An Abaqus-Matlab Tutorial for Jointed Systems

International Committee on Jointed Structures Seminar Series

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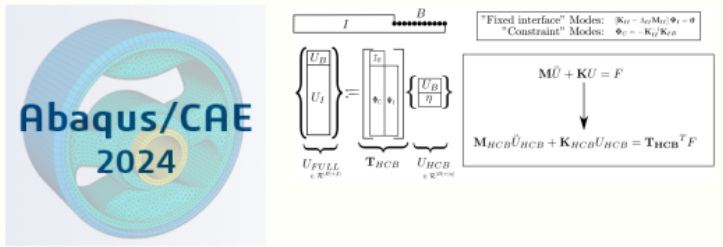
Detailed Instructions are hosted through Github in a repository named Nidish96/Abaqus4Joints

Acknowledgements

- Prof. Matthew Brake
- Dr. Justin Porter, Maeve Karpov
- Prof. Matt Allen

Abaqus Workflow



$\underline{M}, \underline{K}, \underline{F_b}, \underline{R}$

Mass, Stiffness

Bolt load vector

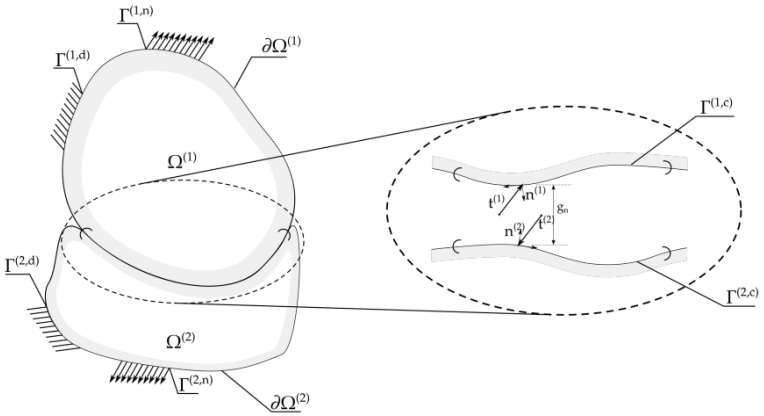
Selected rows for Recovery

DoFs: $3N_{int}+N_{gen}$

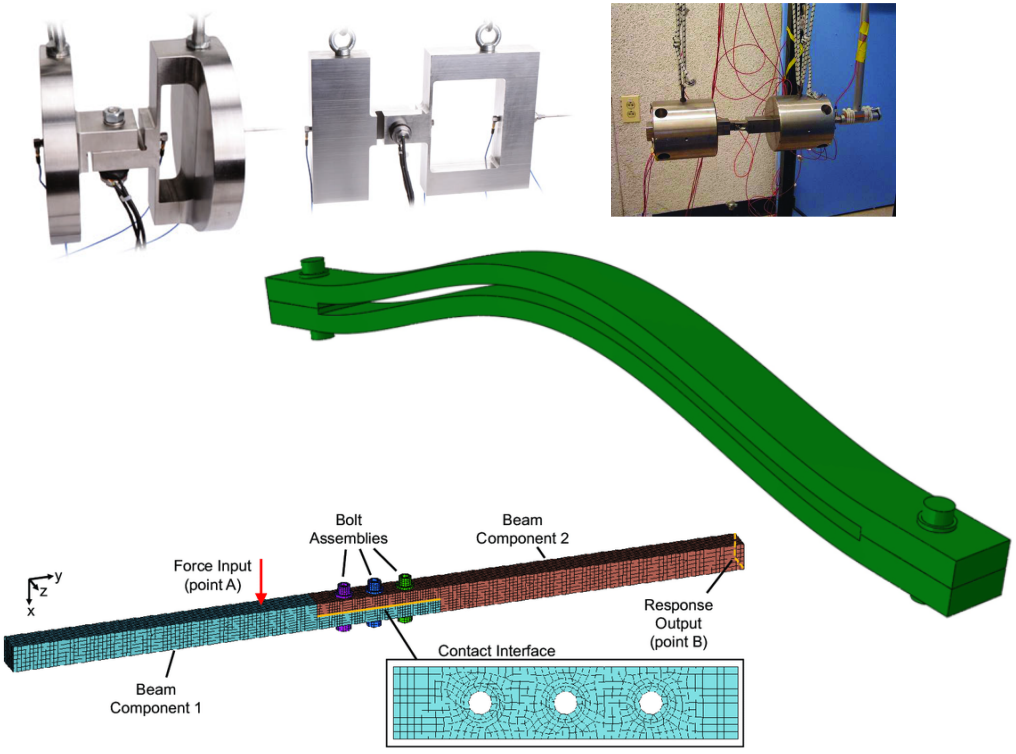
The research needs of the joints community are quite unique and specific

1. Introduction

The Generic Contact Problem



Joints Benchmarks (see jointmechanics.org)



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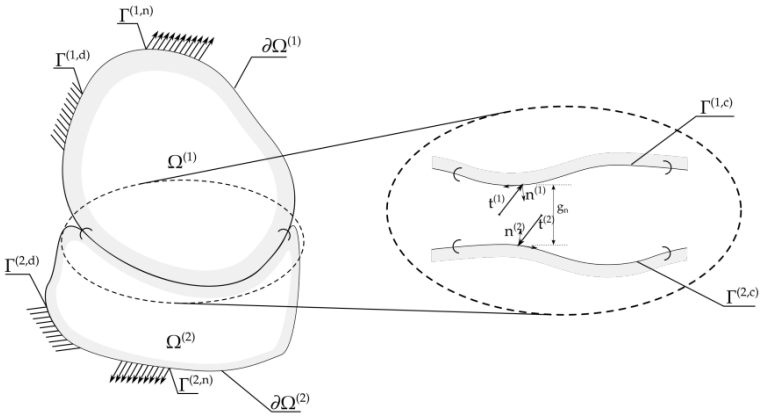

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Linear subcomponents joined through a non-linear contact interface undergoing small deformation vibrations

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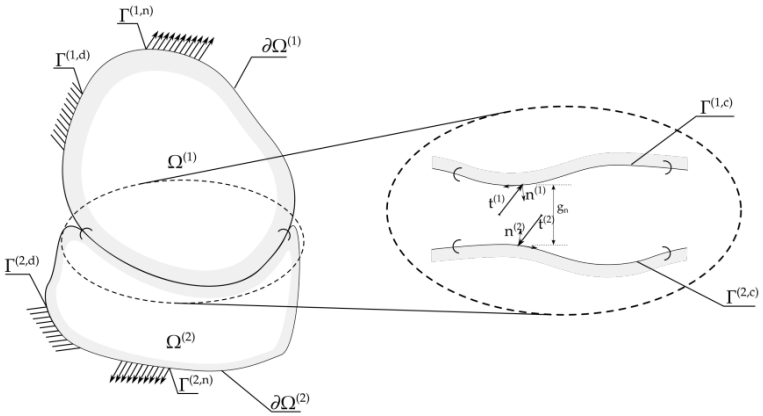

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The HCB/CMS Methodology

"Fixed interface" Modes: $[\mathbf{K}_{II} - \Lambda_{II}\mathbf{M}_{II}]\,\Psi_I = \mathbf{0}$

"Constraint" Modes: $\Phi_C = -\mathbf{K}_{II}^{-1}\mathbf{K}_{IB}$

$$\begin{Bmatrix} U_B \\ U_I \end{Bmatrix} := \begin{bmatrix} \mathcal{I}_B & \\ \Phi_C & \Psi_I \end{bmatrix} \begin{Bmatrix} U_B \\ \eta \end{Bmatrix}$$

$U_{FULL} \in \mathcal{R}^{|B|+|I|}$ $\quad \mathbf{T}_{HCB}$ $\quad U_{HCB} \in \mathcal{R}^{|B|+|\eta|}$

$$\mathbf{M}\ddot{U} + \mathbf{K}U = F$$

$$\downarrow$$

$$\mathbf{M}_{HCB}\ddot{U}_{HCB} + \mathbf{K}_{HCB}U_{HCB} = \mathbf{T_{HCB}}^T F$$

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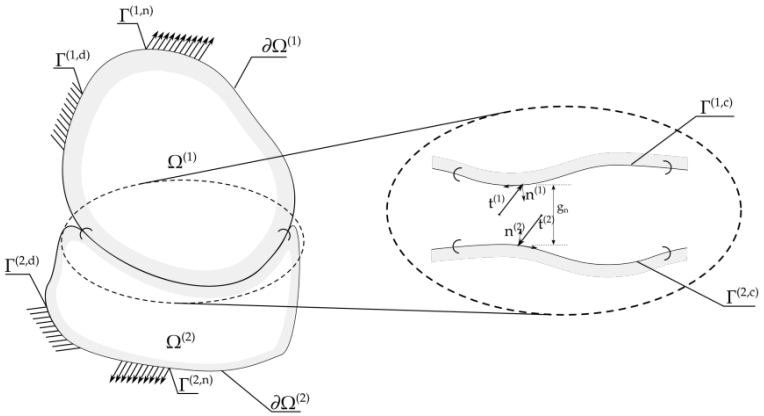

