.AddNodeSet(visibleNodesIds, "bone_top")
   ```

   we now write this

   ```
   visibleNodesIds.SetName("bone_top")
   model.AddNodeSet(visibleNodesIds)
   ```
10. Class `vtkn88FiniteElementRun` is renamed to `vtkn88SolverParameters`.
11. Specify element sets as well as node sets for post-processing. For examples, refer to the tutorials on `vtkn88`, specifically Section 7.6.8 and Section 7.8.14.
12. You should make use of the History and Log fields. See any of the tutorials on `vtkn88` for examples.
13. Instead of `vtkn88FAIMInputWriter` use `vtkn88N88ModelWriter`. Don't forget to use a file name extention ".n88model" instead of ".inp".
14. Don't specify the iteration limit for the convergence tolerance. If you really want to change these from their defaults, use the command line arguments to n88solver.

Appendix B

n88model File Format

The n88model format is a type of NetCDF4/HDF5 file. NetCDF4/HDF5 is a very widely used, high performance and robust file format for scientific and numerical data. Many standard data processing packages are able to read either NetCDF4 or HDF5, which makes it generally straightforward to import Faim data for custom processing.

Note
The curious may be wondering how a file can be both NetCDF4 and HDF5. Historically, NetCDF and HDF were different formats. As they served largely similar purposes, starting with NetCDF 4, NetCDF adopted the HDF5 file format (amongst other options), while retaining its API or programming interface. Functionally, the NetCDF file format is a subset of HDF5, with a somewhat simpler API. HDF5 files must be structured in a specific way to be a NetCDF4 file; not any HDF5 file can be read through the NetCDF4 library.

Converting a n88model file to and from a text file

Sometimes it is useful to examine or modify a data file by hand. Users of faim 5.x may recall that it used a text format, which while subject to many disadvantages, was easy to edit manually. `n88model` files cannot be modified directly by hand, however they can be converted to a type of text file, called CDL, that is human readable. Furthermore, CDL text files, provided they are consistent with the `n88model` format convention, can easily be converted back into an `n88model` file.

To convert an `n88model` file to text, the command `ncdump` can be used. For example:

```
ncdump 1x1x2_uniaxial.n88model > 1x1x2_uniaxial.txt
```

Note
You can create this example file with the command `n88modelgenerator 1x1x2.vti`. The file `1x1x2.vti` can be found in the `data` directory of faim. It is a trivial 2-element geometry.

To convert it back again (perhaps after modifying it), follow this example

```
ncgen -k hdf5 -o 1x1x2_uniaxial.n88model 1x1x2_uniaxial.txt
```

Example n88model file in CDL text format

The easiest way to understand the structure of an `n88model` file is to examine it in text format. Here is the `1x1x2_uniaxial.txt` file, generated in the previous section example. This model has been solved and the file contains solution data. Although it is only two elements, the text representation of the `n88model` file is rather lengthy!

```
netcdf \1x1x2_uniaxial {
dimensions:
    Dimensionality = 3 ;

// global attributes:
        :Conventions = "Numerics88/Finite_Element_Model-1.0" ;
        :ActiveProblem = "Problem1" ;
        :Log = "2012-Jul-18 08:59:45\nn88modelgenerator parameters:\n\ninput_file   = / ↩
           Applications/faim-6.0/data/1x1x2.vti\noutput_file  = 1x1x2_uniaxial.n88model\ ↩
           ntest                          = uniaxial\ntest_axis                  = z\ ↩
           nstrain                        = -0.01\npin                          = off\ ↩
           ntop_surface                   = intersection\nbottom_surface              =  ↩
           intersection\nmaterial_table             = homogeneous\nyoungs_modulus  ↩
                        = 6829\npoissons_ratio              = 0.3\nconnectivity_filter  ↩
                   = warn\n\n2012-Jul-18 09:19:26\nn88solver parameters:\n\nengine  ↩
                           = mt\nthreads                  = 1\nrestart                 = ↩
            0\nlimit                    = 30000\nconvergence tolerance    = 1e-06\nresidual ↩
            tolerance       = 0\nwindow                  = 4\n" ;
        :History = "2012-Jul-18 08:59:45 Model created by n88modelgenerator version 6.0\ ↩
           n2012-Jul-18 09:19:26 Solved by n88solver version 6.0\n2012-Jul-18 09:19:26  ↩
           Derived fields calculated by n88derivedfields version 6.0" ;
        :ActiveSolution = "Solution1" ;

group: MaterialDefinitions {

  group: NewMaterial1 {

    // group attributes:
            :Type = "LinearIsotropic" ;
            :E = 6829. ;
            :nu = 0.3 ;
    } // group NewMaterial1
  } // group MaterialDefinitions

group: Parts {

  group: Part1 {
    dimensions:
        NumberOfNodes = 12 ;
    variables:
        float NodeCoordinates(NumberOfNodes, Dimensionality) ;
    data:

