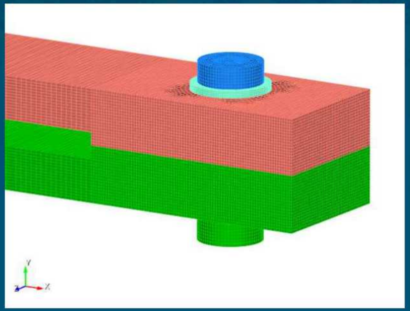
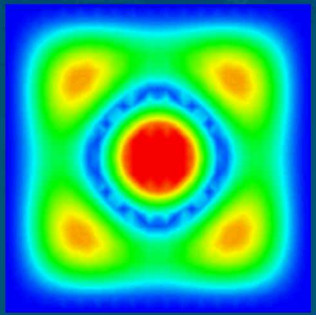
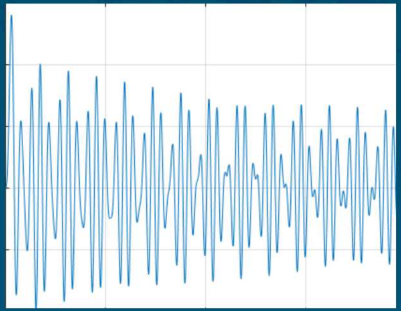
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

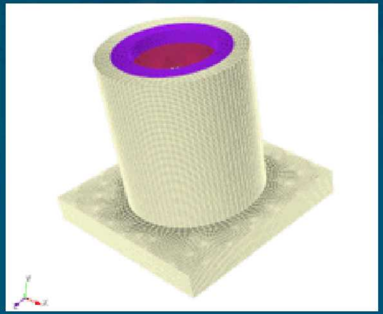
SAND2019-4878C

Structural Dynamics of Mechanical Joints









PRESENTED BY

Robert J. Kuether, Sandia National Laboratories

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Presented at 2019 CAV Workshop on May 8, 2019

SAND2019-???? PE

Who am I?

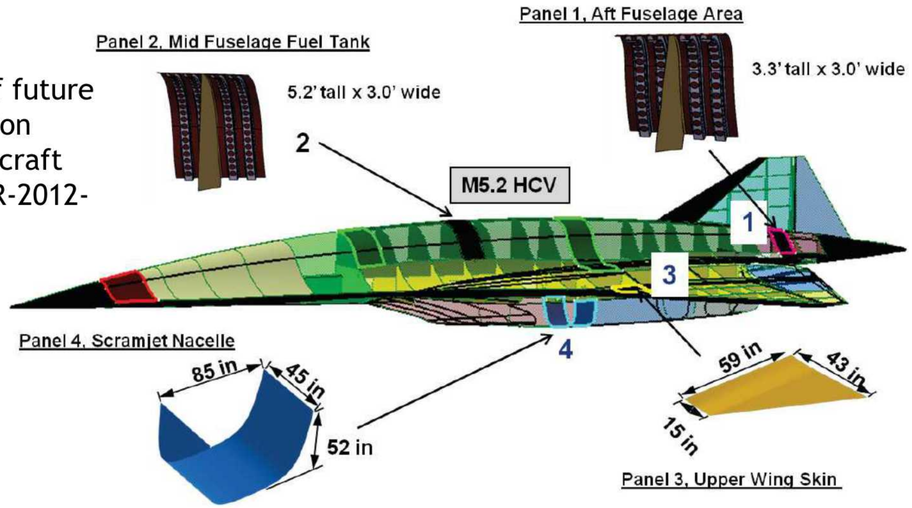
- B.S., M.S. and Ph.D in Engineering Mechanics at University of Wisconsin
  - Focused on computational methods in structural dynamics
  - "Nonlinear Modal Substructuring of Geometrically Nonlinear Finite Element Models"

- Joined Sandia in 2015 as Technical Staff
  - Component Science & Mechanics
  - Research and application work in computational structural dynamics
  - Exploring new nonlinear physics

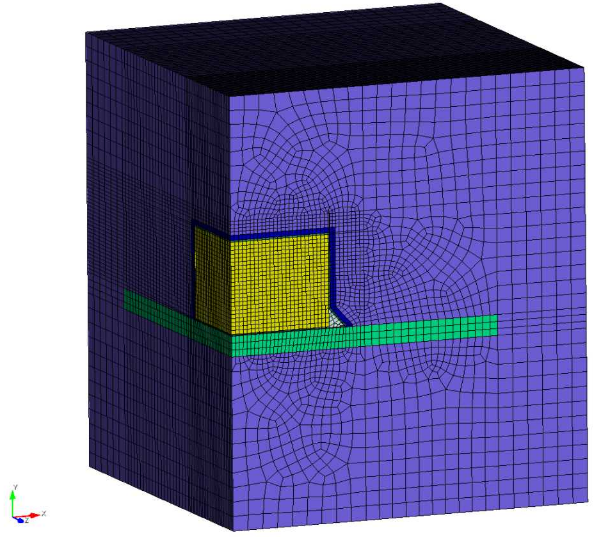
Keywords:

Structural dynamics; reduced order modeling; nonlinear dynamics and vibrations; test-analysis correlation; interface mechanics

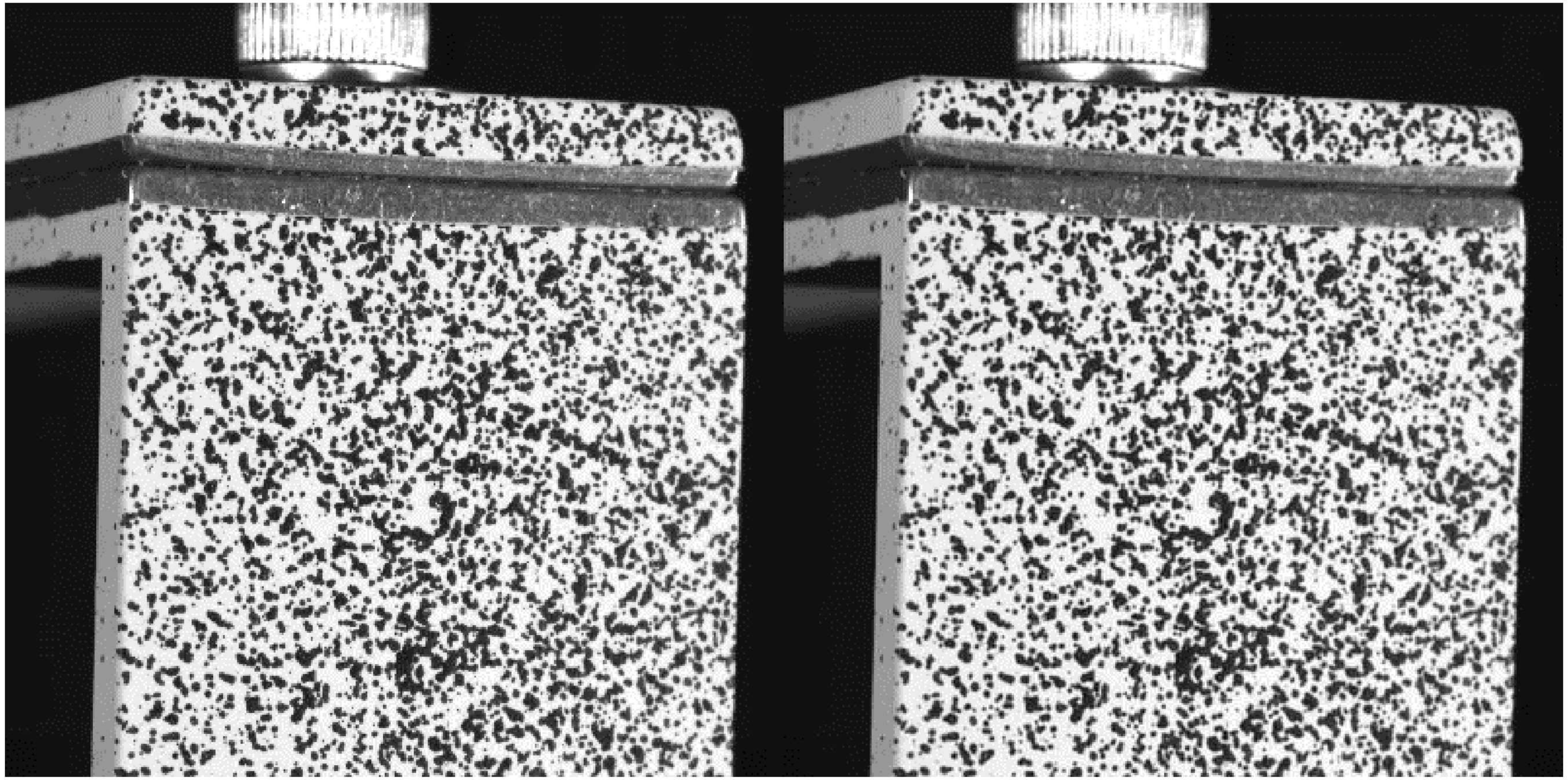
Exploratory design of future reusable, long duration cruise high-speed aircraft from AFRL-RQ-WP-TR-2012-0280



Vibration sensitive electronics potted in foam or polymer to mitigate damaging shock and vibrations



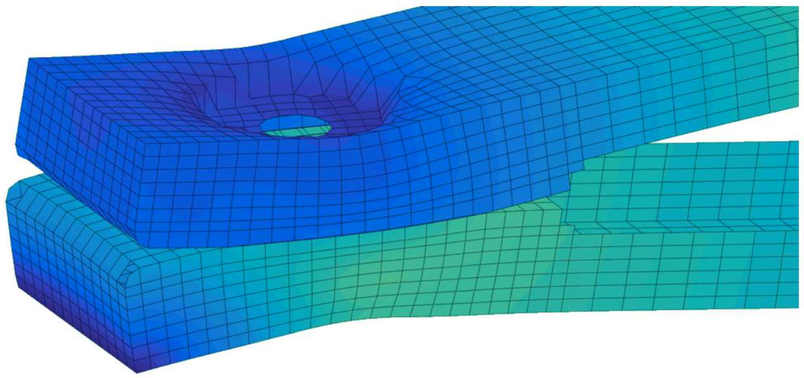
Structural dynamic considerations with joints



Motivation and Existing Challenges

Various industries rely on joining technologies to assemble structural systems

- Automotive, aerospace, civil, etc..

