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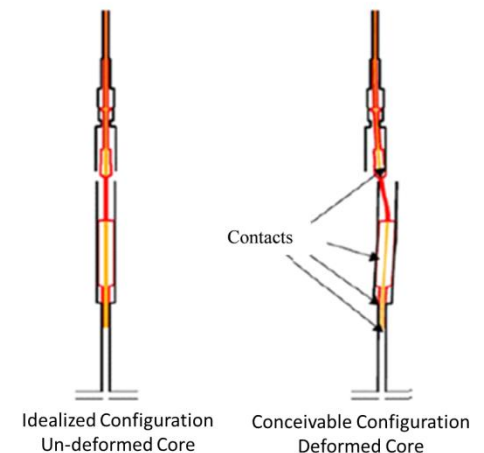
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Validation of PIRAT, a Novel Tool for Beam-Like Structures Subject to Seismic Induced Misalignment of Guiding Sleeves

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- Reactivity Control Systems (RCS) are critical components for any nuclear reactor
- These systems control the output of reactor core
- Seismic vibrations represent the most challenging situation for RCS design
- Fukushima: RCS worked, melt-down caused by Tsunami
- This work focuses on RCS used in Sodium-cooled Fast Reactors, such as Super-Phénix and ASTRID project (currently being designed by CEA, Framatome, and others)

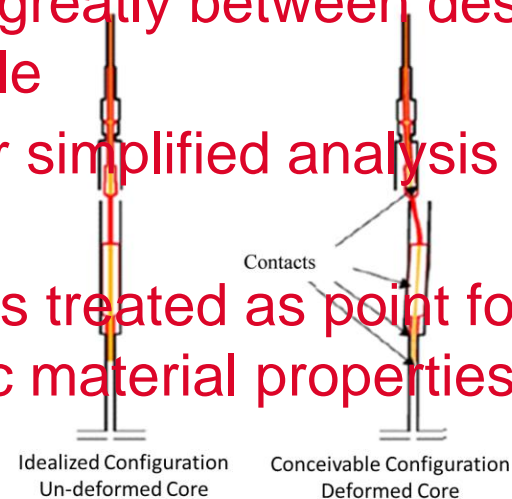
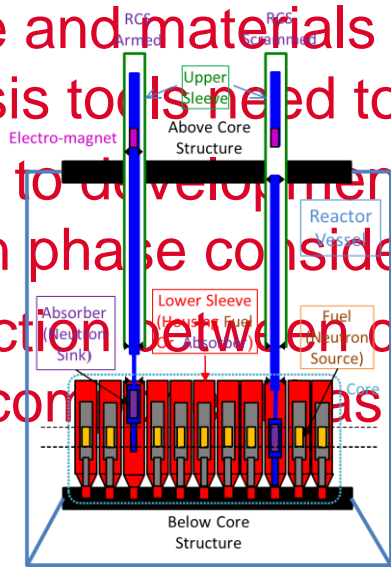