     NodeCoordinates =
  0, 0, 0,
  1, 0, 0,
  0, 1, 0,
  1, 1, 0,
  0, 0, 1,
  1, 0, 1,
  0, 1, 1,
  1, 1, 1,
  0, 0, 2,
  1, 0, 2,
  0, 1, 2,
  1, 1, 2 ;

    group: Elements {

      group: Hexahedrons {
        dimensions:
            NumberOfNodesPerElement = 8 ;
            NumberOfElements = 2 ;
        variables:
            uint ElementNumber(NumberOfElements) ;
            uint NodeNumbers(NumberOfElements, NumberOfNodesPerElement) ;
            ushort MaterialID(NumberOfElements) ;
        data:

         ElementNumber = 1, 2 ;

         NodeNumbers =
  1, 2, 3, 4, 5, 6, 7, 8,
  5, 6, 7, 8, 9, 10, 11, 12 ;

         MaterialID = 127, 127 ;
        } // group Hexahedrons
      } // group Elements

    group: MaterialTable {
      dimensions:
        Size = 1 ;
      variables:
        ushort ID(Size) ;
        string MaterialName(Size) ;
      data:

       ID = 127 ;

       MaterialName = "NewMaterial1" ;
      } // group MaterialTable
    } // group Part1
  } // group Parts

group: Constraints {

  group: bottom_fixed {
    dimensions:
        NumberOfValues = 4 ;
    variables:
        uint NodeNumber(NumberOfValues) ;
        byte Sense(NumberOfValues) ;
        float Value(NumberOfValues) ;

    // group attributes:
            :Part = "Part1" ;
            :Type = "NodeAxisDisplacement" ;
    data:

     NodeNumber = 1, 2, 3, 4 ;

     Sense = 3, 3, 3, 3 ;

     Value = 0, 0, 0, 0 ;
    } // group bottom_fixed

  group: top_displacement {
    dimensions:
        NumberOfValues = 4 ;
    variables:
        uint NodeNumber(NumberOfValues) ;
        byte Sense(NumberOfValues) ;
        float Value(NumberOfValues) ;
    // group attributes:
            :Part = "Part1" ;
            :Type = "NodeAxisDisplacement" ;
    data:

     NodeNumber = 9, 10, 11, 12 ;

     Sense = 3, 3, 3, 3 ;

     Value = -0.02, -0.02, -0.02, -0.02 ;
    } // group top_displacement
  } // group Constraints

group: Sets {

  group: NodeSets {

    group: face_z0 {
      dimensions:
        NumberOfNodes = 4 ;
      variables:
        uint NodeNumber(NumberOfNodes) ;

      // group attributes:
            :Part = "Part1" ;
      data:

       NodeNumber = 1, 2, 3, 4 ;
      } // group face_z0

    group: face_z1 {
      dimensions:
        NumberOfNodes = 4 ;
      variables:
        uint NodeNumber(NumberOfNodes) ;

      // group attributes:
            :Part = "Part1" ;
      data:

       NodeNumber = 9, 10, 11, 12 ;
      } // group face_z1

    group: face_x0 {
      dimensions:
        NumberOfNodes = 6 ;
      variables:
        uint NodeNumber(NumberOfNodes) ;

      // group attributes:
            :Part = "Part1" ;
      data:

       NodeNumber = 1, 3, 5, 7, 9, 11 ;
      } // group face_x0

    group: face_x1 {
      dimensions:
        NumberOfNodes = 6 ;
      variables:
        uint NodeNumber(NumberOfNodes) ;
      // group attributes:
            :Part = "Part1" ;
      data:

       NodeNumber = 2, 4, 6, 8, 10, 12 ;
      } // group face_x1

    group: face_y0 {
      dimensions:
        NumberOfNodes = 6 ;
      variables:
        uint NodeNumber(NumberOfNodes) ;

      // group attributes:
            :Part = "Part1" ;
      data:

       NodeNumber = 1, 2, 5, 6, 9, 10 ;
      } // group face_y0

    group: face_y1 {
      dimensions:
        NumberOfNodes = 6 ;
      variables:
        uint NodeNumber(NumberOfNodes) ;

      // group attributes:
            :Part = "Part1" ;
      data:

       NodeNumber = 3, 4, 7, 8, 11, 12 ;
      } // group face_y1
    } // group NodeSets

  group: ElementSets {

    group: face_z0 {
      dimensions:
        NumberOfElements = 1 ;
      variables:
        uint ElementNumber(NumberOfElements) ;

      // group attributes:
            :Part = "Part1" ;
      data:

       ElementNumber = 1 ;
      } // group face_z0

    group: face_z1 {
      dimensions:
        NumberOfElements = 1 ;
      variables:
        uint ElementNumber(NumberOfElements) ;

      // group attributes:
            :Part = "Part1" ;
      data:

       ElementNumber = 2 ;
      } // group face_z1
    group: face_x0 {
      dimensions:
        NumberOfElements = 2 ;
      variables:
        uint ElementNumber(NumberOfElements) ;

      // group attributes:
            :Part = "Part1" ;
      data:

       ElementNumber = 1, 2 ;
      } // group face_x0

    group: face_x1 {
      dimensions:
        NumberOfElements = 2 ;
      variables:
        uint ElementNumber(NumberOfElements) ;

      // group attributes:
            :Part = "Part1" ;
      data:

       ElementNumber = 1, 2 ;
      } // group face_x1

    group: face_y0 {
      dimensions:
        NumberOfElements = 2 ;
      variables:
        uint ElementNumber(NumberOfElements) ;

      // group attributes:
            :Part = "Part1" ;
      data:

       ElementNumber = 1, 2 ;
      } // group face_y0

    group: face_y1 {
      dimensions:
        NumberOfElements = 2 ;
      variables:
        uint ElementNumber(NumberOfElements) ;

      // group attributes:
            :Part = "Part1" ;
      data:

       ElementNumber = 1, 2 ;
      } // group face_y1
    } // group ElementSets
  } // group Sets

group: Problems {

  group: Problem1 {

    // group attributes:
            :Part = "Part1" ;
            :Constraints = "bottom_fixed,top_displacement" ;
            :PostProcessingNodeSets = "face_z1,face_z0" ;
            :PostProcessingElementSets = "face_z1,face_z0" ;
            :RotationCenter = 0.5, 0.5, 1. ;
    } // group Problem1
  } // group Problems

group: Solutions {

  group: Solution1 {

    // group attributes:
            :Problem = "Problem1" ;

    group: NodeValues {
      dimensions:
        NumberOfNodes = 12 ;
      variables:
        float Displacement(NumberOfNodes, Dimensionality) ;
        float Residual(NumberOfNodes, Dimensionality) ;
        float ReactionForce(NumberOfNodes, Dimensionality) ;
      data:

       Displacement =
  -0.001500001, -0.001500001, 0,
  0.001500001, -0.001500001, 0,
  -0.001500001, 0.001500001, 0,
  0.001500001, 0.001500001, 0,
  -0.001500001, -0.001500001, -0.01000001,
  0.001500001, -0.001500001, -0.01000001,
  -0.001500001, 0.001500001, -0.01000001,
  0.001500001, 0.001500001, -0.01000001,
  -0.001500001, -0.001500001, -0.02,
  0.001500001, -0.001500001, -0.02,
  -0.001500001, 0.001500001, -0.02,
  0.001500001, 0.001500001, -0.02 ;

       Residual =
  -1.528847e-07, -1.528847e-07, 0,
  1.528847e-07, -1.528847e-07, 0,
  -1.528847e-07, 1.528847e-07, 0,
  1.528847e-07, 1.528847e-07, 0,
  1.437116e-05, 1.437116e-05, 3.424616e-05,
  -1.437116e-05, 1.437116e-05, 3.424616e-05,
  1.437116e-05, -1.437116e-05, 3.424616e-05,
  -1.437116e-05, -1.437116e-05, 3.424616e-05,
  1.452404e-05, 1.452404e-05, 0,
  -1.452404e-05, 1.452404e-05, 0,
  1.452404e-05, -1.452404e-05, 0,
  -1.452404e-05, -1.452404e-05, 0 ;