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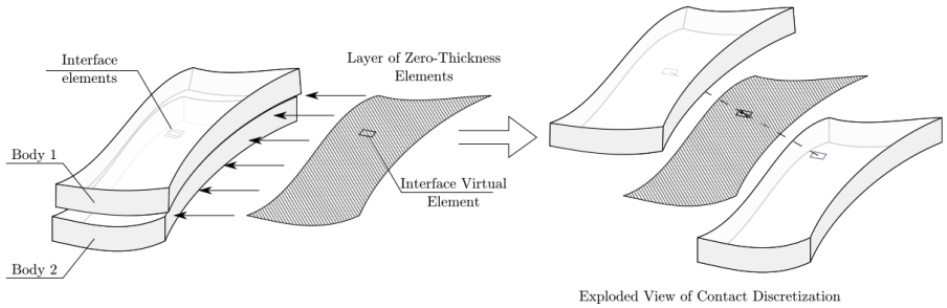
Interface Virtual Element Representations



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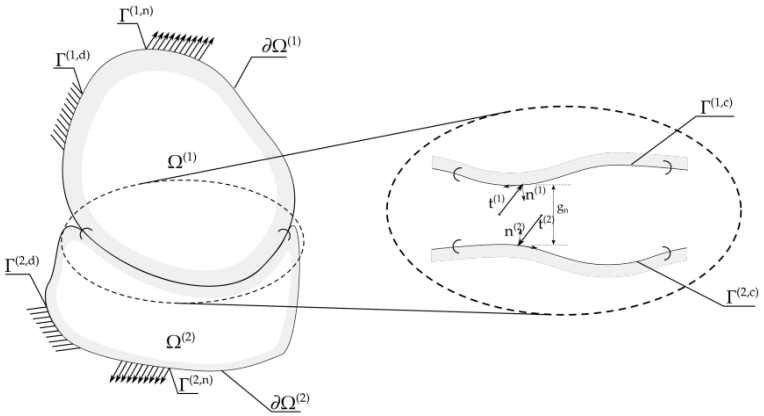

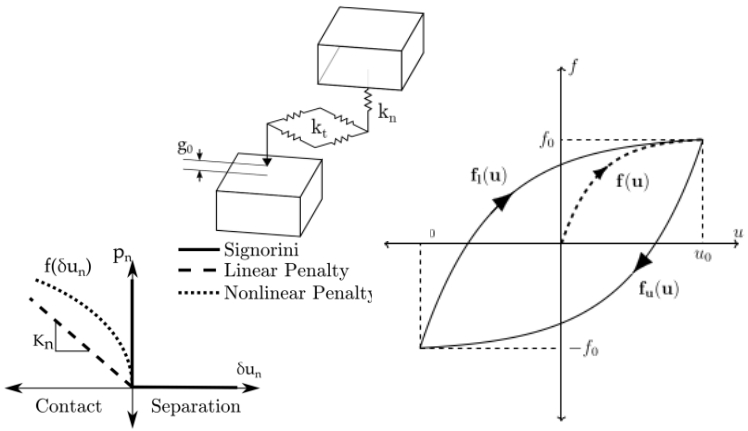

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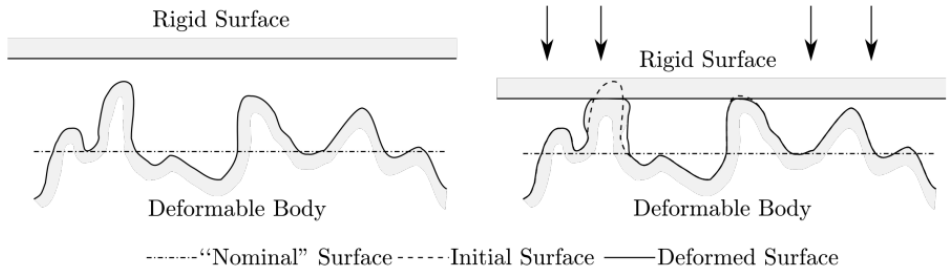
Interface Constitutive Modeling



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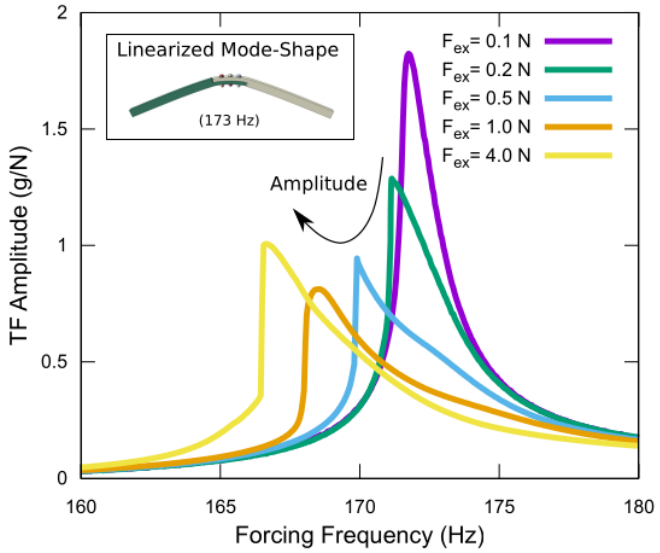
1. Introduction

Nonlinear Responses



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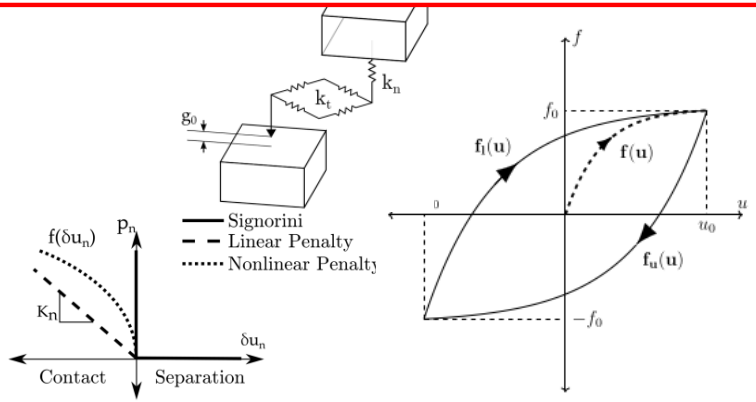

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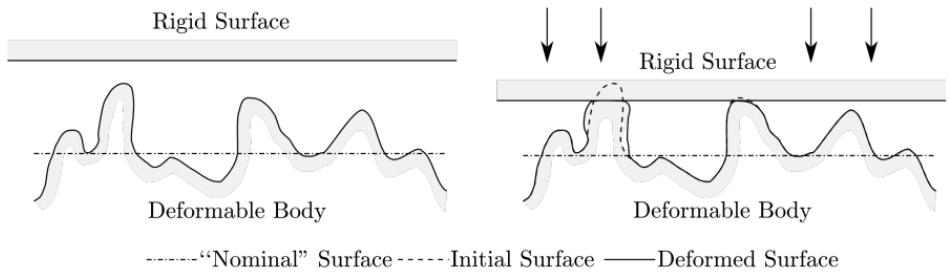

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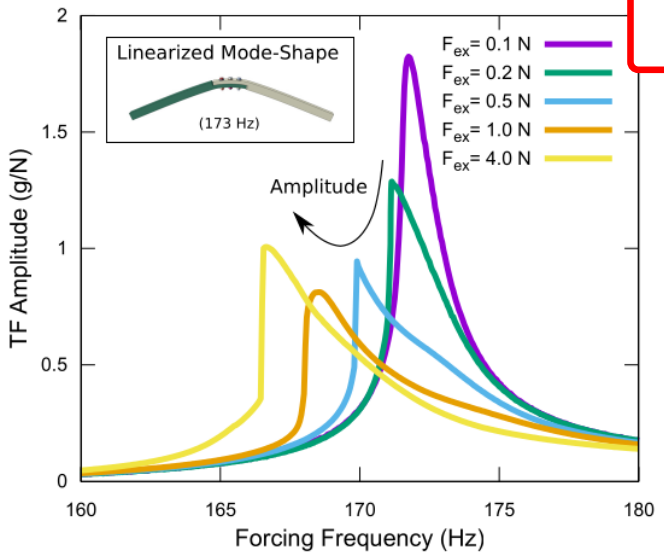
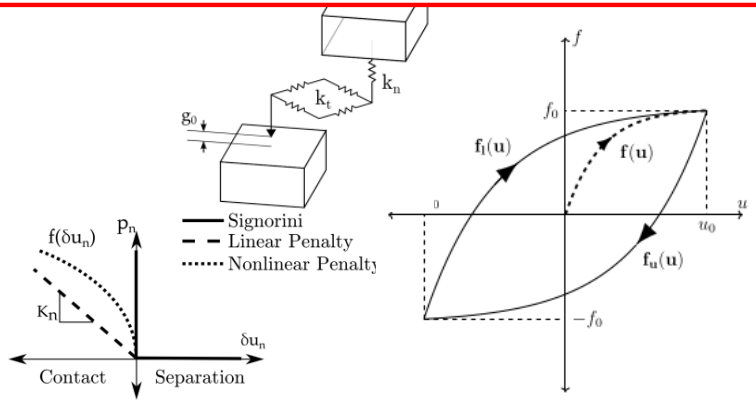


