

An ABAQUS-MATLAB tutorial for Jointed Systems

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1 Preprocess

The Brake-Reuß Beam (BRB) is a 3-bolted lap-joint beam which will serve as our tutorial joint structure (read more about the benchmark here). To make the tutorial self-contained, the tutorial will begin with CAD-modeling of the BRB in ABAQUS and take you all the way to matrix extraction and nonlinear dynamics analysis on MATLAB/OCTAVE. Buckle up! :)

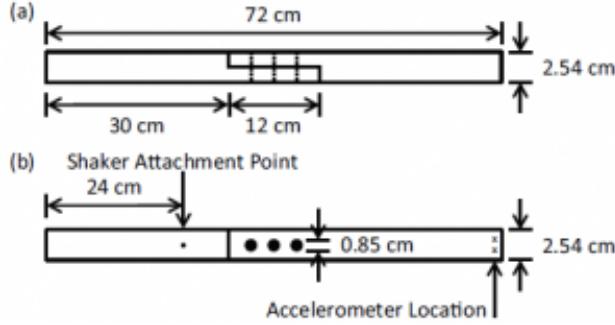


Figure 1: Geometry of the BRB Benchmark

A picture of the parts of the BRB is shown in Fig. 1 and this will be used to guide the modeling here. Standard 5/16 bolt-nut-washers will be used for the assembly. Since Bolt thread interactions won't be modeled here, the bolt shank is modeled as a smooth cylinder (see 2.2 for more details on bolt prestress modeling).

Note: If you already have a model of your structure and want to just apply the node-selection/matrix extraction, you can safely ignore the sections particular to the modeling of the BRB and just go through the remaining, whose instructions are quite general. The general principles in the modeling section are, however, recommended for all jointed structure modeling.

1.1 A Note on Python Scripting

SCRIPT

ABAQUS Python scripting is quite powerful and will be used quite liberally throughout this tutorial. The following are some tips/tricks to get started for beginners:

- For beginners, the easiest way to start scripting is to open up CAE (the GUI) and do the necessary tasks. ABAQUS would have saved the actions in a Python file called `abaqus.rpy`. This is just python code that can be imported into ABAQUS to repeat the same tasks. All standard python commands work so this makes it very helpful.
- On Windows the **work directory** may be an unfamiliar concept (on Linux it is just the directory from which ABAQUS is launched). This directory can be manually set by **File->Set Work Directory**, following which all the files (including the `ABAQUS.rpy` file) will be put in the specified folder.
- Fig 2 shows a pictorial overview of the different options available in ABAQUS for scripting support. The ABAQUS PDE can be used for ABAQUS python script development.

1.2 Modeling Parts

SCRIPT:GUI

We will first model the two "halves" of the BRB. The following steps enumerate the process (can be skipped if you already have a model).

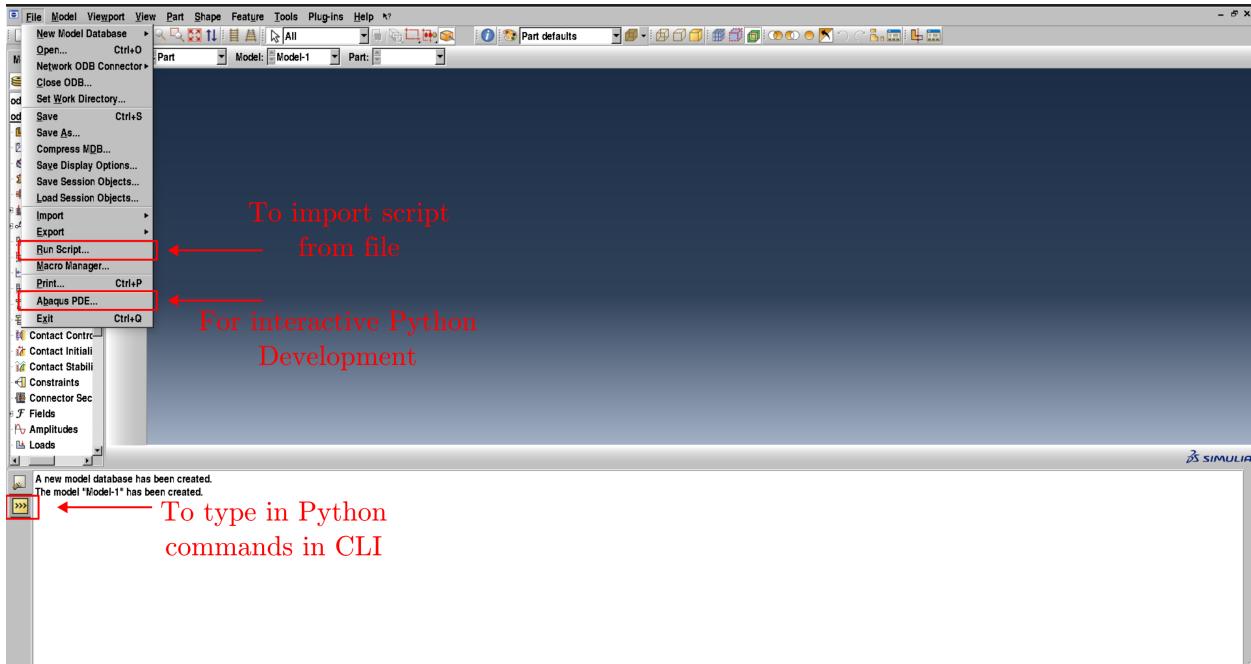


Figure 2: Options in ABAQUS for Scripting

We will do the construction through ABAQUS Python code that can be imported through **File->Run Script** or just typed into the command line.

1. First import the following code to import all the necessary objects and then the material properties (steel, here).

```

1 # -*- coding: utf-8 -*-
2 import sys
3
4 from part import *
5 from material import *
6 from section import *
7 from assembly import *
8 from step import *
9 from interaction import *
10 from load import *
11 from mesh import *
12 from optimization import *
13 from job import *
14 from sketch import *
15 from visualization import *
16 from connectorBehavior import *
17
18 mdb = mdb.models['Model-1']
19 #####
```

```

20 # MATERIAL PROPERTIES: STEEL #
21 #####
22 mdl.Material(name='STEEL')
23
24 steel = mdl.materials['STEEL']
25 steel.Density(table=((7800.0, ), ))
26 steel.Elastic(table=((2e11, 0.29), ))
27 mdl.HomogeneousSolidSection(material='STEEL', name=
28                               'Section-1', thickness=None)

```

The above code creates a new material called "STEEL", with Young's Modulus 200GPa, Poisson's ratio 0.29, and density 7800 kg/m³.

- Now use the following to model the half beam (this can be done on CAE with the GUI quite easily).

```

29 mdl = mdb.models['Model-1']
30
31 #####
32 # PART : HALFBEAM #
33 #####
34 # 1. Sketch and Extrude
35 mdl.ConstrainedSketch(name='__profile__', sheetSize=2.0)
36 sktch = mdl.sketches['__profile__']
37 sktch.Line(point1=(-36e-2, 1.27e-2), point2=(-6e-2, 1.27e-2))
38 sktch.Line(point1=(-6e-2, 1.27e-2), point2=(-6e-2, 0))
39 sktch.Line(point1=(-6e-2, 0), point2=(6e-2, 0))
40 sktch.Line(point1=(6e-2, 0), point2=(6e-2, -1.27e-2))
41 sktch.Line(point1=(6e-2, -1.27e-2), point2=(-36e-2, -1.27e-2))
42 sktch.Line(point1=(-36e-2, -1.27e-2), point2=(-36e-2, 1.27e-2))
43
44 mdl.Part(dimensionality=THREE_D, name='HALFBEAM', type=DEFORMABLE_BODY)
45 hfbm = mdl.parts['HALFBEAM']
46 hfbm.BaseSolidExtrude(depth=25.4e-3, sketch=sktch)
47 del sktch
48
49 # 2. Cut out Holes
50 mdl.ConstrainedSketch(name='__profile__', sheetSize=2.0,
51                       transform=
52                         hfbm.MakeSketchTransform(
53                           sketchPlane=hfbm.faces[2],
54                           sketchPlaneSide=SIDE1,
55                           sketchUpEdge=hfbm.edges[8],
56                           sketchOrientation=RIGHT,
57                           origin=(0.0, 0.0, 1.27e-2)))
58 sktch = mdl.sketches['__profile__']
59 cs = [-3e-2, 0.0, 3e-2];
60 gs = []

```

```

61 for i in range(3):
62     gs.append(sktch.CircleByCenterPerimeter(center=(cs[i], 0),
63                                              point1=(cs[i]+0.85e-2/2, 0)))
64
65 hfbm.CutExtrude(sketchPlane=hfbm.faces[2], sketchPlaneSide=SIDE1,
66                   sketchUpEdge=hfbm.edges[8],
67                   sketchOrientation=RIGHT, sketch=sktch)
68
69
70 # 3. Partition object
71 hfbm.PartitionCellByExtendFace(cells=hfbm.cells,
72                                 extendFace=hfbm.faces[6])
73 hfbm.PartitionCellByExtendFace(cells=hfbm.cells,
74                                 extendFace=hfbm.faces[7])
75
76 mdl.ConstrainedSketch(name='__profile__', sheetSize=2.0,
77                        gridSpacing=30e-3, transform=
78                        hfbm.MakeSketchTransform(
79                            sketchPlane=hfbm.faces[11],
80                            sketchPlaneSide=SIDE1,
81                            sketchUpEdge=hfbm.edges[27],
82                            sketchOrientation=RIGHT,
83                            origin=(0.0, 0.0, 1.27e-2)))
84 sktch = mdl.sketches['__profile__']
85 cs = [-3e-2, 0.0, 3e-2];
86 wor = i2m*0.34375
87 for i in range(3):
88     sktch.CircleByCenterPerimeter(center=(cs[i], 0),
89                                    point1=(cs[i]+wor, 0))
90 hfbm.PartitionCellBySketch(cells=hfbm.cells, sketch=sktch,
91                             sketchUpEdge=hfbm.edges[27],
92                             sketchPlane=hfbm.faces[11])
93 hfbm.PartitionCellByExtrudeEdge(cells=hfbm.cells, edges=hfbm.edges[0],
94                                   line=hfbm.edges[-1], sense=FORWARD)
95 hfbm.PartitionCellByExtrudeEdge(cells=hfbm.cells, edges=hfbm.edges[3],
96                                   line=hfbm.edges[-1], sense=FORWARD)
97 hfbm.PartitionCellByExtrudeEdge(cells=hfbm.cells, edges=hfbm.edges[6],
98                                   line=hfbm.edges[-1], sense=FORWARD)
99
100 pt = hfbm.InterestingPoint(edge=hfbm.edges[-2], rule=MIDDLE)
101 hfbm.PartitionCellByPlanePointNormal(cells=hfbm.cells, point=pt,
102                                         normal=hfbm.edges[-2])
103
104 pt = hfbm.InterestingPoint(edge=hfbm.edges[75], rule=MIDDLE)
105 hfbm.PartitionCellByPlanePointNormal(cells=hfbm.cells, point=pt,
106                                         normal=hfbm.edges[75])
107
108 pt = hfbm.InterestingPoint(edge=hfbm.edges[39], rule=MIDDLE)