       ReactionForce =
  1.528847e-07, 1.528847e-07, 17.07251,
  -1.528847e-07, 1.528847e-07, 17.07251,
  1.528847e-07, -1.528847e-07, 17.07251,
  -1.528847e-07, -1.528847e-07, 17.07251,
  -1.437116e-05, -1.437116e-05, -3.424616e-05,
  1.437116e-05, -1.437116e-05, -3.424616e-05,
  -1.437116e-05, 1.437116e-05, -3.424616e-05,
  1.437116e-05, 1.437116e-05, -3.424616e-05,
  -1.452404e-05, -1.452404e-05, -17.07248,
  1.452404e-05, -1.452404e-05, -17.07248,
  -1.452404e-05, 1.452404e-05, -17.07248,
  1.452404e-05, 1.452404e-05, -17.07248 ;
      } // group NodeValues

    group: ElementValues {
      dimensions:
        NumberOfElements = 2 ;
        NumberOfStressStrainComponents = 6 ;
      variables:
        float Stress(NumberOfElements, NumberOfStressStrainComponents) ;
        float VonMisesStress(NumberOfElements) ;
        float Strain(NumberOfElements, NumberOfStressStrainComponents) ;
        float StrainEnergyDensity(NumberOfElements) ;
      data:

       Stress =
  -6.115387e-07, -6.115387e-07, -68.29005, 0, 0, 0,
  5.809617e-05, 5.809617e-05, -68.28991, 0, 0, 0 ;

       VonMisesStress = 68.29005, 68.28997 ;

       Strain =
  0.003000002, 0.003000002, -0.01000001, 0, 0, 0,
  0.003000002, 0.003000002, -0.009999992, 0, 0, 0 ;