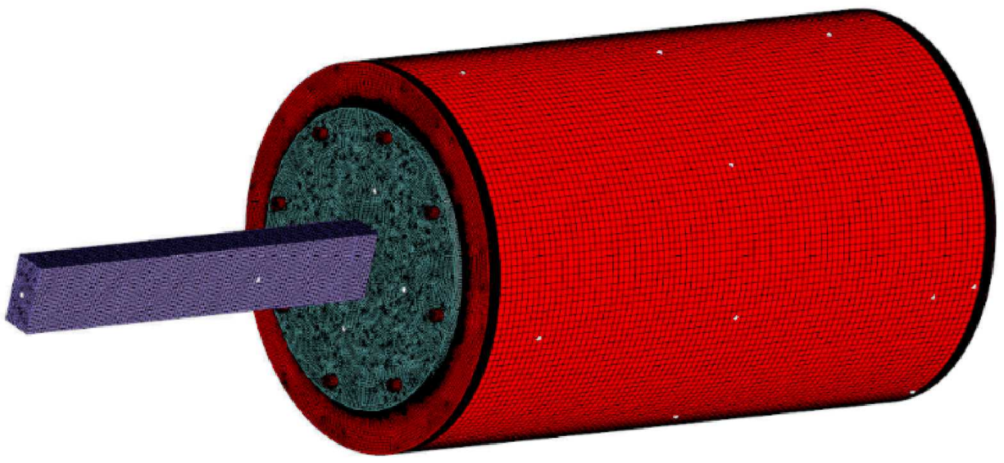


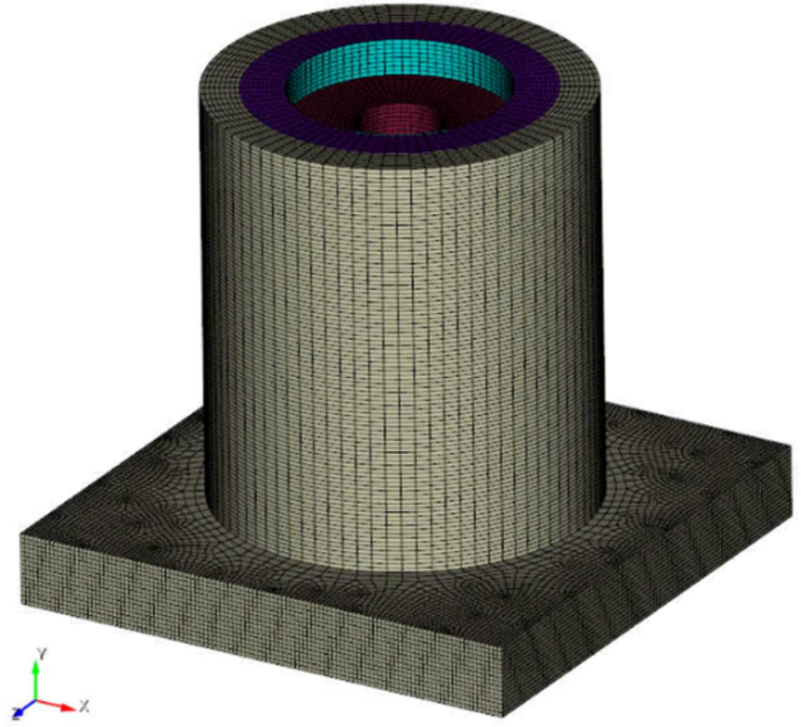
Joints introduce mechanical interfaces, contributing as sources of nonlinearity in vibratory response

- Frictional slip: micro- and macro-slip
- Variable normal pressure distributions

Frictional contact presents various challenges

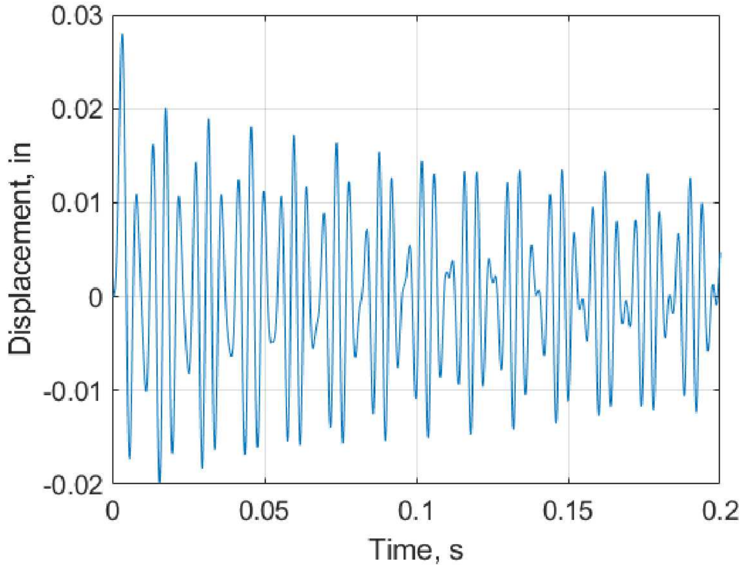
- **Modeling**: simulation cost, stability and convergence, model fidelity and uncertainty
- **Experiments**: measuring kinematics, repeatability, nonlinear dynamics



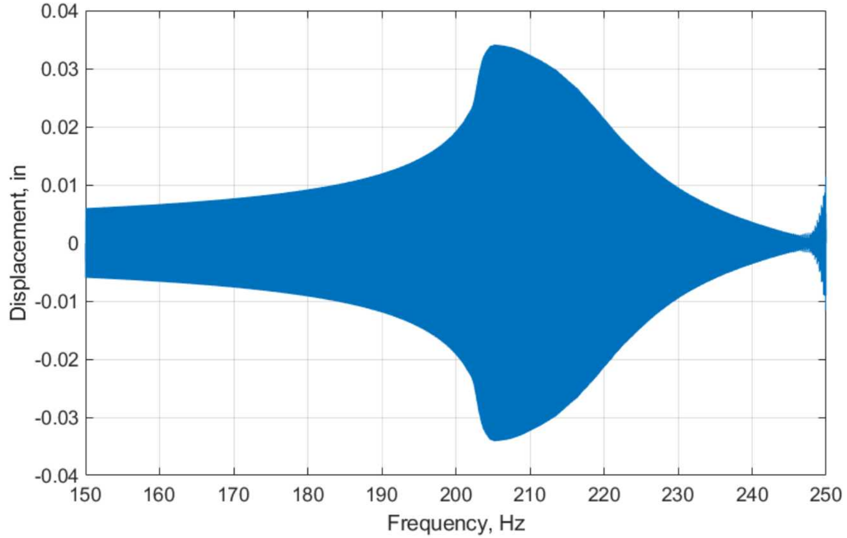


What global response metrics should be preserved?

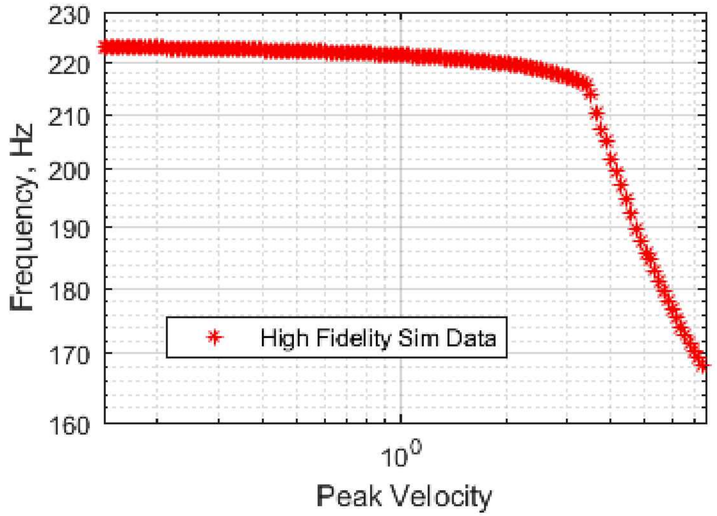
Transient Response?

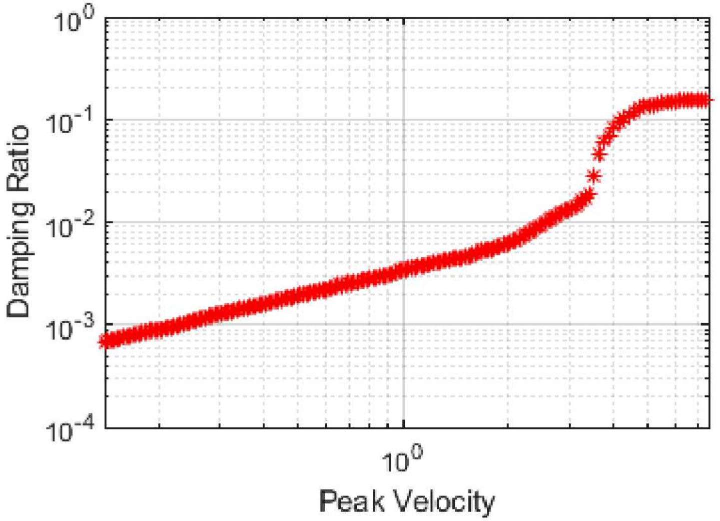


Swept/Stepped Sine Response?



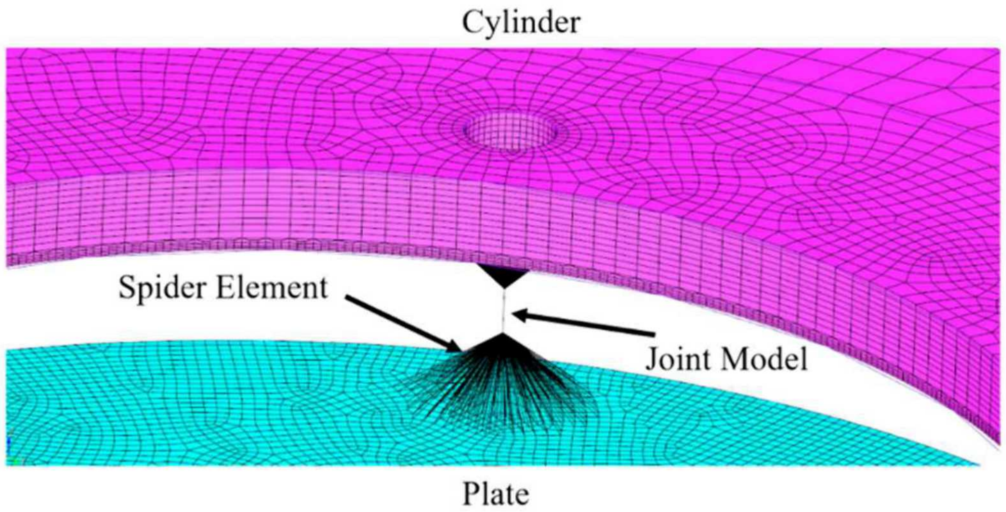
Amplitude dependent natural frequency and damping ratio





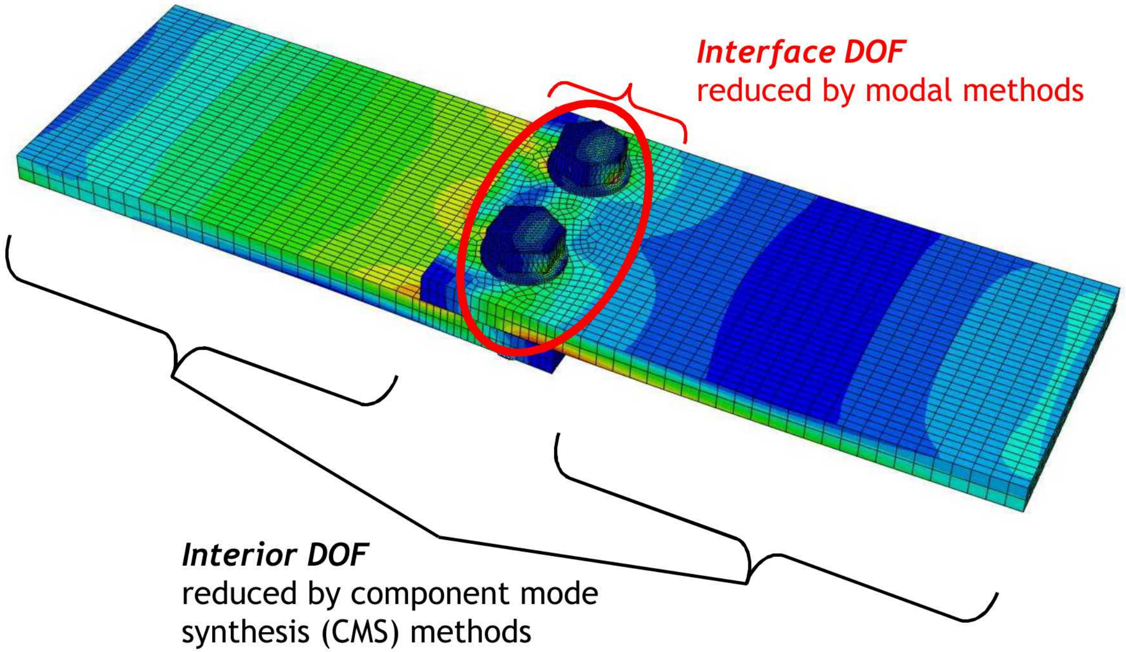
How to efficiently develop models with mechanical interfaces?