Goal: Off-Load as much as possible to **focus on joints.**

Common theme:
Linear subcomponents joined through a non-linear contact interface undergoing small deformation vibrations



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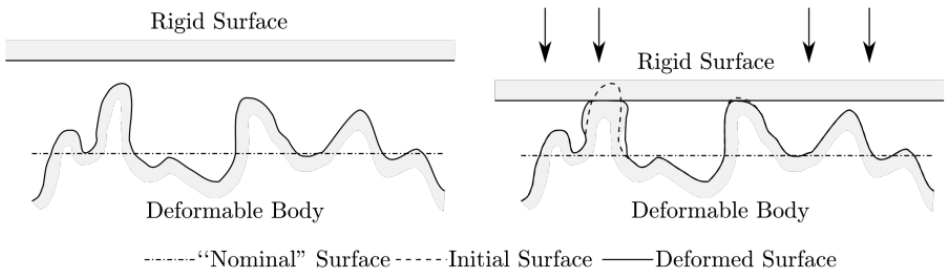
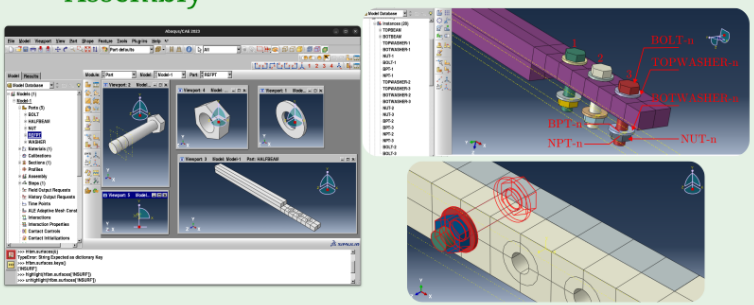


An Overview of the Modeling Pipeline

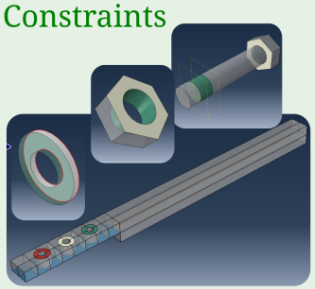
2.Outline of the Steps

Pre-Processing

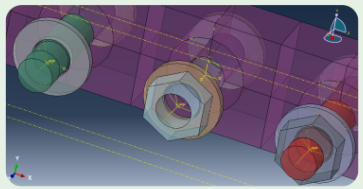
Assembly



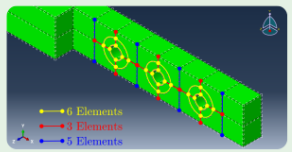
Constraints

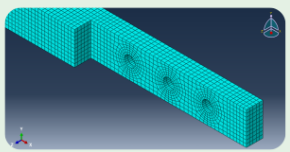


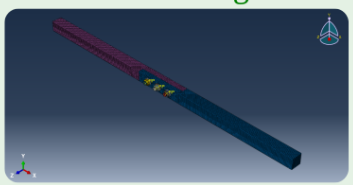
Bolt Prestress as Static Load



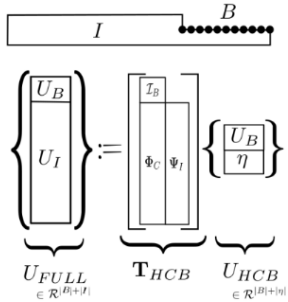
Seeded Meshing, Processing







Component Mode Synthesis



"Fixed interface" Modes: $[\mathbf{K}_{II} - \Lambda_{II}\mathbf{M}_{II}]\,\Psi_I = \mathbf{0}$

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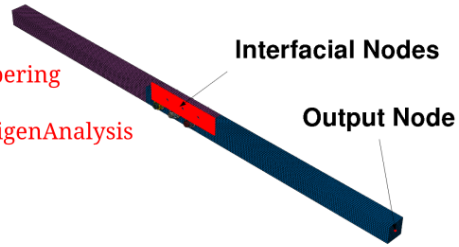
$$\mathbf{M}_{HCB}\ddot{U}_{HCB} + \mathbf{K}_{HCB}U_{HCB} = \mathbf{T_{HCB}}^T F$$

+ Reorganize NodeSet numbering
+ Choose recovery nodes
+ Conduct Fixed Interface EigenAnalysis



Matrix Extraction

+ Use the provided python script to convert the mtx files into MATLAB mat files

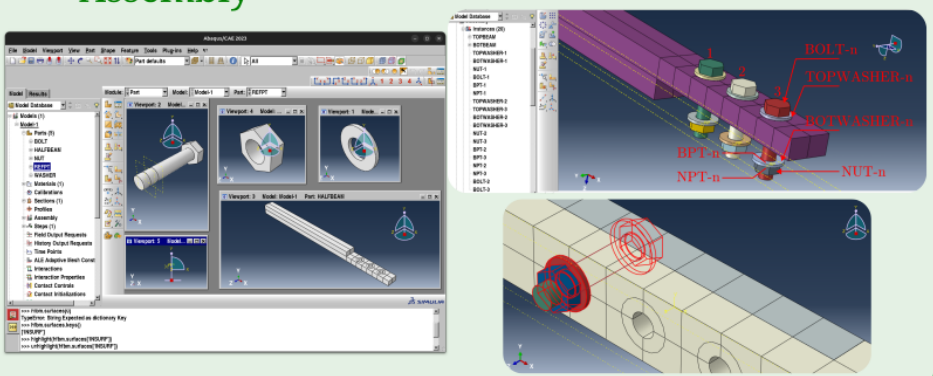
```
**
** STEP: HCBCMS
**
*Step, name=HCBCMS, nlgeom=NO
*Substructure Generate, overwrite, type=Z1, recovery matrix=YES,
      nset=OutNodes, mass matrix=YES
*Select Eigenmodes, generate
1, 20, 1
*Damping Controls, structural=COMBINED, viscous=COMBINED
*Retained Nodal Dofs, sorted=NO
BOTS_NDS, 1, 3
TOPS_NDS, 1, 3
**
** LOAD CASES
**
*Substructure Load Case, name=LCASE
** Name: BoltLoad-1   Type: Concentrated force   Scale factor: 1
*Cload
BPT-1_Set-1, 3, 1.
** Name: BoltLoad-2   Type: Concentrated force   Scale factor: 1
*Cload
BPT-2_Set-1, 3, 1.
** Name: BoltLoad-3   Type: Concentrated force   Scale factor: 1
*Cload
BPT-3_Set-1, 3, 1.
** Name: NutLoad-1   Type: Concentrated force   Scale factor: 1
*Cload
NPT-1_Set-1, 3, -1.
** Name: NutLoad-2   Type: Concentrated force   Scale factor: 1
*Cload
NPT-2_Set-1, 3, -1.
** Name: NutLoad-3   Type: Concentrated force   Scale factor: 1
*Cload
NPT-3_Set-1, 3, -1.
*Substructure Matrix Output, FILE NAME=Modelmats, MASS=YES,
      STIFFNESS=YES, SLOAD=YES, RECOVERY MATRIX=YES
*End Step
```

An Overview of the Modeling Pipeline

2.Outline of the Steps

Pre-Processing

Assembly



Load

Seeded Meshing, Processing

Component Mode Synthesis

"Fixed interface" Modes: $[K_{II} - \Lambda_I M_{II}]\Psi_I = 0$

"Constraint" Modes: $\Phi_C = -K_{II}^{-1} K_{IB}$

$$M\ddot{U} + KU = F$$

$$M_{HCB}\ddot{U}_{HCB} + K_{HCB}U_{HCB} = T_{HCB}{}^T F$$

Reorganize NodeSet numbering
+ Choose recovery nodes
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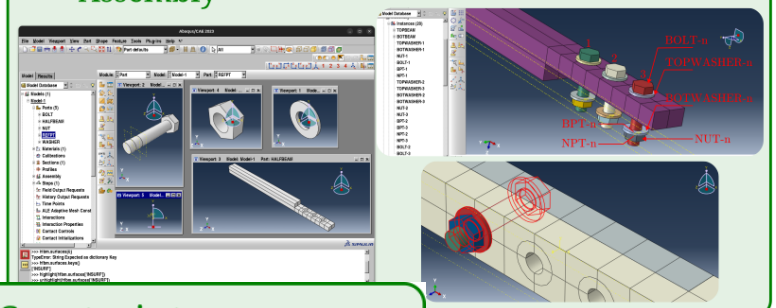
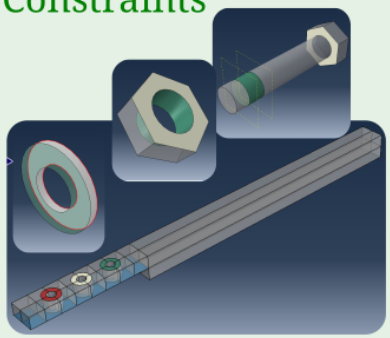