       StrainEnergyDensity = 0.3414505, 0.3414495 ;
      } // group ElementValues
    } // group Solution1
  } // group Solutions
}
```

Specification

NetCDF4 files consist of dimensions, variables and attributes, as well as groups. Groups can contain dimensions, variables and attributes, as well as other groups, thus forming a nested tree structure. Variables can also contain attributes.

Types specified below as “numeric” may be any concrete numeric type. Similarly “integral” may be any concrete integer type.

It is convenient to refer to the text format example when trying to follow the file specification.

Note
In some cases dimensions may be named differently than specified below. (For complex reasons some of the n88 tools are unable to deduce the correct dimension names in certain rare cases.) This should be avoided where possible when writing a file. For reading files, the most reliable method is to inquire about the dimensions of the variables, rather than looking up dimensions by name.

Root group

The root group exists for all NetCDF4 files. It does not need to be created.

attribute [text] *Conventions*
Specifies that this is a `n88model` file. Must be “Numerics88/Finite_Element_Model-1.0”. Required.

attribute [text] *ActiveProblem*
Specifies the problem that will be used as input to the solver. Must be set to a name of a subgroup of the *Problems* group. Required by the solver.

attribute [text] *ActiveSolution*
Specifies the active solution set, which is typically the one that will be used for post-processing or rendering. Must be set to a name of a subgroup of the *Solution* group. Required by `n88postfaim`, but not required by the solver.

attribute [text] *History*
Brief history of the operations that have been performed on the file. By convention, add one line to the history for each operation performed on the file. Each line should start with a time/date stamp. Additional detail should go into the *Log* attribute. Required.

attribute [text] *Log*
As much additional detail as required about operations that have been performed on the file. Each addition or section in *Log* may be multiple lines. It is recommended that each section start with a time/date stamp, in order to make it easy to correlate with *History*. Optional.

dimension *Dimensionality*
Specifies the dimension of the problem. Currently it must be 3, although future versions of Faim might also support 2D models. Required.

MaterialDefinitions group

This group contains material definitions. Each material definition is implemented as a subgroup, where the name of the subgroup is the name of the material being defined. Each subgroup is required to have an attribute *Type*. Required.

subgroups of *MaterialDefinitions* of *Type* "LinearIsotropic"
A subgroup that defines a linear isotropic material. Optional. As many may be defined as required.

attribute [text] *Type*
"LinearIsotropic". Required.

dimension *MaterialArrayLength*
Specifies the number of materials, if a material array if being defined. Optional; if not present a single material is being defined.

attribute [numeric] or variable *E*
Specifies the Young's Modulus of the material, or, if a variable, a sequence of length *MaterialArrayLength* of Young's Modulii for the materials. Required.

attribute [numeric] or variable *nu*
Specifies the Poisson's Ratio of the material, or, if a variable, a sequence of length *MaterialArrayLength* of Poisson's Ratios for the materials. Required.

subgroups of *MaterialDefinitions* of *Type* "LinearOrthotropic"
A subgroup that defines a linear orthotropic material. Optional. As many may be defined as required.

attribute [text] *Type*
"LinearOrthotropic". Required.

dimension *MaterialArrayLength*
Specifies the number of materials, if a material array if being defined. Optional; if not present a single material is being defined.

attribute [numeric, length 3] or variable *E*
Specifies the Young's Modulii of the material as E_{xx}, E_{yy}, E_{zz}. Alternatively, if a variable, must be of dimensions *MaterialArrayLength*$\times$3. Required.

attribute [numeric, length 3] or variable *nu*
Specifies the Poisson's Ratio of the material as ν_{yz}, ν_{zx}, ν_{xy}. Alternatively, if a variable, must be of dimensions *MaterialArrayLength*$\times$3. Required.

attribute [numeric, length 3] or variable *G*
Specifies the Shear Modulus of the material as G_{yz}, G_{zx}, G_{xy}. Alternatively, if a variable, must be of dimensions *MaterialArrayLength*$\times$3. Required.

subgroups of *MaterialDefinitions* of *Type* "LinearAnisotropic"
A subgroup that defines a linear anisotropic material. Optional. As many may be defined as required.

attribute [text] *Type*
"LinearAnisotropic". Required.

dimension *MaterialArrayLength*
Specifies the number of materials, if a material array if being defined. Optional; if not present a single material is being defined.

attribute [numeric, length 36] or variable *StressStrainMatrix*
Specifies the 36 elements of the stress-strain matrix. Note that since the stress-strain matrix is symmetric, there are only 21 unique values, but for a single material all 36 must be given. They must be specified in the order K_{11}, K_{12}, K_{13} . . . K_{66}, but since the matrix is symmetric, this is equivalent to K_{11}, K_{21}, K_{31} . . . K_{66}. Alternatively, if a variable, must be of dimensions *MaterialArrayLength*$\times$21. Note that in the case of a material array, the upper triangular packed form of the matrix stored for efficiency. Then for each material in the array the indices required are K_{11}, K_{12}, K_{22}, K_{13}, K_{23}, K_{33} . . . K_{66} , which are the 21 unique values. Due to symmetry, this sequence is the same as K_{11}, K_{21}, K_{22}, K_{31}, K_{32}, K_{33} . . . K_{66}. Required.