Whole Joint Modeling
(Rigid Interfaces)



- Goal: Estimate/calibrate the joint parameters in the whole joint reduced order models to match response from high-fidelity models and/or experiments

Interface Reduction
(Flexible Interfaces)



- Goal: keep full kinematics and nonlinear elements, and apply interface reduction

Overview of Structural Dynamics of Mechanical Joints

Nonlinear reduced order models with mechanical interfaces
- Whole joint modeling
- Interface reduction

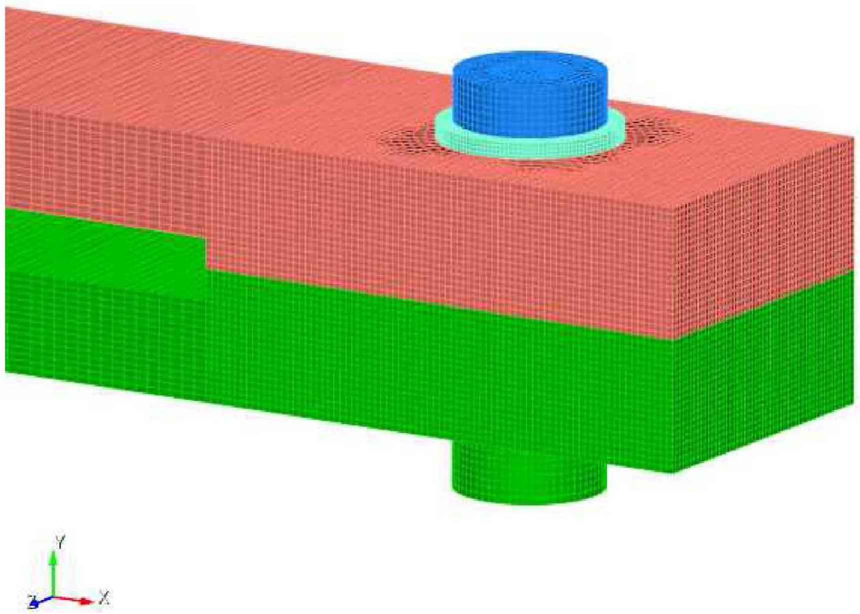
Experimental methods to measure nonlinear frequency and damping characteristics

Comparison of various dissipation models to model jointed structures

Objectives of whole joint modeling R&D

Contact areas in high fidelity finite element models simplified by "spidering" surface to a single node and modeling joint forces as a 1D constitutive law

Global optimization to calibrate whole joint parameters to match global response



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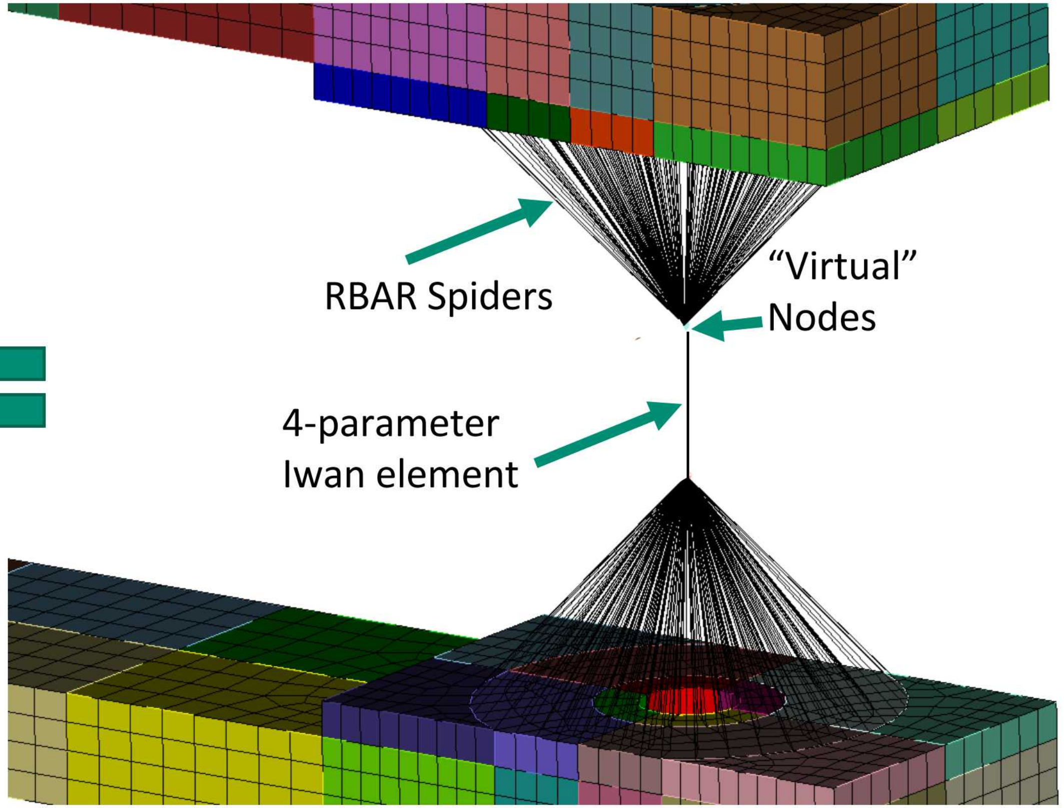

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Quasi-static Modal Analysis

Quasi-static Modal Analysis of Full-order Model

Nonlinear Preload Analysis

$$\mathbf{Kx} + \mathbf{f}_{NL}(\mathbf{x}, \boldsymbol{\theta}) = \mathbf{f}_{pre}$$

↓

Linearized Modal Analysis

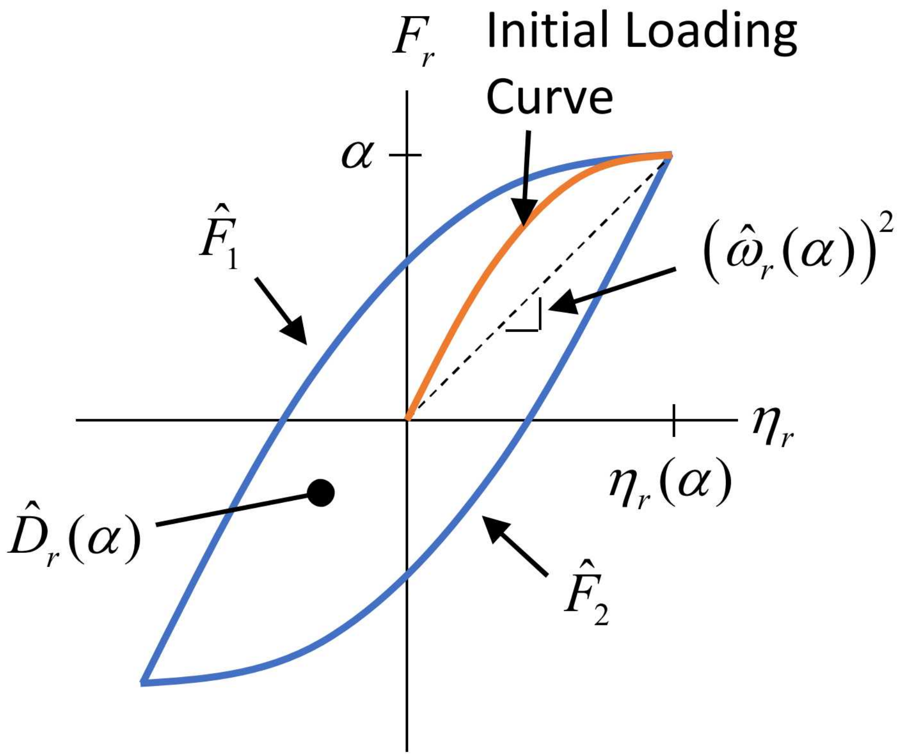
$$\left(\mathbf{K} + \frac{d\mathbf{f}_{NL}(\mathbf{x}, \boldsymbol{\theta})}{d\mathbf{x}}\bigg|_{\mathbf{x}=\mathbf{x}_{pre}} - \omega_r^2\mathbf{M}\right)\boldsymbol{\phi}_r = \mathbf{0}$$

↓

Quasi-static Modal Analysis

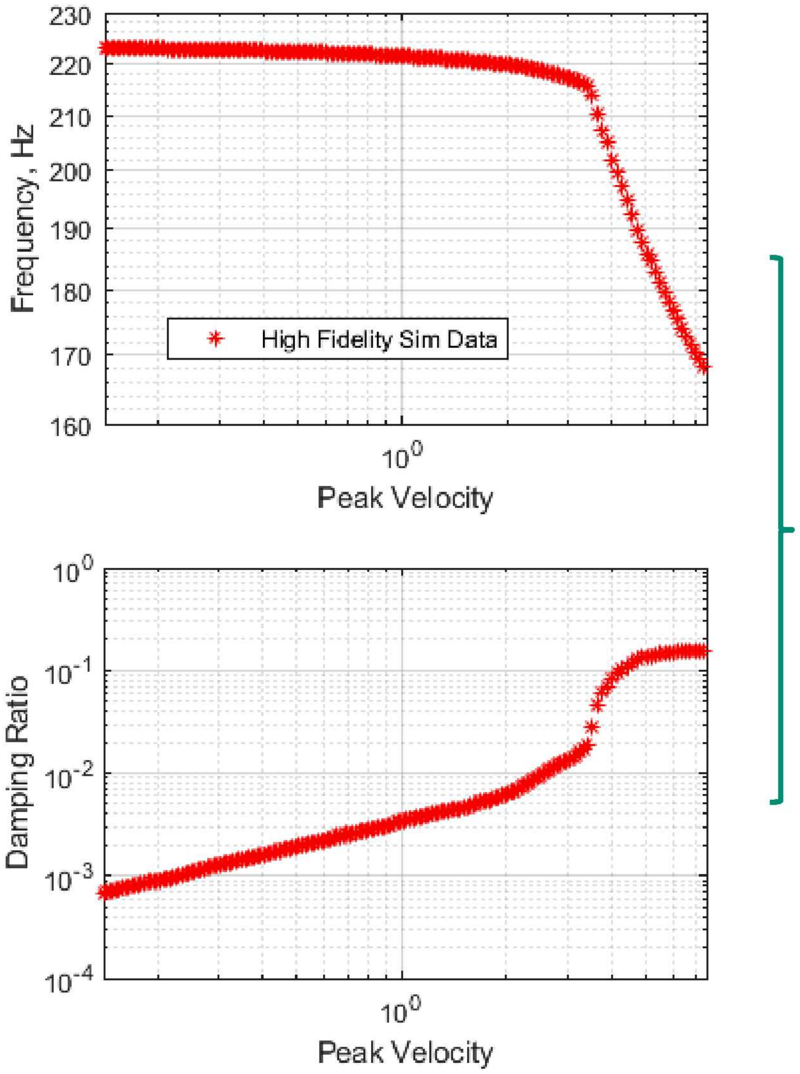
$$\mathbf{Kx} + \mathbf{f}_{NL}(\mathbf{x}, \boldsymbol{\theta}) = \mathbf{f}_{pre} + \mathbf{M}\boldsymbol{\phi}_r\alpha$$