```

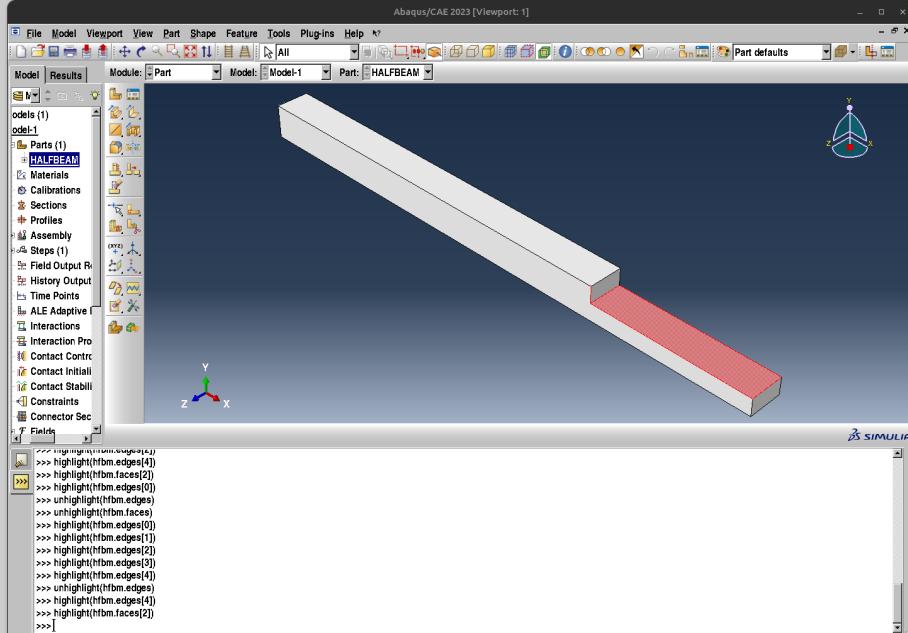
```

109 hfbm.PartitionCellByPlanePointNormal(cells=hfbm.cells, point=pt,
110                                         normal=hfbm.edges[39])
111
112 pt = hfbm.InterestingPoint(edge=hfbm.edges[85], rule=MIDDLE)
113 hfbm.PartitionCellByPlanePointNormal(cells=hfbm.cells, point=pt,
114                                         normal=hfbm.edges[85])
115
116 pt = hfbm.InterestingPoint(edge=hfbm.edges[39], rule=MIDDLE)
117 hfbm.PartitionCellByPlanePointNormal(cells=hfbm.cells, point=pt,
118                                         normal=hfbm.edges[39])
119
120 pt = hfbm.InterestingPoint(edge=hfbm.edges[41], rule=MIDDLE)
121 hfbm.PartitionCellByPlanePointNormal(cells=hfbm.cells, point=pt,
122                                         normal=hfbm.edges[41])
123
124 pt = hfbm.InterestingPoint(edge=hfbm.edges[111], rule=MIDDLE)
125 hfbm.PartitionCellByPlanePointNormal(cells=hfbm.cells, point=pt,
126                                         normal=hfbm.edges[111])
127
128 pt = hfbm.InterestingPoint(edge=hfbm.edges[135], rule=MIDDLE)
129 hfbm.PartitionCellByPlanePointNormal(cells=hfbm.cells, point=pt,
130                                         normal=hfbm.edges[135])
131
132 # 4. Assign Material
133 regn = hfbm.Set(cells=hfbm.cells, name='Set-1')
134 hfbm.SectionAssignment(region=regn, sectionName='Section-1')

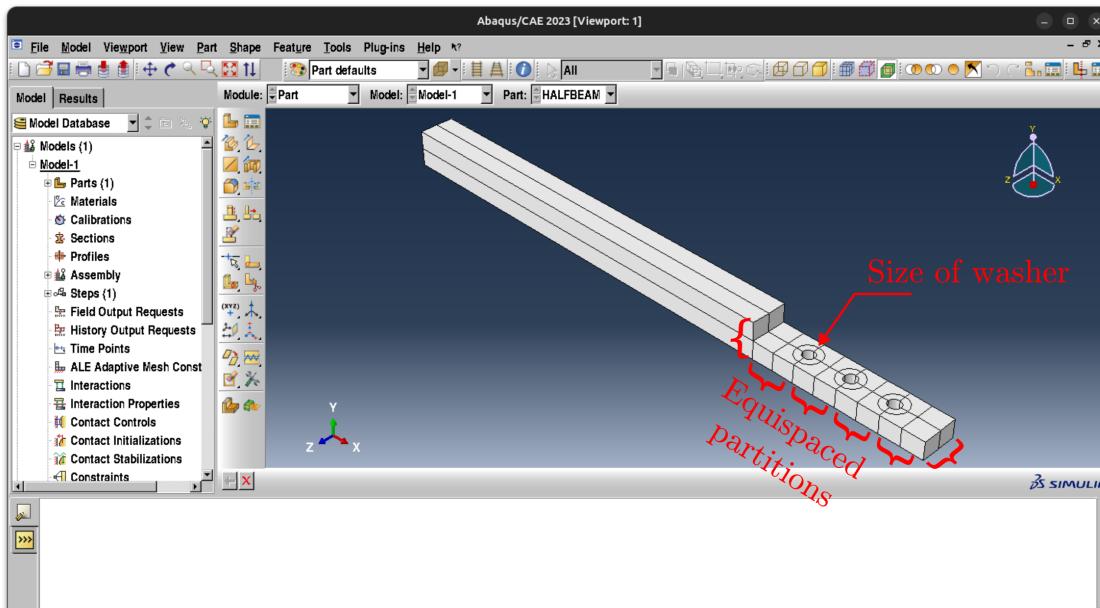
```

Scripting note

You can see that certain faces and edges were used in the above. A quick way to check which face is what will be to use the `highlight` command on the ABAQUS python console. Here is an example:

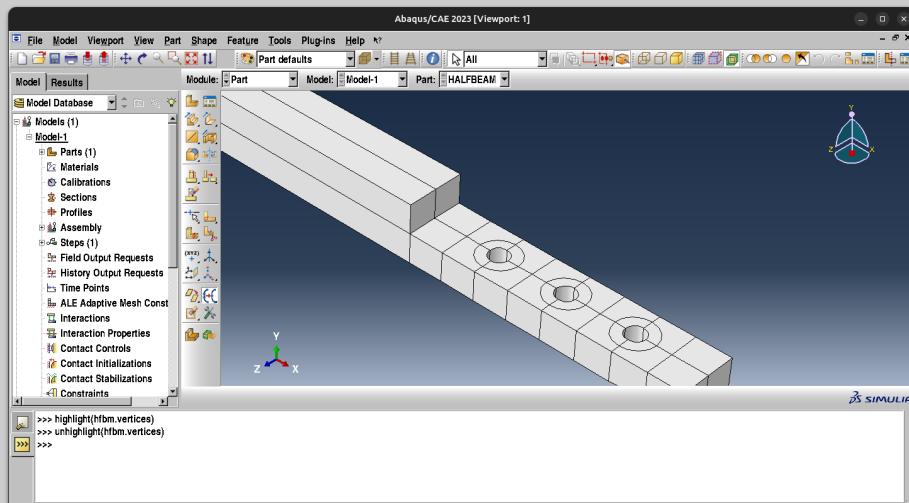


At the end of this step, you should have a partitioned part that looks like this. The partitioning is done in this way to help with the seeded meshing, constraint enforcement, etc.



IMPORTANT! Geometry Correction Note

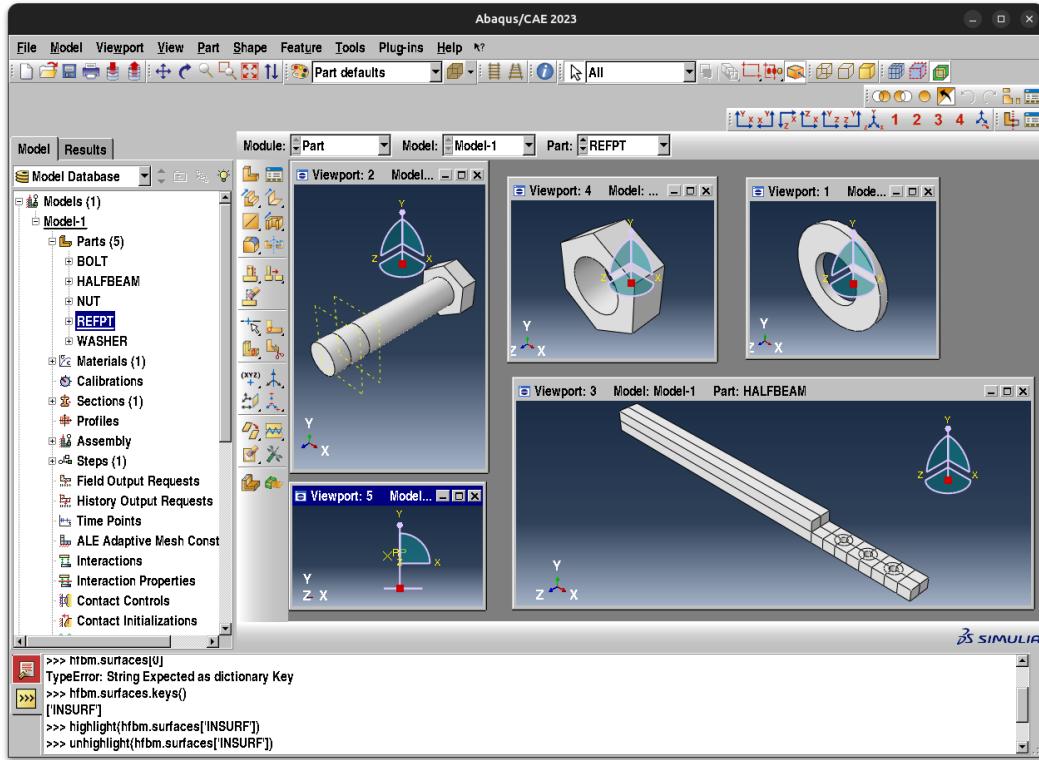
You have to ensure that the curved edges on the above are, indeed, single edges. You will run into meshing issues if this is not the case. If not, you will have to use the "Merge Edges" tool in the Part module and individually select each edge and merge them.



1. Create a Reference Point Part called REFPT. This will be necessary for the application of bolt prestress (see 2.2 below).

```
135 rpt = mdl.Part(name='REFPT', dimensionality=THREE_D,
136                     type=DEFORMABLE_BODY)
137 rpt.ReferencePoint(point=(0.0, 0.0, 0.0))
138
139 rpt.Set(name='Set-1', referencePoints=rpt.referencePoints.values())
```

2. Now import the nuts, washers and bolts by importing the file https://github.com/Nidish96/Abaqus4Joints/blob/main/scripts/c_nutwasherbolt_516.py. You should be able to see the nut, washer and bolt, along with the half beam and reference point created before, as follows after importing:



The Python script also assigns the material "STEEL" (see above) to the parts.

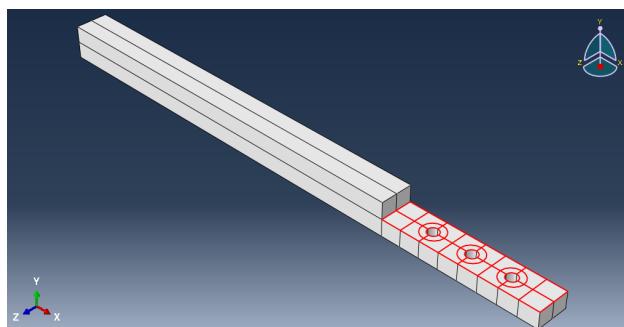
The file `model_step0.cae` stores the CAE file at the end of the above steps (building parts, and partitioning).

1.3 Creating appropriate surface sets

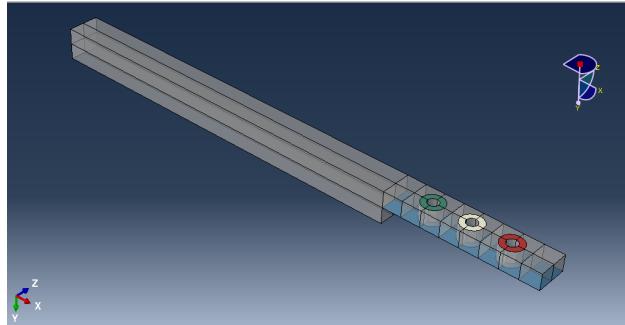
GUI

It is necessary to choose appropriate surface sets for the constraint enforcement and, eventually, the interfacial mesh extraction. Doing this with surfaces (before meshing) is advantageous since the same scripts can be reused even if the model is remeshed.

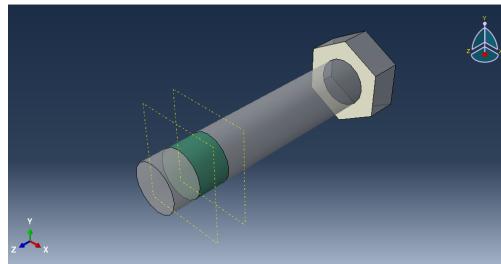
1. First select the **interfacial faces** on the half beam model and assign the name `INSURF` to it. You can do this through Tools->Surface->Create and then selecting the appropriate faces through the GUI. Select the faces by holding Shift and deselect by holding Ctrl. Here is a picture of the surface highlighted in the viewport.