subgroups of *MaterialDefinitions* of *Type* "VonMisesIsotropic"
A subgroup that defines an isotropic von Mises elastoplastic material. Optional. As many may be defined as required.

attribute [text] *Type*
"VonMisesIsotropic". Required.

dimension *MaterialArrayLength*
Specifies the number of materials, if a material array if being defined. Optional; if not present a single material is being defined.

attribute [numeric] or variable *E*
Specifies the Young's Modulus of the material, or, if a variable, a sequence of length *MaterialArrayLength* of Young's Modulii for the materials. Required.

attribute [numeric] or variable *nu*
Specifies the Poisson's Ratio of the material, or, if a variable, a ssequence of length *MaterialArrayLength* of Poisson's Ratios for the materials. Required.

attribute [numeric] *Y*
Specifies the Yield Strength of the material, or, if a variable, a sequence of length *MaterialArrayLength* of Yield Strengths for the materials. Required.

subgroups of *MaterialDefinitions* of *Type* "MohrCoulombIsotropic"
A subgroup that defines an isotropic Mohr Coulomb elastoplastic material. Optional. As many may be defined as required.

attribute [text] *Type*
"MohrCoulombIsotropic". Required.

dimension *MaterialArrayLength*
Specifies the number of materials, if a material array if being defined. Optional; if not present a single material is being defined.

attribute [numeric] or variable *E*
Specifies the Young's Modulus of the material, or, if a variable, a sequence of length *MaterialArrayLength* of Young's Modulii for the materials. Required.

attribute [numeric] or variable *nu*
Specifies the Poisson's Ratio of the material, or, if a variable, a sequence of length *MaterialArrayLength* of Poisson's Ratios for the materials. Required.

attribute [numeric] or variable *c*
Specifies the Mohr Coulomb *c* parameter (cohesion) of the material, or, if a variable, a sequence of length *MaterialArrayLength* of *c* values for the materials. Required.

attribute [numeric] or variable *phi*
Specifies the Mohr Coulomb φ parameter (friction angle) of the material, or, if a variable, a ssequence of length *MaterialArrayLength* of φ values for the materials. Required.

attribute [numeric] or variable *psi*
: Specifies the Mohr Coulomb ψ parameter (dilation angle) of the material, or, if a variable, a sequence of length *MaterialArrayLength* of ψ values for the materials. Optional, assumed zero if not specified.

Parts group

This group defines parts. A part is a geometric collection of elements, along with the associated nodes and the material assignments for the elements. Each part is implemented as a subgroup, where the name of the subgroup is the name of the part being defined.

subgroups of *Part*
: The subgroup name gives the part name. At least one subgroup is required, and multiple ones may be defined.

dimension *NumberOfNodes*
: The number of nodes in the variable NodeCoordinates.

variable *NodeCoordinates* (NumberOfNodes, Dimensionality) [numeric]
: Specifies the x,y,z coordinates of the nodes. The node numbering is implicit, and 1-based. Hence the first row is node 1, the second node 2, etc…

subgroup *MaterialTable* of subgroups of *Part*
: Maps material names, as defined in *MaterialDefinitions*, to material ID numbers. Material ID numbers are then assigned to each element. Required by the solver.

dimension *Size*
: The number of entries in the material table for this part.

variable *MaterialName* (Size) [text]
: The material names, corresponding to subgroups in *MaterialDefinitions*. Required.

variable *ID* (Size) [integral]
: The IDs assigned to to materials. Any IDs in the range 1-32768 may be assigned, provided they are unique. Required.

subgroup *Element* of subgroups of *Part*
: Required. Currently must itself contain exactly the single subgroup, *Hexahedrons*.

subgroup *Hexahedron* of subgroup *Element* of subgroups of *Part*
: Defines the hexahedral elements of the part. Note that the current version of `n88solver` only handles regular hexahedrons, although the file format does not enforce this. Currently required, although in future versions supporting multiple element types, may become optional.

dimension *NumberOfNodesPerElement* [=8]
: The number of nodes per element, which for hexahedrons is 8.

dimension *NumberOfElements*
: The number of hexahedral elements.

variable *ElementNumber* (NumberOfElements) [integral]
: Explicitly assigned element numbers. In the current version, the solver requires consecutively-numbered elements starting with element 1, but this restriction may be relaxed in future versions. Required.

variable *NodeNumbers* (NumberOfElements, NumberOfNodesPerElement)
: The node numbers of the nodes defining each hexahedron. The topology is as the VTK type `VTK_VOXEL`, and is shown in Figure 48. The global node numbers (1-indexed) must be given for each element in the order as shown in the figure. Required.

variable *MaterialID* (NumberOfElements) [integral]