Fukushima

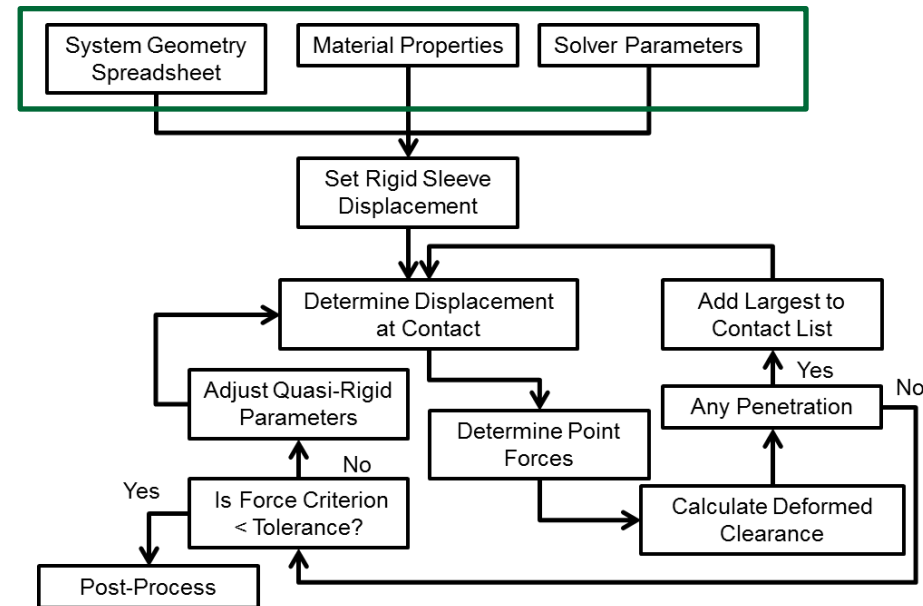


Super-Phénix

- Typically comprised on non-uniform beam-like structures that can be modeled as beam with several sections
- A typical RCS, in particular control rod assembly, is comprised of 3 main components:
 1. A Mobile Part (MP) that contains neutron absorbing material
 2. A Lower Sleeve (LS) that is considered a rigid boundary
 3. An Upper Sleeve (US) is considered a quasi-rigid boundary (within calculations treated as rigid, but equilibrium is checked)
- Shape and materials can change greatly between designs, analysis tools need to be adaptable
- Leads to development of a tool for simplified analysis for design phase consideration
- Interaction between components is treated as point forces and each component has linear-elastic material properties



- PIRAT – Python Implementation for Reliability Assessment Tools
- Toolbox created for analytical reliability analysis
- 3 main tools
 - StaBI – Static Bresse Implementation tool
 - DEBSE – Dynamic Euler-Bernoulli Implementation for Seismic Events tool
 - SIKI – Step-by-step Insertion Kinetic Implementation tool
- Currently in development with StaBI completed and current work on DEBSE
- Uses Python for calculations and Excel for geometry/materials



StaBI

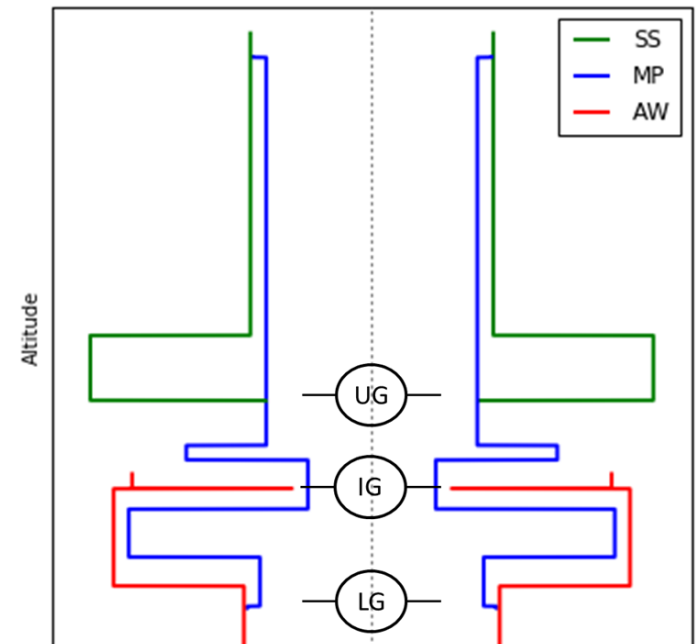
$$v(x) = v(x_0) + \theta(x_0)(x - x_0) + \int_{x_0}^x \frac{M_{fy}(\zeta)}{EI_y(\zeta)} (x - \zeta) d\zeta$$

$$\theta(x) = \theta(x_0) + \int_{x_0}^x \frac{M_{fy}(\zeta)}{EI_y(\zeta)} d\zeta$$