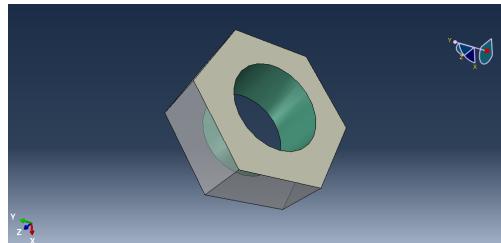
2. Turn to the *outside* of the beam and select the faces around the bolts individually and name them **BmW1**, **BmW2**, and **BmW3** respectively. These will be tied to the washer for the analysis. (**BmWi** denotes the i^{th} Beam-Washer contact). Here is a picture of the relevant surfaces highlighted (using different colors for each).



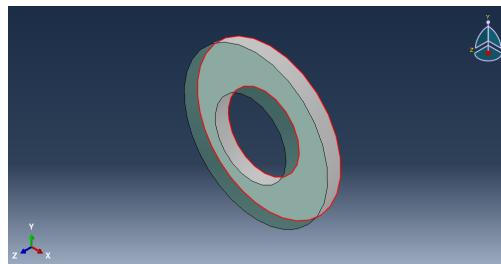
3. Create two surfaces on the **BOLT** model as shown in the figure below. Name the surface marked white as **B1W** and the surface marked green as **BN**. (**B1W** denotes the Bolt-Washer contact surface; **BN** denotes the Bolt-Nut contact surface)



4. Create two surfaces on the **NUT** model as shown in the figure below. Name the white surface as **NW** and the green surface as **NB**. (**NW** denotes the Nut-Washer contact surface; **NB** denotes the Nut-Bolt contact surface) **Note the direction axes carefully.**



5. Create two surface on the **WASHER** model and label them as **WSTOP** and **WSBOT** (short for Washer-Surface Top and Bottom). Here is a graphical depiction of the model with the surfaces.



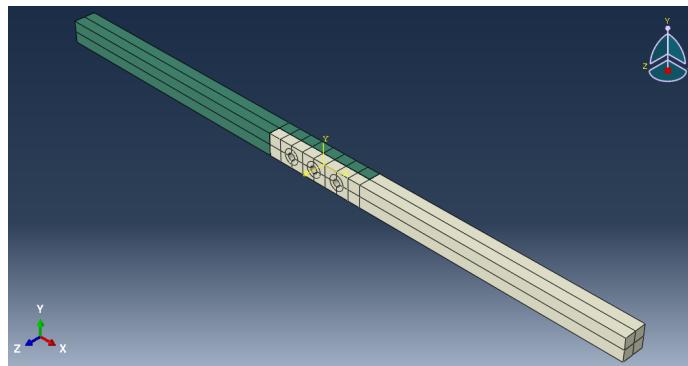
Now all the parts have been created and relevant surfaces have been identified. **Note:** It is important to have traceable but short names so that a lot of the repetitive tasks can be sped up considerably using scripting.

1.4 Create Assembly

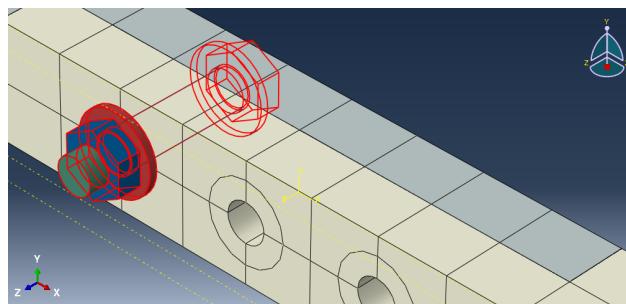
GUI

Note: While importing the parts, choose Instance Type as "Independent (Mesh on Instance)". This will be advantageous if we want to modify the meshes just at the interface for mirror symmetry. We will do independent meshing since it is good practice, although independent meshes are not a requirement for this example (dependent meshes can be used due to symmetry).

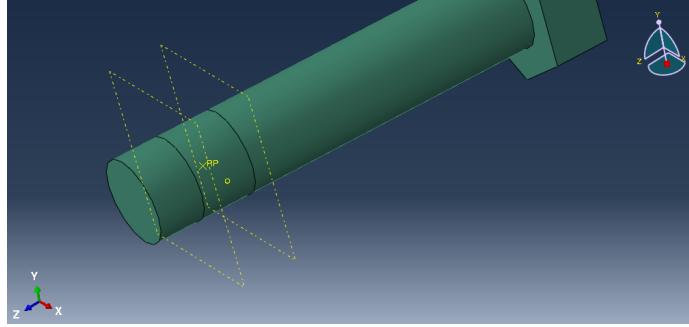
1. Import the two beams and re-orient/move them as follows. **Note that the bolt-axis has to be pointed in the +z direction.** This will be the convention followed throughout this tutorial. The green beam in the following is renamed as TOPBEAM and the white beam in the following is renamed as BOTBEAM.



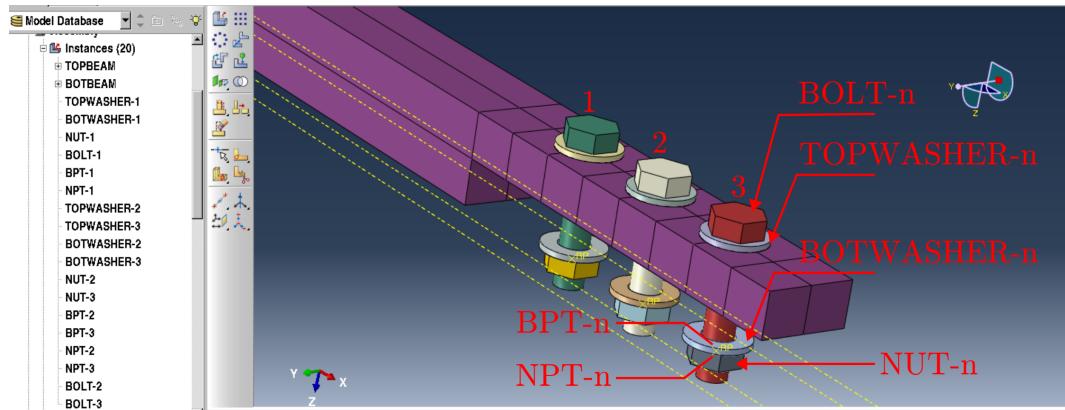
2. Import one instance each of the BOLT and NUT and 2 instances of the WASHER and assemble them as shown. Ensure that the washer is oriented (on each side) with the WSTOP oriented in the -z direction and the WSBOT is oriented in the +z direction. Rename the washer instances in the top and bottom as TOPWASHER-1 and BOTWASHER-1 respectively. Rename the bolt and nut as NUT-1 and BOLT-1 respectively.



3. Import one instance of the reference point REFPT. As mentioned before, this will be used to enforce bolt prestress. This will be achieved by first placing it at the centroid of the intersection of the BOLT and NUT (surfaces BN and NB). It is important that the reference point is placed at the centroid. This can be done in the GUI by first moving it to an external point and then translating it along the axis. The figure below shows an example (a datum point was used for this here). Rename this to BPT-1 (standing for Bolt Point 1).



4. Now import another instance of the reference point **REFPT** and translate it to be coincident with **BPT-1**. Rename this **NPT-1** (standing for Nut Point 1). These two points will have to be on the same geometrical point but equal and opposite forces will be applied for the force application (see 2.2 below for those steps). The point **BPT-1** will be coupled to the bolt surface **BN** and **NPT-1** will be tied to the nut surface **NB** through RBE3 elements.
5. Use the "Linear Pattern" dialog and copy the bolt-washer-washer-nut assembly thrice along the beam such that the assembly is complete. The figure below shows the final assembly along with a representation of the names of the different parts. Recall that the beam shown in the figure below is **TOPBEAM** and the hidden one is **BOTBEAM**.



Now that the assembly is complete, the relevant constraints will have to be enforced, followed by a realization of the bolt preload.

2 Constraints

2.1 Tie-Constraint Enforcement

SCRIPT:GUI

All the following operations can be conducted in the **Interaction** module in CAE. But since selecting each surface can be a time-consuming process, we use the following for-loop in ABAQUS-python (either call it as a script or just copy paste it into the CLI) to make the required tie constraints. Specifically, it ties the Bolt-Washer, Nut-Washer, and Washer-Beam surfaces. Note that in the last set of constraints, we recall the fact that the bottom beam is flipped. So **WASHER-1** is tied to **BmW3** of the bottom beam (and so on for 2,3).

```
1 mdl = mdb.models['Model-1']
```

```

2 ras = mdl.rootAssembly
3
4 for i in range(1, 4):
5     # Bolt-Washer Constraints
6     mdl.Tie(name='BW-%d' %(i),
7             main=ras.instances['TOPWASHER-%d' %(i)].surfaces['WSTOP'],
8             secondary=ras.instances['BOLT-%d' %(i)].surfaces['BLW'],
9             positionToleranceMethod=COMPUTED, adjust=ON,
10            tieRotations=ON, thickness=ON)
11
12     # Nut-Washer Constraints
13     mdl.Tie(name='NW-%d' %(i),
14             main=ras.instances['BOTWASHER-%d' %(i)].surfaces['WSBOT'],
15             secondary=ras.instances['NUT-%d' %(i)].surfaces['NW'],
16             positionToleranceMethod=COMPUTED, adjust=ON,
17            tieRotations=ON, thickness=ON)
18
19     # TopWasher-Beam Constraints
20     mdl.Tie(name='BmTW-%d' %(i),
21             main=ras.instances['TOPBEAM'].surfaces['BmW%d' %(i)],
22             secondary=ras.instances['TOPWASHER-%d' %(i)].surfaces['WSBOT'],
23             positionToleranceMethod=COMPUTED, adjust=ON,
24            tieRotations=ON, thickness=ON)
25
26     # BotWasher-Beam Constraints
27     mdl.Tie(name='BmBW-%d' %(i),
28             main=ras.instances['BOTBEAM'].surfaces['BmW%d' %((3-i)%3+1)],
29             secondary=ras.instances['BOTWASHER-%d' %(i)].surfaces['WSTOP'],
30             positionToleranceMethod=COMPUTED, adjust=ON,
31            tieRotations=ON, thickness=ON)

```

2.2 Bolt Preload Realization

SCRIPT:GUI

You might already have encountered the different parts of the model above that were carefully constructed for the bolt preload application (bolt-shank partitioning, reference points, etc.).

What's wrong with the inbuilt Bolt Pretension in ABAQUS?

The ABAQUS Approach

- You can find the ABAQUS documentation for the bolt load [here](#).
- ABAQUS/CAE applies bolt load by specifying a **bolt cross-section**, a **bolt axis**, and the **bolt load**.
- The documentation for the ABAQUS implementation can be found [here](#).
- The load is applied in the context of a constraint:
 - It can be a load constraint wherein the displacements/strains at the cross-section are adjusted to match the load.
 - It can be a deformation constraint, wherein the loads are adjusted.
- In either case, the bolt load **can not be written down as a constant load vector** that can be exported/used elsewhere.
- It is therefore not possible to use the inbuilt bolt pretension in a substructured analysis, for example.
- Here are the documented limitations:
 - An assembly load cannot be specified within a substructure.
 - If a submodeling analysis is performed, any pre-tension section should not cross regions where driven nodes are specified.
 - Nodes of a pre-tension section should not be connected to other parts of the body through multi-point constraints.

Our Approach

- Our method of bolt pretension application addresses all the above issues pertaining to substructuring/submodeling by using **Distributed Coupling** elements (aka RBE3/Spider elements in other FE software).
- We will first couple the bolt-shank area that is in contact with the nut (the thread area) to a 6DOF point (3 translations + 3 rotations), and do the same for the nut inner surface, with another point, using **Distributed coupling** elements.
- The bolt and nut will be "fastened" by arresting every DOF in these two nodes except the axial DOF. This will ensure that the only relative displacement between the bolt and nut are axial, which may result from tightening/loosening of the bolt.
- A "**pulling force**" is applied on the **bolt-coupling node**, which acts as the tension on the bolt, and a "**pushing force**" is applied on the **nut-coupling node**, which acts to maintain the system's equilibrium, i.e., fastening.
- It is understood that there is an interface that the assembly is tightening, which should provide the required reaction forces to balance everything out.
- Now, the bolt load is merely a **constant** force vector which can be manipulated as one desires.

We will now go through the process of specifying this.