: The material IDs of the materials assigned to each element. IDs correspond to values in the MaterialTable for this part. Required.

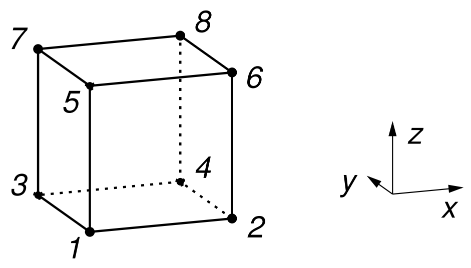

Figure B.1: Topology of hexahedral elements in n88model file (1-indexed).

Warning
The ordering of the elements in the input file has a strong influence on the solver. Certain orderings are optimal and will solve in the fastest time. There exist orderings which will cause the solver to fail with an error. A future version of Faim might reorder the input elements as required, but in the current version, we strongly recommend that elements be ordered in the file according to “x fastest, z slowest”.

Constraints group

Constraints are sets of values assigned to nodes, and used to define both boundary conditions and applied loads. Each constraint (which itself is a set of values) is implemented as a subgroup, where the name of the subgroup is the name of the constraint being defined. Optional, although a well-defined problem will always have some constraints.

Note
`vtkbone` supports constraints defined on elements as well, which the `n88model` file format does not currently support. This is the natural way to define applied loads. The file writers in `vtkbone` distribute element forces appropriately on to the nodes on writing. Because of this, `vtkboneN88ModelWriter` and `vtkboneN88ModelReader` are not quite inverses. Using them in sequence can result in a model with a different, although physically equivalent, set of constraints.

subgroups of *Constraints*
The subgroup name gives the Constraint name. Optional. Any number of subgroups may be defined.

attribute [text] *Part*
The part to which the constraint is associated. Note that this does not necessarily imply that the constraint will in fact be applied to the named part. Refer to the attribute *Constraints* in the *Problems* group.

attribute [text] *Type*
Currently two types are supported, *NodeAxisDisplacement* and *NodeAxisForce*. For the former, specific displacements for given nodes along given axis directions (the “sense”) are defined. The latter is similar but the specified values are forces.

dimension *NumberOfValues*
The number of values specified by this constraint.

variable *NodeNumber* (NumberOfValues) [integral]
A list of the node numbers to which the constraint is applied.

variable *Sense* (NumberOfValues) [integral]
A list of the senses along which the constraint is applied. Valid values are 1,2,3 for x,y,z respectively.

variable *Value* (NumberOfValues) [integral]
A list of the values (displacement or force) of the constraint.

Sets group

Sets are collections of nodes or of elements. The primary use of sets in `n88model` files is for post-processing. `n88postfaim` requires at least two-post processing sets of nodes, which must be matched by sets of the corresponding elements. Quantities (*e.g.* the difference between the sum of the forces on the node sets) are then calculated between pairs of sets. A secondary use of sets is simply to store sets that can be further refined and transformed into boundary conditions during model generation. This is particularly useful when the model generation occurs in several stages.

subgroup *NodeSets* of *Sets*
Defines node sets. Each node set is implemented as a subgroup, where the name of the subgroup is the name of the node set being defined. Required by `n88postfaim`.

subgroups of subgroup *NodeSets* of *Sets*
The subgroup name gives the node set name. Optional. As many may be defined as required.

attribute [text] *Part*
The part with which the node set is associated.

dimension *NumberOfNodes*
The number of nodes in the node set.

variable *NodeNumber*
A list of the node numbers of the nodes in the set.

subgroup *ElementSets* of *Sets*
Defines element sets. Each element set is implemented as a subgroup, where the name of the subgroup is the name of the element set being defined. Optional, although element sets must be defined if `n88postfaim` is to be used.

subgroups of subgroup *ElementSets* of *Sets*
The subgroup name gives the element set name. Optional. As many may be defined as required.

attribute [text] *Part*
The part with which the element set is associated.

dimension *NumberOfElements*
The number of elements in the element set.

variable *ElementNumber*
A list of the element numbers of the elements in the set.

Problems group

The *Problems* group defines problems that can be solved by the solver. Multiple problems may be defined. Each problem is implemented as a subgroup, where the name of the subgroup is the name of the problem being defined. In the current version, only the problem specified by the root-level attribute *ActiveProblem* will be solved when the file is submitted to the solver. Required by the solver.

subgroups of *Problem*
The subgroup name gives the problem name. Optional. As many may be defined as required.

attribute [text] *Part*
Gives the part that will be used for this problem. Required.

attribute [text] *Constraints*
Gives a list of constraints that will be applied to the problem. Takes the form of a list of constraint names separated by commas. It is clearly a logical error to assign constraints that are associated with a different part. Required.

attribute [numeric] ***ConvergenceTolerance***