Constraints



Bolt Prestress as Static Load

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$$\{U_B\} \quad \{U_I\} := \begin{bmatrix} I_B \\ \Phi_C \ \Psi_I \end{bmatrix} \{U_B \ \eta\}$$

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U_{FULL} T_{HCB} U_{HCB}

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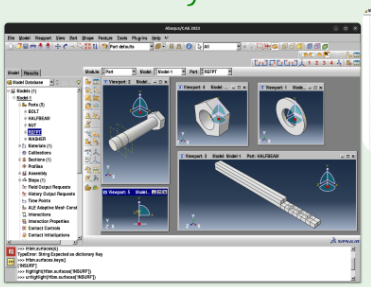
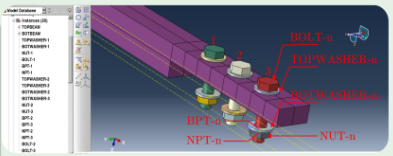
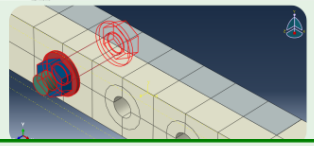
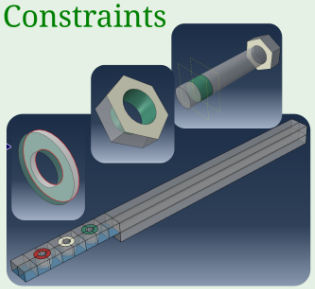






Constraints



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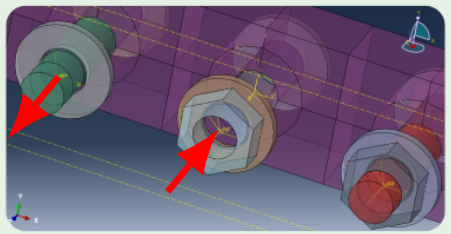

Processing

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"Pull the Bolts, Push the Washers"

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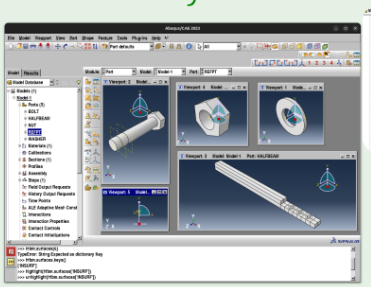
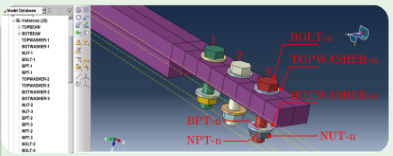
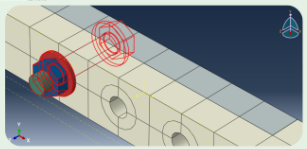
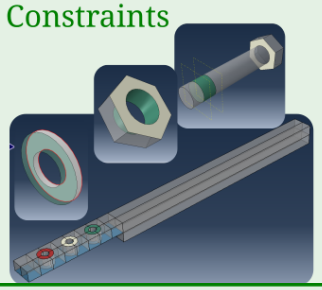


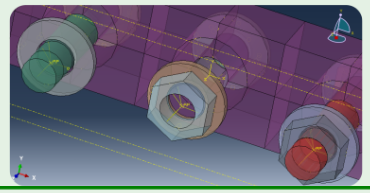




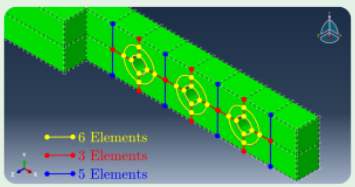
Constraints

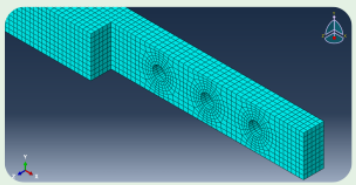


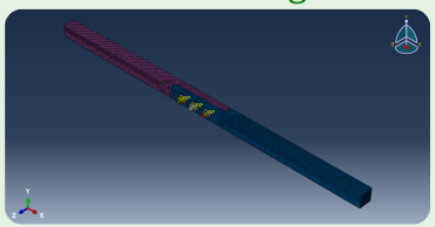
Bolt Prestress as Static Load



Seeded Meshing, Processing







Component Mode Synthesis

"Fixed interface" Modes: $[K_{II} - \Lambda_I M_{II}]\Psi_I = 0$

"Constraint" Modes: $\Phi_C = -K_{II}^{-1} K_{IB}$

$$M\ddot{U} + KU = F$$

$$M_{HCB}\ddot{U}_{HCB} + K_{HCB}U_{HCB} = T_{HCB}{}^T F$$

+ Reorganize NodeSet numbering
+ Choose recovery nodes
+ Conduct Fixed Interface EigenAnalysis

Matrix Extraction

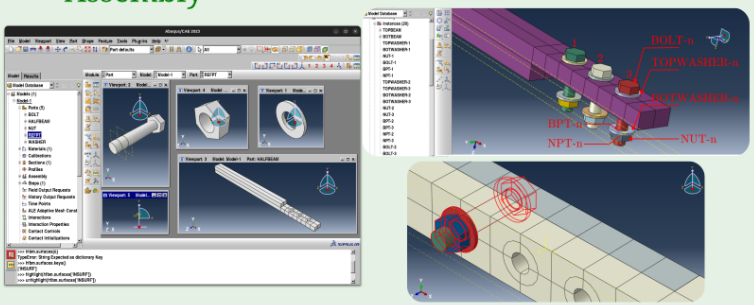
+ Use the provided python script to convert the mtx files into MATLAB mat files

An Overview of the Modeling Pipeline

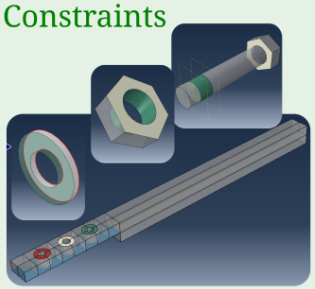
2.Outline of the Steps

Pre-Processing

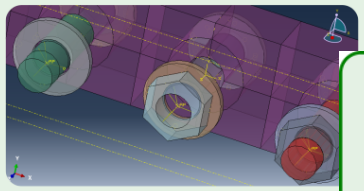
Assembly



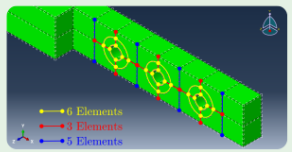
Constraints

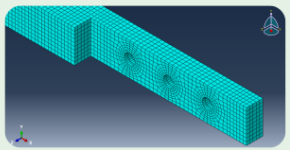


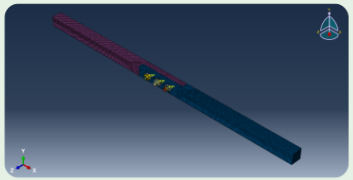
Bolt Prestress as Static Load



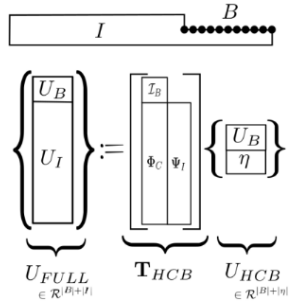
Seeded Meshing, Processing







Component Mode Synthesis



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$$\mathbf{M}\ddot{U} + \mathbf{K}U = F$$

$$\mathbf{M}_{HCB}\ddot{U}_{HCB} + \mathbf{K}_{HCB}U_{HCB} = \mathbf{T_{HCB}}^T F$$

+ Reorganize NodeSet numbering
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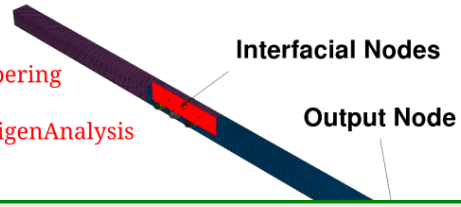

Matrix Extraction

+ Use the provided python script to convert the mtx files into MATLAB mat files

```
** ----------------------------------------------------------------
**
** STEP: HCBCMS
**
*Step, name=HCBCMS, nlgeom=NO
*Substructure Generate, overwrite, type=Z1, recovery matrix=YES,
        nset=OutNodes, mass matrix=YES
*Select Eigenmodes, generate
1, 20, 1
*Damping Controls, structural=COMBINED, viscous=COMBINED
*Retained Nodal Dofs, sorted=NO
BOTS_NDS, 1, 3
TOPS_NDS, 1, 3
**
** LOAD CASES
**
*Substructure Load Case, name=LCASE
** Name: BoltLoad-1   Type: Concentrated force   Scale factor: 1
*Cload
BPT-1_Set-1, 3, 1.
** Name: BoltLoad-2   Type: Concentrated force   Scale factor: 1
*Cload
BPT-2_Set-1, 3, 1.
** Name: BoltLoad-3   Type: Concentrated force   Scale factor: 1
*Cload
BPT-3_Set-1, 3, 1.
** Name: NutLoad-1   Type: Concentrated force   Scale factor: 1
*Cload
NPT-1_Set-1, 3, -1.
** Name: NutLoad-2   Type: Concentrated force   Scale factor: 1
*Cload
NPT-2_Set-1, 3, -1.
** Name: NutLoad-3   Type: Concentrated force   Scale factor: 1
*Cload
NPT-3_Set-1, 3, -1.
*Substructure Matrix Output, FILE NAME=Modelmats, MASS=YES,
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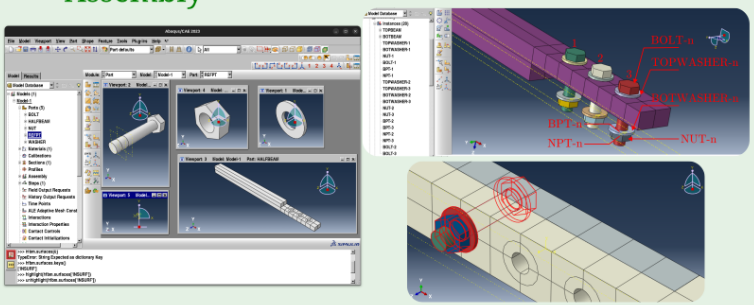
*End Step
```