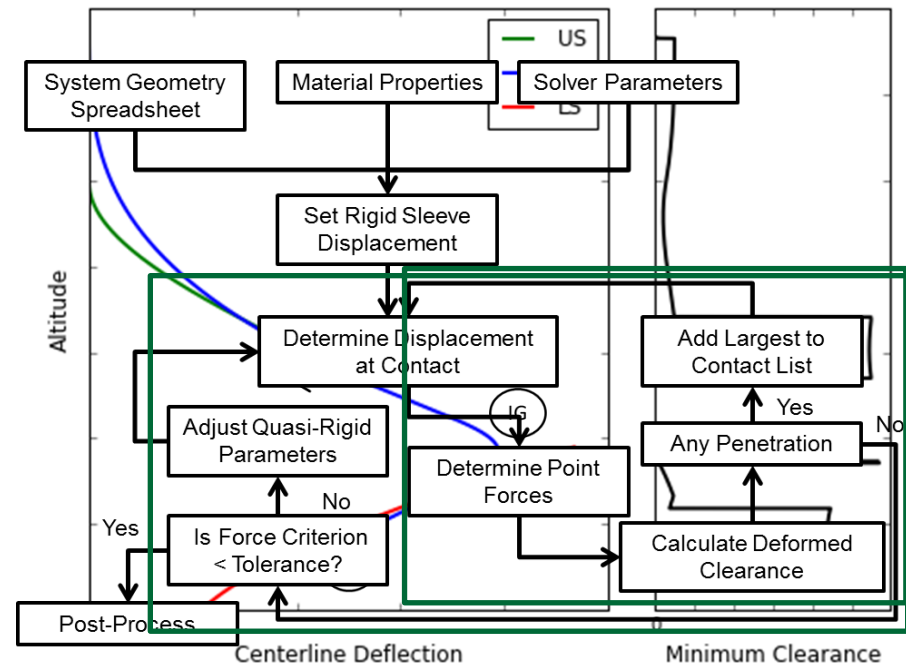
- Based on Bresse's formulation (Euler-Bernoulli Beam)
- MP is cantilevered at top with displacement and slope continuous across sections
- In this analysis, force magnitude is unknown, but displacement of MP and force location is known
- Obtain deflection of beam due to unit forces, then invert to find actual forces using superposition

$$F_k = [\bar{V}(x_k)]^{-1} \phi_k$$

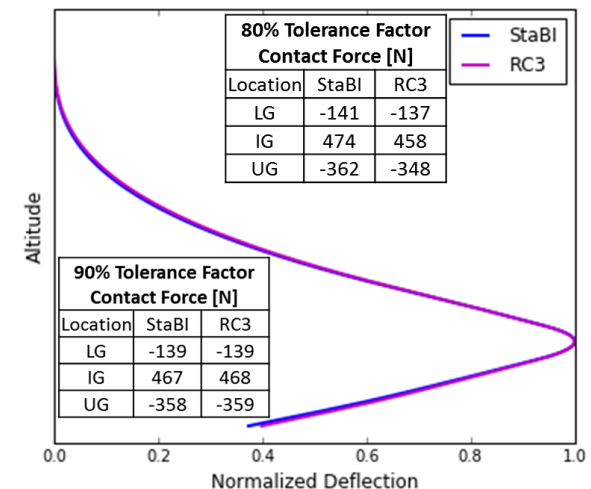
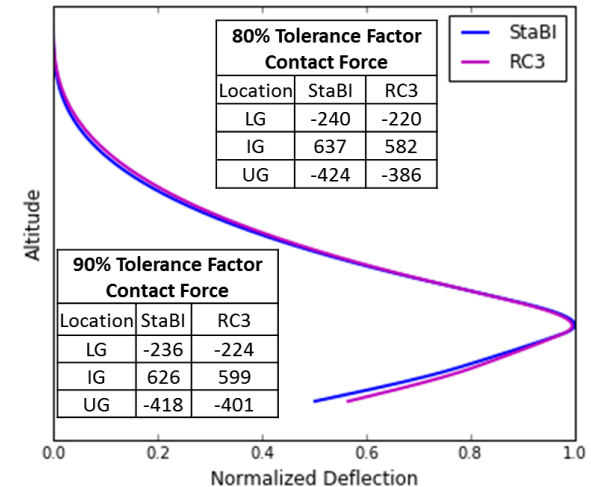
- Simplified RCS geometry
- Segmented Beams
- Homogeneous slices/sections with step changes
- 3 main guide regions with expected contacts
- StaBI
- Can handle functional geometry or material
- Uses Bresse's formulations with slope continuity
- DEBSE
- Mode shape continuous up to 3rd derivative at transitions
- Externally driven boundaries formulation
- Piece-wise mode shapes



- 2 main loops: convergence and contact
- Contact adds a new force when penetration is detected with Adjustment Factor
- Convergence compares force value at UG to establish static equilibrium (Only if semi-rigid)
- User specify contact at UG and deflection of LS
- 3 main outputs:
 1. Contact force vectors
 2. MP deflection
 3. Displacement at UG

