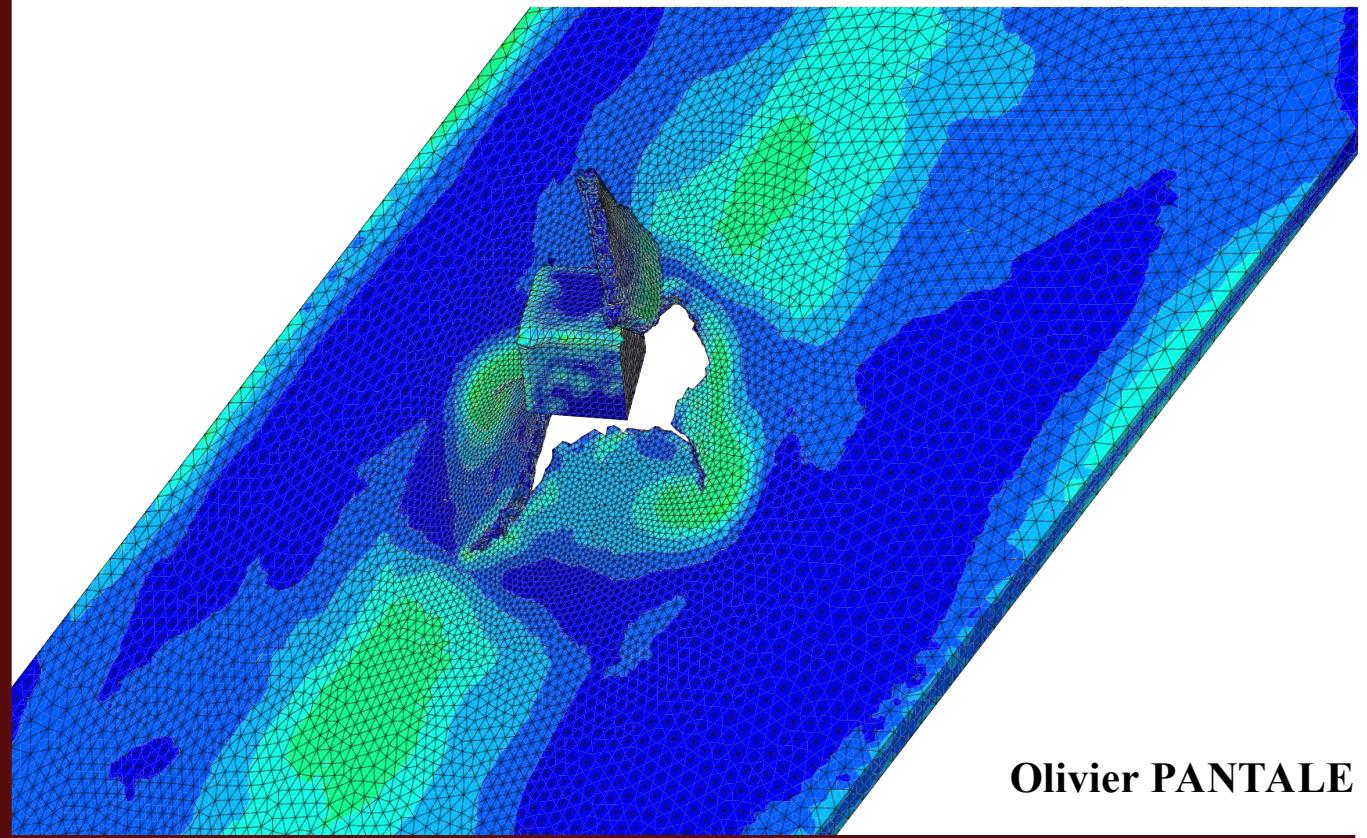


# **DynELA Finite Element Code**

## **v.3.0**



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## Part I

# DynELA FEM code theory

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# Notations

**F**rom a general point of view, it is usual to observe that one of the main difficulties in the field of mechanics, as in other fields, is the non-homogeneity of notations between the various authors.

It is then easy to make completely incomprehensible the slightest theory when one decides to change notation. As the notion of universal notation is not yet valid (even if certain conventions can be assimilated to universal concepts), then we present below the set of notations used throughout this document and in a broader way in all the other documents in that series.

## Notations Conventions

$a$	Scalar
$\vec{a}$	Vector
$A$	$2^{nd}$ order Tensor or matrix
$\mathcal{A}$	$3^{rd}$ order Tensor
$\mathbb{A}$	$4^{th}$ order Tensor

## Linear Algebra and Mathematical Operators

$\vec{a} \cdot \vec{b}$	Dot product of the vectors $\vec{a}$ and $\vec{b}$
$\vec{a} \otimes \vec{b}$	Tensor (or Dyadic) product of the vectors $\vec{a}$ and $\vec{b}$
$\vec{a} \wedge \vec{b}$	Vectorial product of the vectors $\vec{a}$ and $\vec{b}$
$A : B$	Double contracted product of the two tensors A et B
$\dot{\square}$	Time derivative of quantity $\square$
$\ddot{\square}$	Second order time derivative of quantity $\square$
$\square, \square$	Partial derivative of quantity $\square$ with respect to $\square$
$\square^T$	Transpose of a matrix or a vector $\square$
$\text{tr } \square$	Trace of a matrix or a tensor $\square$ ( $\text{tr } \square = \sum \square_{ii}$ )
$\text{dev } \square$	Deviatoric part of a tensor $\square$ ( $\text{dev } \square = \square - \frac{1}{3} \text{tr } \square \mathbf{1}$ )
$\delta_{ij}$	Kronecker delta identity
$\mathbf{1}$	Unity matrix or second order tensor
$\mathbb{I}$	Unity fourth order tensor

## Basic Continuum Mechanics

$\vec{x} = [x \ y \ z]^T$	Coordinates in the physical domain
$\vec{u} = [u \ v \ w]^T$	Displacement field

$\vec{\omega} = [ \omega_x \ \omega_y \ \omega_z ]^T$	Rotation field
$\Omega$	Arbitrary body in the current configuration
$\Gamma$	Boundary of an arbitrary body $\Omega$ in the current configuration
$\rho$	
$E$	Young's modulus of a material
$\nu$	Poisson's ratio of a material
$K$	Bulk modulus of a material
$\lambda$	Lamé's first parameter of a material
$\mu = G$	Lamé's second parameter / Coulomb's shear modulus
$\vec{F}$	External load vector
$\vec{f}$	External load vector
$\varepsilon$	Green-Lagrange strain tensor
$\sigma$	Cauchy stress tensor
$s$	Deviatoric part of the Cauchy stress tensor
$\alpha$	Backstress tensor
$\phi$	

## Constitutive laws

$f$	
$n$	Direction of the plastic flow
$q$	Heredity variables in an elastoplastic behavior
$\bar{\sigma}$	von Mises equivalent stress
$\bar{\varepsilon}^p$	Equivalent plastic strain
$\dot{\bar{\varepsilon}}^p$	Equivalent plastic strain rate
$\Lambda$	Norm of the plastic strain
$\sigma^v$	
$\sigma_0^v$	
$\sigma_\infty^v$	

## Large Deformations

$\vec{X} = [ X \ Y \ Z ]^T$	Coordinates in the reference domain
$E$	Green-Lagrange deformation tensor
$F$	Deformation gradient tensor
$U, V$	Right and left pure deformation tensors
$R$	Rotation tensor
$L$	Deformation speed tensor
$D$	Symmetric part of the L tensor
$W$	Skew-symmetric part of the L tensor

## Finite Element Data Structures

$N$	Shape functions matrix
$\vec{\xi} = [ \xi \ \eta \ \zeta ]^T$	Coordinates in the parent domain
$B$	Derivatives of the shape functions
$\square^e$	Quantity $\square$ related to element $e$
$J$	Jacobian matrix

M	Mass matrix
K	Stiffness matrix
$\bar{F}$	External surfacic load vector
F	External load vector
$\bar{f}$	External volumic load vector
q	Nodal unknowns vector
$n_g$	Number of nodes of the current element
$n_Q$	Number of integration points of the current element



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## Part II

# DynELA Programming

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# Chapter 1

## *DynELA programming language*

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This chapter deals about the DynELA Finite Element Code programming language. This language is based on Python 3 and all models must be described using this formalism. Therefore, this chapter will describe step by step how to build a Finite Element Model for the DynELA Finite Element Code, using the Python language.

### 1.1 Introduction

#### 1.1.1 Calling the python interpreter

After the compilation phase of the code, the DynELA Finite Element Code can be launch using the following command:

`python <'model.py'>`: where model.py is the source Python 3 file defining the DynELA Finite Element Code. The model.py file contains all the definitions of the Finite Element Model using a Python 3 language and calling DynELA methods written in C++.

#### 1.1.2 Formalism of a DynELA python file

In order to build a Finite Element Model, it is necessary to import the dnlPython interpreter from the .py script. Conforming to this formalism, the minimal piece of Python code to setup a Finite

Element Model is given hereafter.

```

1 #!/usr/bin/env python3
2 import dnlPython as dnl # Imports the dnlPython library as dnl
3 model = dnl.DynELA()    # Creates the main Object
4 ...                      # Set of instructions to build the FE model
5 ...                      # and conforming to the DynELA language and Python 3
6 model.solve()            # Runs the solver

```

In the preceding piece of code, line 2 is used to load into memory the module `dnlPython` containing the interface to all C++ methods of the DynELA Finite Element Code based on the use of the SWIG Python interface. Therefore, all public methods of the DynELA Finite Element Code written in C++ can be called from the Python script to build the FEM model, lanch teh solver, produce output results...

In the minimal proposed example, line 3 is used to create an object of type `DynELA` (the higher object type in the DynELA Finite Element Code library) and instantiate it as the `model` object<sup>(1)</sup>, while line 6, the solver of the DynELA Finite Element Code library is called to solve the problem and produce the results.

As the interpreter of the DynELA Finite Element Code is based on Python 3 language, all kind of instructions valid in Python 3 can be used along with the specific DynELA instructions.

## 1.2 The Kernel library

```
#include "LogFile.h"
#include "MacAddress.h"
#include "Settings.h"
#include "String.h"
#include "System.h"
#include "Timer.h"
#include "Field.h"
```

## 1.3 The Maths library

```
#include "DiscreteFunction.h"
#include "DiscreteFunctionSet.h"
#include "Function.h"
#include "Matrices.h"
#include "Matrix.h"
#include "MatrixDiag.h"
#include "PolynomialFunction.h"
#include "RampFunction.h"
```

---

<sup>(1)</sup>For the rest of this chapter, we will assume that the name of the instanciated DynELA object is `model`.

```
#include "SinusFunction.h"
#include "SymTensor2.h"
#include "Tensor2.h"
#include "Tensor3.h"
#include "Tensor4.h"
#include "Vec3D.h"
#include "Vector.h"
#include "ColorMap.h"
```

## 1.4 Nodes and elements

All Finite Element Models involves nodes and elements. The very first part of the model is therefore to create the nodes and the elements of the structure to setup a FE Model. The DynELA Finite Element Code library doesn't include any meshing procedure yet, therefore, it is mandatory to create all elements and all nodes by hand or using Python loops in case it can be used. Another way is to use an external meshing program and convert the output of this program to produce the ad-hoc lines of Python to describe the elements and the nodes of the model. This has been used many times by the author, and the Abaqus Finite Element code, is an efficient way to create the mesh using the .inp text file generated by the CAE Abaqus program.

### 1.4.1 Definition of the Model

### 1.4.2 Definition of the nodes

In the DynELA Finite Element Code, creation of nodes is done by calling the `DynELA.createNode()` method. Therefore, a node is created by calling the `createNode()` method and giving the new node number and the  $x$ ,  $y$  and  $z$  coordinates of the new node as presented just below.

```
1 model.createNode(1, 0.0, 0.0, 0.0) # Node 1 (0.0, 0.0, 0.0)
2 model.createNode(2, 1.0, 2.0, -1.0) # Node 2 (1.0, 2.0, -1.0)
```

A check of the total number of nodes of the structure can be done using the `DynELA.getNodesNumber()` method that returns the total number of nodes created.

### 1.4.3 Definitions of the elements

In the DynELA Finite Element Code, creation of elements is done by calling the `DynELA.createElement()` method. An element is created by calling the `createNode()` method and giving the new element number and the list of nodes defining the element shape separated by commas and ordered tanks to the element definition as presented just below. Before creating the very first element of the structure, it is necessary to define the element shape using the `DynELA.setDefaultElement()` method as presented hereafter.

```
1 model.setDefaultElement(dnl.Element.EIQua4N2D) # Defines the default element
2 model.createElement(1, 1, 2, 3, 4) # Creates element 1 with nodes 1,2,3,4
```

The following elements are available in the DynELA Finite Element Code.

**ElQua4n2D** : 4 nodes bi-linear 2D quadrilateral element.

**ElQua4NAx** : 4 nodes bi-linear axisymmetric quadrilateral element.

**ElTri3N2D** : 3 nodes 2D triangular element.

**ElHex8N3D** : 8 nodes 3D hexahedral element.

**ElTet4N3D** : 4 nodes 3D tetrahedral element.

**ElTet10N3D** : 10 nodes 3D tetrahedral element.

A check of the total number of elements of the structure can be done using the `DynELA.getElementsNumber()` method that returns the total number of elements created.