An Overview of the Modeling Pipeline

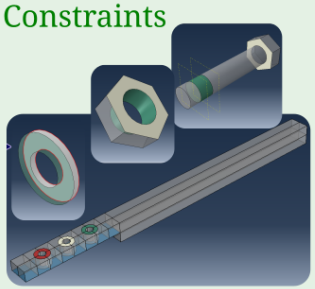
2.Outline of the Steps

Pre-Processing

Assembly



Constraints



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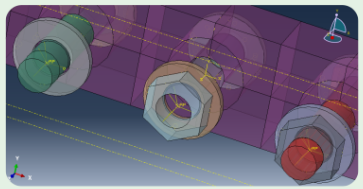

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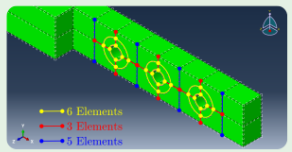

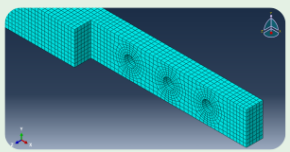

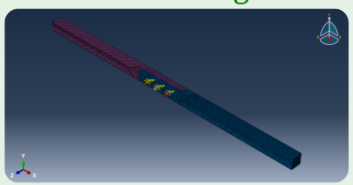

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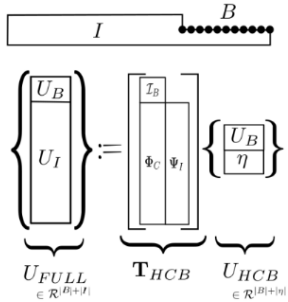

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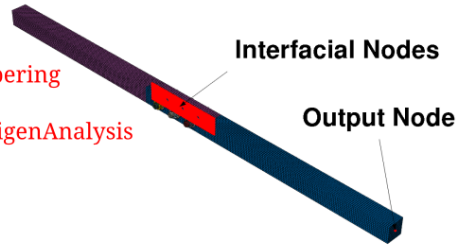