Specifies the convergence tolerance to be used by the solver. Optional, and recommended that you not set this in the `n88model` file, because the optimum value depends on the solver. The solver will typically choose an appropriate value, but the choice can be specified with a command line option to `n88solver`, which is the recommended way to set the convergence tolerance should you wish to change it.

attribute [numeric] ***ConvergenceWindow***

Specifies the convergence window to be used by the solver. Optional, and recommended that you not set this in the `n88model` file, because the optimum value depends on the solver. The solver will typically choose an appropriate value, but the choice can be specified with a command line option to `n88solver`, which is the recommended way to set the convergence window should you wish to change it.

attribute [integral] ***MaximumIterations***

Specifies the maximum iterations to be used by the solver. Optional, and recommended that you not set this in the `n88model` file, because the optimum value depends on the solver. The solver will typically choose an appropriate value, but the choice can be specified with a command line option to `n88solver`, which is the recommended way to set the maximum iterations should you wish to change it.

attribute [text] ***PostProcessingNodeSets***

Gives a list of node sets that will be used for post-processing. Takes the form of a list of node set names separated by commas. `n88postfaim` requires that at least two post-processing node sets to be defined. `n88postfaim` has an equivalent command-line option which takes precedence.

attribute [text] ***PostProcessingElementSets***

Gives a list of element sets that will be used for post-processing. Takes the form of a list of element set names separated by commas. `n88postfaim` requires that every node set specified in *PostProcessingNodeSets* be exactly matched with an element set of the associated elements. `n88postfaim` has an equivalent command-line option which takes precedence.

attribute [numeric, length 3] ***RotationCenter***

Gives the rotation center. This value is used only for post-processing. Optional.

Solutions group

The solutions group contains solution values as calculated by `n88solver` or `n88derivedfields`. Any number of solution sets may be defined (including multiple solution sets per problem). Each solution set is implemented as a subgroup, where the name of the subgroup is the name of the problem being defined. The solution set specified by the root level attribute *ActiveSolution* is the one that will be used for post-processing.

subgroups of ***Solutions***

The subgroup name gives the solution set name. Optional. As many may be defined as required.

attribute [text] ***Problem***

The problem to which the solution applies. Required.

subgroup ***NodeValues*** **of subgroups of** ***Solutions***

A group containing variables that specify values on each node. Variables are identified by name, and may be either one-dimensional (scalar values on the nodes), or two-dimensional (vector values on the nodes).

dimension ***NumberOfNodes***

The number of nodes in the problem. This is redundant with the number of nodes defined in the part, and must be equal to it. (The NetCDF4 format requires that it be re-defined here.) Required.

typical variables in ***NodeValues***

- *Displacement* (NumberOfNodes, Dimensionality)
- *Residual* (NumberOfNodes, Dimensionality)
- *ReactionForce* (NumberOfNodes, Dimensionality)

subgroup ***ElementValues*** **of subgroups of** ***Solutions***

A group containing variables that specify values on each element. Variables are identified by name, and may be either one-dimensional (scalar values on the elements), or two-dimensional (vector values on the elements).

dimension *NumberOfElements*
The number of elements in the problem. This is redundant with the number of elements defined in the part, and must be equal to it. (The NetCDF4 format requires that it be re-defined here.) Required.

dimension *NumberOfStressStrainComponents* [=6]
Stress and strain are defined on the elements, and have 6 components, so a dimension equal to 6 must be defined. The order must be xx,yy,zz,yz,zx,xy.

typical variables in *ElementValues*

- *Stress* (NumberOfElements, NumberOfStressStrainComponents)
- *Strain* (NumberOfElements, NumberOfStressStrainComponents)
- *VonMisesStress* (NumberOfElements)
- *StrainEnergyDensity* (NumberOfElements)

Writing code to read and write n88model files

The following methods are possible for reading and writing n88model files:

1. Use the `vtkbone` classes vtkboneN88ModelReader and vtkboneN88ModelWriter , either in C++ or in python.
2. Use the python class `N88ModelReader` which is part of n88tools.
3. Directly read or write the file with the netCDF4 library in C or C++, following the above file standard. Refer to http://www.unidata.u software/netcdf/docs/ for documentation on using the NetCDF interface.
4. Directly read or write the file with the netCDF4 python module (http://unidata.github.io/netcdf4-python/), following the above file standard. See for example the source file `modelinfo.py` which is part of n88tools. If you have installed n88tools using Anaconda Python, then the netCDF4 module is automatically installed as a dependency.

Chapter 11

Index

Colophon

This documentation was written with asciidoc (http://www.methods.co.nz/asciidoc/). The PDF is generated by compiling asciidoc into DocBook (http://www.oasis-open.org/docbook/) and processing with dblatex (http://dblatex.sourceforge.net/).