#### 1.4.4 Nodes sets

Manipulation of nodes, application of boundaries conditions, etc... is done through the definition of nodes sets. Such nodes sets are used to group nodes under a `NodeSet` object for further use. A `NodeSet` object contains a reference to a name (a string use to identify the object), and a list of nodes. Creation of a `NodeSet` is done using the `DynELA.NodeSet()` method that returns an new `NodeSet` instance. The `NodeSet` can be named during the creation by specifying its name as a string.

```
1 nset = dnl.NodeSet("NS_All")
```

When the `NodeSet` has been created, one can now define the list of nodes constituting the `NodeSet` with the generic `DynELA.add()` method with the following formalism `add(nodeset, start, end, increment)`. Hereafter are some self explaining examples to illustrate this process.

```
1 nset = dnl.NodeSet("NS_All")
2 model.add(nset, 2)      # Add node number 2 to node set
3 model.add(nset, 1, 4)    # Add nodes number 1 to 4 to node set
4 model.add(nset, 1, 4, 2) # Add nodes number 1 and 3 to node set
```

#### 1.4.5 Element sets

Application of materials, application of boundaries conditions, etc... is done through the definition of elements sets. Such elements sets are used to group elements under an `ElementSet` object for further use. An `ElementSet` object contains a reference to a name (a string use to identify the object), and a list of elements. Creation of an `ElementSet` is done using the `DynELA.ElementSet()` method that returns an new `ElementSet` instance. The `ElementSet` can be named during the creation by specifying its name as a string.

```
1 eset = dnl.ElementSet("ES_All")
```

When the `ElementSet` has been created, one can now define the list of nodes constituting the `ElementSet` with the generic `DynELA.add()` method with the following formalism `add(elementset, start, end, increment)`. Hereafter are some self explaining examples to illustrate this process.

```

1 eset = dnl.ElementSet("ES_All")
2 model.add(eset, 2)      # Add elemeny number 2 to element set
3 model.add(eset, 1, 4)    # Add elements number 1 to 4 to element set
4 model.add(eset, 1, 4, 2) # Add elements number 1 and 3 to element set

```

## 1.5 Coordinates transformations

When the mesh has been created, it is always possible to modify the geometry of the structure by applying some geometrical operations such as translations, rotations and change of scale. Those operations apply on a `NodeSet`.

### 1.5.1 Translations

One can define a translation of the whole model or a part of the model by defining a translation vector (an instance of the DynELA Finite Element Code `Vec3D`) and apply this translation to the whole structure (without specifying the `NodeSet`) or a `NodeSet` using the `DynELA.translate()` method with the following syntax.

```

1 vector = dnl.Vec3D(1.0, 0.0, 0.0) # Defines the translation vector
2 model.translate(vector)           # Translates the whole model along (1.0, 0.0, 0.0)
3 model.translate(vector, nset)     # Translates the NodeSet ns along (1.0, 0.0, 0.0)

```

### 1.5.2 Rotations

One can define a rotation of the whole model or a part of the model by defining a rotation vector (global axes  $\vec{x}$ ,  $\vec{y}$ ,  $\vec{z}$  or an instance of the DynELA Finite Element Code `Vec3D`) and an angle  $\alpha$  and apply this rotation to the whole structure (without specifying the `NodeSet`) or a `NodeSet` using the `DynELA.rotate()` method with the following syntax.

```

1 axis = dnl.Vec3D(1.0, 1.0, 1.0) # Defines the axis of rotation
2 model.rotate('X', angle)          # Rotation of the whole structure around X
3 model.rotate('X', angle, ns)      # Rotation of NodeSet ns around X
4 model.rotate(axis, angle)         # Rotation of the whole structure around axis
5 model.rotate(axis, angle, ns)     # Rotation of NodeSet ns around axis

```

### 1.5.3 Scaling

One can define a scaling of the whole model or a part of the model by defining a scale factor or a scale vector (an instance of the DynELA Finite Element Code `Vec3D`) and apply this scaling operation to the whole structure (without specifying the `NodeSet`) or a `NodeSet` using the `DynELA.scale()` method with the following syntaxes.

```

1 vector = dnl.Vec3D(2.0, 1.0, 1.0) # Defines the scale vector
2 model.scale(value)                 # Scales the whole structure by factor value
3 model.scale(value, ns)             # Scales the NodeSet ns by factor value
4 model.scale(vector)               # Scales the whole structure by a factor of 2.0 on x
5 model.scale(vector, ns)            # Scales the NodeSet ns by a factor of 2.0 on x

```

## 1.6 Materials

### 1.6.1 General properties

General properties of materials in Dynela concerns the general constants such as Young's modulus, Poisson's ratio, density,... The complete list of parameters is given hereafter.

**youngModulus** : The young modulus  $E$  of the material to define the elastic behaviour of the material.

**poissonRatio** : The Poisson ratio  $\nu$  of the material to define the elastic behaviour of the material.

**density** : The density  $\rho$  of the material.

**heatCapacity** : The heat capacity  $C_p$  of the material.

**taylorQuinney** : The Taylor-Quinney coefficient  $\eta$  defining the amount of plastic energy converted into heat during a plastic transformation of the material.

**initialTemperature** : The initial temperature  $T_0$  of the material at the beginning of the computation.

After creating an instance of the object `dnl.Material`, one can apply the prescribed values to all those parameters using the following syntax.

```

1 # Creates the material
2 steel = dnl.Material("Steel")
3 # Apply all parameters
4 steel.youngModulus = 206e9
5 steel.poissonRatio = 0.3
6 steel.density = 7830
7 steel.heatCapacity = 46
8 steel.taylorQuinney = 0.9
9 steel.initialTemperature = 25

```

And, the material can be affected to the elements of the model by the `DynELA.add()` method as proposed hereafter.

```

1 # Creates the material
2 steel = dnl.Material("Steel")
3 # Apply all parameters
4 ...
5 # Affect the material to the element set
6 model.add(steel, eset)

```

### 1.6.2 Johnson-Cook constitutive law

The Johnson-Cook constitutive law is an hardening law defining the yield stress  $\sigma^y(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p, T)$  by the following equation:

$$\sigma^y = (A + B\bar{\varepsilon}^{p^n}) \left[ 1 + C \ln \left( \frac{\dot{\bar{\varepsilon}}^p}{\dot{\bar{\varepsilon}}_0} \right) \right] \left[ 1 - \left( \frac{T - T_0}{T_m - T_0} \right)^m \right] \quad (1.1)$$

where  $\dot{\bar{\varepsilon}}_0$  is the reference strain rate,  $T_0$  and  $T_m$  are the reference temperature and the melting temperature of the material respectively and  $A$ ,  $B$ ,  $C$ ,  $n$  and  $m$  are the five constitutive flow law parameters. Therefore, this kind of hardening law can be defined by using the following piece of code:

```

1 hardLaw = dnl.JohnsonCookLaw() # Hardening law
2 hardLaw.setParameters(A, B, C, n, m, depsp0, Tm, T0) # Parameters of the law in order

```

Once the hardening law has been created, one have to link this hardening law to a material already defined using the following piece of code:

```

1 # Creates the material
2 steel = dnl.Material("Steel")
3 # Creates the hardening law
4 hardLaw = dnl.JohnsonCookLaw()
5 # Attach hardening law to material
6 steel.setHardeningLaw(hardLaw)

```

## 1.7 Boundaries conditions

### 1.7.1 Restrain boundary condition

```

1 # Declaration of a boundary condition for top part
2 topBC = dnl.BoundaryRestrain('BC_top')
3 topBC.setValue(0, 1, 1)
4 model.attachConstantBC(topBC, topNS)

```

### 1.7.2 Amplitude

```

1 # Declaration of a ramp function to apply the load
2 ramp = dnl.RampFunction("constantFunction")
3 ramp.set(dnl.RampFunction.Constant, 0, stopTime)

```

### 1.7.3 Constant speed

```

1 # Declaration of a boundary condition for top part
2 topSpeed = dnl.BoundarySpeed()
3 topSpeed.setValue(displacement, 0, 0)
4 topSpeed.setFunction(ramp)
5 model.attachConstantBC(topSpeed, topNS)

```

### 1.7.4 Initial speed

```

1 # Declaration of a ramp function to apply the load
2 ramp = dnl.RampFunction("constantFunction")
3 ramp.set(dnl.RampFunction.Constant, 0, stopTime)

```

## 1.8 Fields

### 1.8.1 Nodal fields

Nodal fields are defined at nodes and cover types defined in table II.1.1. Concerning those fields, some of them are directly defined at nodes, some other are extrapolated from integration points and transferred to nodes as reported in column loc of table II.1.1. Concerning types, scalars, vec3D and tensors are available. Depending in the type of data, different methods can be used to acces those data:

**scalar** : Direct access to the value as it is unique.

**vec3D** : Access to all 3 components of a vec3D using nameX, nameY, nameZ or the norm of the vec3D using name.

**tensor** : Access to all 9 components of a tensor using nameXX, nameXY,..., nameZZ or the norm of the tensor using name.

name	type	label	loc	description
density	scalar		IntPt	
displacementIncrement	vec3D		node	
displacement	vec3D		node	
energyIncrement	scalar		IntPt	
energy	scalar		IntPt	
gammaCumulate	scalar		IntPt	
gamma	scalar		IntPt	
internalEnergy	scalar		IntPt	
mass	scalar		node	
nodeCoordinate	vec3D		node	
normal	vec3D		node	
PlasticStrainInc	tensor		IntPt	
plasticStrainRate	scalar		IntPt	
plasticStrain	scalar		IntPt	
PlasticStrain	tensor		IntPt	
pressure	scalar		IntPt	
speedIncrement	vec3D		node	
speed	vec3D		node	
StrainInc	tensor		IntPt	
Strain	tensor		IntPt	
Stress	tensor		IntPt	
temperature	scalar		IntPt	
vonMises	scalar		IntPt	
yieldStress	scalar		IntPt	

*Table II.1.1 – Nodal fields*

## 1.8.2 Element fields

Element fields are defined at integration points and cover types defined in table II.1.2. Concerning types, scalars, vec3D and tensors are available. Depending in the type of data, different methods can be used to acces those data:

**scalar** : Direct access to the value as it is unique.

**vec3D** : Access to all 3 components of a vec3D using nameX, nameY, nameZ or the norm of the vec3D using name.

**tensor** : Access to all 9 components of a tensor using nameXX, nameXY,..., nameZZ or the norm of the tensor using name.

name	type	label	description
density	scalar		
gammaCumulate	scalar		
gamma	scalar		
internalEnergy	scalar		
plasticStrainRate	scalar		
plasticStrain	scalar		
PlasticStrain	tensor		
PlaticStrainInc	tensor		
pressure	scalar		
StrainInc	tensor		
Strain	tensor		
Stress	tensor		
temperature	scalar		
vonMises	scalar		
yieldStress	scalar		

*Table II.1.2 – Element fields*

## 1.8.3 Global fields

name	type	label	description
kineticEnergy	scalar		
realTimeStep	scalar		
timeStep	scalar		

*Table II.1.3 – Global fields*

## 1.9 Data Output during computation

### 1.9.1 Database files

### 1.9.2 VTK Data files

```
1 model.setSaveTimes(0, stopTime, stopTime/nbreSaves)
```

### 1.9.3 History files

```
1 dtHist = dnl.HistoryFile("dtHistory")
2 dtHist.setFileName(dnl.String("dt.plot"))
3 dtHist.add(dnl.Field.timeStep)
4 dtHist.setSaveTime(stopTime/nbrePoints)
5 model.add(dtHist)
```

## 1.10 Solvers

```
1 # Declaration of the explicit solver
2 solver = dnl.Explicit("Solver")
3 solver.setTimes(0, stopTime)
4 solver.setTimeStepSafetyFactor(1.0)
5 model.add(solver)
```

### 1.10.1 Parallel solver

```
1 # Parallel solver with two cores
2 model.parallel.setCores(2)
```

### 1.10.2 Solving procedure

```
1 # Run the main solver
2 model.solve()
```

## 1.11 Vectorial contourplots

### 1.11.1 SVG datafile

## 1.12 Utilities

```
1 # Plot the results as curves
2 import dnlCurves as cu
3 curves = cu.Curves()
4 curves.plotFile('Curves.ex')
```



# Chapter 2

## *Curves utility*

2.1 Introduction and presentation of the script . . . . .	21
2.2 Configuration file to define the plots . . . . .	22

This chapter deals about the curves utility of the DynELA Finite Element Code. This curve utility is a Python library used to produce plots (vector or bitmap plots) from DynELA Finite Element Code history files by reading a configuration file describing the way to produce those plots from a simple syntax language. The core of the library uses the matplotlib library implemented using the Python3 language. With this curve utility library, it is therefore possible to produce output graphics and curves directly from the python model file at the end of the solve.

### 2.1 Introduction and presentation of the script

#### 2.1.1 Usage of the Python script

The Curve library is called from a Python script with the following minimal form.

```
1 import dnlCurves           # Import the dnlCurve library
2 curves = dnlCurves.Curves() # Creates an instance of the Curve object
3 curves.plotFile('Curves.ex') # Plot the curves defined by the 'Curves.ex' file
```

#### 2.1.2 Datafile format

The datafile format is the plot file used by DynELA Finite Element Code. This file is a text file with  $\vec{x}$  and  $\vec{y}$  datas defined by two or more series of floating point data on two or more columns separated by spaces. This file should contain two header lines on top and should conform to the following for a datafile containing one data.

```
1 #DynELA_plot history file
2 #plotted :timeStep
3 1.0596474E-06 1.0596474E-06
4 1.0058495E-04 1.0572496E-06
5 ...
6 1.0000000E-02 1.4838518E-07
```

In this file, the very first line is ignored by the script, while the second one is used to define the default name of the variable to be plotted (here 'timeStep' in this case). Here after is a example of a datafile containing more columns.

```

1 #DynELA_plot history file
2 #plotted :s11 s22 s33
3 1.0596474E-06 1.0596474E+06 2.0596474E+06 -1.0596474E+06
4 1.0058495E-04 1.0572496E+06 2.0572496E+06 -1.0572496E+06
5 .....
6 1.0000000E-02 1.4838518E+07 2.4838518E+07 -1.4838518E+07

```

In this case, one can specify which columns will be used for plotting the curves as it will be presented just later.