1. First couple the bolt-shank surface BN with the appropriate reference point (BPT-n). This can be done in CAE through **Interaction->Create Constraint->Tie**. The following is python code that will do this in a loop.

```

32 # Bolt and Nut Point Coupling
33 for i in range(1, 4):
34     mdl.Coupling(name='BPC-%d' %(i),
35                 controlPoint=ras.instances['BPT-%d' %(i)].sets['Set-1'],
36                 surface=ras.instances['BOLT-%d' %(i)].surfaces['BN'],
37                 influenceRadius=WHOLE_SURFACE, couplingType=STRUCTURAL,
38                 weightingMethod=UNIFORM)
39
40     mdl.Coupling(name='NPC-%d' %(i),
41                 controlPoint=ras.instances['NPT-%d' %(i)].sets['Set-1'],
42                 surface=ras.instances['NUT-%d' %(i)].surfaces['NB'],
43                 influenceRadius=WHOLE_SURFACE, couplingType=STRUCTURAL,
44                 weightingMethod=UNIFORM)

```

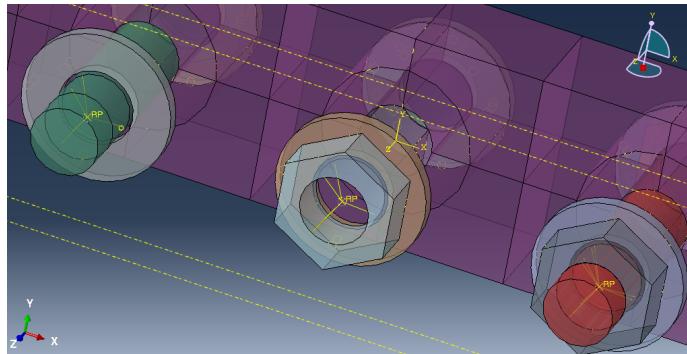
2. Now we constrain the X, Y, Rx, Ry, and Rz DOFs (all 5 DOFs other than the Z DOF, which is the bolt-axis) using equation constraints. If the bolt axis is not a principal direction in the model, then the constraint equations must be modified appropriately. Note that this can also be used in the large deformation context through the use of a local coordinate system (the global CS is used here, so **applicability is restricted to small deformations**). This can be done in CAE through **Interaction->Create Constraint->Coupling**. The following code does this through a nested loop such that **BNEQn-m** represents the mth DOF constraint at the nth location.

```

45 # Equation Constraints constraining bolt and nut ref-points to each other
46 for i in range(1, 4):
47     for j in [1, 2, 4, 5, 6]:
48         mdl.Equation(name='BNEQ%d-%d' %(i, j),
49                     terms=((1.0, 'BPT-%d.Set-1' %(i), j),
50                            (-1.0, 'NPT-%d.Set-1' %(i), j)))

```

Here is an image showing the constraints applied graphically.



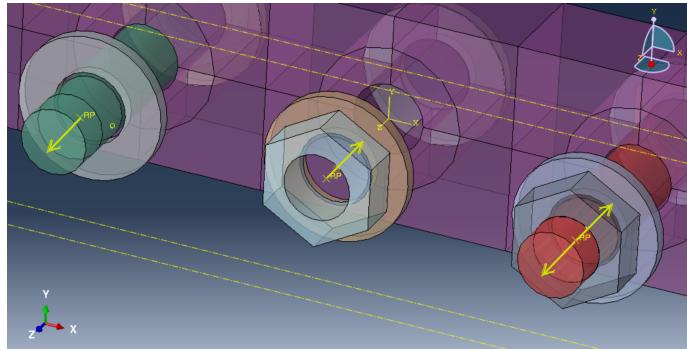
3. We next create a static analysis step (`Step->Create Step->Static, General`) named as PRESTRESS. This can be done in CAE, but here is the Python code.

```
51 mdl.StaticStep(name='PRESTRESS', previous='Initial', nlgeom=ON)
```

Note: Nonlinear Geometric effects (`nlgeom`) is set to ON since this was found to be helpful for convergence of prestress analysis.

4. We finally apply bolt forces as concentrated forces at the BPT-n and NPT-n reference points. Switch to the Load module to do this from CAE. The following python code applies a tightening load of 12kN to each bolt.

```
52 # Apply forces
53 bpmag = 12e3 # 12kN bolt-load
54 for i in range(1, 4):
55     # Force in +z on bolt-points
56     mdl.ConcentratedForce(name='BoltLoad-%d' %(i), createStepName='PRESTRESS',
57                             region=ras.instances['BPT-%d' %(i)].sets['Set-1'],
58                             cf3=bpmag, distributionType=UNIFORM)
59
60     # Force in -z on bolt-points
61     mdl.ConcentratedForce(name='NutLoad-%d' %(i), createStepName='PRESTRESS',
62                           region=ras.instances['NPT-%d' %(i)].sets['Set-1'],
63                           cf3=-bpmag, distributionType=UNIFORM)
```



5. **Note** that the bolt load constructed in the above manner is a "linear" load - i.e., the load can be increased/decreased by scaling the resulting force vector. It is assumed here that all 3 bolts are loaded equally. If this is not the case, the different loads can be exported separately and scaled appropriately (for external analysis). It is, however, a physical requirement for equilibrium that `BoltLoad-n` and `NutLoad-n` have to be of equal magnitude and opposite signs.

The file `model_step1.cae` stores the CAE-file generated after the end of the above steps. We will now proceed with meshing.

3 Meshing

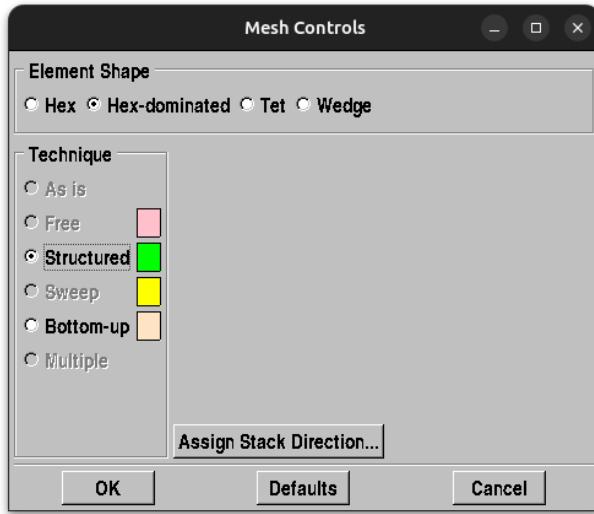
Since the model is perfectly symmetric, it is sufficient to mesh the model with a global seed, after seeding the interface area locally. Switch to the **Mesh** module for this section.

If such symmetry is not available, one may choose a more direct approach by using the **bottom-up** meshing to copy the mesh from one interface to another directly. Please write to me if you'd like an example for this.

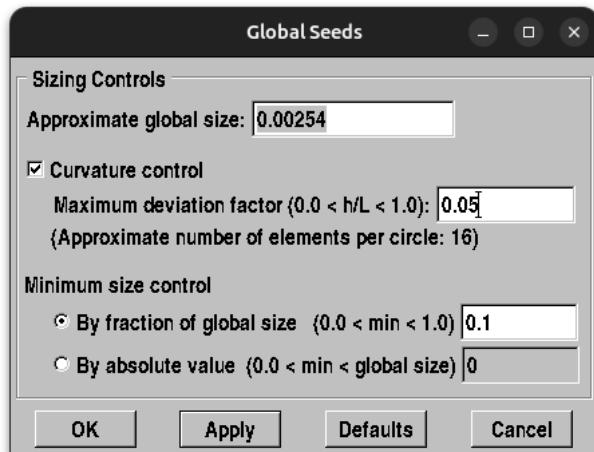
3.1 Meshing Instructions

GUI

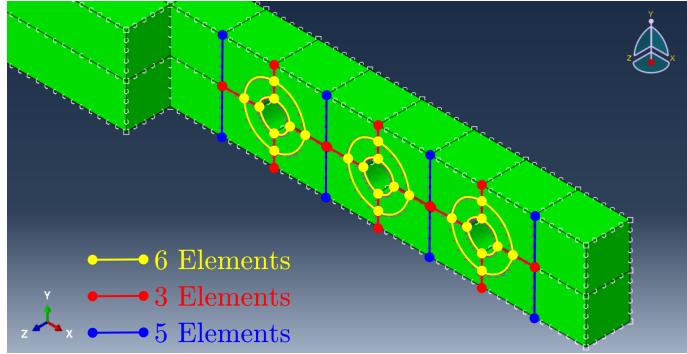
1. Choose **Mesh->Assign Mesh Controls** and select the whole assembly (all the instances). We will use a structured hex-dominated element type for the full model (it will give a warning that this is not possible for certain regions. This is okay).



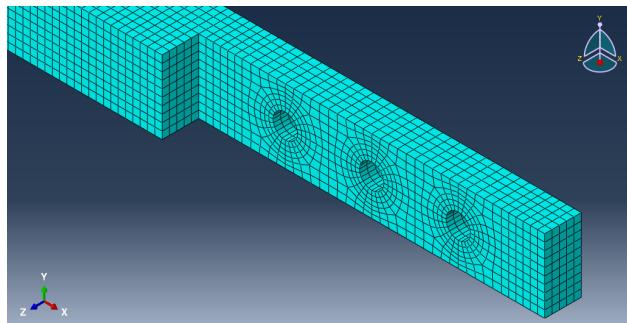
2. Now choose **Mesh->Seed Part Instance** and select all the instances again. Set 0.00254 as the global mesh seed (to ensure 10 elements across thickness) and 0.05 for curvature control.



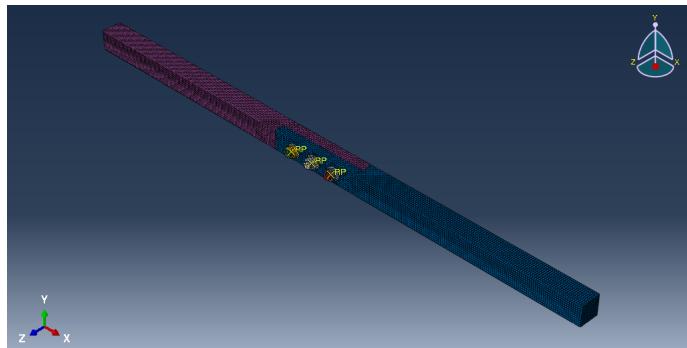
3. Apply local seeds at the interface as shown here (on both interfaces). Use the **Mesh->Seed Edges** tool by choosing the Method as "By Number" and specify the number of elements.



4. Now mesh the assembly using **Mesh->Mesh Part Instance** and selecting all the part instances. Here is a view of the interfacial mesh you should get after the above seeding.



5. Here is an image of the total assembly with the mesh.

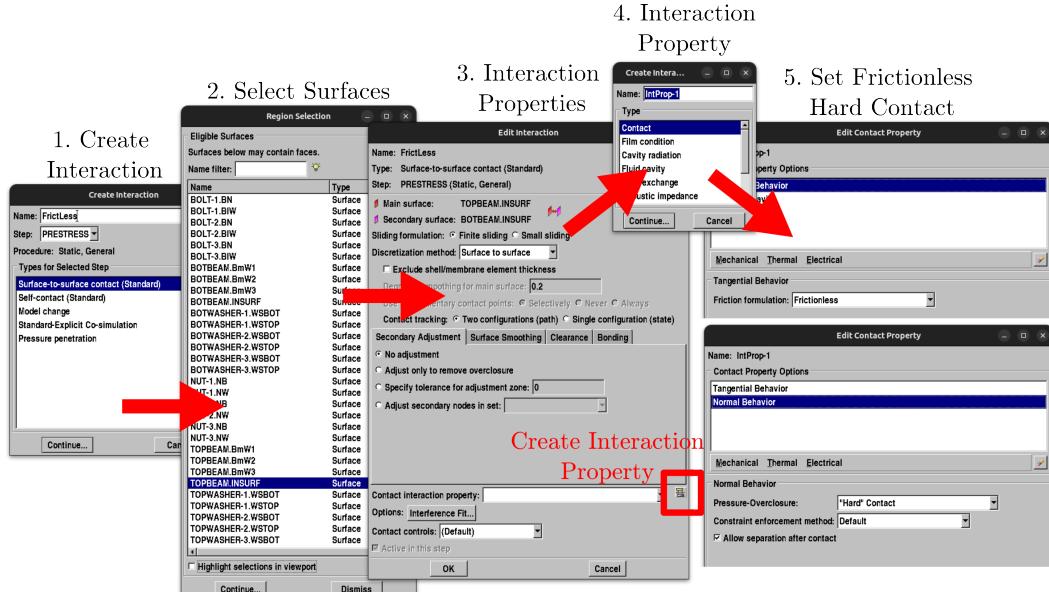


The file `model_step1.cae` stores the CAE-file along with the mesh.