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*End Step
```

2.1. Relative Coordinates Pipeline

Outline of the Steps

- Suppose that $\underline{u}_T, \underline{u}_B, \underline{u}_I$ are the vectors of top, bottom, and internal nodal DoFs.
- Then the governing equations look like:

$$\begin{bmatrix} \underline{\underline{M}}_{TT} & \underline{\underline{M}}_{TB} & \underline{\underline{M}}_{TI} \\ & \underline{\underline{M}}_{BB} & \underline{\underline{M}}_{BI} \\ \text{sym} & & \underline{\underline{M}}_{II} \end{bmatrix} \begin{bmatrix} \ddot{\underline{u}}_T \\ \ddot{\underline{u}}_B \\ \ddot{\underline{u}}_I \end{bmatrix} + \begin{bmatrix} \underline{\underline{K}}_{TT} & \underline{\underline{K}}_{TB} & \underline{\underline{K}}_{TI} \\ & \underline{\underline{K}}_{BB} & \underline{\underline{K}}_{BI} \\ \text{sym} & & \underline{\underline{K}}_{II} \end{bmatrix} \begin{bmatrix} \underline{u}_T \\ \underline{u}_B \\ \underline{u}_I \end{bmatrix} + \begin{bmatrix} \underline{F}_T^{(c)} \\ \underline{F}_B^{(c)} \\ \underline{0} \end{bmatrix} = \underline{F}_e(t)$$

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- Under the relative coordinate transformation,

$$\begin{bmatrix} \underline{u}_T \\ \underline{u}_B \\ \underline{u}_I \end{bmatrix} = \begin{bmatrix} \underline{\underline{I}}_T & \underline{\underline{I}}_T & \underline{\underline{0}} \\ \underline{\underline{0}} & \underline{\underline{I}}_T & \underline{\underline{0}} \\ \underline{\underline{0}} & \underline{\underline{0}} & \underline{\underline{I}}_I \end{bmatrix} \begin{bmatrix} \Delta\underline{u} \\ \underline{u}_B \\ \underline{u}_I \end{bmatrix}, \qquad \Delta\underline{u} = \underline{u}_T - \underline{u}_B.$$

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- Under the relative coordinate transformation,

Transformed Equations of Motion

$$\begin{bmatrix} \underline{\underline{M}}_{TT} & \underline{\underline{M}}_{TT} + \underline{\underline{M}}_{TB} & \underline{\underline{M}}_{TI} \\ & \underline{\underline{M}}_{TT} + \underline{\underline{M}}_{BB} + \underline{\underline{M}}_{TB} + \underline{\underline{M}}_{TB}^T & \underline{\underline{M}}_{TI} + \underline{\underline{M}}_{BI} \\ \text{sym} & & \underline{\underline{M}}_{II} \end{bmatrix} \begin{bmatrix} \Delta\ddot{\underline{u}} \\ \ddot{\underline{u}}_B \\ \ddot{\underline{u}}_I \end{bmatrix} + \begin{bmatrix} & \overline{K} & \\ & & \end{bmatrix} \begin{bmatrix} \Delta\underline{u} \\ \underline{u}_B \\ \underline{u}_I \end{bmatrix} + \begin{bmatrix} \underline{F}_T^{(c)} \\ \underline{0} \\ \underline{0} \end{bmatrix} = \underline{F}_e(t).$$

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Outline of the Steps

- Suppose that $\underline{u}_T, \underline{u}_B, \underline{u}_I$ are the vectors of top, bottom, and internal nodal DoFs.