## 2.2 Configuration file to define the plots

A configuration file is used to define the plots and is read by the `curves.plotFile()` method of the Curves object. Global parameters are defined using the keyword `Parameters` at the beginning of a line of the parameter file. The keyword `parameter` is followed by a set of commands used to set some global parameters for all the subsequent generated graphs by overwriting the default parameters, before generating the very first graph.

```

1 Parameters , xname=Displacement x , crop=True

```

Then all parameters can also be altered within the definition of a plot. A definition of a plot is done by a line without the `Parameters` keyword. The first element on this line is the name of the generated graph, followed by a set of parameters defining the generated plot.

```

1 # Plot of Temp.plot to Temp.svg file
2 Temp, name=$T$, Temp.plot
3 # Plot of column 1 of Stress.plot file to S11.svg file
4 S11, name=$\sigma_{xx}$, legendlocate=topleft, Stress.plot(0:1)
5 # Plot of column 2 of Stress.plot file to S22.svg file
6 S22, name=$\sigma_{yy}$, legendlocate=bottomleft, Stress.plot(0:2)
7 # Plot of dt.plot and Abaqus/Step.plot files to TimeStep.svg file
8 TimeStep, name=$\Delta t$, dt.plot, name=Abaqus $\Delta t$, Abaqus/Step.plot

```

In the proposed example we have the following.

- Line 2: plots the content of the `Temp.plot` file with legend  $T$  in a `Temp.svg` file using default parameters.
- Line 4: plots the content of the `Stress.plot` file with legend  $\sigma_{xx}$  in a `S11.svg` file using data from columns 0 for  $\vec{x}$  and from column 1 for  $\vec{y}$  and with a legend located in the top left part of the figure.
- Line 6: plots the content of the `Stress.plot` file with legend  $\sigma_{yy}$  in a `S22.svg` file using data from columns 0 for  $\vec{x}$  and from column 2 for  $\vec{y}$  with a legend located in the bottom left part of the figure.
- Line 8: plots the content of the `dt.plot` file with legend  $\Delta t$  and `Abaqus/Step.plot` file with legend `Abaqus  $\Delta t$`  in a `TimeStep.svg` file.

As presented just before, L<sup>A</sup>T<sub>E</sub>X can be used for names and legends by using the escape character \\$ and remembering that space character has to be defined by the combination of an escape '\\' character followed by the space '' so that '\'.

Comments can be inserted as presented briefly earlier by using the '#' character. Everything after the '#' character and up to the end of the line is ignored and treated as comment. Blank lines are also allowed in the file to help human readability of the file.

### 2.2.1 Global parameters for a graph

- `outputformat = <'format'>`: is used to define the format of the output file, *i.e.* pdf, svg, png,... (default value is svg file).
- `transparent = <True, False>`: is used to define if the background should be or not transparent (default value is False).
- `crop = <True, False>`: is used to define if the output image should be or not cropped (default value is False).
- `grid = <True, False>`: is used to define if the output graph should contain or not a grid (default value is True).
- `title = <'name'>`: defines the title of the graph on the top part of the plot ( default value 'Default title of the graph')
- `xname, yname = <'name'>`: defines the names of the  $\vec{x}$  and  $\vec{y}$  axis for the plot (default value are 'x-axis' and 'y-axis').
- `titlefontsize = <size>`: defines the font size of the title on the top part of the plot (default value is 20).
- `xfontsize, yfontsize = <size>`: defines the font size of the  $\vec{x}$  and  $\vec{y}$  axis names for the plot (default value is 20).
- `xlabelfontsize, ylabelfontsize = <size>`: defines the font size of the values along the  $\vec{x}$  and  $\vec{y}$  axis for the plot (default value is 16).
- `xrange, yrangle = <range>`: remaps the range of the curves for the  $\vec{x}$  and  $\vec{y}$  axis to the given value. For example, setting `xrange=10` will remap the x-data within the range [0, 10].
- `xscale,yscale = <range>`: multiply the  $\vec{x}$  or the  $\vec{y}$  data by a given factor. For example, setting `xscale=10` will multiply all x-data by a factor of 10.

### 2.2.2 Plotting curve parameters

- `name = <'name'>`: defines a new name for the next curve in the legend and overrides the one defined by the datafile.
- `removename = <'name'>`: removes from the names of the curves a given pattern for the legends. Example: `removename = -S11` will convert 'data-S11' into 'data'. This is not a very useful method and one should prefer the `name` command to redefine the name of the plotting curve.
- `linewidth = <'width'>`: defines the line width for all subsequent plots (default value is 2).

- **marks = <'symbol'>**: is used to define the next marker to use for all subsequent plots (default value is ""). If the value is void, markers are cycled through the default markers list.
- **marksnumber = <number>**: defines the total number of markers on the curves for all subsequent plots (default value is 20).
- **markersize = <size>**: defines the size of the marker symbols to use for all subsequent plots (default value is 10).

### 2.2.3 Legend definition

- **legendcolumns = <columns>**: defines the number of columns to use for the legend (default value is 1).
- **legendshadow = <True, False>**: is used to define if the output graph legend should contain or not a shadow box (default value is True).
- **legendanchor = <'position'>**: defines the position of the legend anchor independently from the legend position parameter.
- **legendposition = <'position'>**: defines the position of the legend position independently from the legend anchor parameter.
- **legendlocate = <'position'>**: defines the position of the legend with the following four options: 'topleft', 'topright', 'bottomleft' and 'bottomright' (default value is 'topright').
- **legendfontsize = <size>**: defines the font size of the text in the legend (default value is 16).

# Chapter 3

## *Abaqus extractor utility*

3.1 Introduction and presentation of the script . . . . .	25
3.2 Syntax of the configuration file . . . . .	25

This chapter deals about the Abaqus extractor utility of the DynELA Finite Element Code. This extractor is a Python library used to extract results from an Abaqus odb datafile by reading a configuration file describing the way to produce those extracts from a simple syntax language.

### 3.1 Introduction and presentation of the script

The AbaqusExtract library is called from a Python script with the following minimal form.

```

1 # import the AbaqusExtract library
2 import AbaqusExtract
3 # Extract data using datafile Extract.ex
4 AbaqusExtract.AbaqusExtract('Extract.ex')
```

Assuming that the Python script containing this piece of code is named 'Extract.py', therefore this script must be called from the Abaqus main program using the following command:

abaqus python Extract.py

### 3.2 Syntax of the configuration file

Different forms are used depending on the nature of the data to extract, but everything conforms to the Abaqus Python command syntax. The AbaqusExtract library uses some keywords to define the nature of the data to extract as proposed here after.

- TimeHistory: is a keyword defining that the line contains the instructions to extract a time history from an Abaqus odb file.
- job: is used to define the name of the odb file to use for the extraction of the results i.e. it's the name of the odb file without the extension .odb.

- **value:** is the nature of the variable to extract conforming to the variables names of Abaqus.
- **name:** is the given name of the plotting file to generate, *i.e.* the name of the plotting file without the .plot extension.
- **region:** is used to define the location of the data to extract. This one is more complex, as it can be a global location, a node location or an integration point location as described hereafter.
- **operate:** is an optional parameter defining what to do when multiple regions are defined.

As an example, the following piece of code gives some application examples.

```

1 # Extraction of a time history node data
2 TimeHistory , job=Torus , value=U1 , name=dispX , region=Node SQUARE-1.3
3 # Extraction of a time history integration point data
4 TimeHistory , job=Torus , value=MISES , name=vonMises , region=Element SQUARE-1.1 Int Point 1
5 # Extraction of a time history global variable
6 TimeHistory , job=Torus , value=DT , name=timeStep , region=Assembly ASSEMBLY

```

In the previous example:

- line 2 is used to extract the nodal displacement U1 from the odb file Torus.odb and produce the dispX.plot file for node 3 of the SQUARE-1 piece.
- line 4 is used to extract the integration point value MISES from the odb file Torus.odb and produce the vonMises.plot file for integration point 1 of element 1 of the SQUARE-1 piece.
- line 6 is used to extract the global timestep DT from the odb file Torus.odb and produce the timeStep.plot file.

Concerning the definition of the region to use, it is possible to define more than 1 region by using the '+' sign in the definition of the region. When this is used, the optional parameter operate is used to define what to do with this multiple data. The operation is defined by:

- **operate = none:** or no operate parameter defined, therefore, all values are reported to the plotting file separated by a white space.
- **operate = mean:** the mean value is computed and reported to the plotting file.
- **operate = sum:** the sum of the values is computed and reported to the plotting file.

---

## Part III

# DynELA Samples

---



# Chapter 1

## *DynELA single element sample cases*

1.1 Uniaxial tensile tests . . . . .	30
1.2 Uniaxial one element shear test . . . . .	39

This chapter deals with some numerical applications of the DynELA Finite Element Code for dynamic applications in 2D, axi-symmetric and 3D cases. In the subsequent tests, if not specified, a Johnson-Cook constitutive law is used to model the behavior of the material. The Johnson-Cook hardening flow law is probably the most widely used flow law for the simulation of high strain rate deformation processes taking into account plastic strain, plastic strain rate and temperature effects. Since a lot of efforts have been made in the past to identify the constitutive flow law parameters for many materials, it is implemented in numerous Finite Element codes such as Abaqus [?]. The general formulation of the Johnson-Cook law  $\sigma^y(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p, T)$  is given by the following equation:

$$\sigma^y = (A + B\bar{\varepsilon}^{pn}) \left[ 1 + C \ln \left( \frac{\dot{\bar{\varepsilon}}^p}{\dot{\bar{\varepsilon}}_0} \right) \right] \left[ 1 - \left( \frac{T - T_0}{T_m - T_0} \right)^m \right] \quad (1.1)$$

where  $\dot{\bar{\varepsilon}}_0$  is the reference strain rate,  $T_0$  and  $T_m$  are the reference temperature and the melting temperature of the material respectively and  $A$ ,  $B$ ,  $C$ ,  $n$  and  $m$  are the five constitutive flow law parameters. A 42CrMo4 steel following the Johnson-Cook behavior law has been selected for all those tests, and material properties are reported in Table III.3.1.

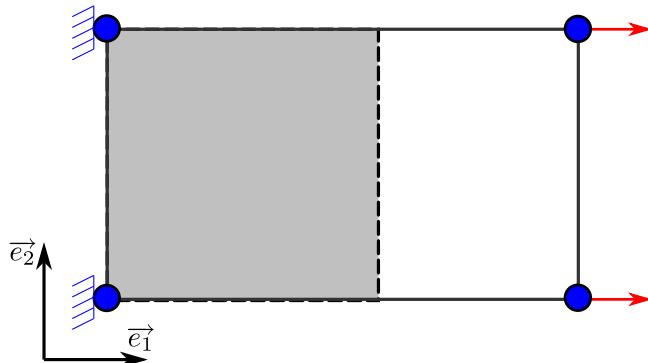
$E$ (GPa)	$\nu$	$A$ (MPa)	$B$ (MPa)	$C$	$n$	$m$
206.9	0.3	806	614	0.0089	0.168	1.1
$\rho$ (kg/m <sup>3</sup> )	$\lambda$ (W/m°C)	$C_p$ (J/Kg°C)	$\eta$	$\dot{\bar{\varepsilon}}_0$ (s <sup>-1</sup> )	$T_0$ (°C)	$T_m$ (°C)
7830	34.0	460	0.9	1.0	20	1540

*Table III.1.1 – Material parameters of the Johnson-Cook behavior for the numerical tests*

## 1.1 Uniaxial tensile tests

### 1.1.1 Element plane tensile test

The uniaxial one element tensile test is a numerical test where an plane element (with a square prescribed shape) is subjected to pure tensile as presented in figure III.1.1. The initial shape of



*Figure III.1.1 – Numerical model for the one element tensile test*

the specimen is  $10\text{ mm} \times 10\text{ mm}$ , the two left nodes of the element are encasted and a prescribed horizontal displacement  $d = 10\text{ mm}$  is applied on the two right nodes of the same element as illustrated in Figure III.1.1. As we are using an explicit integration scheme, the total simulation time is set to  $t = 0.01\text{ s}$ .

All the properties of the constitutive law reported in Table III.3.1 are used and the material is assumed to follow the Johnson-Cook behavior described by equation 3.1.

Figure III.1.2 shows the comparison of the DynELA solver results (plotted in red) and the Abaqus numerical results (plotted in blue) concerning the evolution of the stress components  $\sigma_{11}$ ,  $\sigma_{22}$ ,  $\sigma_{12}$ ,  $\bar{\sigma}$ ,  $\bar{\varepsilon}^p$  and  $T$  vs. the horizontal displacement of the right edge of the specimen along the horizontal axis. For the Abaqus model, the exact same mesh has been used. Comparison of Abaqus and DynELA results is made by averaging the DynELA results on the 4 integration points of the element. This has been done because DynELA Finite Element Code uses full integrated elements while Abaqus have reduced integrated elements only but in fact, the DynELA results at the 4 integration points are the same in this benchmark test.