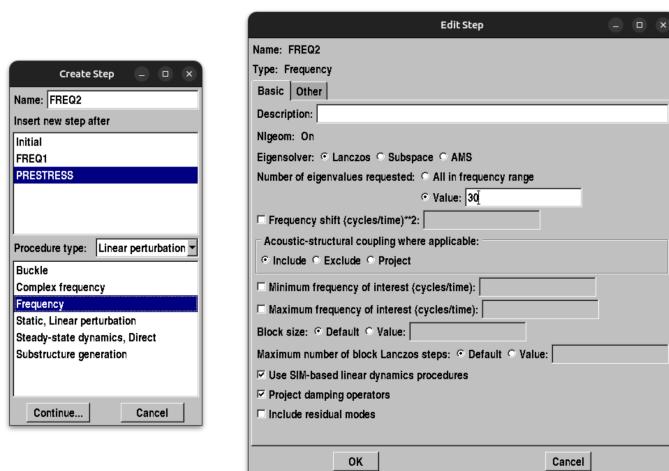
3.2 (Optional, recommended) Verify correctness of model through frictionless prestress GUI

We will now conduct a simple frictionless contact analysis to verify the correctness of the model.
Setup

1. For the static prestress analysis, first a surface-to-surface contact interaction property has to be created and assigned. You can do this from CAE starting from **Interaction->Create Interaction** and following the steps in the figure below.



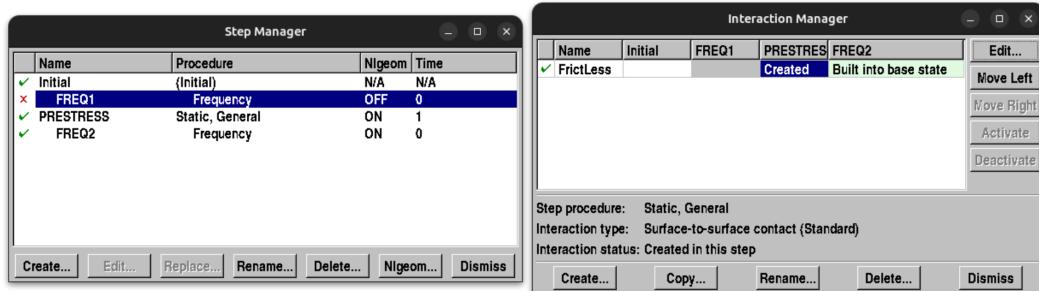
2. Now create two linear frequency steps, one before and one after the static prestress step, as shown in the figure below. Request 30 eigenvalues in each case.



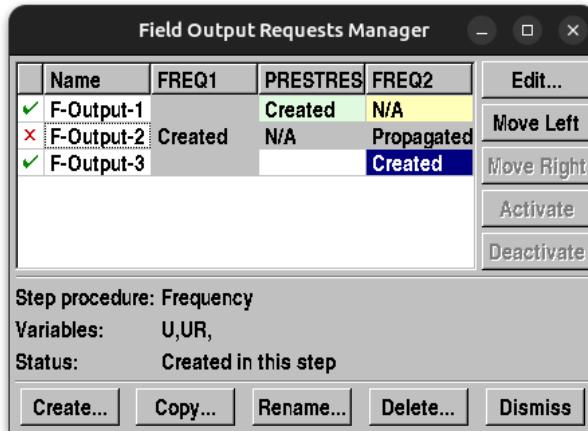
3. Create 2 jobs. Suppress the interaction property in the first one and have just FREQ1 active (see figure below).

Step Manager		Interaction Manager	
Name	Procedure	Name	Initial
Initial	(Initial)	FrictLess	Created
FREQ1	Frequency		Built into base state
PRESTRESS	Static, General		
FREQ2	Frequency		

For the second job, suppress FREQ1 and resume the other steps. Resume the surface interaction properties (see figure below).



Optionally, field outputs for FREQ2 (by default it will be set to none if FREQ1 is suppressed). You can do this in Step->Create Field Outputs.

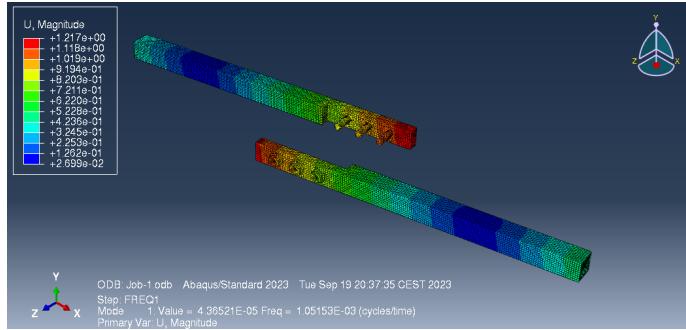


Results

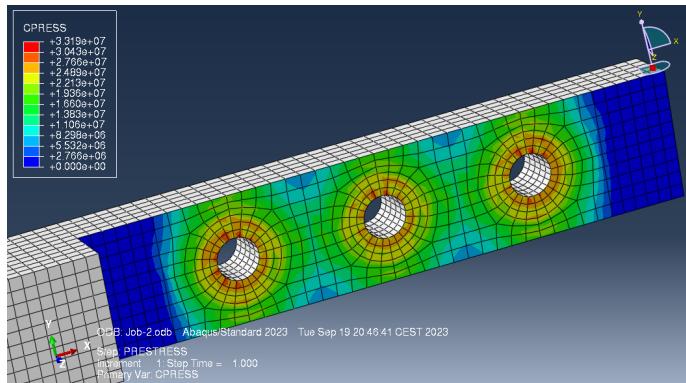
1. The first analysis should reveal that the system has **7 Rigid Body Modes** (RBMs). This is because the two beams are constrained together in all directions except the axial (where tightening has to happen). So the number of RBMs has to be $2 \times 6 - 5 = 7$. The first 10 modal frequencies have to be (frequencies in cycles/time, or Hz):

Index	Frequency
1	1.0515e-3
2	1.2851e-3
3	1.4602e-3
4	1.6246e-3
5	1.6592e-3
6	1.8082e-3
7	1.9025e-3
8	70.323
9	151.26
10	609.25

In the above, modes 1-7 are RBMs and modes 8 onwards are the elastic modes. Looking at the mode-shapes should make it clear that the two beams are free to move axially (the following is mode 1, for eg).



2. The second analysis should converge within a few iterations. If not, the "Initial Increment Size" in Step->PRESTRESS->Edit->Increment->Initial Increment Size has to be reduced. If it doesn't converge, try to apply a boundary condition to make the problem well-posed, and try again. If it still doesn't converge, check your model again. Here is a picture of the contact pressures at the interface at the end of the static prestress step.



3. By default, ABAQUS fuses the nodes that are in contact at the end of the hard contact step, for the eigenvalue analysis that follows it (Linear Perturbation step). Since we are using frictionless tangential here, the tangential DOFs are not fused. Here are the first 10 frequencies from the FREQ2 step (frequencies in cycles/time, or Hz):

Index	Frequency
1	0.00
2	0.00
3	0.00
4	0.00
5	0.00
6	2.2068e-3
7	141.10
8	152.42
9	570.33
10	643.49

It must be observed that the model, under the prestressed state, **has only 6 RBMs**. In other words, the bolt-axial direction has now been fixed due to the fact that the contact constraints are active on at least one spot on the interface.

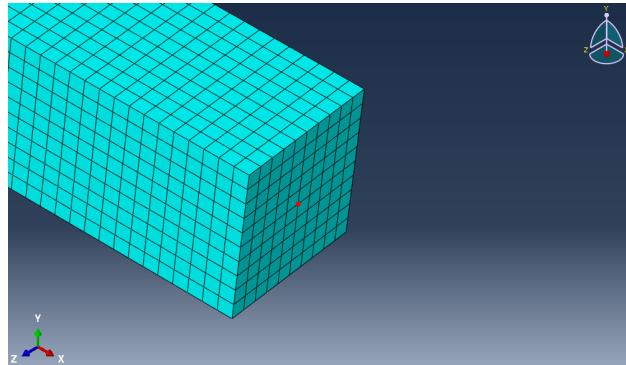
4. If your model passes all the above, then you are ready to proceed.
5. **Note, however, that this does not imply accuracy of the model. One would have to do a mesh convergence analysis in this case.** For contact problems, it is well known that the interfacial discretization must be very fine for convergence. Much coarser meshes are, however, found to be sufficient for predicting global quantities such as natural frequency and (nonlinear) damping estimates, etc. Such a convergence analysis is presented in the appendix of this thesis.

The file `model_step2.cae` is the cae file containing the model with the above tests included.

4 Postprocess

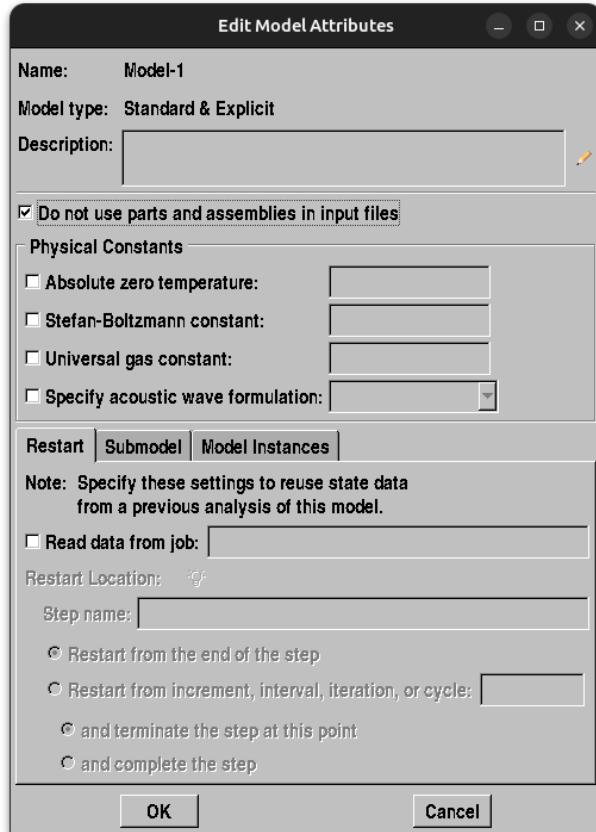
Now that the model is verified to be correct/consistent, we will proceed with the steps necessary for substructured Matrix Extraction.

Before proceeding it is necessary to first identify nodes on the meshed model that correspond to the input and output locations. Choose the mid point on the right end as the output node for this tutorial. Create a node set called `OutNodes` by selecting `Mesh->Tools->Set->Create->Node` and choosing the node. Select "unsorted node set" if available.



It is possible to choose multiple nodes here if you have a MIMO case.

It is also helpful to use global node and element indexing henceforth. This can be specified in `Model->Edit Attributes->Model-1` as follows:



4.1 Reorganize Interfacial Node Sets (readjust if necessary)

SCRIPT

Although we have taken care to ensure that the mesh of the TOPBEAM and BOTBEAM are conformal at the interface, minor imperfections in the nodal locations may exist. Furthermore, the ordering of the nodes on the top interface will be different from that on the bottom interface. Through some scripting, we can create node sets in such a way that the top and bottom interface nodesets are ordered in a convenient fashion.

You can use the model_step1a.cae and work along if you are here just for this section.