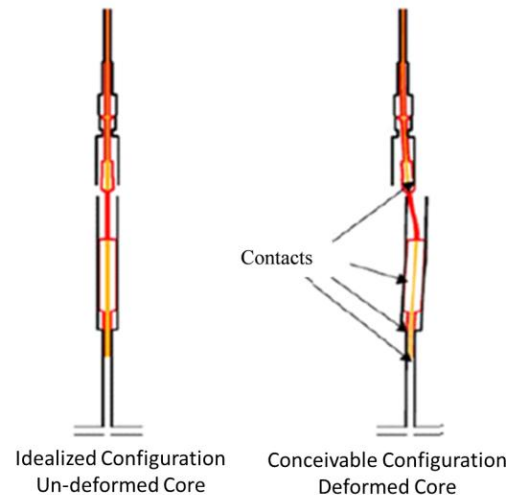


- In order to validate the results, a comparison to finite elements is performed
- Finite elements performed in Cast3M – a CEA FE Software
- Used a custom made implementation used for previous work (RC3) that requires the deflection of the UG
- 8 simulations for various MP positions
- For 80% Tolerance Factor: mean error = 5.6% and maximum of 9.9%
- For 90% Tolerance Factor: mean error = 1.5% and maximum of 5.0%



- The static analysis is based on accumulation of multiple misalignments including:

- Static base deflection
- Maximum dynamic deflection
- Installation tolerance
- Manufacturing tolerance
- Etc.



- While this can give a “worst-case scenario”, it is important to know how the system reacts during the actual earthquake
- First step is to look at dynamic effects to verify if they can be neglected (only the maximum deflection to be used) or if they contribute to resonance based motion that might cause failure

DEBSE

- Based on dynamic Euler-Bernoulli beam with Kelvin-Voigt damping

$$EI \frac{\partial^4 w(x, t)}{\partial x^4} + cI \frac{\partial^5 w(x, t)}{\partial x^4 \partial t} + \rho A \frac{\partial^2 w(x, t)}{\partial t^2} = \sum F_k \delta(x - x_k)$$

- Since the ends of the MP are not necessarily stationary, change of variable to account and modal decomposition

$$w(x, t) = \phi_0(t) \frac{(L - x)}{L} + \phi_L(t) \frac{x}{L} + \sum \psi_n(x) q_n(t)$$

- This work is preliminary dynamic analysis
- Focus on mode shapes and natural frequencies
- Time dependent analysis work presented in a separate journal paper

Natural Frequencies and Mode Shapes

- Based on BC and general form of mode shapes

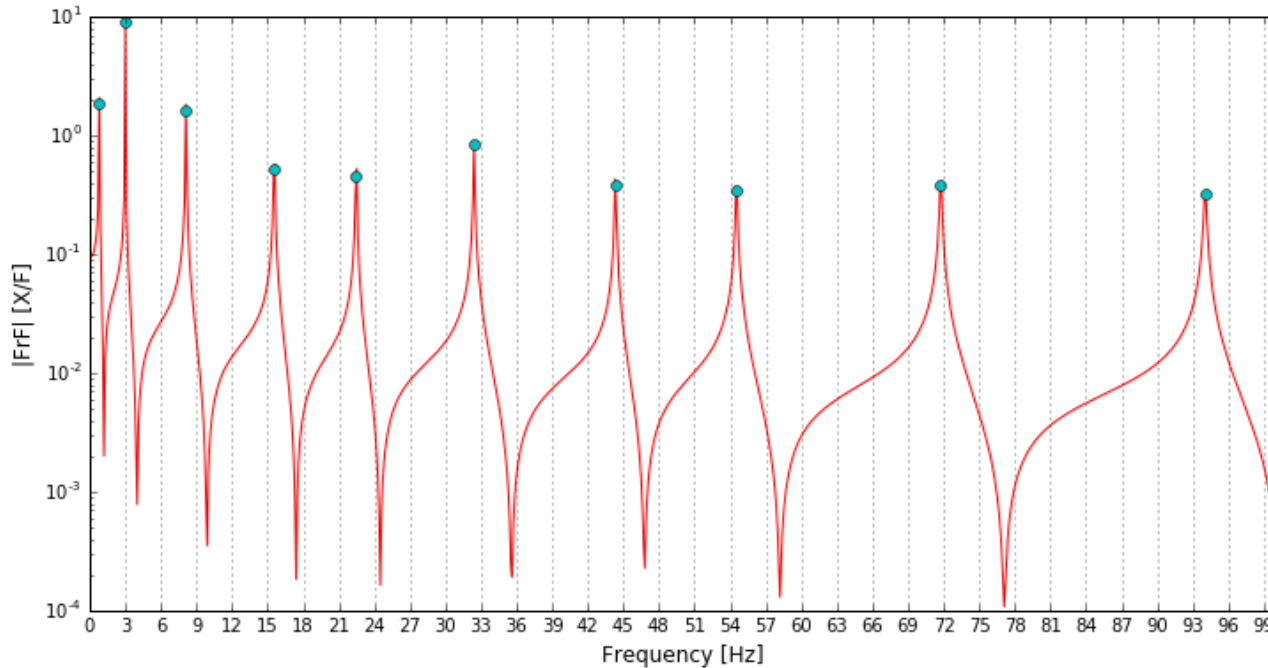
$$\psi_n(x) = a_{1n} \sin(\beta(\omega)x) + a_{2n} \cos(\beta(\omega)x) + a_{3n} \sinh(\beta(\omega)x) + a_{4n} \cosh(\beta(\omega)x)$$