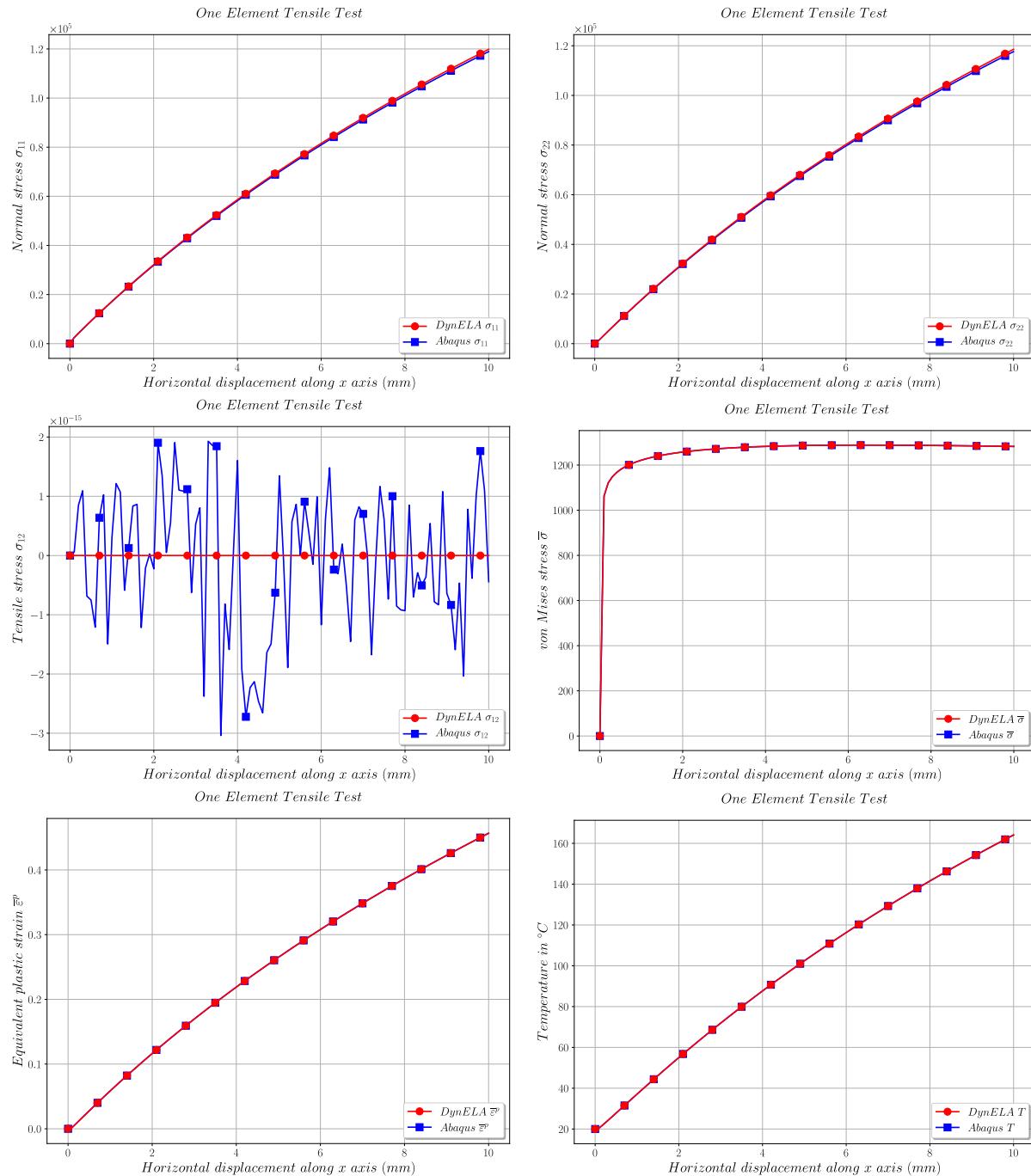


Figure III.1.2 – Comparison of numerical and analytical results for the one element tensile test

### 1.1.2 Element 3D tensile test

The uniaxial one element 3D tensile test is a numerical test where a 3D brick element (with a cubic prescribed shape) is subjected to radial tensile as presented in figure III.1.3. No boundary condition has been prescribed on the  $\vec{z}$  direction, so that the reduction of the width during the test can occur. The initial shape of the specimen is  $10\text{ mm} \times 10\text{ mm} \times 10\text{ mm}$  and the two left nodes of the element are restrained for their displacements along the  $\vec{x}$  and  $\vec{y}$  directions and a prescribed horizontal displacement  $d = 10\text{ mm}$  is applied on the two right nodes of the same element as illustrated in Figure III.1.3. As we are using an explicit integration scheme, the total simulation time is set to  $t = 0.01\text{ s}$ .

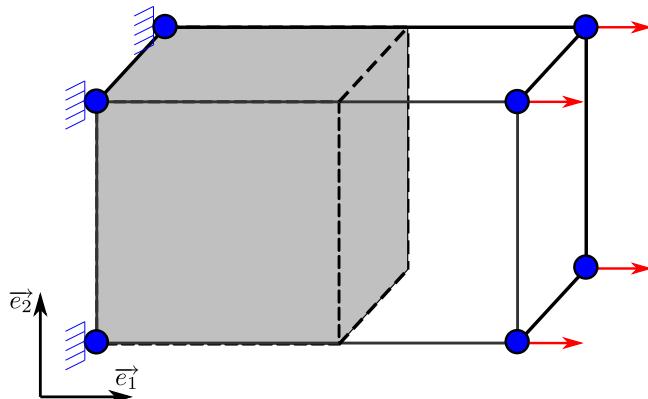


Figure III.1.3 – Numerical model for the one element tensile test

All the properties of the constitutive law reported in Table III.3.1 are used and the material is assumed to follow the Johnson-Cook behavior described by equation 3.1.

Figure III.1.4 shows the comparison of the DynELA solver results (plotted in red) and the Abaqus numerical results (plotted in blue) concerning the evolution of the stress components  $\sigma_{11}$ ,  $\sigma_{22}$ ,  $\sigma_{12}$ ,  $\bar{\sigma}$ ,  $\bar{\varepsilon}^p$  and  $T$  vs. the horizontal displacement of the right edge of the specimen along the horizontal axis. For the Abaqus model, the exact same mesh has been used. Comparison of Abaqus and DynELA results is made by averaging the DynELA and the Abaqus results on the 8 integration points of the element.

### 1.1.3 Element radial tensile test

The uniaxial one element radial tensile test is a numerical test where an axisymmetric element (with a square prescribed shape) is subjected to pure radial tensile as presented in figure III.1.1. The initial shape of the specimen is  $10\text{ mm} \times 10\text{ mm}$  and the two left nodes of the element are encasted and a prescribed horizontal displacement  $d = 10\text{ mm}$  is applied on the two right nodes of the same element as illustrated in Figure III.1.1. As we are using an explicit integration scheme, the total simulation time is set to  $t = 0.01\text{ s}$ .

All the properties of the constitutive law reported in Table III.3.1 are used and the material is assumed to follow the Johnson-Cook behavior described by equation 3.1.

Figure III.1.5 shows the comparison of the DynELA solver results (plotted in red) and the Abaqus numerical results (plotted in blue) concerning the evolution of the stress components  $\sigma_{11}$ ,  $\sigma_{22}$ ,  $\sigma_{12}$ ,  $\bar{\sigma}$ ,  $\bar{\varepsilon}^p$  and  $T$  vs. the horizontal displacement of the right edge of the specimen along the horizontal axis. Again, comparison of Abaqus and DynELA results is made by averaging the DynELA results on the 4 integration points of the element because DynELA Finite Element Code uses full integrated

elements while Abaqus have reduced integrated elements only but in fact, the DynELA results at the 4 integration points are the same in this benchmark test.

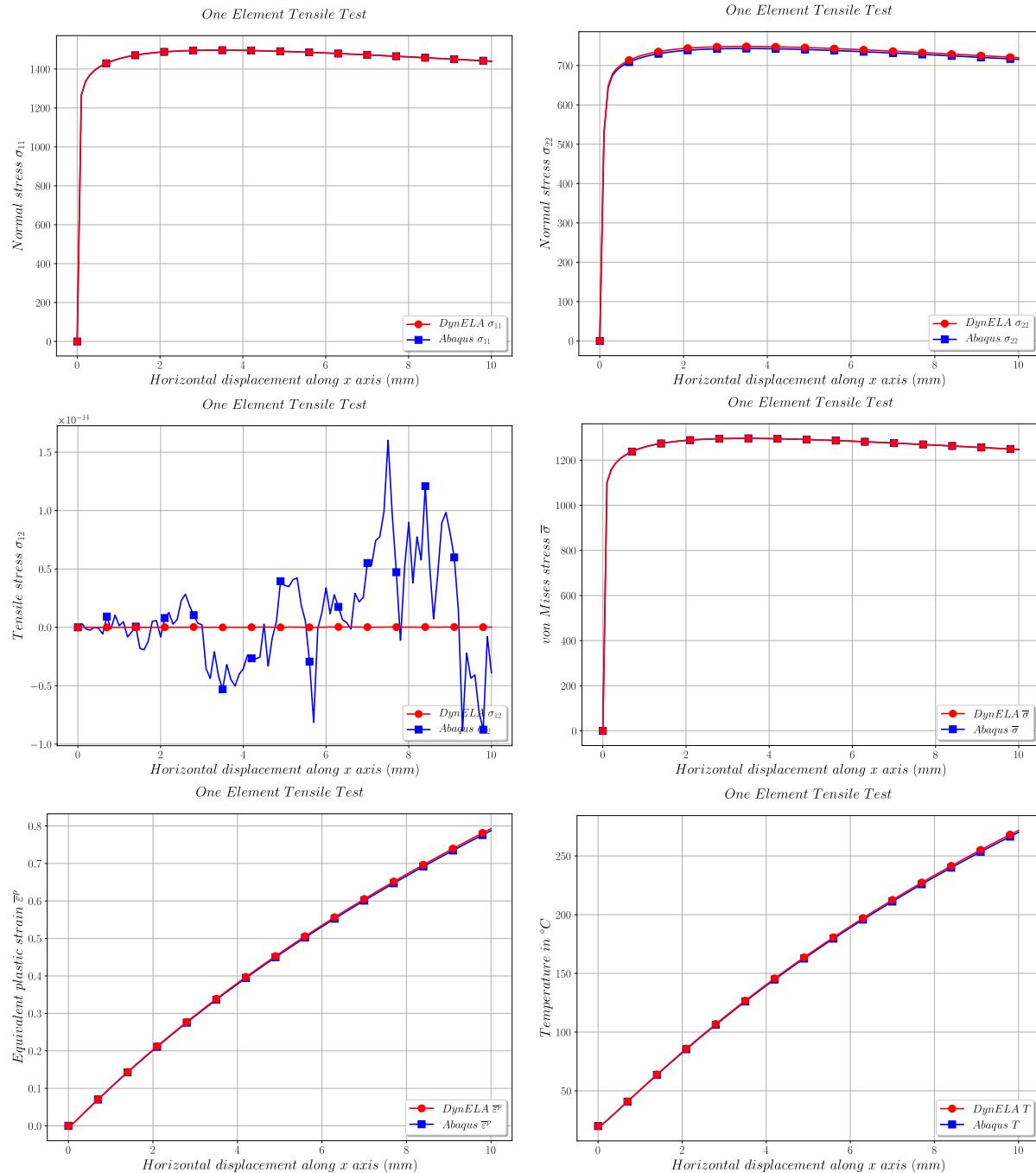
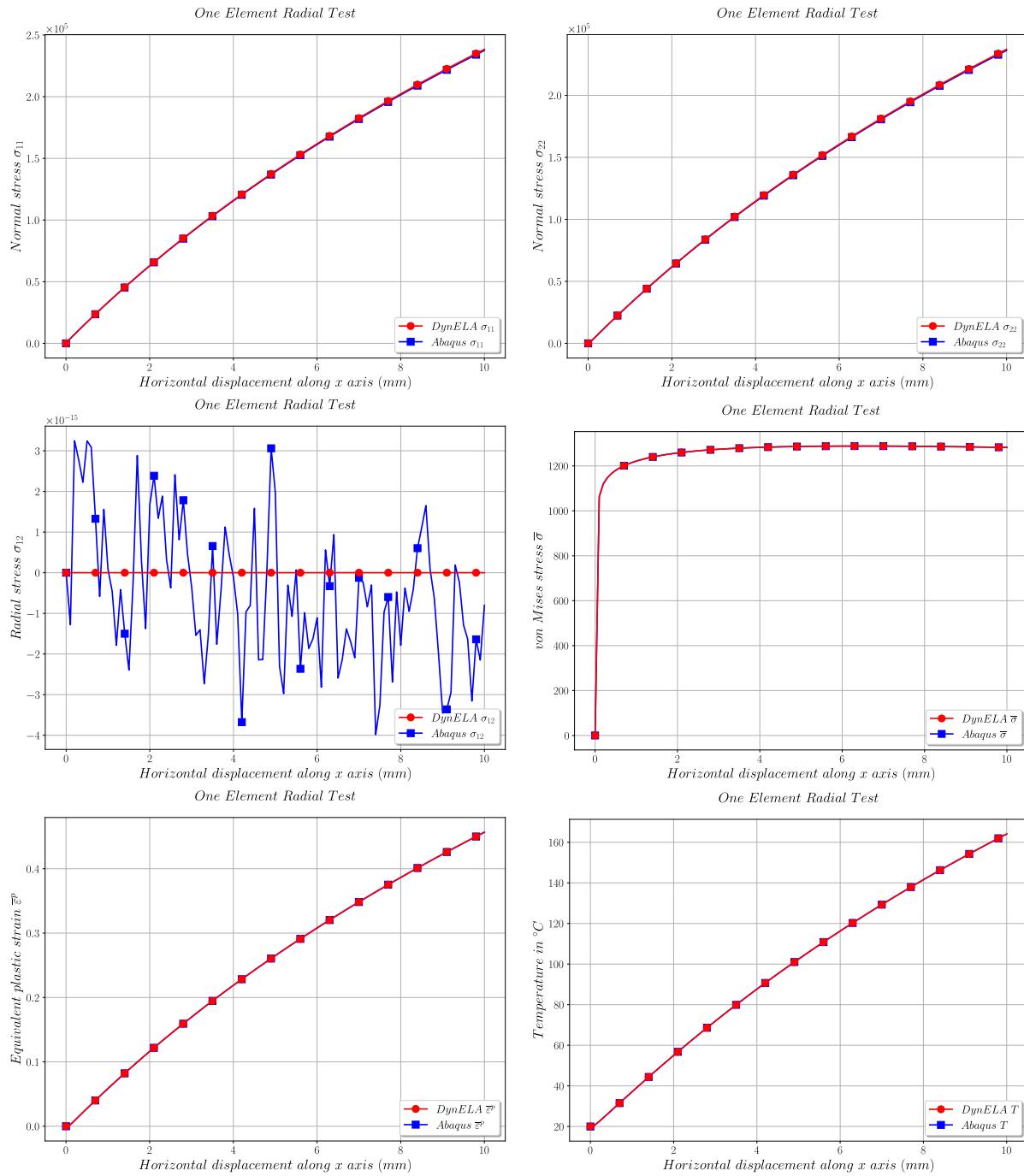