1. We use the following slightly modified header for this script:

```

1 # -*- coding: utf-8 -*-
2 # 1. Preamble
3 import sys
4 import numpy as np
5
6 from part import *
7 from material import *
8 from section import *
9 from assembly import *
10 from step import *
11 from interaction import *
12 from load import *

```

```

13 from mesh import *
14 from optimization import *
15 from job import *
16 from sketch import *
17 from visualization import *
18 from connectorBehavior import *
19
20 from abaqus import *
21 from abaqusConstants import *
22 from caeModules import *
23 import regionToolset
24 import job
25 import step
26 import sets
27
28 mdb = mdb.models['Model-1']
29 ras = mdb.rootAssembly
30
31 mdb.setValues(noPartsInputFile=ON)

```

2. Now we identify the top and bottom surface nodes, and store the top nodes and elements into separate variables. The node and element ordering of the top nodes will be preserved, and the nodes in the bottom will be resorted according to this in #3 below.

```

32 # 2. Get top and bottom surfaces and nodes
33 topsurf = ras.instances['TOPBEAM'].surfaces['INSURF']
34 botsurf = ras.instances['BOTBEAM'].surfaces['INSURF']
35
36 topnodes = topsurf.nodes
37 botnodes = botsurf.nodes
38 N = len(topnodes) # Number of nodes
39
40 # Top Nodes and Coordinates
41 Topnd_dict = dict(zip([topnodes[i].label
42                         for i in range(N)], range(N)))
43 # maps original node ID (in FE model) to
44 # node ID in interface node set
45 TopNdCds = np.array([topnodes[i].coordinates
46                         for i in range(N)])
47
48 # Top Elements
49 TopEls = np.array([topsurf.elements[i].connectivity
50                     for i in range(len(topsurf.elements))])
51 ELS = np.zeros((TopEls.shape[0], 5), dtype=int)
52 for ne in range(TopEls.shape[0]):
53     elefac = topsurf.elements[ne].getElemFaces()
54
55     # Gives you the list of faces on the interface

```

```

56     # (we only expect a single face here)
57     fe = np.argwhere([all([Topnd_dict.has_key(x) for x in
58                         [elefac[k].getNodes()[i].label
59                         for i in range(4)]])
60                         for k in range(6))][0,0]
61     ELS[ne, 0] = ne
62     # Searches for the face where all the nodes are in the interface
63     # and returns those nodes
64     ELS[ne, 1:] = [Topnd_dict[x] for x in
65                     [elefac[fe].getNodes()[k].label
66                     for k in range(4)]]
67     ELS[ne, :] += 1
68
69     # Save interfacial nodes and elements to txt files
70     np.savetxt('Nodes.dat', TopNdCds) # Save to dat file
71     np.savetxt('Elements.dat', ELS, fmt='%d')

```

3. Now we extract the bottom nodes and sort them.

```

72 # 3. Node Pairing. We assume len(botnodes)=len(topnodes).
73 botleft = range(N)
74 bts = []
75 tmi = 0
76 for i in range(N):
77     # Calculates deviation of selected node coordinate on bottom to each
78     # node coordinate on top and "assigns" the closest one to the index.
79     devns = topnodes[i].coordinates - np.array([botnodes[j].coordinates
80                                                 for j in botleft])
81     bts.append(
82         botleft.pop(
83             np.argmin(
84                 np.linalg.norm(
85                     devns, axis=1)
86             )
87         )
88     )

```

4. We now adjust the nodes on the bottom (this affects the FE mesh directly!)

```

89 # 4. Adjust Nodes on Bottom Beam Interface to Match Top Beam Exactly
90 for i in range(N):
91     ras.editNode(nodes=botnodes[bts[i]:bts[i]+1],
92                  coordinates=(topnodes[i].coordinates,))

```

5. We now create nodesets for the top (TOPS_NDS) and bottom (BOTS_NDS).

```

93 # 5. Create Node Sets
94 botpairednds = botnodes.sequenceFromLabels(tuple([botnodes[i].label

```

```

95                                     for i in bts)))
96 # Reordering from the sorting above
97
98 ras.SetFromNodeLabels(name="TOPS_NDS",
99                         nodeLabels=((topnodes[0].instanceName,
100                           tuple([topnodes[i].label
101                             for i in range(N)])),),
102                           unsorted=True)
103 ras.SetFromNodeLabels(name="BOTS_NDS",
104                         nodeLabels=((botpairednds[0].instanceName,
105                           [botpairednds[i].label
106                             for i in range(len(botpairednds))])),),
107                           unsorted=True)

```

Note that we've used the unsorted keyword to ensure that ABAQUS does not reorder the nodesets (default behavior).

6. We now simplify the model by removing all interaction properties and steps (except initial). One side-effect of doing this is that this removes the bolt loads also, since loads can only be saved when there is a corresponding step! So we will reintroduce the bolt loads in the substructuring step in #8 below.

```

108 # 6. Simplify model (remove interactions, all steps, etc.)
109 tmp = mdl.interactions
110 while len(tmp) > 0:
111     del tmp[tmp.keys()[-1]]
112
113 tmp = mdl.interactionProperties
114 while len(tmp) > 0:
115     del tmp[tmp.keys()[-1]]
116
117 # Remove all steps except initial
118 tmp = mdl.steps
119 while len(tmp) > 1:
120     del tmp[tmp.keys()[-1]]

```

4.2 Setup Fixed interface CMS (HCB-CMS) with linear frequency and sub-structure steps

1. We are interested in **Fixed-Interface Component Mode Synthesis** with 20 retained modes. So we first do a fixed interface modal analysis and request $20 \times 3 = 60$ modes (for ensuring accuracy of the first 20 modes). We fix all the nodes in the nodesets TOPS_NDS and BOTS_NDS.

```

121 # 7. Create a Frequency Step for fixed interface modal analysis
122 mdl.FrequencyStep(name="Fixed-Int-Modal", previous="Initial",
123                     normalization=MASS, eigensolver=LANCZOS,
124                     numEigen=60)
125 mdl.EncastreBC(name="TOPFIX", createStepName="Fixed-Int-Modal",

```

```

126         region=ras.sets['TOPS_NDS'])
127     mdl.EncastreBC(name="BOTFIX", createStepName="Fixed-Int-Modal",
128                     region=ras.sets['BOTS_NDS'])

```

2. Next, we create the substructuring step and re-specify the bolt loads (these were removed in #6 above). The bolt loads are specified of unit magnitude and can be scaled during analysis. **This by default uses the mode shapes from the previous step and calculates static constraint modes automatically.**

```

129 # 8. Create a substructuring step, specify the modes and retained DOFs
130 mdl.SubstructureGenerateStep(name="HCBCMS", previous="Fixed-Int-Modal",
131                             substructureIdentifier=1,
132                             retainedEigenmodesMethod=MODE_RANGE,
133                             modeRange=((1, 20, 1),),
134                             recoveryMatrix=REGION,
135                             recoveryRegion=ras.sets['OutNodes'],
136                             computeReducedMassMatrix=True)
137
138 # The name dictates ordering. A comes before B.
139 mdl.RetainedNodalDofsBC(name="A", createStepName="HCBCMS",
140                           region=ras.sets['TOPS_NDS'],
141                           u1=ON, u2=ON, u3=ON)
142 mdl.RetainedNodalDofsBC(name="B", createStepName="HCBCMS",
143                           region=ras.sets['BOTS_NDS'],
144                           u1=ON, u2=ON, u3=ON)
145
146 # Apply Bolt Loads (1N magnitude)
147 for i in range(1, 4):
148     mdl.ConcentratedForce(name='BoltLoad-%d' %(i), createStepName="HCBCMS",
149                            cf3=1.0,
150                            region=ras.instances['BPT-%d' %(i)].sets['Set-1'])
151     mdl.ConcentratedForce(name='NutLoad-%d' %(i), createStepName="HCBCMS",
152                            cf3=-1.0,
153                            region=ras.instances['NPT-%d' %(i)].sets['Set-1'])
154
155 sbs = mdl.steps['HCBCMS']
156 sbs.LoadCase(name="LCASE",
157               loads=tuple(('BoltLoad-%d' %(i), 1.0) for i in range(1, 4)) +
158               tuple(('NutLoad-%d' %(i), 1.0) for i in range(1, 4)))

```

Note, in the above that the ordering of the two sets is controlled by the name given to the `RetainedNodalDofsBC` function. Although the node sets themselves are not sorted, the order in which the nodesets appear is sorted by default.

3. We finally need to request matrix output. Here is the ABAQUS documentation for the `*Substructure Matrix Output` card. Thus far (until version 2023) ABAQUS CAE doesn't support requesting matrix output from Substructure steps. We have to request this manually in the .inp files. Thankfully we can write to the keywords directly from CAE. Go to

Model->Edit Keywords->Model-1 to do this in the GUI. In scripting, this is known as a "synch" operation, which is done as follows:

```

159 # 9. Request substructure matrix outputs
160 # ABAQUS CAE doesn't support this yet (GUI or scripting),
161 # so the keywords need to be manually modified.
162 mdl.keywordBlock.synchVersions(storeNodesAndElements=False)
163
164 li = np.argwhere([mdl.keywordBlock.sieBlocks[i][0:20] == "*Retained Nodal Dofs"
165                     for i in range(len(mdl.keywordBlock.sieBlocks))])[0][0]
166 txi = mdl.keywordBlock.sieBlocks[li]
167 mdl.keywordBlock.replace(li, "*Retained Nodal Dofs, sorted=NO"+txi[20:])
168
169 mdl.keywordBlock.insert(len(mdl.keywordBlock.sieBlocks)-2,
170                         "*Substructure Matrix Output, FILE NAME=Modelmats, "
171                         "MASS=YES, STIFFNESS=YES, SLOAD=YES, "
172                         "RECOVERY MATRIX=YES")

```

4. We then create a job and write it to an "inp" file that can be run from ABAQUS.

```

173 # 10. Create a job and write an inp file
174 mdb.Job(name="Job", model='Model-1')
175 mdb.jobs['Job'].writeInput()

```

5. Here is what the final HCBCMS step looks like in this case. The most important part is the ***Substructure Matrix Output** card in the bottom, which we introduced through the "synch" step in #3 above. Here is the ABAQUS documentation for the ***Substructure Matrix Output** card.

```

1  ** -----
2  **
3  ** STEP: HCBCMS
4  **
5  *Step, name=HCBCMS, nlgeom=NO
6  *Substructure Generate, overwrite, type=Z1, recovery matrix=YES,
7  nset=OutNodes, mass matrix=YES
8  *Select Eigenmodes, generate
9  1, 20, 1
10 *Damping Controls, structural=COMBINED, viscous=COMBINED
11 *Retained Nodal Dofs, sorted=NO
12 BOTS_NDS, 1, 3
13 TOPS_NDS, 1, 3
14 **
15 ** LOAD CASES
16 **
17 *Substructure Load Case, name=LCASE
18 ** Name: BoltLoad-1    Type: Concentrated force    Scale factor: 1
19 *Cload

```

```

20 BPT-1_Set-1, 3, 1.
21 ** Name: BoltLoad-2    Type: Concentrated force    Scale factor: 1
22 *Cload
23 BPT-2_Set-1, 3, 1.
24 ** Name: BoltLoad-3    Type: Concentrated force    Scale factor: 1
25 *Cload
26 BPT-3_Set-1, 3, 1.
27 ** Name: NutLoad-1    Type: Concentrated force    Scale factor: 1
28 *Cload
29 NPT-1_Set-1, 3, -1.
30 ** Name: NutLoad-2    Type: Concentrated force    Scale factor: 1
31 *Cload
32 NPT-2_Set-1, 3, -1.
33 ** Name: NutLoad-3    Type: Concentrated force    Scale factor: 1
34 *Cload
35 NPT-3_Set-1, 3, -1.
36 *Substructure Matrix Output, FILE NAME=Modelmats, MASS=YES,
37      STIFFNESS=YES, SLOAD=YES, RECOVERY MATRIX=YES
38 *End Step

```

You can find the inp-file generate from the above in Job.inp.

4.3 Run Job and Generate the mtx file.

SCRIPT:GUI

You can now run the Job named "Job" in the GUI, or directly run the "Job.inp" file from the command line using

```
abaqus job=Job inp=Job.inp cpus=2 interactive
```

Once the job is done, it will output the matrix file "Modelmats.mtx" into the working directory. This, along with the "Nodes.dat" and "Elements.dat" files that were written out earlier, are all we need for external analyses.

5 Matrix Extraction + NL-Analysis

By default, ABAQUS uses the matrix market format for the outputted matrices. Note the following, in terms of format:

- Each line that starts with an asterix ("*") is a comment.
- The linear matrices of the current model are fully symmetric.
- So only the upper triangular parts of the matrices are exported.
- The load vector is exported as a vector.
- Columns of the recovery matrix R , defined by

$$x_{out} = Rx_{cms}$$

where x_{cms} is the vector of DOFs of the CMS model (substructure) and x_{out} are the output DOFs. Each column of R is $N_{out} \times 1$, and R is $N_{out} \times N_{cms}$.