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2.1. Relative Coordinates Pipeline

- Suppose that $\underline{u}_T, \underline{u}_B, \underline{u}_I$ are the vectors of top, bottom, and internal nodal DoFs.
- Then the governing equations look like:

$$\begin{bmatrix} \underline{\underline{M}} & & \\ & & \\ \text{sy} & & \end{bmatrix} \begin{bmatrix} \ddot{\underline{u}}_T \\ \ddot{\underline{u}}_B \\ \ddot{\underline{u}}_I \end{bmatrix} + \begin{bmatrix} \overline{K} \end{bmatrix} \begin{bmatrix} \underline{u}_T \\ \underline{u}_B \\ \underline{u}_I \end{bmatrix} + \begin{bmatrix} \underline{F}_T^{(c)} \\ \underline{0} \\ \underline{0} \end{bmatrix} = \underline{F}_e(t)$$

It is clearly advantageous (when possible) to use the relative coordinate transformation as early as possible in the CMS process.

Thankfully, this is possible fully in Abaqus itself!

- Under the relative coordinate transformation,

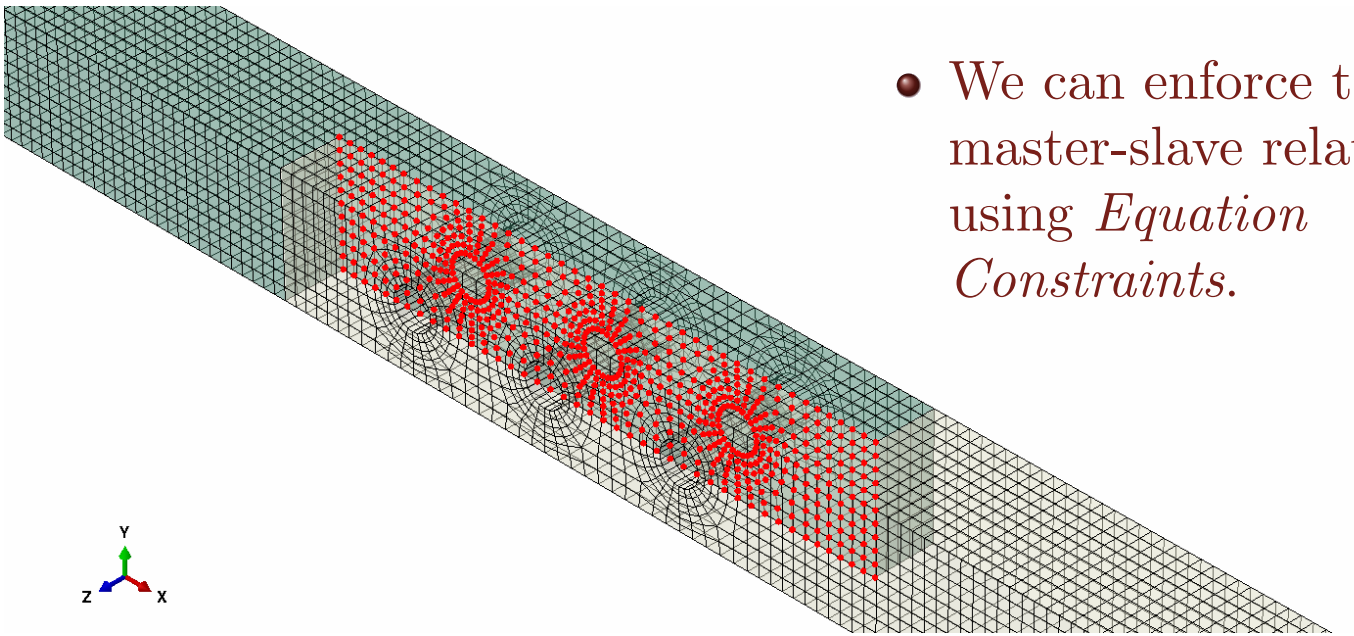
Transformed Equations of Motion

$$\begin{bmatrix} \underline{\underline{M}}_{TT} & \underline{\underline{M}}_{TT} + \underline{\underline{M}}_{TB} & \underline{\underline{M}}_{TI} \\ & \underline{\underline{M}}_{TT} + \underline{\underline{M}}_{BB} + \underline{\underline{M}}_{TB} + \underline{\underline{M}}_{TB}^T & \underline{\underline{M}}_{TI} + \underline{\underline{M}}_{BI} \\ \text{sym} & & \underline{\underline{M}}_{II} \end{bmatrix} \begin{bmatrix} \Delta\ddot{\underline{u}} \\ \ddot{\underline{u}}_B \\ \ddot{\underline{u}}_I \end{bmatrix} + \begin{bmatrix} \overline{K} \end{bmatrix} \begin{bmatrix} \Delta\underline{u} \\ \underline{u}_B \\ \underline{u}_I \end{bmatrix} + \begin{bmatrix} \underline{F}_T^{(c)} \\ \underline{0} \\ \underline{0} \end{bmatrix} = \underline{F}_e(t).$$

2.1. Relative Coordinates Pipeline

Outline of the Steps

- By adding Reference Points to the model at the location of the interfacial nodes, we can create **slave nodes whos DoF will be the relative DoF of the corresponding nodes on the interface**.
- This can be done quite easily with Python scripting (the website has a script for the BRB which can be adapted to arbitrary contexts).



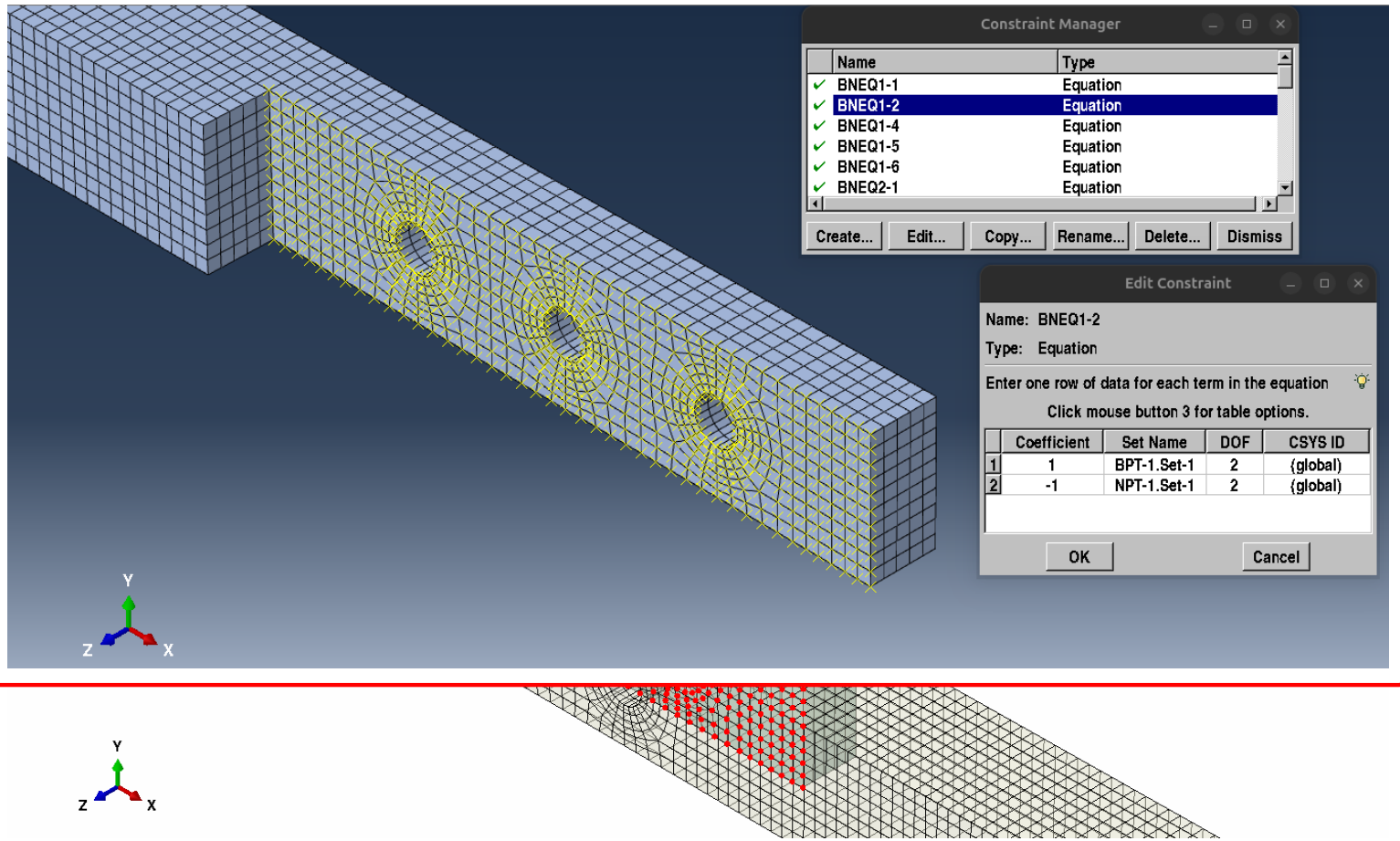
- We can enforce the master-slave relationship using *Equation Constraints*.

2.1. Relative Coordinates Pipeline

Outline of the Steps

- By adding Reference Points to the model at the location of the interfacial no
- Th

...And this is what it looks like on ABAQUS.



2.1. Relative Coordinates Pipeline

Outline of the Steps

- By adding Reference Points to the model at the location of the interfacial no
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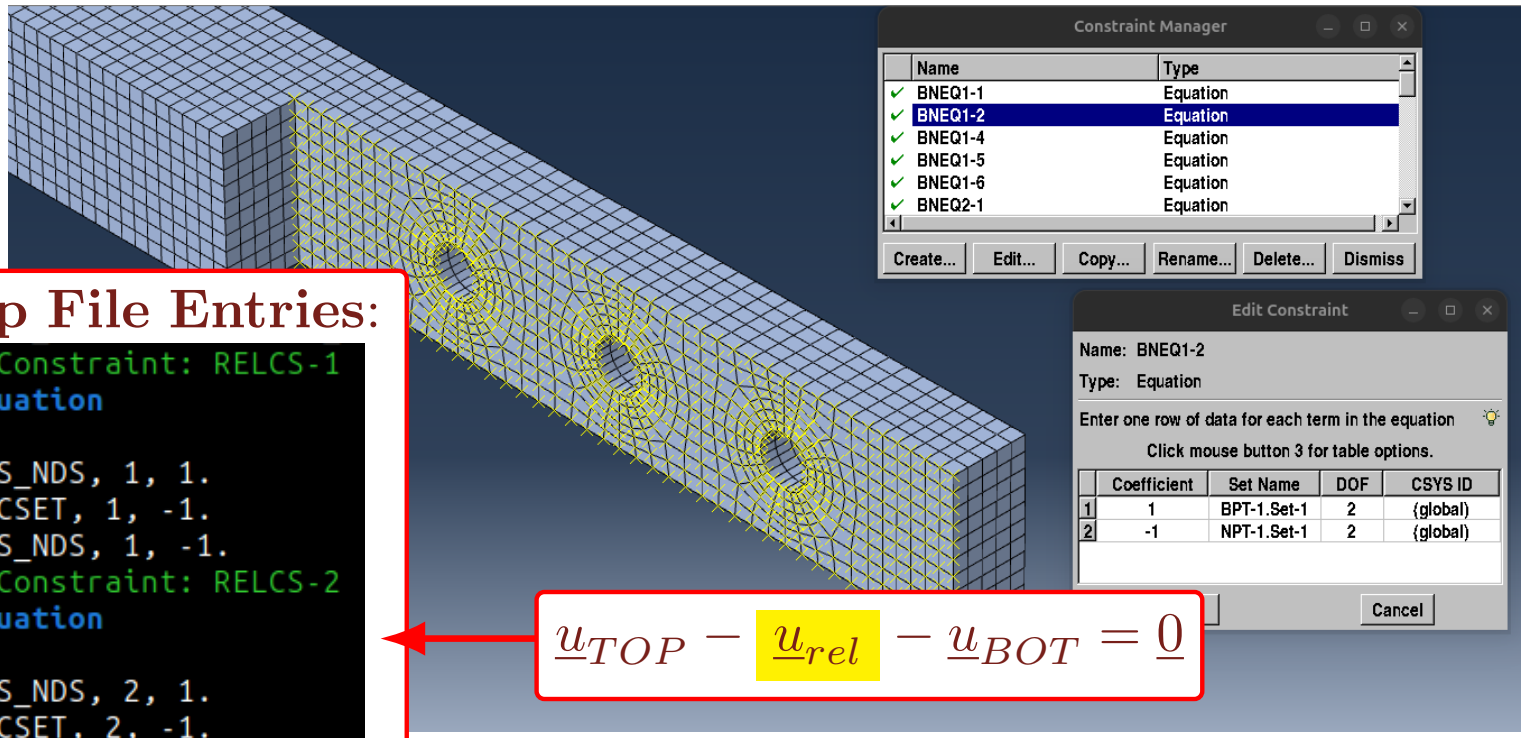
...And this is what it looks like on ABAQUS.



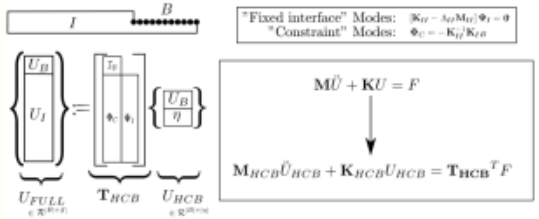
$$u_{TOP} - u_{rel} - u_{BOT} = 0$$

.inp File Entries:

```
** Constraint: RELCS-1
*Equation
3
TOPS_NDS, 1, 1.
RELCSET, 1, -1.
BOTS_NDS, 1, -1.
** Constraint: RELCS-2
*Equation
3
TOPS_NDS, 2, 1.
RELCSET, 2, -1.
BOTS_NDS, 2, -1.
** Constraint: RELCS-3
*Equation
3
TOPS_NDS, 3, 1.
RELCSET, 3, -1.
BOTS_NDS, 3, -1.
```

Nonlinear Analysis in Sub-100 Lines of MATLAB Code!

Abaqus Workflow



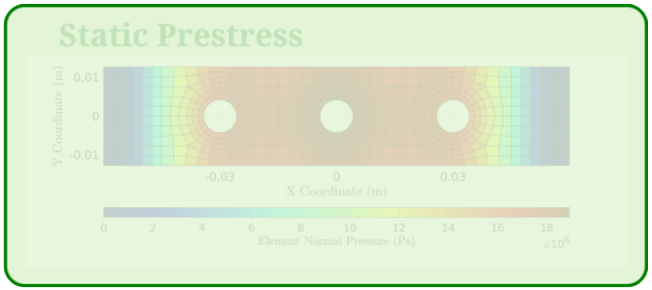
$$\underline{M}, \underline{K}, \underline{F_b}, \underline{R}$$

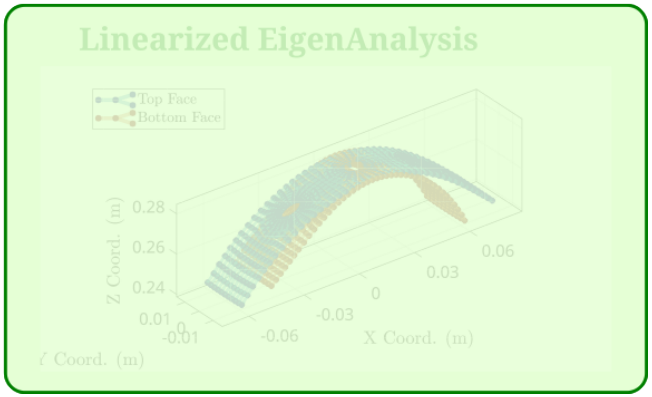
Mass, Stiffness

Bolt load vector

Selected rows for Recovery

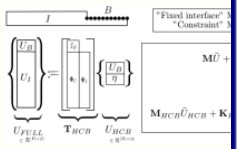
DoFs: $3N_{int}+N_{gen}$





Nonlinear Analysis in Sub-100 Lines of MATLAB Code!

Abaqus Workflow



$\underline{M}$, $\underline{K}$, $\underline{F_b}$

Mass, Stiffness

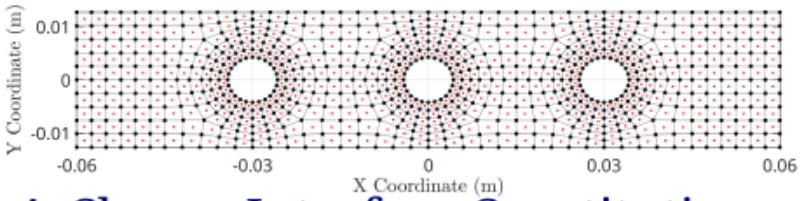
Bolt load vector

Selected rows for Recovery

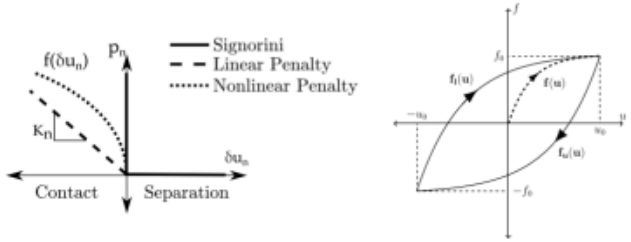
DoFs: $3N_{int}+N_{gen}$

MATLAB Workflow

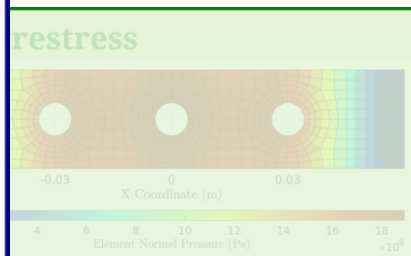
1. Read in Nodes and Elements (Only interface)
2. Read in Matrices, vector (s)
3. Choose Quadrature Rule

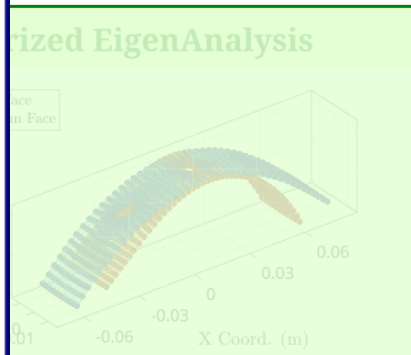


4. Choose Interface Constitution



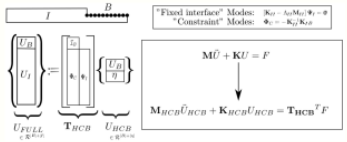
5. Apply Loads and Solve!





Nonlinear Analysis in Sub-100 Lines of MATLAB Code!

Abaqus Workflow



$$M\ddot{U} + KU = F$$

$$\mathbf{M}_{HCB}\ddot{U}_{HCB} + \mathbf{K}_{HCB}U_{HCB} = \mathbf{T}_{\mathbf{HCB}}{}^{T}F$$

M, K, F_b, R

Mass, Stiffness

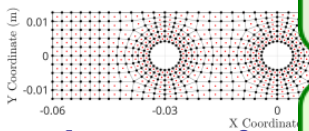
Bolt load vector

Selected rows for Recovery

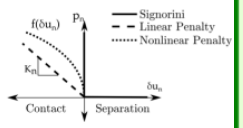
DoFs: $3N_{int}+N_{gen}$

MATLAB Workflow

1. Read in Nodes an
2. Read in Matrices,
3. Choose Quadratu

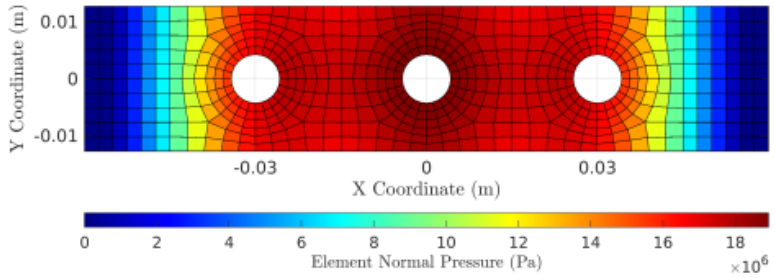


4. Choose Interface

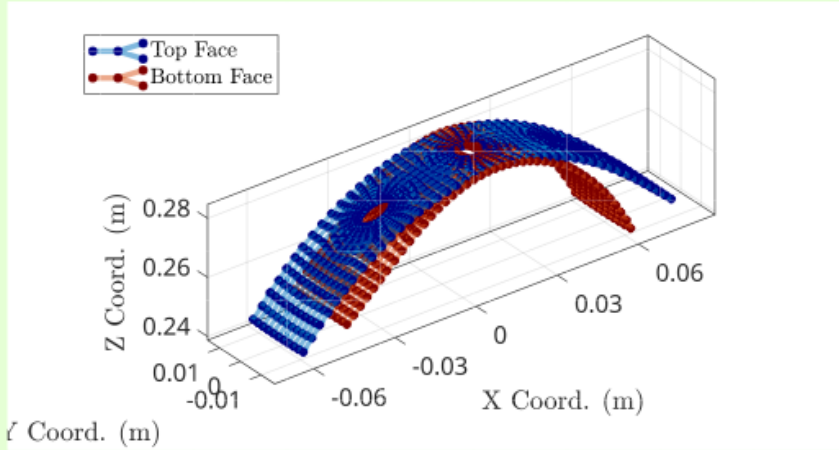


5. Apply Loads and

Static Prestress

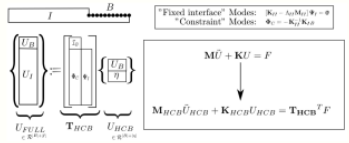


Linearized EigenAnalysis



Nonlinear Analysis in Sub-100 Lines of MATLAB Code!

Abaqus Workflow



$$\underline{M}, \underline{K}, \underline{F_b}, \underline{R}$$

Mass, Stiffness

Bolt load vector

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MATLAB Workflow

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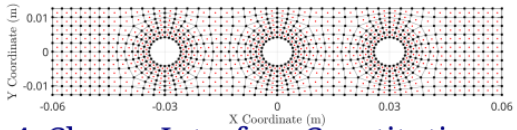
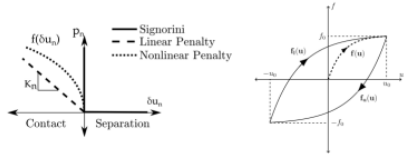
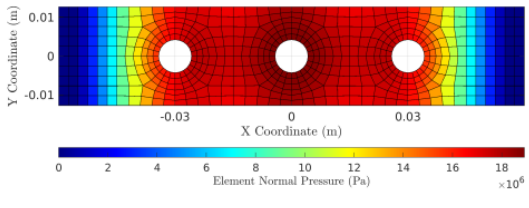


4. Choose Interface Constitution

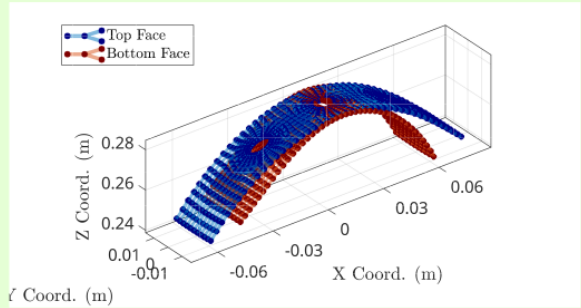


5. Apply Loads and Solve!

Static Prestress



Linearized EigenAnalysis



Comparison Between Absolute and Relative Coordinate Pipelines

Nonlinear Analysis in MATLAB

Component-Mode Synthesis

Absolute Coordinates (AC) Fixed interface HCB/CMS.

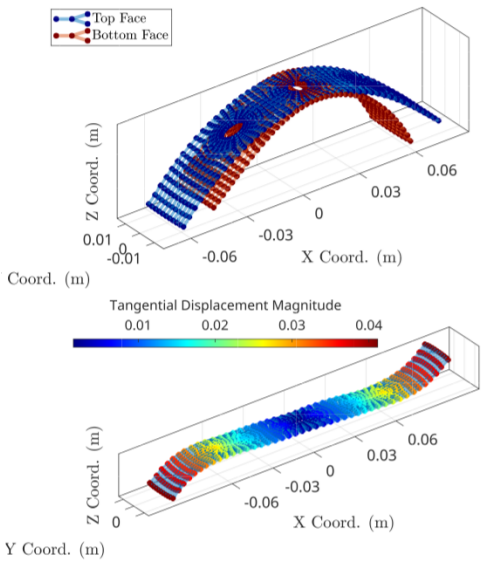
Relative Coordinates (RC) Relative DoFs are fixed. Not exactly HCB.

Numerical Comparison

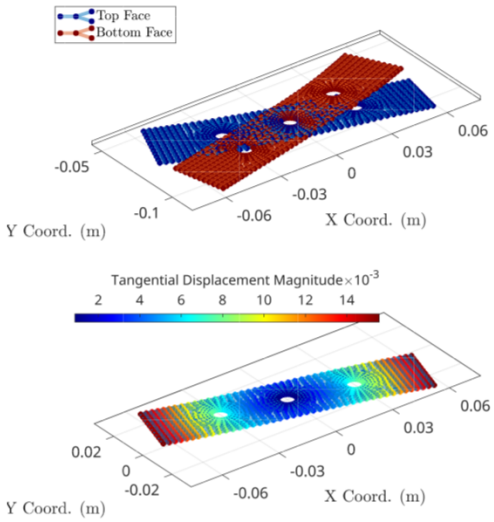
Type	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Time (s)
AC	143.74	151.30	575.08	642.81	870.59	39.86 s
RC	143.74	151.30	575.04	642.77	870.5	8.33 s

First Five Mode-Shapes At the Interface

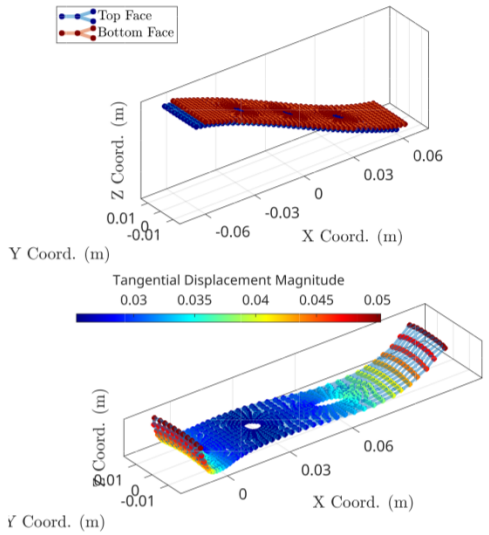
Mode 1



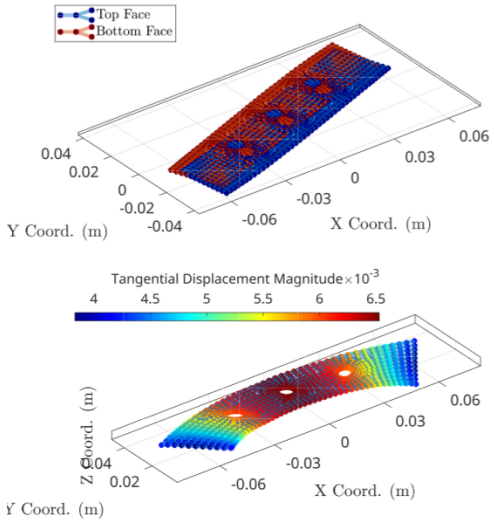
Mode 2



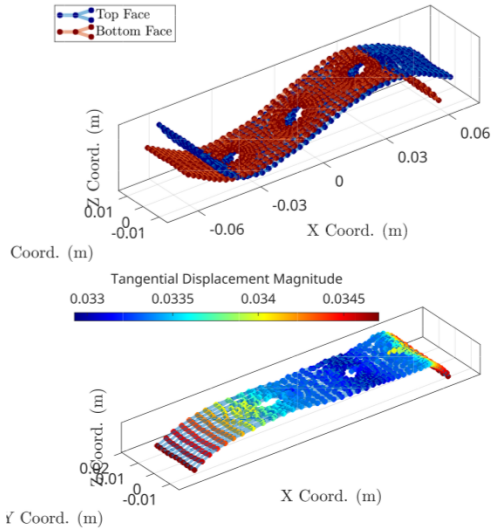
Mode 3



Mode 4



Mode 5



4. Outro and Recommendations

- When we're interested in working on friction modeling at the interfacial level, it makes sense to off-load everything else to a software.
- Try to think of ways to utilize the ABAQUS solvers as much as possible (for CMS modal analysis, etc.).

Some Drawbacks of this Pipeline

- Applicability is **strictly restricted to small displacement contact**.
- Geometrical Nonlinearities can't be present. If so, try an ICE fitting coupled with the relative coordinates approach.

We've GOT to Speak About Free and Open Source Software!

Outro and Recommendations

- ABAQUS is an impressive piece of software.
- MATLAB is great, too!

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Less Annoying Alternatives?

- Do check out Julia!
- Python has a great ecosystem too.

python™

We've GOT to Speak About Free and Open Source Software!

Outro and Recommendations

- ABAQUS is an impressive piece of software.
- MATLAB is great, too!

FOSS Alternatives

- Calculix: input very similar to ABAQUS, very practical.
- Code_Aster: Feature Rich!, super functional GUI front-end through Salome.

Less Annoying Alternatives?

- Do check out Julia!
- Python has a great ecosystem too.

code_aster

julia

python™

salome_meca
EXPERIENCE OPEN SIMULATION

Thank You!

All the detailed instructions are hosted through Github in a repository named Nidish96/Abaqus4Joints

Comments, suggestions and contributions welcome!
Please email me at nidish@iitm.ac.in.