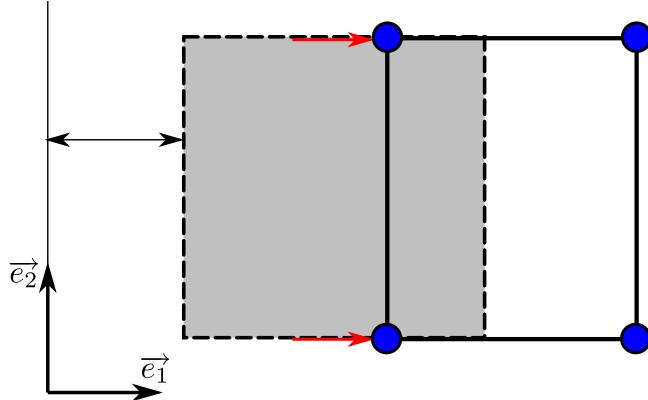
Figure III.1.4 – Comparison of numerical and analytical results for the 3D one element tensile test



**Figure III.1.5 – Comparison of numerical and analytical results for the one element radial tensile test**

### 1.1.4 Element radial torus test

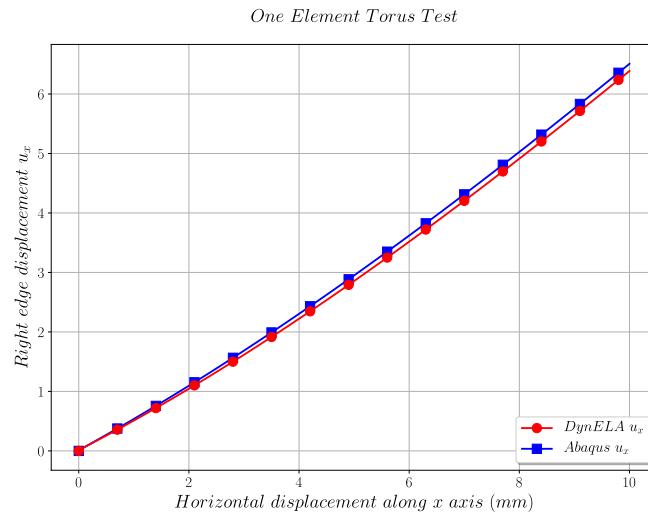
The uniaxial one element torus tensile test is a numerical test where an axisymmetric element (with a square prescribed shape) is subjected to radial tensile as presented in figure III.1.6. The difference



*Figure III.1.6 – Numerical model for the one element torus test*

with the previous test is that the left edge of the specimen is not aligned with the symmetry axis, the radial coordinate of the left edge is  $r = 10 \text{ mm}$ . The initial shape of the specimen is  $10 \text{ mm} \times 10 \text{ mm}$  and a prescribed horizontal displacement  $d = 10 \text{ mm}$  is applied on the two left nodes of the element as illustrated in Figure III.1.6. As we are using an explicit integration scheme, the total simulation time is set to  $t = 0.01 \text{ s}$ . All the properties of the constitutive law reported in Table III.3.1 are used and the material is assumed to follow the Johnson-Cook behavior described by equation 3.1.

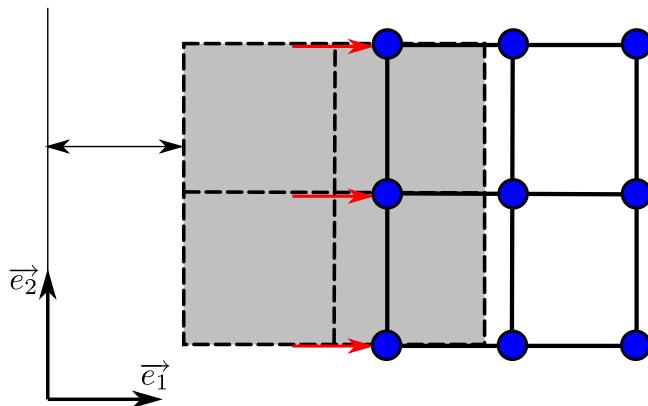
As a global comparison, Figure III.1.7 show the comparison of the right edge displacement vs. the left edge displacement for both the DynELA and the Abaqus simulations.



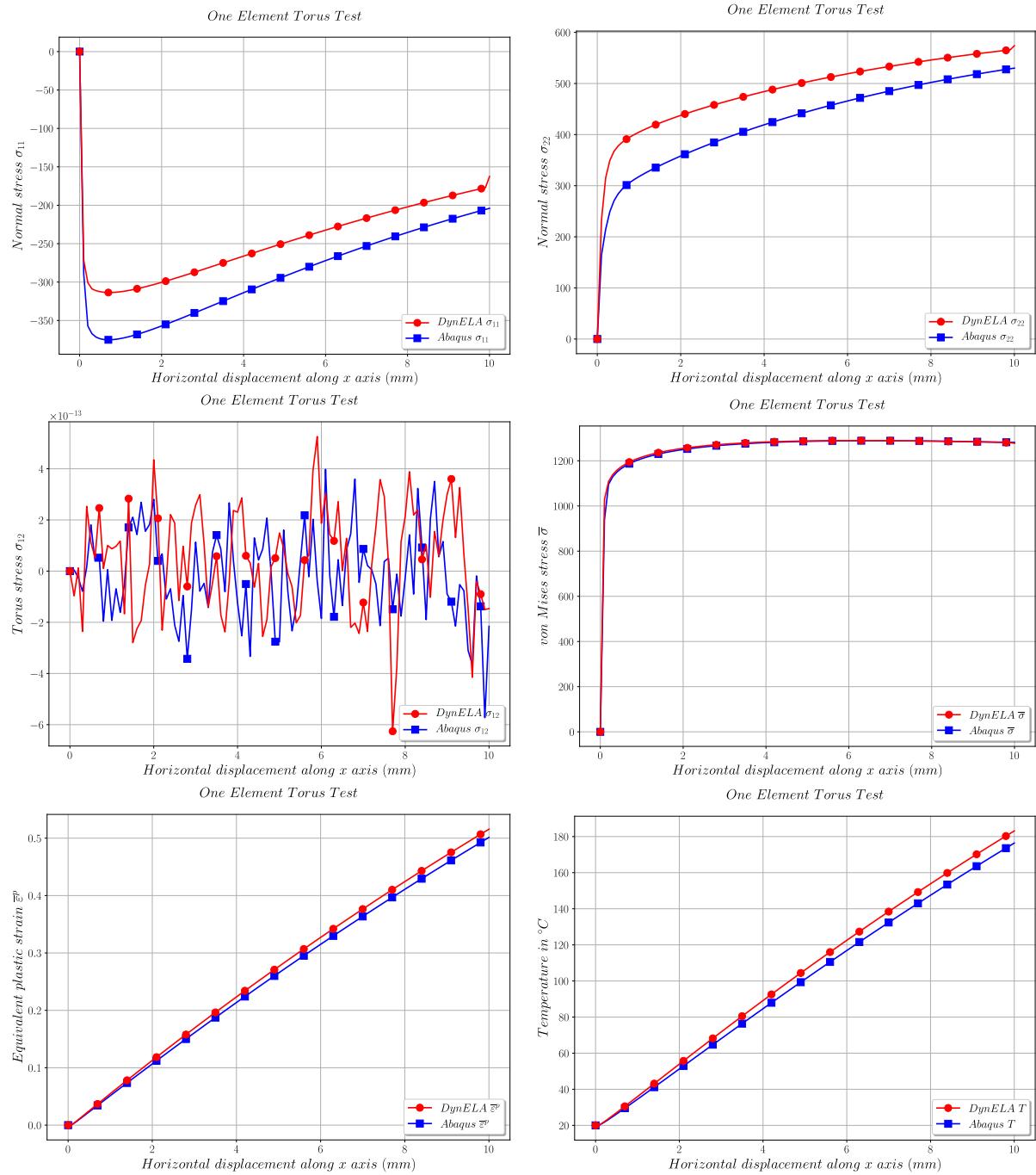
*Figure III.1.7 – Comparison of the right edge displacement for the one element torus test*

Figure III.1.9 shows the comparison of the DynELA solver results (plotted in red) and the Abaqus numerical results (plotted in blue) concerning the evolution of the stress components  $\sigma_{11}$ ,  $\sigma_{22}$ ,  $\sigma_{12}$ ,  $\bar{\varepsilon}^p$  and  $T$  vs. the horizontal displacement of the right edge of the specimen along the horizontal axis. As the Abaqus software only provides under-integrated elements, we are using a  $2 \times 2$  elements mesh for the Abaqus model, as presented in Figure III.1.8, to compare the results. On abaqus, the

mean value of the results of the 4 elements is computed and compared to the mean value of the 4 integration points of the DynELA simulation.



*Figure III.1.8 – Numerical model for the one element torus test under Abaqus*



**Figure III.1.9 – Comparison of numerical results for the one element torus tensile test**

## 1.2 Uniaxial one element shear test

The uniaxial one element shear test is a numerical test where an element (with a square prescribed shape) is subjected to pure shear test as presented in figure III.1.10. The initial shape of the specimen

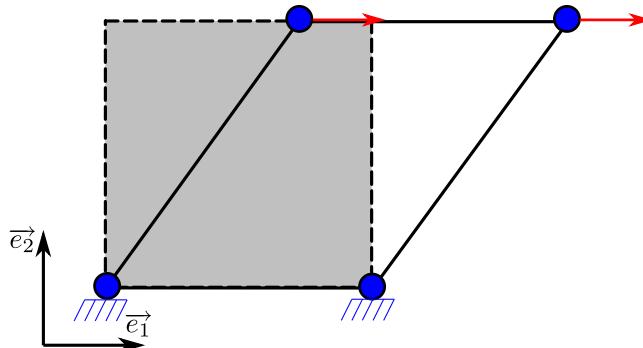


Figure III.1.10 – Numerical model for the one element shear test

is  $10\text{ mm} \times 10\text{ mm}$  and the two bottom nodes of the element are encastered and a prescribed horizontal displacement  $d = 100\text{ mm}$  is applied on the two upper nodes of the same element as illustrated in Figure III.1.10. As we are using an explicit integration scheme, the total simulation time is set to  $t = 0.01\text{ s}$ . Mechanical properties of the material are reported in Table III.3.1.