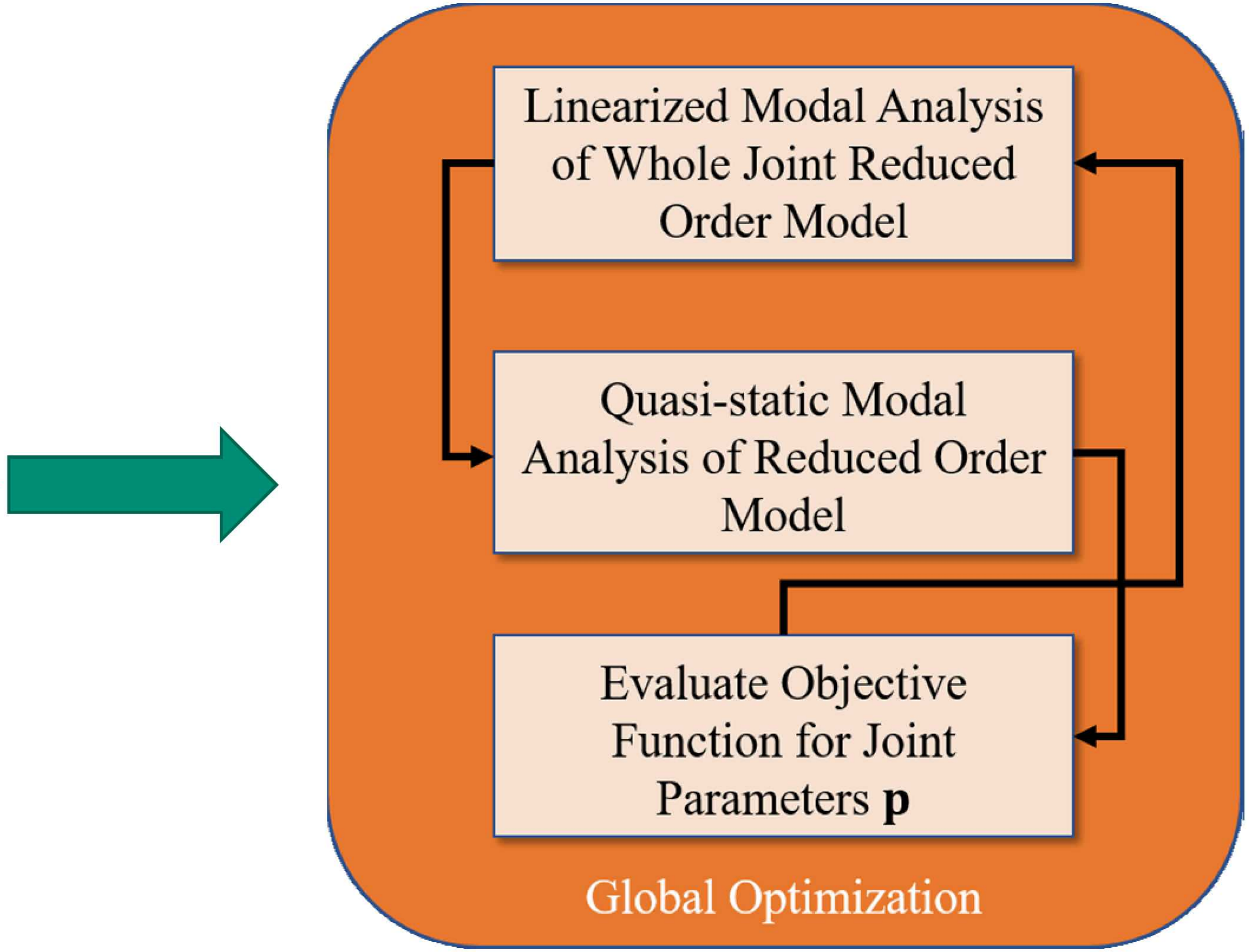
Estimate modal amplitude dependent natural frequencies, $\omega_r(\alpha)$, and damping ratios, $\zeta_r(\alpha)$, of high-fidelity model and reduced models with whole joints [1]



[1] M. S. Allen, R. M. Lacayo, and M. R. W. Brake, "Quasi-static Modal Analysis based on Implicit Condensation for Structures with Nonlinear Joints," presented at the ISMA2016 - International Conference on Noise and Vibration Engineering, Leuven, Belgium, 2016.

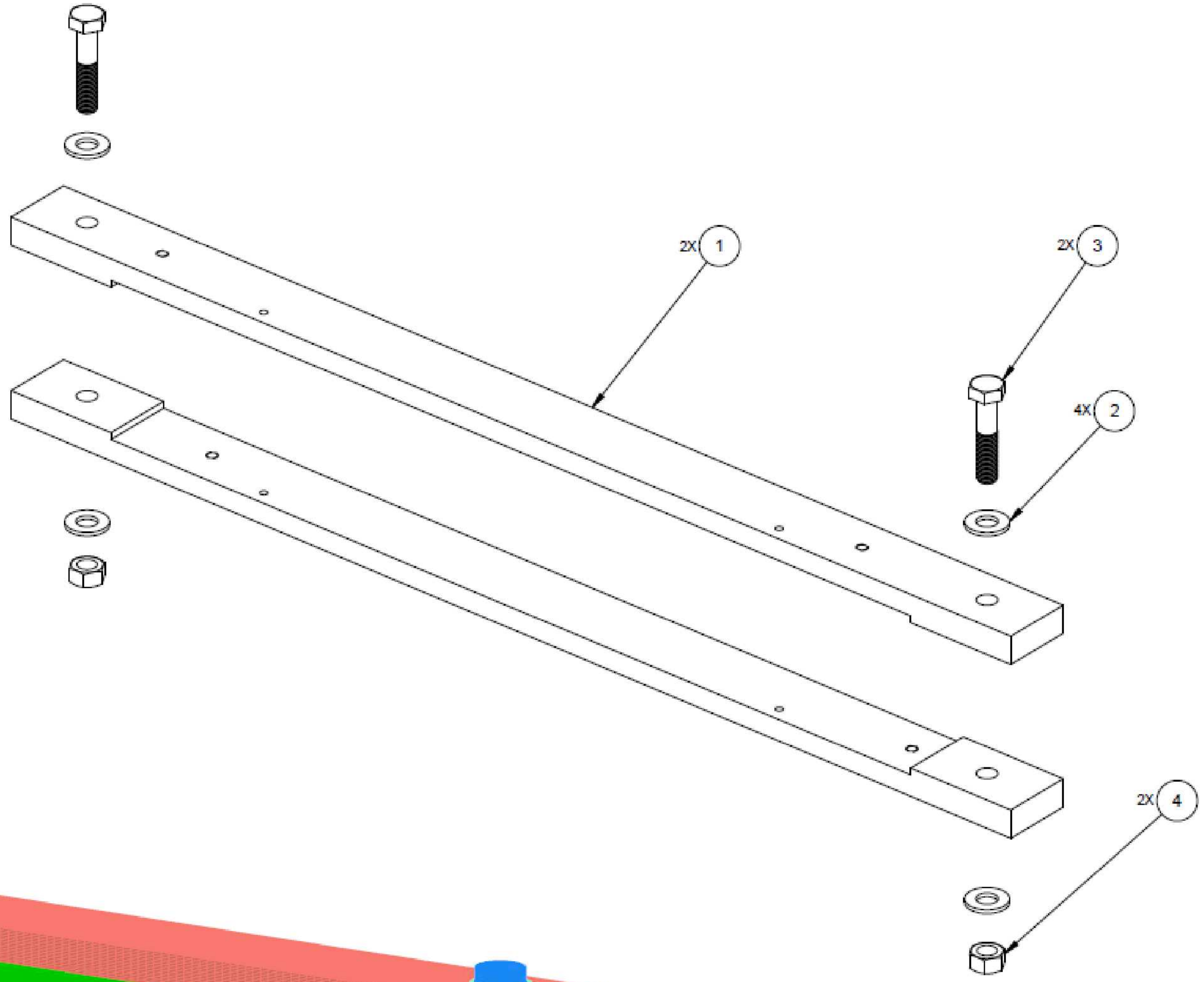
Whole joint calibration via multi-objective optimization [1]

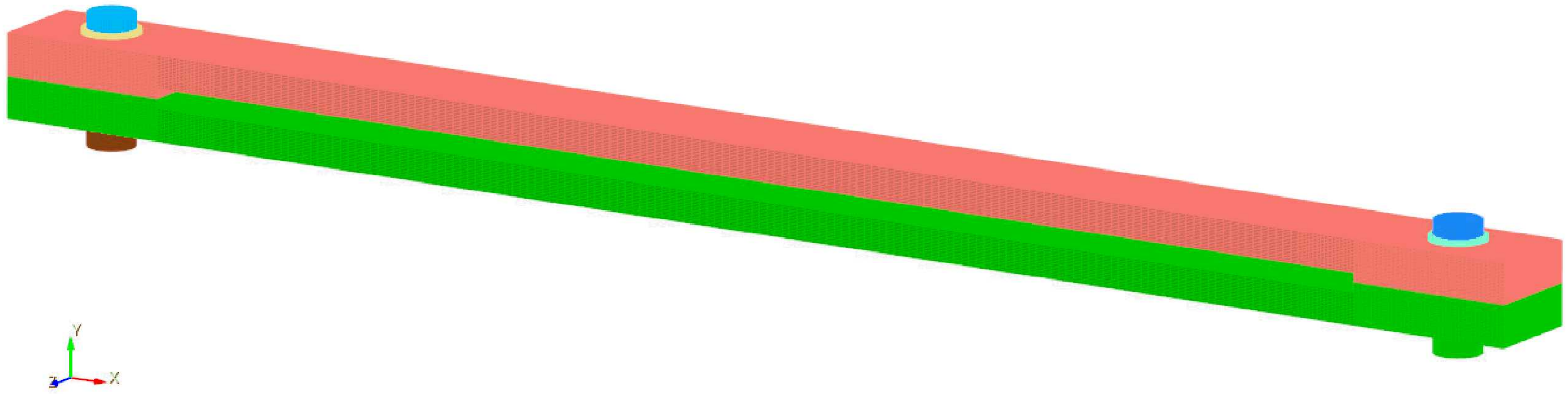




[1] F.-A. Fortin, F.-M. D. Rainville, M.-A. Gardner, M. Parizeau, and C. Gagné, "DEAP: Evolutionary algorithms made easy," *Journal of Machine Learning Research,* vol. 13, pp. 2171-2175, 2012.