- Requires that displacement, slope, sheer, and moment to be continuous across section changes
- Apply mode shapes to BC for characteristic equation

$$\begin{bmatrix} E_{BC} \\ I_{BC} \end{bmatrix}(\omega)[a_{in}] = [0]$$

- Use Newton-Raphson method to find $\omega \Rightarrow \omega_n$
- Use Modal Assurance Criteria (MAC) to compare mode shapes

$$MAC_{ij} = \frac{(\psi_i^T \psi_j)^2}{\dots}$$

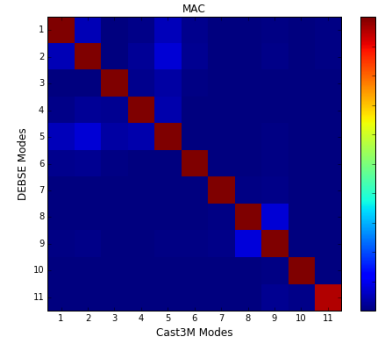


- Similar method to get FRF data
- Replace [0] with a forced excitation using stepped-sine
- Used as verification check that all modes are included
- Interactive display

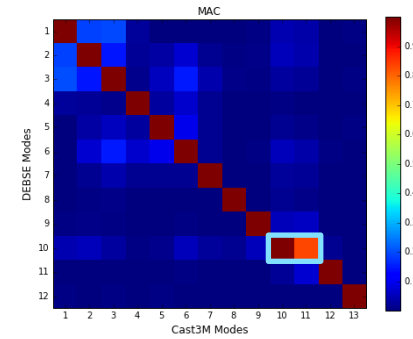
- Tested various BC for natural frequencies and mode shapes
- Compared to dynamic finite element model
- Initial starting points for Newton-Raphson method based on uniform beam and FE solution
- Investigated frequencies less than 100 Hz
- Nearly identical natural frequencies
- Maximum error of 0.36%

| Boundary Condition | N_{modes} | Mean % | Max % |
|--------------------|-------------|--------|-------|
| Clamp-Clamp | 11 | 0.14 | 0.34 |
| Pin-Pin | 11 | 0.13 | 0.33 |
| Free-Free | 11 | 0.16 | 0.36 |
| Free-Pin | 10 | 0.13 | 0.34 |
| Free-Clamp | 12 | 0.14 | 0.34 |
| Pin-Clamp | 11 | 0.14 | 0.33 |

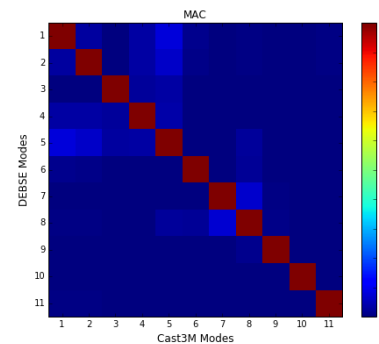
- Some MAC values between DEBSE and Cast3M
- Free-Free, Clamp-Clamp, Pin-Pin, and Pin-Clamp shows nearly perfect agreement
- Free-Clamp and Free-Pin show some correlation in a couple modes
- Also shows a mode that is not described in DEBSE