5.1 Postprocessing Exported Matrices

SCRIPT

1. The first few lines provide the generalized coordinates of the model. The nodes are listed as positive integers and the "modal" DOFs are listed as negative integers. This is followed by a list of DOFs active in each set.
2. The STIFFNESS and MASS matrices are respectively prepended by

```
*      MATRIX,TYPE=STIFFNESS
      <Stiffness matrix entries in upper triangular form>

*      MATRIX,TYPE=MASS
      <Mass matrix entries in upper triangular form>
```

3. The load vector (the bolt prestress load, here) is written as,

```
** SUBSTRUCTURE LOAD CASE VECTOR. SLOAD CASE <name>
***CLOAD
** 1, 1, <entry>
** 1, 2, <entry>
** 1, 3, <entry>
.
.
.
```

4. Finally, the recovery matrix is provided row-by-row as

```
*      SUBSTRUCTURE RECOVERY VECTOR CORRESPONDING TO RETAINED DOFS NUMBER 1
      <entries>
*      SUBSTRUCTURE RECOVERY VECTOR CORRESPONDING TO RETAINED DOFS NUMBER 2
      <entries>
.
.
.
```

5. In the actual file, the order is STIFFNESS, LOAD, MASS, then SUBSTRUCTURE.
6. The following Bash script processes the output (a stiffness, a mass, a load case, and recovery entries are expected)

```
1  #!/bin/sh
2
3  if [ $# = 2 ]
4  then
5      echo "Correct call!"
6      OUT=$2
7  elif [ $# = 1 ]
8  then
9      echo "Acceptable call!"
```

```

10      a="$1"
11      OUT="${a%.*}.mat"
12  else
13      echo "Wrong call - quitting!"
14  fi
15 echo "Preprocessing mtx files"
16 awkcmd1='BEGIN{mstart=0;'}
17     ($1~/^/*M/){mstart++; next}
18     (mstart==1){if($1!~/^/*/){print}else{exit}}'
19 awkcmd2='BEGIN{RS=", ";ORS="\n"}{print}'
20 gawk "$awkcmd1" $1|gawk "$awkcmd2"|gawk '(NF!=0){print}' > ./STIFFNESS.mtx
21
22 awkcmd1='BEGIN{mstart=0;'}
23     ($1~/^/*M/){mstart++; next}
24     (mstart==2){if($1!~/^/*/){print}else{exit}}'
25 awkcmd2='BEGIN{RS=", ";ORS="\n"}{print}'
26 gawk "$awkcmd1" $1|gawk "$awkcmd2"|gawk '(NF!=0){print}' > ./MASS.mtx
27
28 awkcmd1='BEGIN{vstart=0;'}
29     ($0~/^/*\*\*/C/){vstart++; next}
30     (vstart>0){print $2,$3,$4}
31     (vstart>0 && $1!~/^/*\*/){exit}'
32 awkcmd2='BEGIN{FS=", "}'
33     {for(i=1;i<=NF;i++)
34         printf("%s ", $i);
35         printf("\n")}'
36 gawk "$awkcmd1" $1|gawk "$awkcmd2" > ./FVEC.mtx
37
38 awkcmd1='BEGIN{rstart=0}
39     ($0~/^/*\*\* SUBSTRUCTURE REC/){rstart++;
40     if(rstart>1){printf("\n")}
41     next}
42     (rstart!=0 && $1~/^/*\*/){
43     for(i=2;i<=NF;i++)printf("%s",$i);}''
44 awkcmd2='BEGIN{FS=", "}'
45     {for(i=1;i<=NF;i++)
46         printf("%s ",$i);
47         printf("\n");}'
48 gawk "$awkcmd1" $1|gawk "$awkcmd2" > .RECOV.mtx
49
50 echo "Preprocessing mtx files done"
51
52 python <<EOF
53 import numpy as np
54 import scipy.io as io
55
56 print("Reading Mass Matrix from mtx file.");
57 Mv = np.loadtxt('.MASS.mtx');

```

```

58 print("Done.");
59
60 print("Reading Stiffness Matrix from mtx file.");
61 Kv = np.loadtxt('.STIFFNESS.mtx');
62 print("Done.");
63
64 print("Reading Recovery Matrix from mtx file.");
65 R = np.loadtxt('.RECOV.mtx');
66 print("Done.");
67
68 print("Processing Matrices.")
69
70 Nelm = len(Mv);
71 Nelk = len(Kv);
72 if (Nelm!=Nelk):
73     sys.exit("GIGO - Mass & Stiffness not of same length.");
74 Nel = Nelm;
75
76 Nd = ((np.sqrt(1+8*Nel)-1)/2).astype(int); # Solution of Nd(Nd+1)/2-Nel = 0
77
78 M = np.zeros((Nd,Nd));
79 K = np.zeros((Nd,Nd));
80
81 (xi,yi) = np.tril_indices(Nd);
82 M[xi,yi] = Mv;
83 M[yi,xi] = Mv;
84 K[xi,yi] = Kv;
85 K[yi,xi] = Kv;
86
87 print("Done.")
88
89 print("Reading Forcing Vector from mtx file.");
90 Fvdat = np.loadtxt('.FVEC.mtx');
91 print("Done.");
92
93 print("Processing Force Vector.");
94 Fv = np.zeros(M.shape[0]);
95 ids = range(np.where(np.diff(Fvdat[:, 1])==0)[0][0], Fvdat.shape[0])
96 n1dofnds = Fvdat[ids, 0].astype(int)
97 n3dofnds = Fvdat[list(set(range(Fvdat.shape[0]))-set(ids)), 0].astype(int)
98 Fv[((n3dofnds-1)*3+np.kron(np.ones(int(len(n3dofnds)/3)), [0, 1, 2])).astype(int)] = \
99 Fvdat[list(set(range(Fvdat.shape[0]))-set(ids)), 2]
100 print("Whew.")
101 Fv[range(-len(n1dofnds), 0)] = Fvdat[ids, 2]
102 print("Done.")
103
104 print("Matrix extraction complete - writing mat file")
105 dict = {"M": M, "K": K, "R": R.T, "Fv": Fv.reshape((len(Fv),1))};

```

```

106 io.savemat(".out.mat",dict);
107 print("Processing Over")
108 EOF
109 mv .out.mat $OUT
110 rm .STIFFNESS.mtx .MASS.mtx .RECOV.mtx .FVEC.mtx

```

- This bash script first uses GNU Awk, a simple but powerful utility that allows line-by-line parsing of files.
 - The script also uses the cut utility from GNU coreutils for manipulations.
 - Finally, the script uses Python (compatible with 2/3), involving numpy and scipy.io, for converting the quantities into a MATLAB mat-file that can be loaded on MATLAB.
 - This script can be called as follows:
- ```
./readwritematvec.sh Modelmats.mtx
```
- In windows, this can be done either through Cygwin or Windows Subsystem for Linux.
7. It may be possible to do this natively in MATLAB, but since this requires a line-parser, awk is better suited for the job than MATLAB. A MATLAB implementation might require loading the whole file into memory for speed. Line-parsing on MATLAB was extremely slow for me.

The file model\_step3.cae is the final cae file that contains all of the above.

## 5.2 Nonlinear Analysis on MATLAB/OCTAVE in under 100 lines of code SCRIPT

We will now do our first nonlinear analysis on MATLAB/OCTAVE with the exported matrices. We will conduct a **Nonlinear Prestress Analysis** for a frictionless contact with a unilateral spring on the normal direction.

It is assumed that the readwritematvec.sh routine has been called on matrix file named `Modelmats.mtx` to produce `Modelmats.mat` mat-file. Further, the nodes and elements on the interface are taken to be available in `Nodes.dat` and `Elements.dat` files respectively. The below tutorial is meant to be minimal so it is assumed that all the elements are linear QUAD elements.

1. We start with the preamble for the MATLAB file, then read the mesh information, and then load up the matrices from the `Modelmats.mat` file.

```

1 clc
2 clear all
3
4 set(0,'defaultAxesTickLabelInterpreter', 'default');
5 set(0,'defaultTextInterpreter','latex');
6 set(0, 'DefaultLegendInterpreter', 'latex');
7 set(0,'defaultAxesFontSize',13);
8
9 %% Read Nodes and Elements
10 Nodes = dlmread('./Nodes.dat');
11 Elements = dlmread('./Elements.dat');
12 N = size(Nodes,1); % Number of nodes per side

```

```

13 Ne = size(Elements,1); % Number of elements
14
15 %% Load Matrices
16 fname = './Modelmats.mat';
17 load(fname, 'M', 'K', 'R', 'Fv');
18
19 % Number of generalized modal DOFs
20 Nint = size(M,1)-(2*N)*3;

```

2. It may be tempting to want to use **node-to-node contact elements**. But this is **inconsistent here** since the elements have non-uniform area and have non-trivial connectivity. In the continuous case, the nodal-force-traction relationship is expressed as

$$f_j = \int_{\Omega} \mathbb{N}_j t(\curvearrowright) d\Omega,$$

where  $\mathbb{N}_j$  is the  $j^{th}$  shape function,  $f_j$  is the nodal force of the  $j^{th}$  node, and  $t(\curvearrowright)$  is the traction-field (of the appropriate traction).

**Contact-constitutive models are understood as local relationships between the relative displacement and contact tractions.** Nodal forces are merely integral effects of the local traction distributions.

It is therefore **necessary to employ quadrature integration** for consistency.

3. The implementation greatly simplifies if we were to employ only a single Quadrature Point (QP) per element. We construct two matrices,  $Q_m$  and  $T_m$  such that

$$\begin{aligned} x_{QP} &= Q_m x_N, \text{ and} \\ f_N &= T_m t_{QP}. \end{aligned}$$

Here,  $x_{QP}$  and  $x_N$  are the vector of displacements at quadrature points and nodal points respectively; and  $f_N$  and  $t_{QP}$  are the vector of nodal forces and quadrature point tractions respectively.

```

21 %% Single-Point-Quadrature Matrices
22 Qm = zeros(Ne, N); % Each element has one quadrature point
23 Tm = zeros(N, Ne); % Each quadrature pt integrated to 4 nodes
24 Ars = zeros(Ne, 1); % Vector of areas of each element
25 for ei=1:Ne
26 ndis = Elements(ei, 2:end); % Nodes of the current element
27 Qm(ei, ndis) = ones(1, 4)/4;
28 % value @ QP = avg of nodal values
29
30 Ars(ei) = polyarea(Nodes(ndis,1), Nodes(ndis,2));
31
32 Tm(ndis, ei) = ones(4, 1)*Ars(ei)/4;
33 % (integrated) nodal value = value @ QP times element Area/4
34 end
35 % Qm is quadrature interpolation matrix
36 % Tm is quadrature integration matrix

```

```

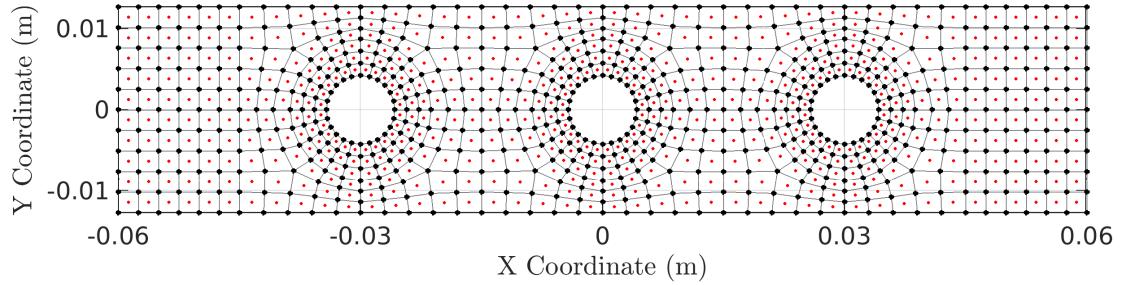
37
38 Ar_tot = 120e-3*25.4e-3-3*pi*(0.85e-2/2)^2; % True total area
39 % Rectangle-3*Circles
40 Ar_avg = Ar_tot/Ne; % Average element area

```

The fact that for a single quadrature point case, the quadrature point is exactly at the centroid of the element. For the integral, this assumes that the traction field within each element is uniform, so the integral may be simplified as

$$f_j = \int_{\Omega_e} \mathbb{N}_j t(\curve) d\Omega \approx t_{QP} \underbrace{\int_{\Omega_e} \mathbb{N}_j d\Omega}_{A_e/4},$$

with  $A_e$  denoting element area, and  $\Omega_e$  denoting element domain (surface). The interpolation and integration weights are, therefore, easily specified. The following is a depiction of the quadrature points against the interfacial elements.



4. We now construct a matrix  $L_{rel}$  such that  $L_{rel}x_{cms}$  gives an  $N \times 1$  array of interfacial relative displacements in the normal direction. This is written based on the fact that the CMS model first lists out all the nodal DOFs of the top interface ( $x, y, z$ , in that order), and then lists out the DOFs of the bottom interface nodes. So the relative normal displacement is defined as  $\Delta z := x_{z,top} - x_{z,bot}$ , such that  $\Delta z > 0$  implies contact and  $\Delta z < 0$  implies separation.