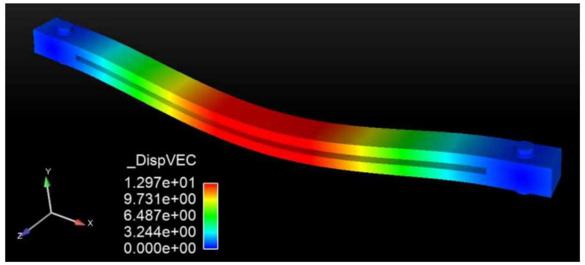
C-Beam Benchmark Example

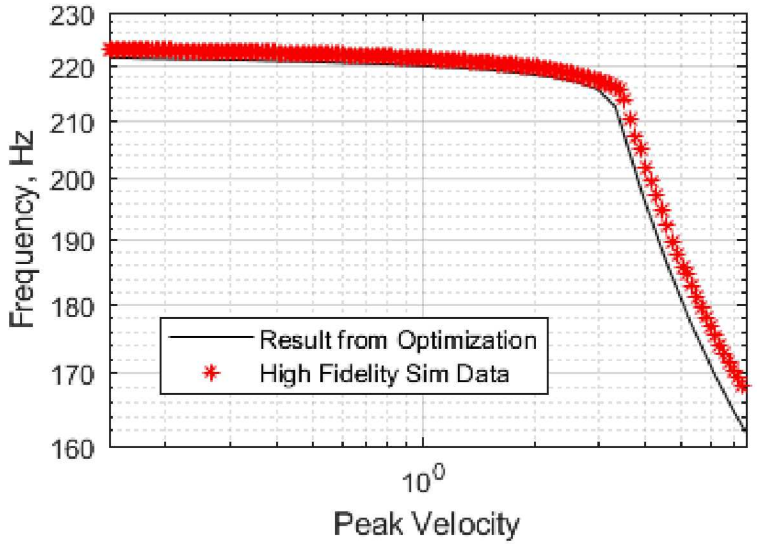


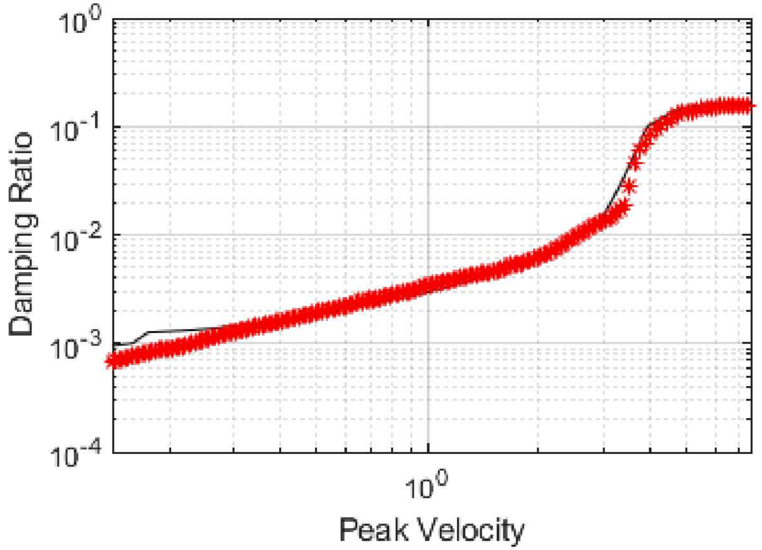


Multi-mode whole joint model calibration

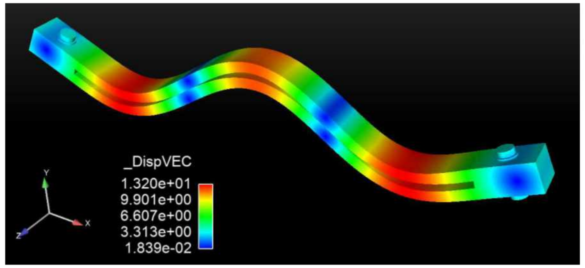
Mode 1 223 Hz

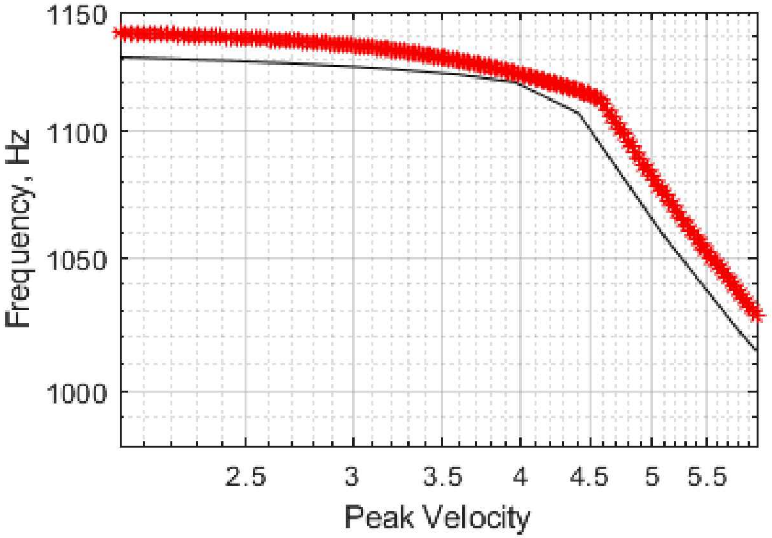


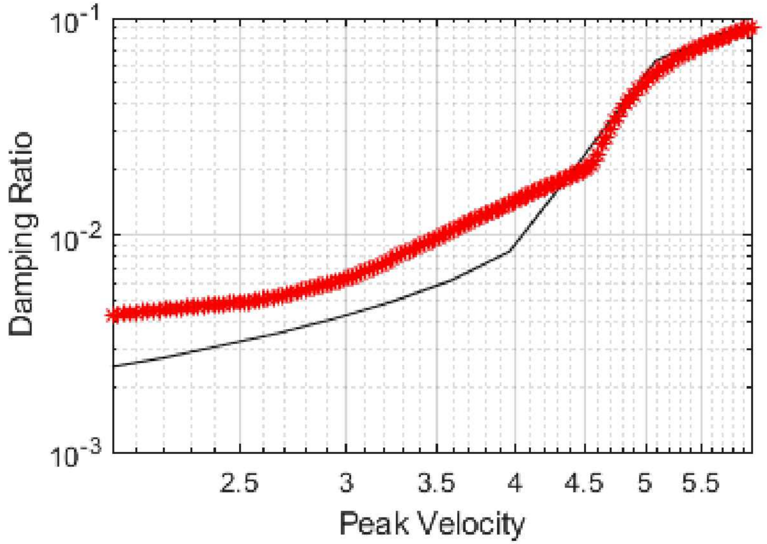




Mode 8 1142 Hz







Overview of Structural Dynamics of Mechanical Joints

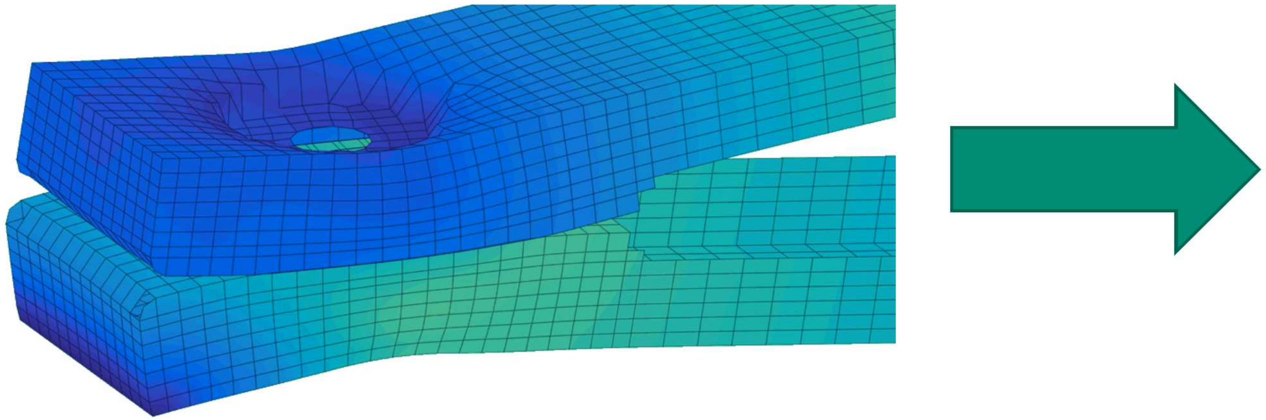
Nonlinear reduced order models with mechanical interfaces

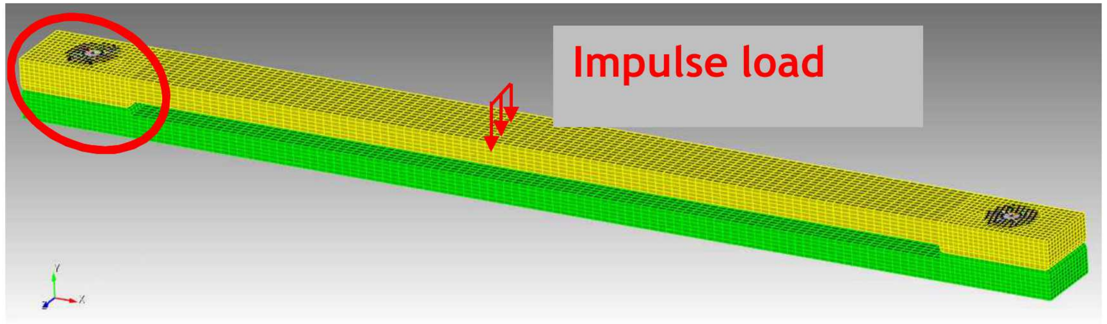
- Whole joint modeling
- Interface reduction

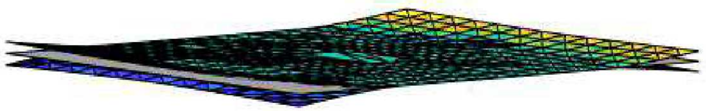
Experimental methods to measure nonlinear frequency and damping characteristics

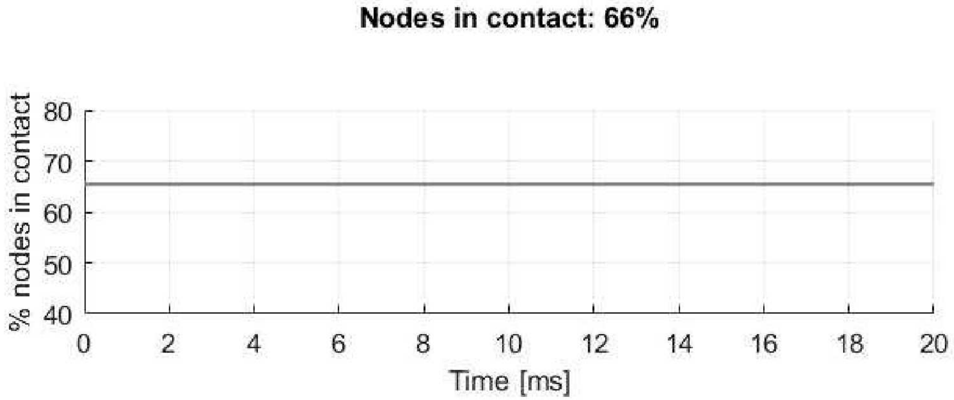
Comparison of various dissipation models to model jointed structures

What if the joint is flexible?