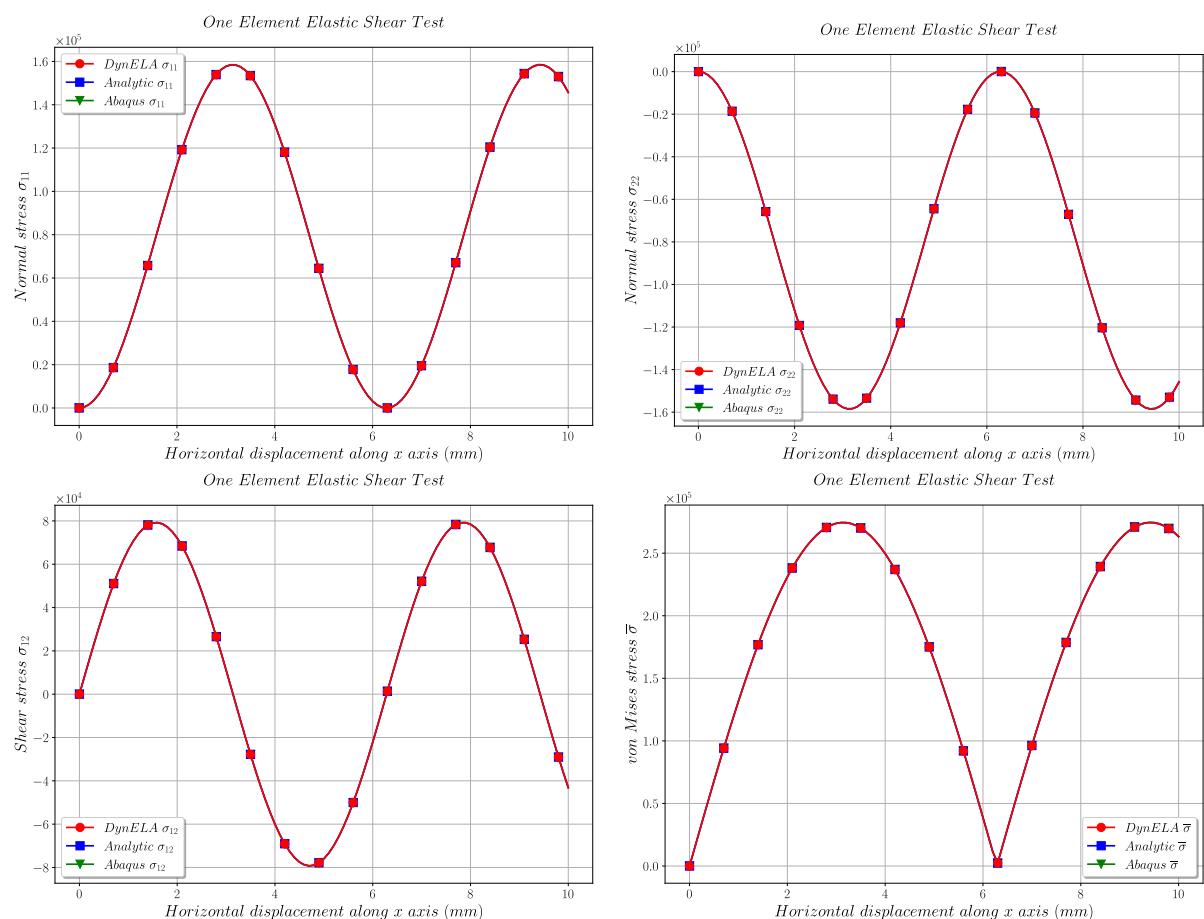
Comparison of Abaqus and DynELA results is made by averaging the DynELA results on the 4 integration points of the element. This has been done because DynELA Finite Element Code uses full integrated elements while Abaqus have reduced integrated elements only but in fact, the DynELA results at the 4 integration points are the same in this benchmark test.

### 1.2.1 Elastic case

In this case, only the elastic properties of the constitutive law reported in Table III.3.1 are used and the material is assumed to be hyper-elastic. As we are using a Jaumann objective rate within the DynELA Finite Element Code, one can obtain, using an analytical development, the following results for the proposed case:

$$\boldsymbol{\sigma} = G \begin{bmatrix} 1 - \cos e & \sin e & 0 \\ & \cos e - 1 & 0 \\ sym & & 0 \end{bmatrix}, \quad (1.2)$$

where  $G = \mu = \frac{E}{2(1+\nu)}$  is the shear modulus of the material and  $e$  is the elongation along the horizontal axis with  $e_{max} = 10$  conforming to the prescribed boundaries conditions. Figure III.1.11 shows the comparison of the DynELA solver results (plotted in red) and both the analytical (plotted in blue) and the Abaqus numerical results (plotted in green) concerning the evolution of the stress components  $\sigma_{11}$ ,  $\sigma_{22}$ ,  $\sigma_{12}$  and  $\bar{\sigma}$  vs. the horizontal displacement of the top edge of the specimen along the horizontal axis. A perfect match between all those results can be seen from this later.



**Figure III.1.11 – Comparison of numerical and analytical results for the one element elastic shear test**

## 1.2.2 Johnson-Cook plastic behaviour

In this case, all the properties of the constitutive law reported in Table III.3.1 are used and the material is assumed to follow the Johnson-Cook behavior described by equation 3.1. Figure III.1.12 shows the comparison of the DynELA solver results (plotted in red) and the Abaqus numerical results (plotted in blue) concerning the evolution of the stress components  $\sigma_{11}$ ,  $\sigma_{22}$ ,  $\sigma_{12}$ ,  $\bar{\sigma}$ ,  $\bar{\varepsilon}^p$  and  $T$  vs. the horizontal displacement of the top edge of the specimen along the horizontal axis.

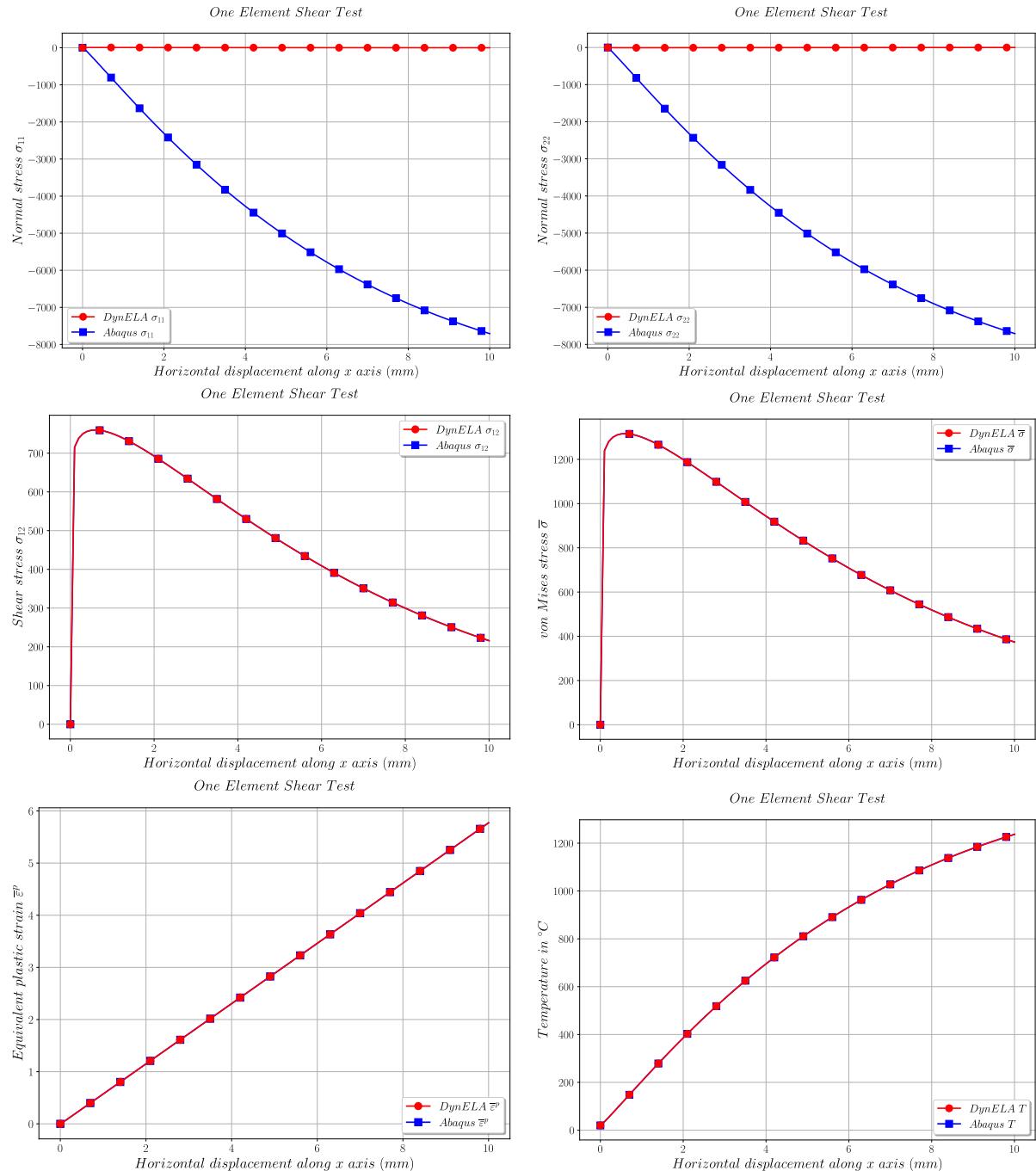


Figure III.1.12 – Comparison of numerical and analytical results for the one element shear test



# Chapter 2

## *DynELA plasticity sample cases*

2.1 Necking of a circular bar ..... 44

This chapter deals with some numerical applications of the DynELA Finite Element Code for plasticity applications in 2D, axi-symmetric and 3D cases. In the subsequent tests, if not specified, a Johnson-Cook constitutive law is used to model the behavior of the material. The Johnson-Cook hardening flow law is probably the most widely used flow law for the simulation of high strain rate deformation processes taking into account plastic strain, plastic strain rate and temperature effects. Since a lot of efforts have been made in the past to identify the constitutive flow law parameters for many materials, it is implemented in numerous Finite Element codes such as Abaqus [?]. The general formulation of the Johnson-Cook law  $\sigma^y(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p, T)$  is given by the following equation:

$$\sigma^y = (A + B\bar{\varepsilon}^{pn}) \left[ 1 + C \ln \left( \frac{\dot{\bar{\varepsilon}}^p}{\dot{\bar{\varepsilon}}_0} \right) \right] \left[ 1 - \left( \frac{T - T_0}{T_m - T_0} \right)^m \right] \quad (2.1)$$

where  $\dot{\bar{\varepsilon}}_0$  is the reference strain rate,  $T_0$  and  $T_m$  are the reference temperature and the melting temperature of the material respectively and  $A$ ,  $B$ ,  $C$ ,  $n$  and  $m$  are the five constitutive flow law parameters. A 42CrMo4 steel following the Johnson-Cook behavior law has been selected for all those tests, and material properties are reported in Table III.3.1.

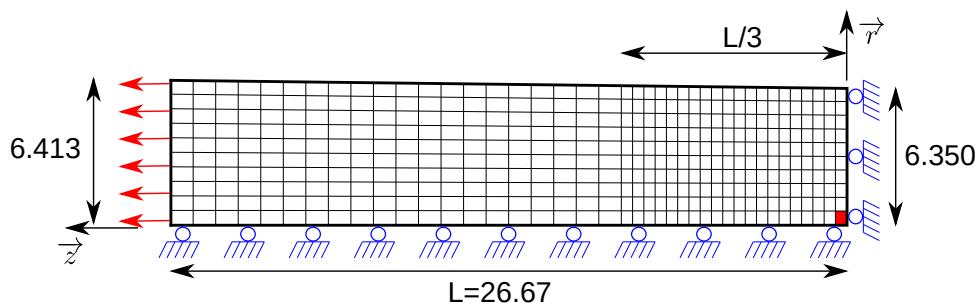
$E$ (GPa)	$\nu$	$A$ (MPa)	$B$ (MPa)	$C$	$n$	$m$
206.9	0.3	806	614	0.0089	0.168	1.1
$\rho$ (kg/m <sup>3</sup> )	$\lambda$ (W/m°C)	$C_p$ (J/Kg°C)	$\eta$	$\dot{\bar{\varepsilon}}_0$ (s <sup>-1</sup> )	$T_0$ (°C)	$T_m$ (°C)
7830	34.0	460	0.9	1.0	20	1540

Table III.2.1 – Material parameters of the Johnson-Cook behavior for the numerical tests

## 2.1 Necking of a circular bar

### 2.1.1 Axisymmetric Bar Necking

The necking of a circular bar test is useful to evaluate the performance of VUMAT subroutine for materials in presence of plasticity and large deformation [?,?]. Because of the symmetric structure, an axisymmetric quarter model of the specimen is established. Dimensions of the specimen are reported in Figure III.2.1. The loading is realized through an imposed total displacement of 7 mm along the  $\vec{z}$  axis on the left side of the specimen while the radial displacement of the same edge is supposed to remain zero. On the opposite side the axial displacement is restrained while the radial displacement is free. The mesh consists of 400 CAX4RT elements with a refined zone of 200 elements on the right side on 1/3 of the total height. Again, the total simulation time is set to  $t = 0.01\text{ s}$  because of the explicit integration scheme adopted.



*Figure III.2.1 – Numerical model for the necking of a circular bar*

Figures III.2.2 and III.2.3 shows the temperature  $T$  and the von Mises stress  $\bar{\sigma}$  contourplots of the deformed rod for both the DynELA Finite Element Code and Abaqus. The distributions of the temperatures and stresses are almost the same for both models. The maximum temperature  $T$  is located into the center element of the model (the red element in Figure III.2.1) and the models give quite the same results as reported in Table III.2.2 for  $\bar{\varepsilon}^p$ ,  $T$  and the final dimensions of the specimen  $D_f$  (final diameter of the necking zone).

Figure III.2.4 shows the evolution of the the final dimensions of the specimen  $L_f$  (final length) and  $R_f$  (final radius of the impacting face), the equivalent plastic strain  $\bar{\varepsilon}^p$ , the temperature  $T$ , the von Mises stress  $\bar{\sigma}$  and the timeStep  $\Delta t$  for the different models for the element at the center of the impacting face (the red element in Figure III.2.1).