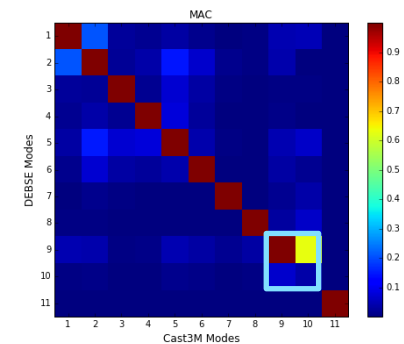
Clamp-Clamp



Free-Clamp

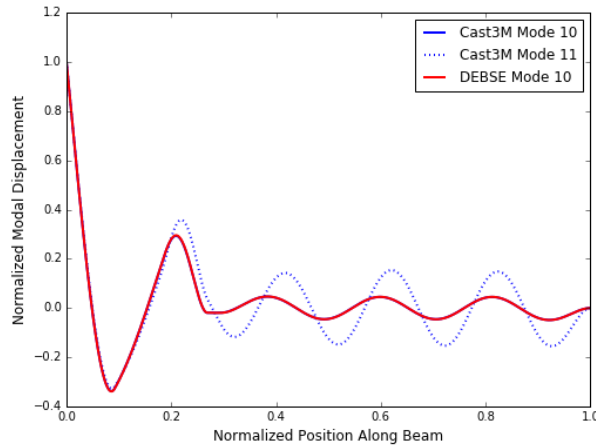


Pin-Pin

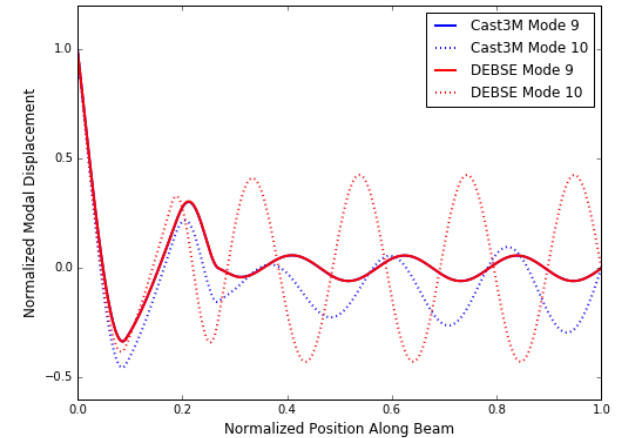


Free-Pin

INVESTIGATION INTO CORRELATION



Free-Clamp



Free-Pin

- Both situations have a 1-to-1 matching of a single mode with other modes being correlated
- Free-Clamp : Mode 11 seems to have some axial stretching near 20% along the length of beam
- Free-Pin : Mode 10s have similar shapes but different magnitudes and phase. Might be caused by stretching or FEs being used/ mesh

- **Force determination as time-history**
 - Explicit determination
 - Work presented in upcoming journal paper
- **Semi-Permanent Contact Determination**
 - Impact and separation in real-time
- **Validation Testing**
 - Designing benchmark tests for static and dynamic excitation of RCS representative system
 - Never performed for RC3
 - Can validate both PIRAT (StaBI and DEBSE) as well as RC3
- **Insertion Tests**
 - Main qualification criteria
 - Historical data for various designs (Experimental)
 - Utilize SIKI for either static or dynamic

- PIRAT is a novel toolbox to analyze RCS designs, but can also be used for any beam that is deformed by guiding sleeves
- StaBI uses static deformations and DEBSE uses dynamic deformation to determine: Contact forces and beam deflection
- The use of these tools is to perform preliminary evaluations during the design phase of a new nuclear reactor, particularly focused for applications to the ASTRID reactor project
- This is thought of as a method to reject and rank possible design configuration for future in depth computational analysis and prototype testing
- The use of Python and Excel greatly increase the ease-of-use and allows for simple and rapid changes to geometric and material properties

**THANK YOU FOR YOUR ATTENTION
AND TIME**

ANY QUESTIONS?

- Adjustment Factor is added to reconcile contact loop issue
- Contact only enforces displacement due to point force

$$v_{MP} = v_{sleeve} \pm AF * Clearance$$

- Similar to FE models, represent a small contact area as a point
- Sometimes, contact algorithm specifies 2 points to represent the area
- Creates very large forces required to prevent penetration
 - For Example: AF=80% => Force = -166 N
 - AF=99.9% => Force = {5027 & -5274} N
- Multiple contacts do not affect other contacts significantly
- Beam deflection is nearly identical, change in slope for contact region
- Greater chance if large contact region