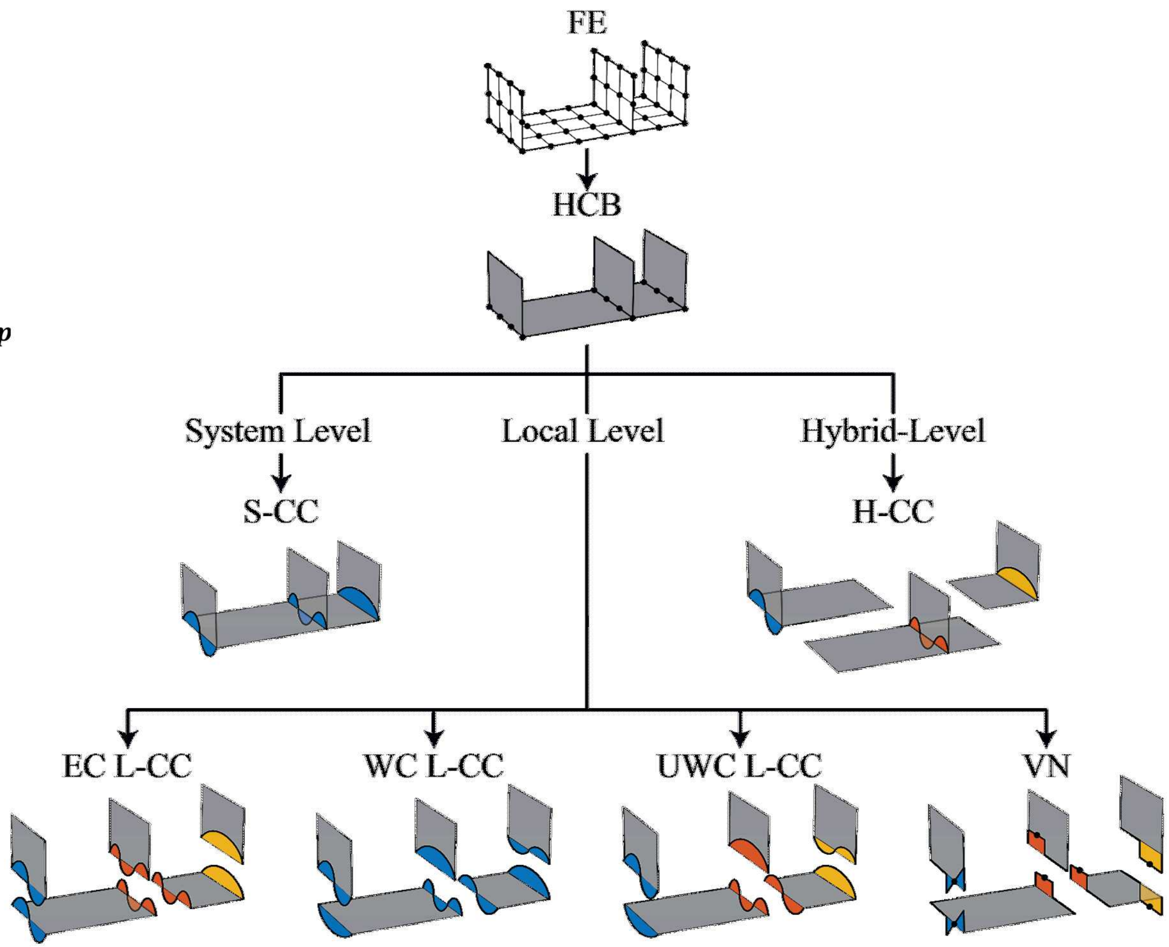
Interface reduction applied to Hurty/Craig-Bampton (HCB) substructures

HCB reduced model dominated by potentially thousands of r-set DOF

$$\begin{bmatrix} \mathbf{I}_{ii} & \mathbf{M}_{ir}^{HCB} & \mathbf{M}_{ip}^{HCB} \\ \mathbf{M}_{ri}^{HCB} & \mathbf{M}_{rr}^{HCB} & \mathbf{M}_{rp}^{HCB} \\ \mathbf{M}_{pi}^{HCB} & \mathbf{M}_{pr}^{HCB} & \mathbf{M}_{pp}^{HCB} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{q}}_i \\ \ddot{\mathbf{u}}_r \\ \ddot{\mathbf{u}}_p \end{Bmatrix} + \begin{bmatrix} \mathbf{\Lambda}_{ii}^{FI} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{K}_{rr}^{HCB} & \mathbf{K}_{rp}^{HCB} \\ \mathbf{0} & \mathbf{K}_{pr}^{HCB} & \mathbf{K}_{pp}^{HCB} \end{bmatrix} \begin{Bmatrix} \mathbf{q}_i \\ \mathbf{u}_r \\ \mathbf{u}_p \end{Bmatrix} + \begin{Bmatrix} \mathbf{0} \\ \mathbf{f}_r(\mathbf{u}_r) \\ \mathbf{0} \end{Bmatrix} = \begin{Bmatrix} \\ \\ \mathbf{f}_p \end{Bmatrix}$$

Research challenge: how can we further reduce these equations?

Explored the extension of interface reduction techniques [1] to problems involving nonlinear contact [2,3]



[1] Krattiger, D. et al. "Interface reduction for Hurty/Craig-Bampton substructured models: Review and improvements," Mechanical Systems and Signal Processing, 114, pp 579-603, 2019.
[2] Kuether RJ, Coffin PB, Brink AR "On Hurty/Craig-Bampton Substructuring With Interface Reduction on Contacting Surfaces," ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, *Volume 8: 29th Conference on Mechanical Vibration and Noise*.
[3] Hughes, P.J. et al. "Interface Reduction on Hurty/Craig-Bampton Substructures with Frictionless Contact," 2018 International Modal Analysis Conference (IMAC) XXXVI, Orlando, FL, 2018.

System-level characteristic constraint modes

Solve the quasi-static version of the HCB model for preloaded equilibrium

$$\begin{bmatrix} \mathbf{\Lambda}_{\mathrm{ii}}^{\mathrm{FI}} & 0 & 0 \\ 0 & \mathbf{K}_{\mathrm{rr}}^{\mathrm{HCB}} & \mathbf{K}_{\mathrm{rp}}^{\mathrm{HCB}} \\ 0 & \mathbf{K}_{\mathrm{pr}}^{\mathrm{HCB}} & \mathbf{K}_{\mathrm{pp}}^{\mathrm{HCB}} \end{bmatrix} \begin{Bmatrix} \mathbf{q}_{\mathrm{i}} \\ \mathbf{u}_{\mathrm{r}} \\ \mathbf{u}_{\mathrm{p}} \end{Bmatrix} + \begin{Bmatrix} 0 \\ \mathbf{f}_{\mathrm{r}}(\mathbf{u}_{r}) \\ 0 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ \mathbf{f}_{\mathbf{pre}} \end{Bmatrix}$$

Apply a secondary reduction about the preloaded equilibrium such that

$$\mathbf{v} = \begin{Bmatrix} \mathbf{q}_{\mathrm{i}} \\ \mathbf{u}_{\mathrm{r}} \\ \mathbf{u}_{\mathrm{p}} \end{Bmatrix} = \mathbf{v}_{\mathrm{pre}} + \begin{bmatrix} \mathbf{I} & 0 & 0 \\ 0 & \mathbf{\Phi}^{\mathrm{SCC}} & \mathbf{\Psi}^{\mathbf{SCCe}} \\ 0 & 0 & \mathbf{I} \end{bmatrix} \begin{Bmatrix} \mathbf{q}_{\mathrm{i}} \\ \mathbf{q}_{\mathrm{r}} \\ \mathbf{u}_{\mathrm{p}} \end{Bmatrix} = \mathbf{v}_{\mathrm{pre}} + \mathbf{T}^{\mathrm{SCCe}}\mathbf{w}$$

where the tangent S-CC modes and static constraint modes computed about preloaded state

$$\left[\mathbf{K}_{\mathrm{rr}}^{\mathrm{HCB}} + \left. \frac{\partial \mathbf{f}_{\mathrm{r}}(\mathbf{u}_{r})}{\partial \mathbf{u}_{r}} \right|_{\mathbf{v}_{\mathrm{pre}}} - \left(\omega^{\mathrm{SCC}}\right)^{2} \mathbf{M}_{\mathrm{rr}}^{\mathrm{HCB}} \right] \boldsymbol{\phi}_{\mathrm{s}}^{\mathrm{SCC}} = 0 \qquad \mathbf{\Psi}^{\mathbf{SCCe}} = -\left(\mathbf{K}_{\mathrm{rr}}^{\mathrm{HCB}} + \left. \frac{\partial \mathbf{f}_{\mathrm{r}}(\mathbf{u}_{r})}{\partial \mathbf{u}_{r}} \right|_{\mathbf{v}_{\mathrm{pre}}} \right)^{-1} \mathbf{K}_{\mathrm{rp}}^{\mathrm{HCB}}$$

Tangent stiffness contributions about deformed state

Enhance basis with trial vector derivatives

Using the S-CC modes from the initial reduction on the interface

$$\mathbf{v} = \begin{Bmatrix} \mathbf{q}_{\mathrm{i}} \\ \mathbf{u}_{\mathrm{r}} \\ \mathbf{u}_{\mathrm{p}} \end{Bmatrix} = \mathbf{v}_{\mathrm{pre}} + \begin{bmatrix} \mathbf{I} & 0 & 0 \\ 0 & \mathbf{\Phi}^{\mathrm{SCC}} & \mathbf{\Psi}^{\mathrm{SCCe}} \\ 0 & 0 & \mathbf{I} \end{bmatrix} \begin{Bmatrix} \mathbf{q}_{\mathrm{i}} \\ \mathbf{q}_{\mathrm{r}} \\ \mathbf{u}_{\mathrm{p}} \end{Bmatrix} = \mathbf{v}_{\mathrm{pre}} + \mathbf{T}^{\mathrm{SCCe}}\mathbf{w}$$

Take Taylor series expansion around preloaded configuration to get modal derivatives

$$\mathbf{T}_{\boldsymbol{i}(\mathbf{w})} = \mathbf{T}_{\boldsymbol{i}}\Big|_{\mathrm{c}} + \sum_{\boldsymbol{j}=1}^{\boldsymbol{n_w}} \frac{\partial \mathbf{T}_{\boldsymbol{i}}}{\partial w_{\boldsymbol{j}}}\bigg|_{\mathbf{c}} \left(w_{\boldsymbol{j}} - \mathrm{w_j(PL)}\right) + \mathrm{H.O.T.}$$

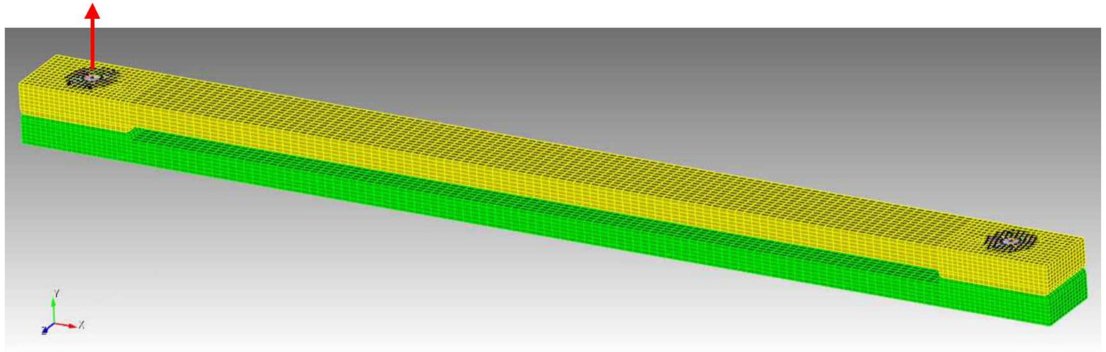
Describe how modes change for a given modal amplitude of response