As reported in this figure and according to the results presented in Table III.2.2, a quite good agreement between the results is obtained.

code	$D_f$ (mm)	$T$ (°C)	$\bar{\varepsilon}^p$
DynELA	2.71	642.78	2.07
Abaqus	2.35	658.91	2.12

*Table III.2.2 – Comparison of numerical results for the necking of a circular bar test*

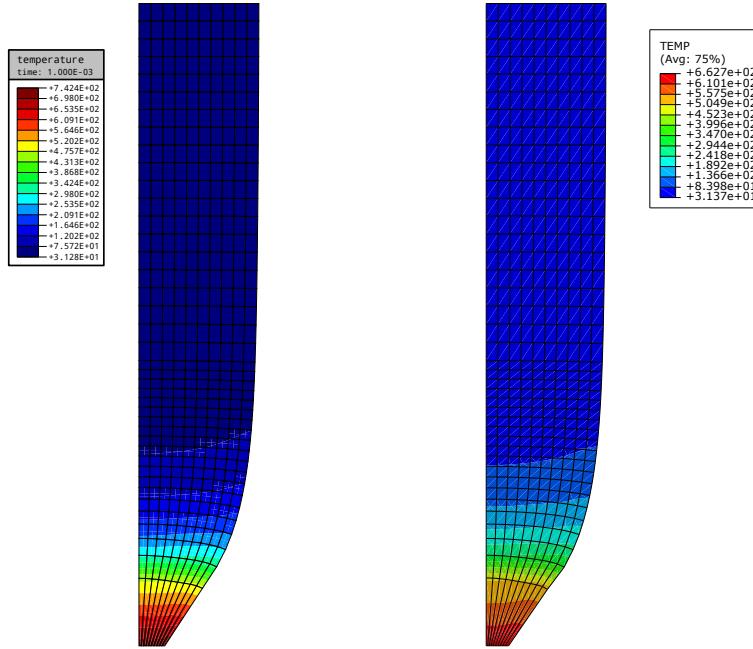


Figure III.2.2 – Temperature  $T$  contourplot for the necking of a circular bar (DynELA left and Abaqus right)

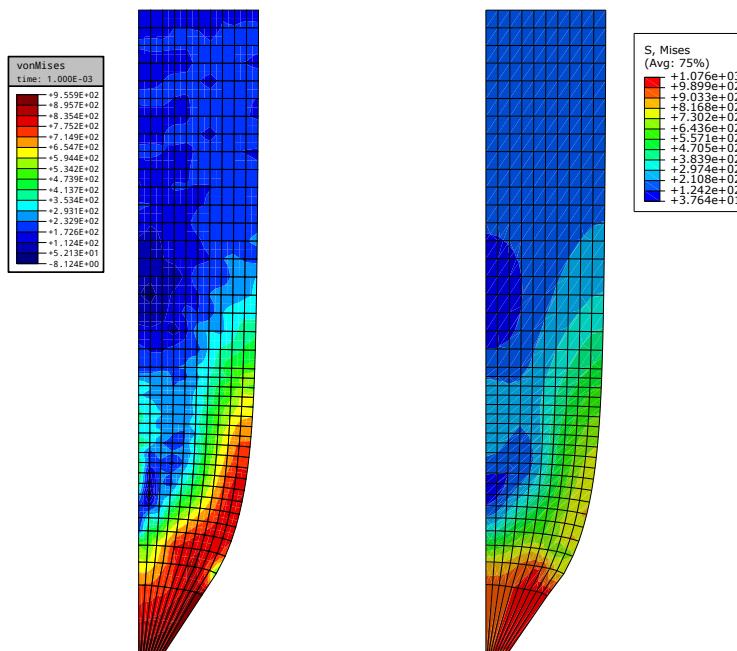
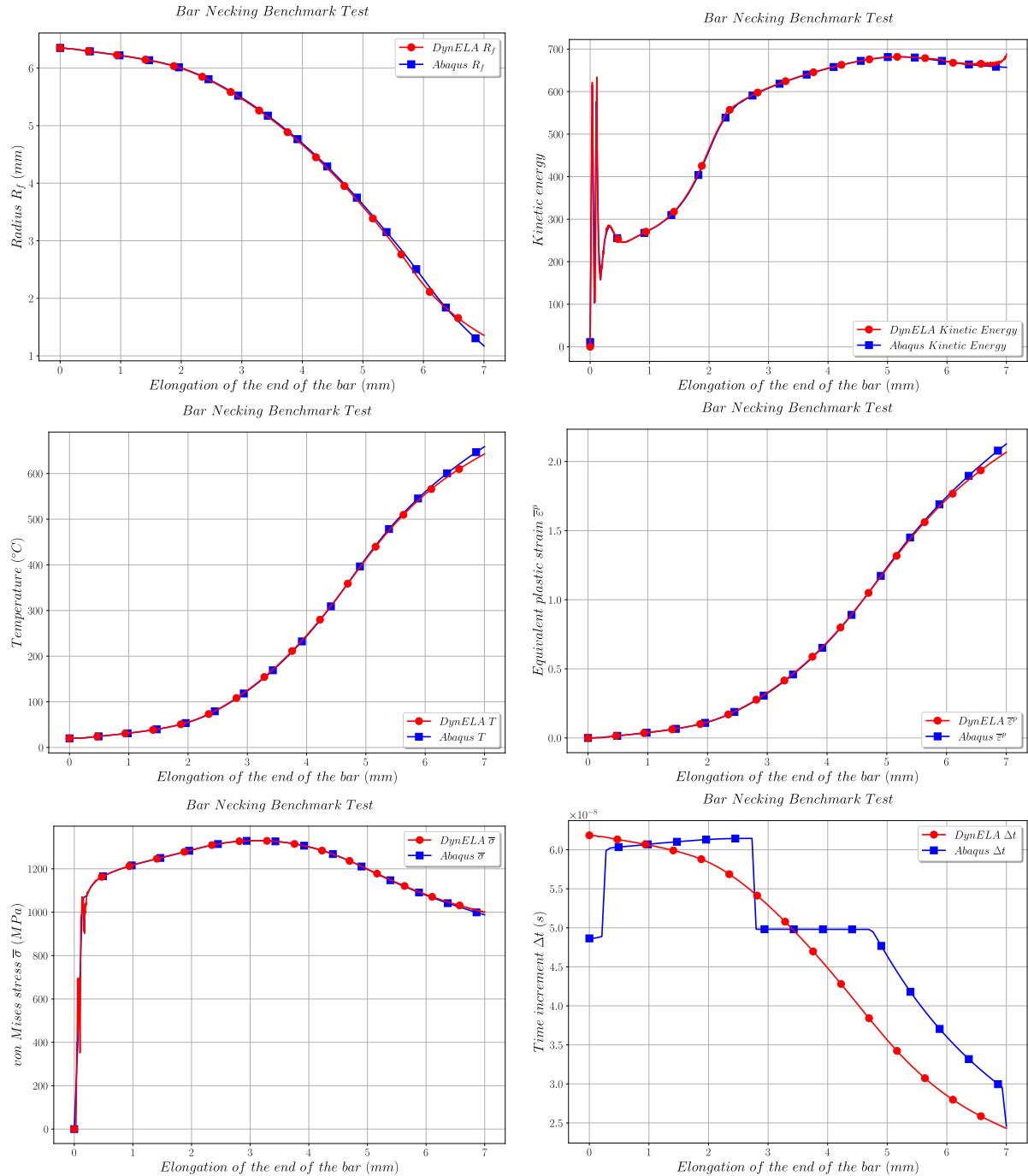


Figure III.2.3 – von Mises stress  $\bar{\sigma}$  contourplot for the necking of a circular bar (DynELA left and Abaqus right)



**Figure III.2.4 – Comparison of numerical and analytical results necking of a circular bar test**

# Chapter 3

## *DynELA impact sample cases*

3.1 Taylor impact sample . . . . . 48

This chapter deals with some numerical applications of the DynELA Finite Element Code for impact applications in 2D, axi-symmetric and 3D cases. In the subsequent tests, if not specified, a Johnson-Cook constitutive law is used to model the behavior of the material. The Johnson-Cook hardening flow law is probably the most widely used flow law for the simulation of high strain rate deformation processes taking into account plastic strain, plastic strain rate and temperature effects. Since a lot of efforts have been made in the past to identify the constitutive flow law parameters for many materials, it is implemented in numerous Finite Element codes such as Abaqus [?]. The general formulation of the Johnson-Cook law  $\sigma^y(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p, T)$  is given by the following equation:

$$\sigma^y = (A + B\bar{\varepsilon}^{p^n}) \left[ 1 + C \ln \left( \frac{\dot{\bar{\varepsilon}}^p}{\dot{\bar{\varepsilon}}_0} \right) \right] \left[ 1 - \left( \frac{T - T_0}{T_m - T_0} \right)^m \right] \quad (3.1)$$

where  $\dot{\bar{\varepsilon}}_0$  is the reference strain rate,  $T_0$  and  $T_m$  are the reference temperature and the melting temperature of the material respectively and  $A$ ,  $B$ ,  $C$ ,  $n$  and  $m$  are the five constitutive flow law parameters. A 42CrMo4 steel following the Johnson-Cook behavior law has been selected for all those tests, and material properties are reported in Table III.3.1.

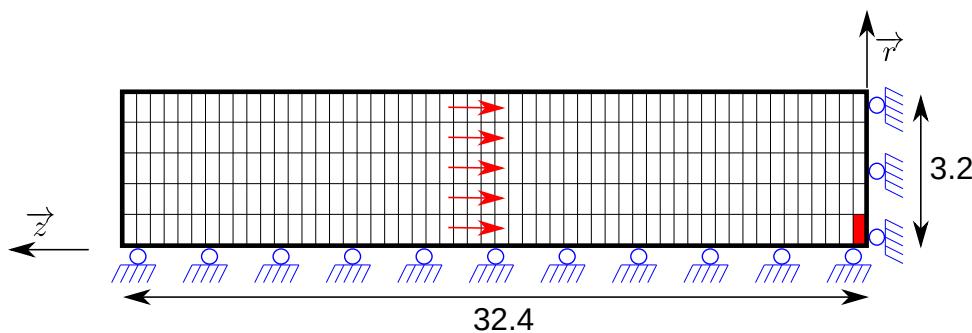
$E$ (GPa)	$\nu$	$A$ (MPa)	$B$ (MPa)	$C$	$n$	$m$
206.9	0.3	806	614	0.0089	0.168	1.1
$\rho$ (kg/m <sup>3</sup> )	$\lambda$ (W/m°C)	$C_p$ (J/Kg°C)	$\eta$	$\dot{\bar{\varepsilon}}_0$ (s <sup>-1</sup> )	$T_0$ (°C)	$T_m$ (°C)
7830	34.0	460	0.9	1.0	20	1540

Table III.3.1 – Material parameters of the Johnson-Cook behavior for the numerical tests

## 3.1 Taylor impact sample

### 3.1.1 Axisymmetric Taylor impact

The performance of the proposed code is validated under high deformation rate with the simulation of the Taylor impact test [?]. In the Taylor impact test, a cylindrical specimen is launched to impact a rigid target with a prescribed initial velocity. The numerical model, reported in Figure III.3.1 is established as axisymmetric. The height is  $32.4\text{ mm}$  and the radius is  $3.2\text{ mm}$ . The axial displacement is restrained on the right side of the specimen while the radial displacement is free (to figure a perfect contact without friction of the projectile onto the target). A predefined velocity of  $V_c = 287\text{ m/s}$  is imposed on the specimen. The mesh consists of 250 elements ( $5 \times 50$  elements). The total simulation time for the Taylor impact test is  $t = 8.0 \cdot 10^{-5}\text{ s}$ .



*Figure III.3.1 – Numerical model for the Axisymmetric Taylor impact test*

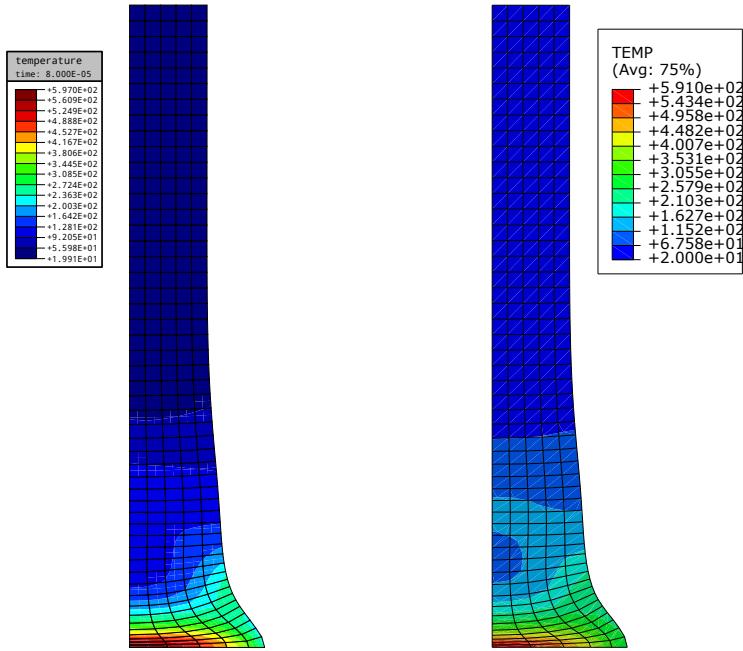
Figure III.3.2 shows the temperature contourplot of the deformed rod for both the DynELA Finite Element Code and Abaqus. The distributions of the temperatures are almost the same for both models. The maximum temperature  $T$  is located into the center element of the model (the red element in Figure III.3.1) and the models give quite the same results as reported in Table III.3.2 for  $\bar{\varepsilon}^p$ ,  $T$  and the final dimensions of the specimen  $L_f$  (final length) and  $D_f$  (final diameter of the impacting face).

Figure III.3.3 shows the evolution of the the final dimensions of the specimen  $L_f$  (final length) and  $R_f$  (final radius of the impacting face), the equivalent plastic strain  $\bar{\varepsilon}^p$ , the temperature  $T$ , the von Mises stress  $\bar{\sigma}$  and the timeStep  $\Delta t$  for the different models for the element at the center of the impacting face (the red element in Figure III.3.1).