The following code derives the matrix  $L_{rel}$  to obtain the relative displacement at the quadrature location from the system's global vector of DOFs (CMS DOFs). Further, a matrix  $G_{rel}$  is also constructed such that  $G_{rel}t_{z,rel,QP}$  represents the nodal forces when  $t_{z,rel,QP}$  is the normal tractions at the quadrature points. Finally, nodal relative displacements are also computed (just for plotting purposes).

```

41 %% Contact Relative Displacements
42 Lz = kron(Qm, [0 0 1]); % Get only normal displacement
43 Lrel = [Lz -Lz zeros(Ne, Nint)];
44 % Lrel defd such that Lrel*x>0 implies contact and Lrel*x<0 implies separation.
45
46 Gz = kron(Tm, [0; 0; 1]);
47 Grel = [Gz; -Gz; zeros(Nint, Ne)];
48

```

```

49 % Nodal relative disp (only for plotting)
50 Lz_n = kron(eye(N), [0 0 1]); % Get only normal displacement
51 Lrel_n = [Lz_n -Lz_n zeros(N, Nint)];
```

5. Now we construct a null-space projection matrix  $L_n$  such that  $x_{cms} = L_n x_{nred}$ , where  $x_{nred}$  is the null space reduced set of DOFs ( $N_{cms} - 6$ ). Note that the matrix  $L_1^T K L_1$  has only 6 RBMs (and not 7) since the interfaces have been stuck together by the  $L_1$  matrix.

```

52 %% Remove fixed interface null-space
53 L1 = null(Lrel);
54 [V,D] = eigs(L1'*K*L1, L1'*M*L1, 20, 'SM'); % Get first 20 modes
55 Ln = null(V(:, 1:6)'*L1'*M); % First six modes are RBMs
56
57 Nn = size(Ln, 2); % Null-reduced DOFs
```

6. Now conduct the nonlinear prestress simulation using a uniform penalty stiffness of  $5 \times 10^6 \text{ Pam}^{-1}$  (units of traction per displacement). The normal contact is simulated using a penalty stiffness formulation for simplicity.

```

58 %% Solve the Nonlinear Static Prestress Problem
59 bpmag = 12e3;
60 knl = 5e6/(Ar_tot/Ne); % knl divided by avg element area
61 U0 = (Ln'*K*Ln + (Grel'*Ln)'*(Lrel*Ln)*knl)\(Ln'*Fv*bpmag);
62
63 opt = optimoptions('fsolve', 'specifyObjectiveGradient', true, ...
64 'Display', 'iter');
65 [U0, ~, ~, ~, J0] = fsolve(@(U) RESFUN([U; bpmag], Ln'*K*Ln, Ln'*Fv, ...
66 Lrel*Ln, Ln'*Grel, knl), U0, opt);
67
68 %% Linearized Modal Analysis
69 [V0, D0] = eigs(J0, Ln'*M*Ln, 10, 'SM');
70 W0 = sqrt(diag(D0));
71 disp(table((1:10)', W0/2/pi, 'VariableNames', ...
72 {'Index', 'Frequency (Hz)'}))
```

The last few lines conduct a modal analysis from the prestressed state. As of the time of writing, convergence was observed in about 21 iterations (using MATLAB R2022a). This prints the following table of the elastic modes:

| Index | Frequency (Hz) |
|-------|----------------|
| 1     | 143.74         |
| 2     | 151.3          |
| 3     | 575.08         |
| 4     | 642.81         |
| 5     | 870.59         |
| 6     | 945.37         |
| 7     | 1130.3         |
| 8     | 1476.4         |
| 9     | 1701.3         |
| 10    | 1893.6         |

This completes the analysis, and the next two action points will do some plotting of the results.

#### Static Residue Routine RESFUN.m

The following routine returns the quasi-static residue for a given normal load. Only a unilateral spring is considered in the normal direction.

```
function [R, dRdU, dRdf] = RESFUN_el2el(Uf, K, Fv, Lc, Gc, knl)
 fnl_pred = knl*Lc*Uf(1:end-1); % Predicted normal force
 fnl = max(fnl_pred, 0); % Saturated @ 0: unilateral spring

 jnl = knl*Lc; % Jacobian
 jnl(fnl==0,:) = 0;

 % Static Residue
 R = K*Uf(1:end-1)+Gc*fnl - Fv*Uf(end);
 dRdU = K+Gc*Lc*knl;
 dRdf = -Fv;
end
```

#### 5.2.1 Plotting

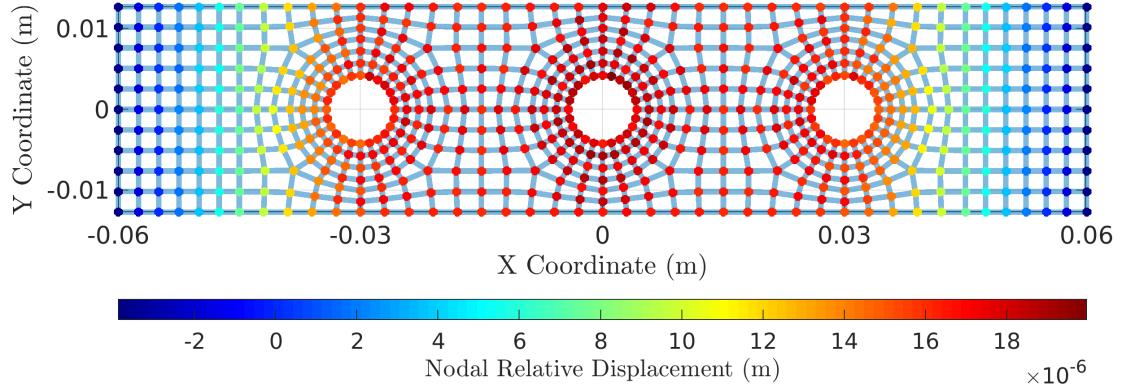
1. We next construct a MATLAB Graph object using the element information and plot out the relative normal displacements at the interface as a graph.

```
%% Depict Interfacial Displacement Field
A = zeros(N); % Graph adjacency matrix
for ei=1:Ne
 ndis = Elements(ei, 2:end); % Nodes of the current element
 A(ndis, ndis([2:end 1])) = A(ndis, ndis([2:end 1])) + eye(4);
 A(ndis([2:end 1]), ndis) = A(ndis([2:end 1]), ndis) + eye(4);
end
G = graph(A);

figure(1)
pos=get(gcf, 'Position');
set(gcf, 'Position', [pos(1:2) 900 320], 'Color', 'white')
clf()
plot(G, 'XData', Nodes(:,1), 'YData', Nodes(:,2), ...
 'NodeCData', Lrel_n*Ln*U0, ...
 'MarkerSize', 4, 'LineWidth', 3)
colormap(jet)
grid on
axis equal
axis tight
set(gca, 'XTick', (-6:3:6)*1e-2)
xlabel('X Coordinate (m)')
ylabel('Y Coordinate (m)')
xx=colorbar('SouthOutside');
xlabel(xx, 'Nodal Relative Displacement (m)', ...
```

```
'interpreter', 'latex', 'fontsize', 13)
```

The following is the output figure, showing the relative normal displacements at each node, with the nodes connected through the undirected graph constructed using the element information.

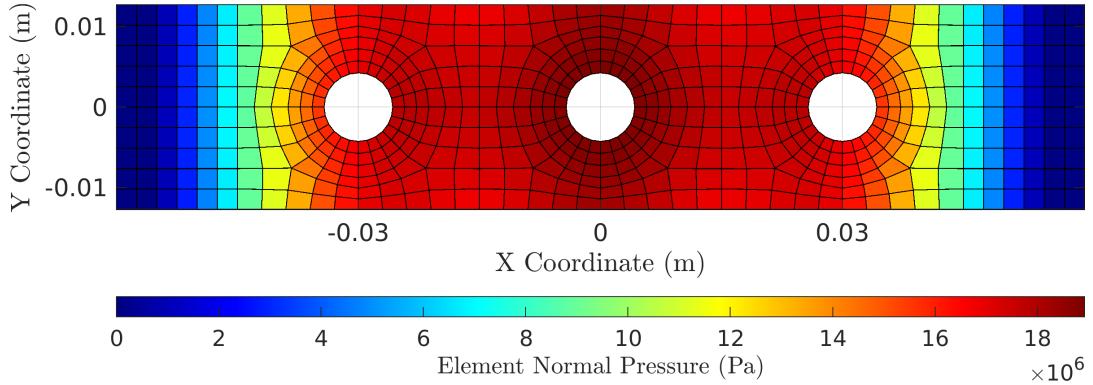


2. We can also plot the interfacial normal tractions by evaluating the contact model at the quadrature points and plotting them. Since we have just a single quadrature point per element, each element is filled in with a constant color. If multiple quadrature points are available, we can do a least-squares solve to obtain "nodal traction values", which will show the intra-element gradients also.

```
%% Show Pressure field
pvals = max(knl*Lrel*Ln*U0, 0); % pressure @ QPs
figure(3)
pos=get(gcf, 'Position');
set(gcf, 'Position', [pos(1:2) 900 320], 'Color', 'white')
clf()
for ei=1:Ne
 ndis = Elements(ei, 2:end); % Nodes of the current element
 fill(Nodes(ndis,1), Nodes(ndis,2), pvals(ei));
 hold on
end
colormap(jet)
grid on
axis equal
axis tight
set(gca, 'XTick', (-6:3:6)*1e-2)
xlabel('X Coordinate (m)')
ylabel('Y Coordinate (m)')
xx=colorbar('SouthOutside');
xlabel(xx, 'Element Normal Pressure (Pa)', ...
'interpreter', 'latex', 'fontsize', 13)
```

Here is the output of the above plotting. The non-trivial normal traction distribution is clearly observed. Higher values of  $knl$  will obtain a better estimate of the "hard" contact

results obtained from ABAQUS earlier. An alternative would be to implement a lagrange multiplier method for conducting hard contact simulations directly.



### 5.2.2 Miscellanies

1. Even if all the nodes have equal areas, **node-to-node contact elements are still inconsistent in this context**, since contact interactions can be understood to be a fundamentally local interaction, which need to be integrated to have global influence. Quadrature-based integration of local tractions to nodal forces conducts exactly this. Please see this paper for a quadrature-based implementation for the BRB using a rough contact-based frictional model in the interface.
2. You can quite easily implement a friction model also in `RESFUN.m` above. This, along with appropriately defined relative displacement matrices will be all you need to get started with your first nonlinear dynamic analysis (that may take more than just 100 lines of code, however ;-)! You can look at this paper for a list of potential contact models to employ.
3. Do check out QSMA (Quasistatic Modal Analysis) and RQNM (Rayleigh Quotient-based Nonlinear Modal Analysis). These are two powerful quasi-static nonlinear modal analysis approaches that can be implemented using a routine that is not so much more complicated than the above. The advantage will be that using such cheap simulations, remarkable insights can be gathered about the (near-resonant) vibration behavior of the structure.
4. It is often beneficial in this context to use **relative coordinates** at the interface (so we can get a 2x reduction in the total number of unknowns in the problem). You can do this in MATLAB on the HCB reduced model, or you can do this directly in the ABAQUS model by introducing ghost nodes representing the relative displacements. Please write to me if you're having trouble with this particular aspect.

## 6 Outro/Contact

In summary, all the scripts used in the tutorial are provided in

1. `a_steelemat.py`: Loading material

2. b\_halfbm.py: Building the half-beam model
3. c\_nutwasherbolt\_516.py: Building the bolt, nut, and washer models.
4. d\_applyconstraints.py: Applying the relevant constraints and introducing bolt prestress.
5. e\_nodeproc.py: The postprocessing script create surface node sets and setting up substructure analysis.
6. readwritematvec.sh: Contains the mtx reading script written with **bash** and **python**.
7. main.m: Contains the MATLAB file for doing the nonlinear static prestress analysis (also see RESFUN.m for the residue routine).

Don't forget to check out the repository in github at <https://github.com/Nidish96/Abaqus4Joints>. It has the above scripts as well as all the cae files.

You can contact me at nidish.balaji@ila.uni-stuttgart.de or nidbid@gmail.com for any questions/suggestions.

If you found this useful, please consider citing this paper and/or this thesis.