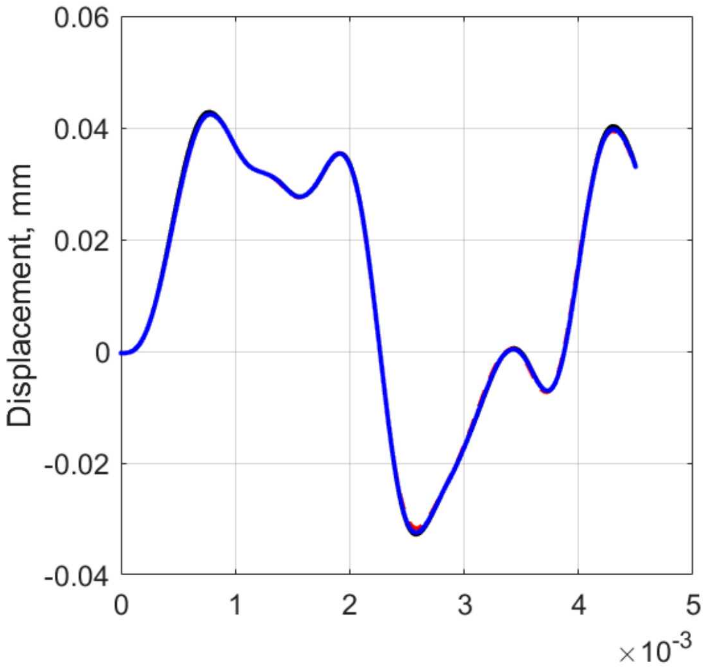
Take Taylor series expansion around preloaded configuration to get modal derivatives

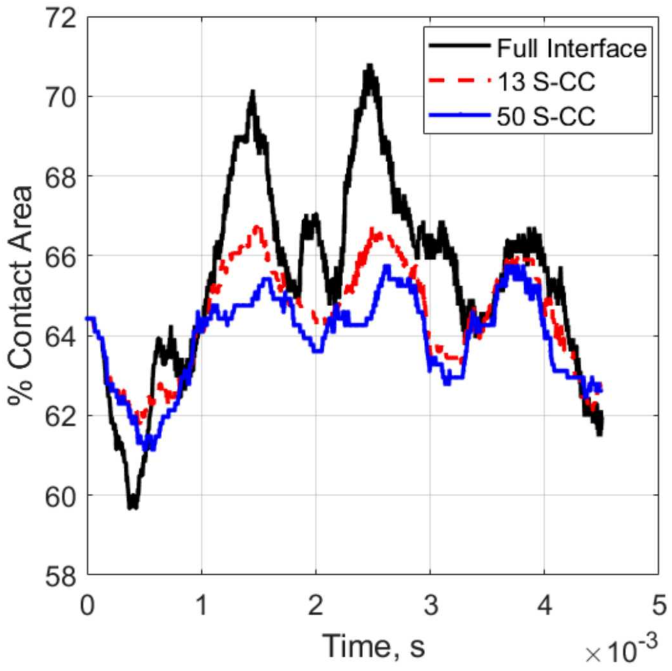
$$\mathbf{T}^{\mathrm{TVD}} = \left[\mathbf{T}^{\mathrm{SCCe}} \quad \frac{\partial \mathbf{T}^{\mathrm{SCCe}}}{\partial \mathbf{w}}\right]$$

Time-domain simulations due to impulse load

Impulse load A = 2000 N

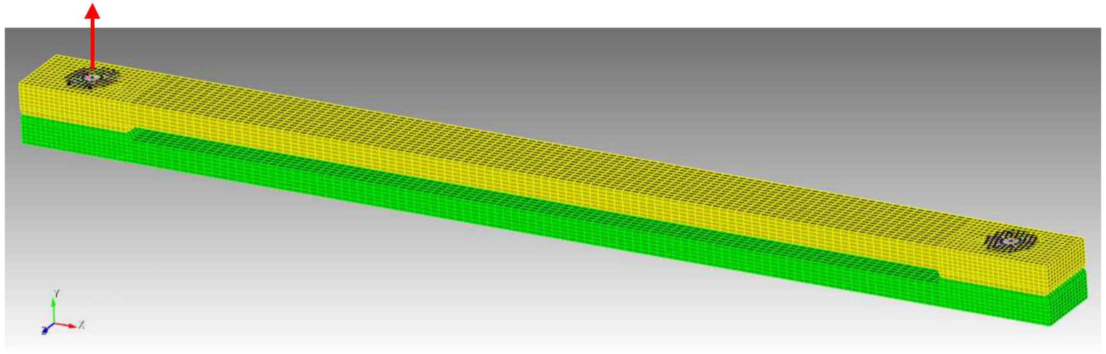




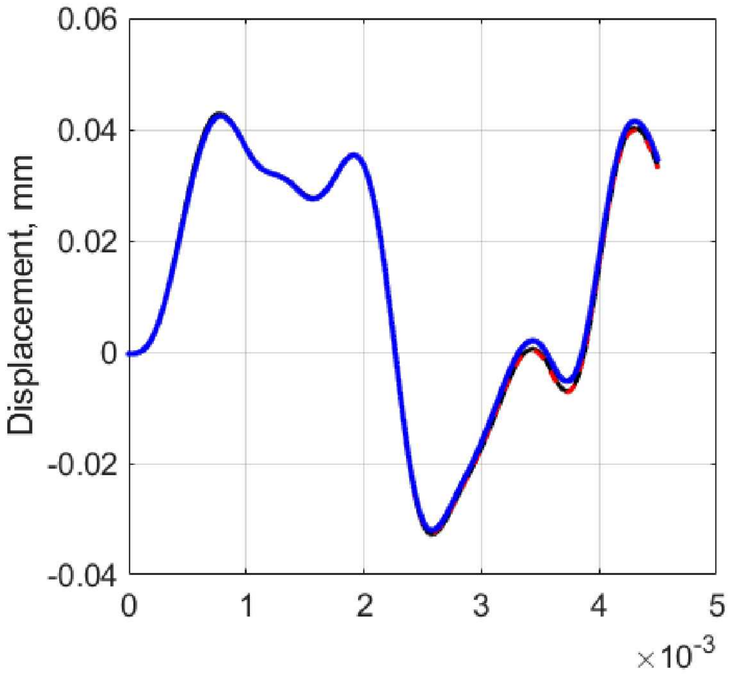


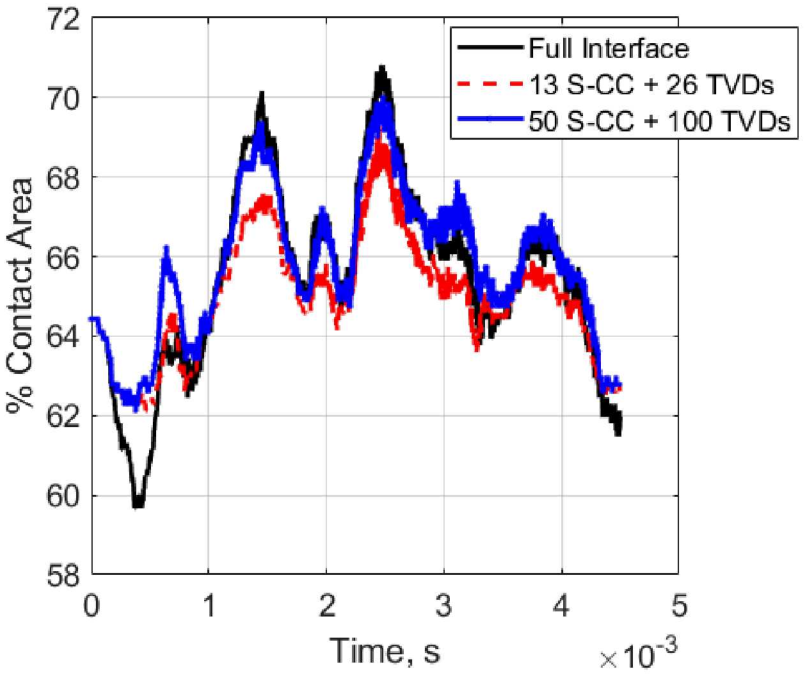
Time-domain simulations due to impulse load

Impulse load A = 2000 N



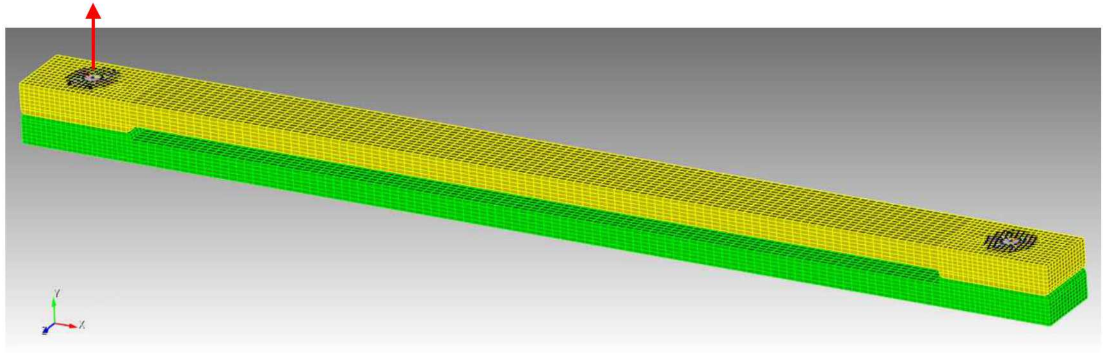
*Full interface ~ 90 minutes
** IR ROMs – 2 minutes