As reported in this figure and according to the results presented in Table III.3.2, a quite good agreement between the results is obtained.

code	$L_f$ (mm)	$D_f$ (mm)	$T$ (°C)	$\bar{\varepsilon}^p$
DynELA	26.52	11.15	582.34	1.78
Abaqus	26.56	11.16	590.96	1.81

*Table III.3.2 – Comparison of numerical results for the Axisymmetric Taylor impact test*



**Figure III.3.2 – Temperature contourplots for Axisymmetric Taylor impact test (DynELA left and Abaqus right)**

### 3.1.2 3D Taylor impact

The performance of the proposed code is validated under high deformation rate with the simulation of the Taylor impact test [?]. In the Taylor impact test, a cylindrical specimen is launched to impact a rigid target with a prescribed initial velocity. The numerical model, reported in Figure III.3.4 is established as axisymmetric. The height is  $32.4\text{ mm}$  and the radius is  $3.2\text{ mm}$ . The axial displacement is restrained on the right side of the specimen while the radial displacement is free (to figure a perfect contact without friction of the projectile onto the target). A predefined velocity of  $V_c = 287\text{ m/s}$  is imposed on the specimen. The mesh consists of 4455 elements ( $55 \times 81$  elements). The total simulation time for the Taylor impact test is  $t = 8.0 \cdot 10^{-5}\text{ s}$ .

Figure III.3.5 shows the temperature contourplot of the deformed rod for both the DynELA Finite Element Code and Abaqus. The distributions of the temperatures are almost the same for both models. The maximum temperature  $T$  is located into the center element of the model (the red element in Figure III.3.4) and the models give quite the same results as reported in Table III.3 for  $\bar{\varepsilon}^p$ ,  $T$  and the final dimensions of the specimen  $L_f$  (final length) and  $D_f$  (final diameter of the impacting face).

Figure III.3.6 shows the evolution of the the final dimensions of the specimen  $L_f$  (final length) and  $R_f$  (final radius of the impacting face), the equivalent plastic strain  $\bar{\varepsilon}^p$ , the temperature  $T$ , the von Mises stress  $\bar{\sigma}$  and the timeStep  $\Delta t$  for the different models for the element at the center of the impacting face (the red element in Figure III.3.4).

As reported in this figure and according to the results presented in Table III.3, a quite good agreement between the results is obtained.

code	$L_f$ (mm)	$D_f$ (mm)	$T$ (°C)	$\bar{\varepsilon}^p$
DynELA	26.52	11.18	597.10	1.84
Abaqus	26.55	11.22	597.01	1.84

Table III.3.3 – Comparison of numerical results for the 3D Taylor impact test

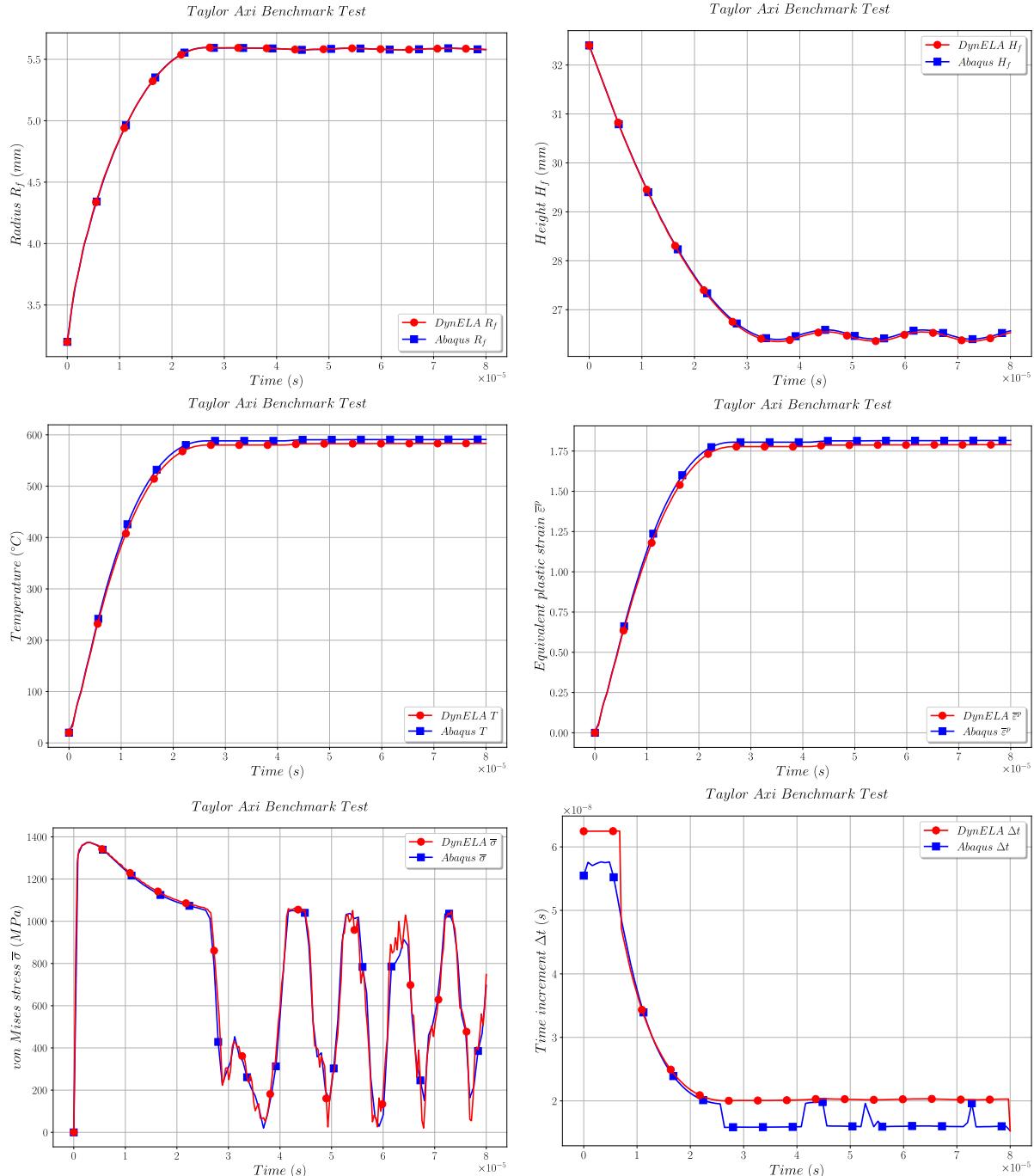


Figure III.3.3 – Comparison of numerical and analytical results for the Axisymmetric Taylor impact test

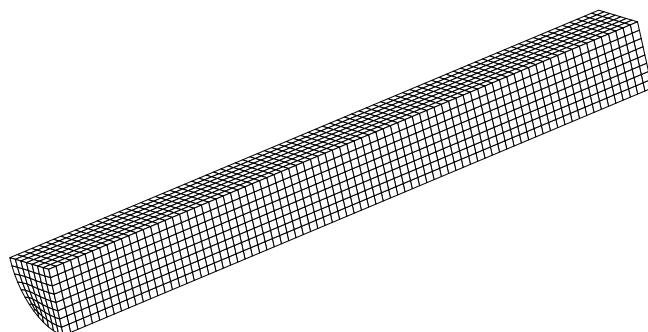


Figure III.3.4 – Numerical model for the 3D Taylor impact test

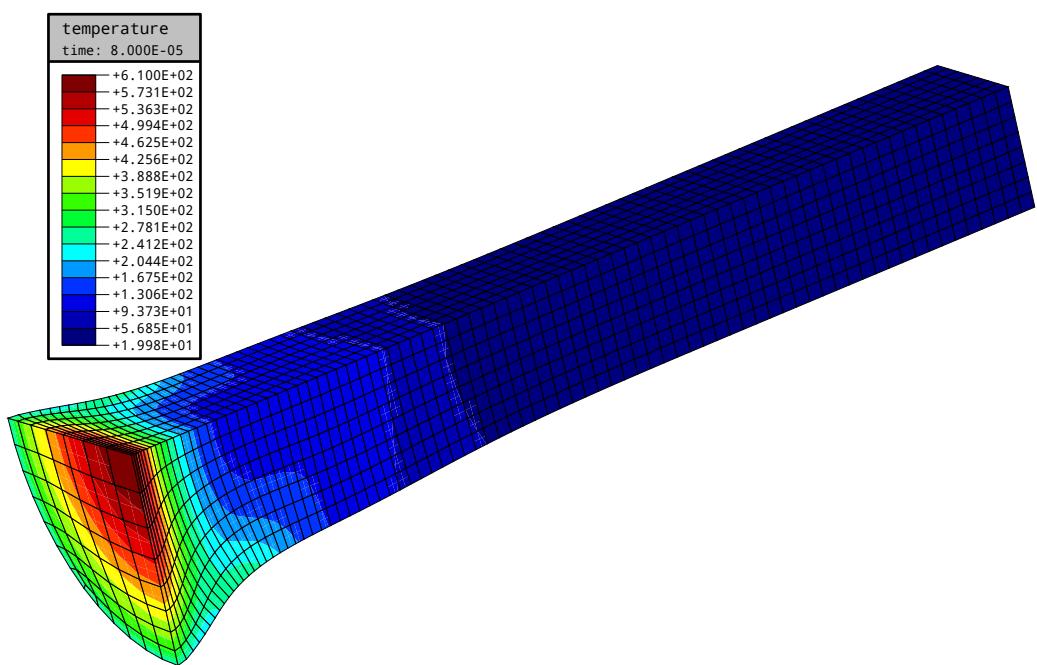


Figure III.3.5 – Temperature contourplot for the 3D Taylor impact test

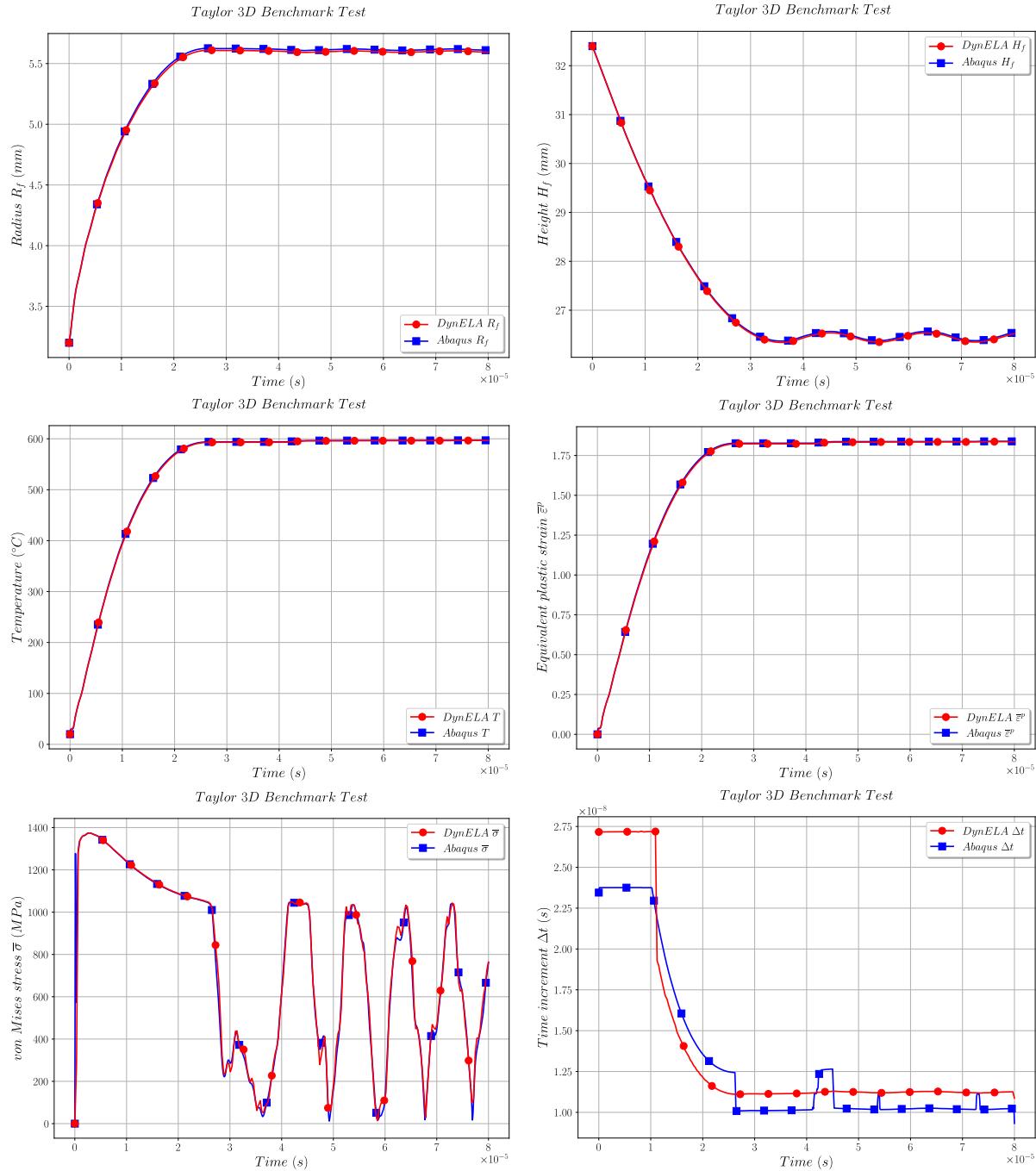


Figure III.3.6 – Comparison of numerical and analytical results for the 3D Taylor impact test

[1]

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