Time-domain simulations due to impulse load

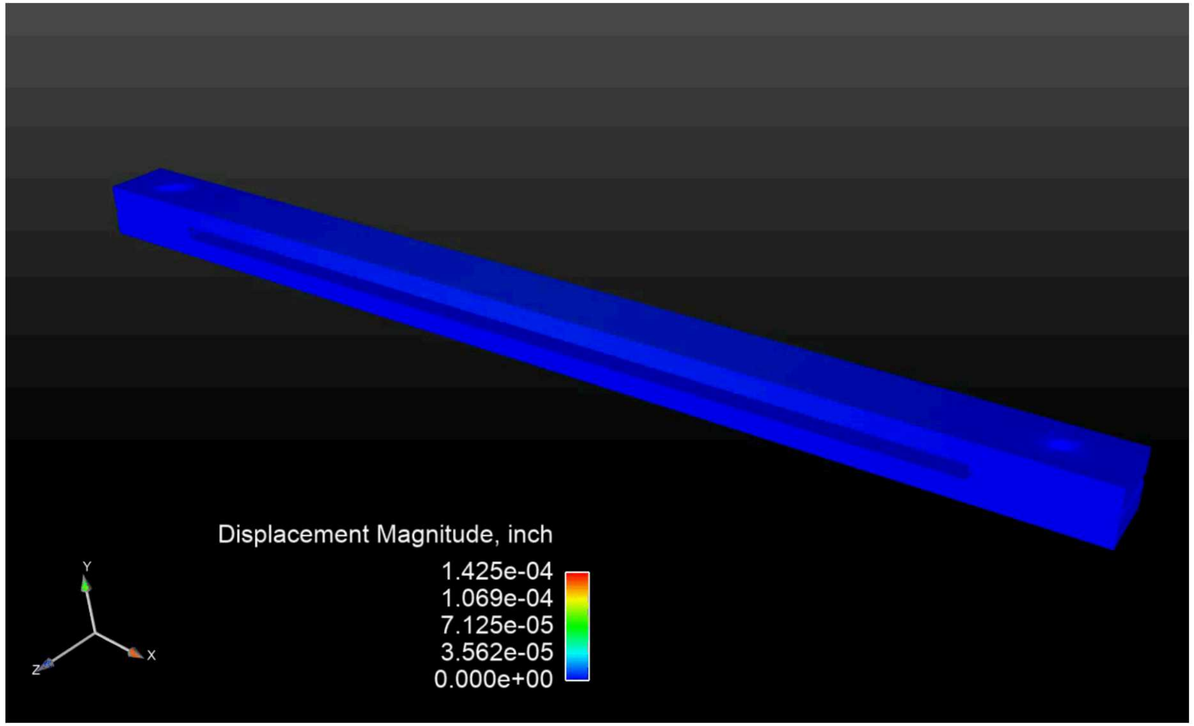
Impulse load A = 2000 N

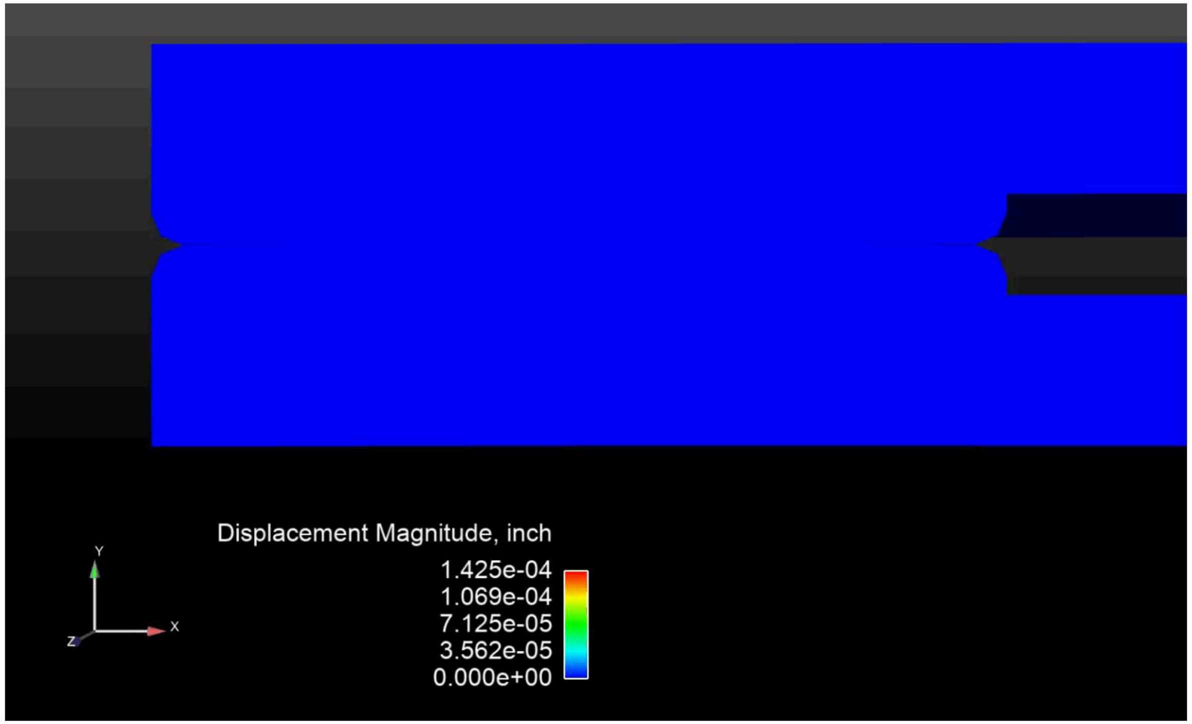


HCB-SCCe-TVD ROM

272 DOF

2.0 min





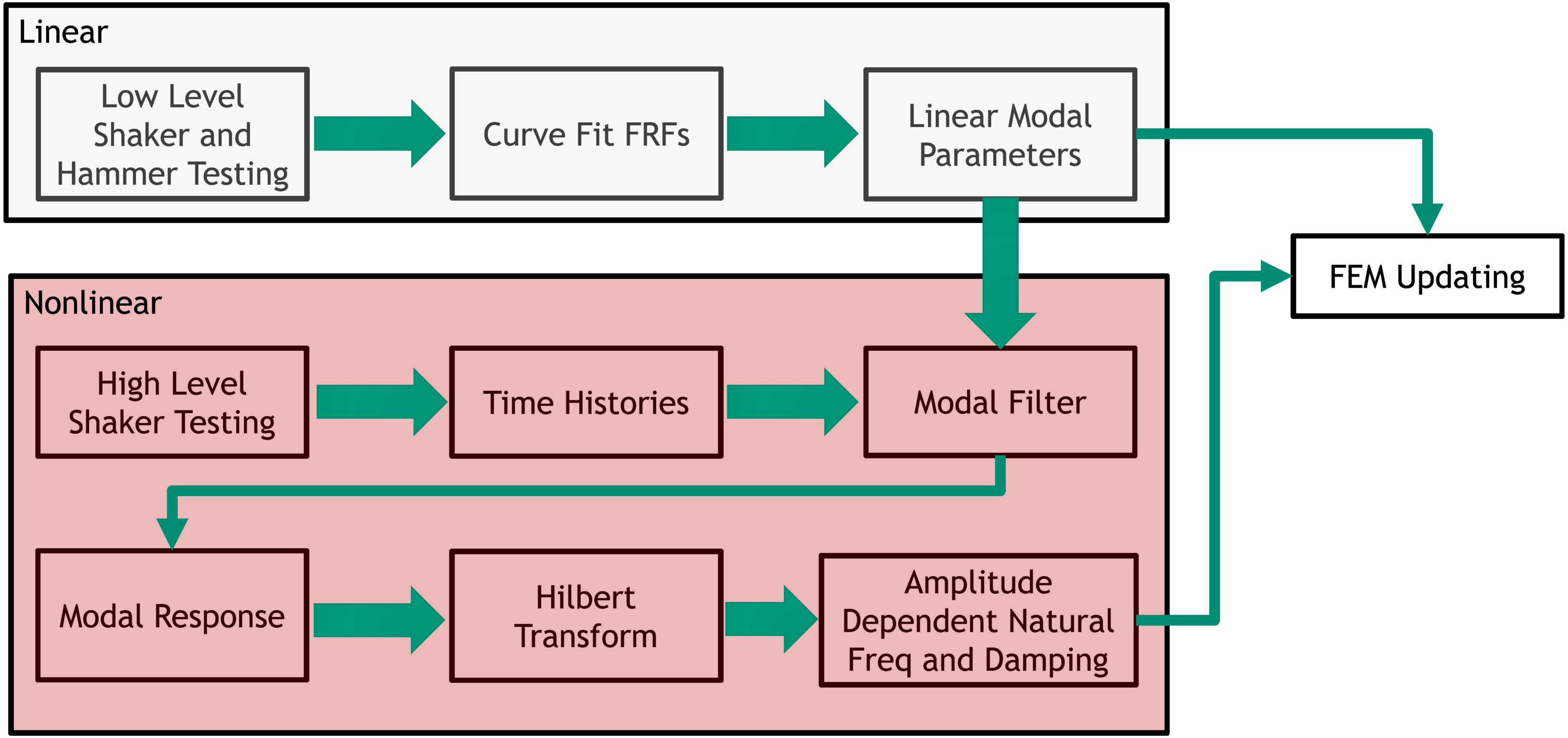
Overview of Structural Dynamics of Mechanical Joints

Nonlinear reduced order models with mechanical interfaces
- Whole joint modeling
- Interface reduction

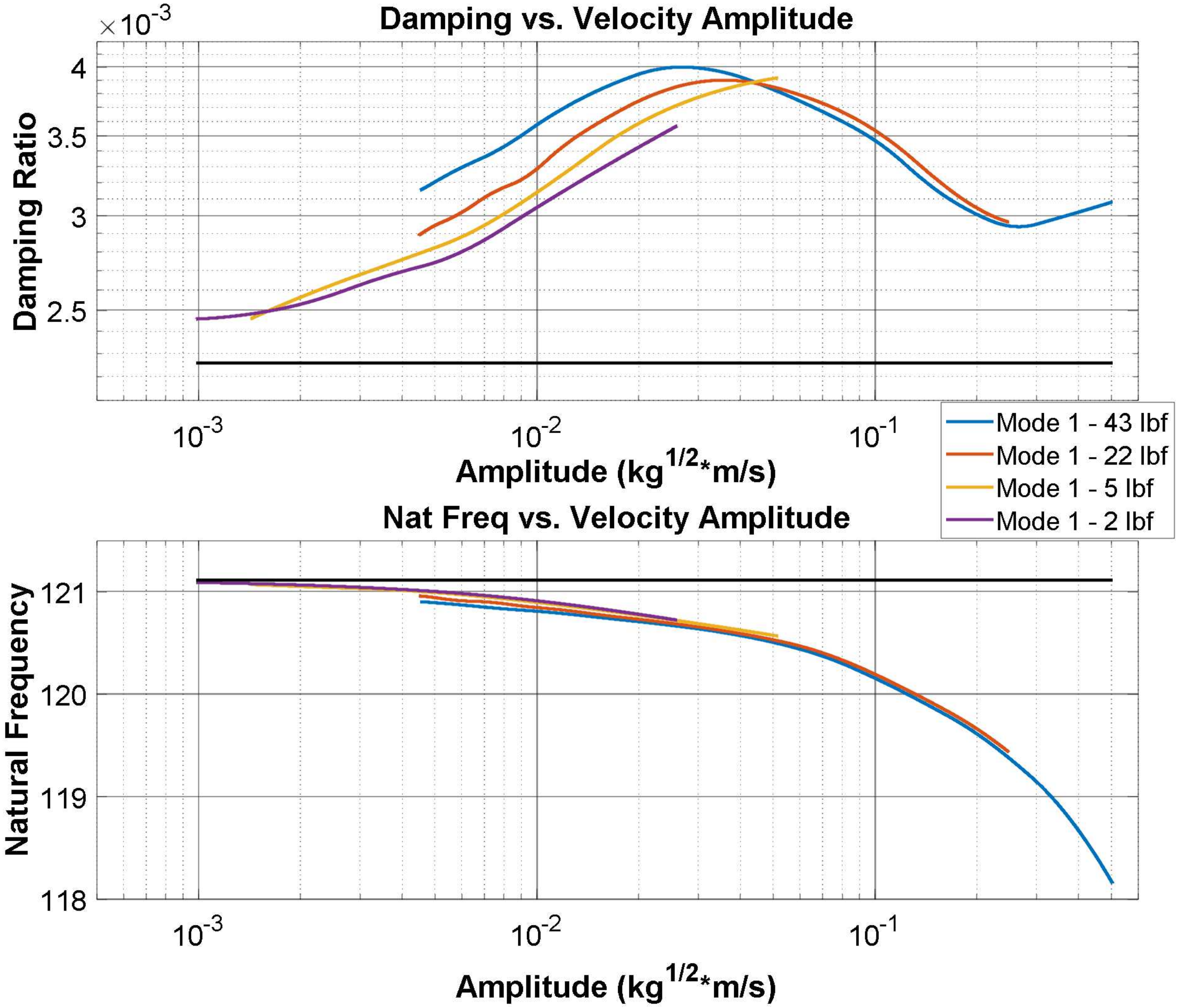
Experimental methods to measure nonlinear frequency and damping characteristics

Comparison of various dissipation models to model jointed structures

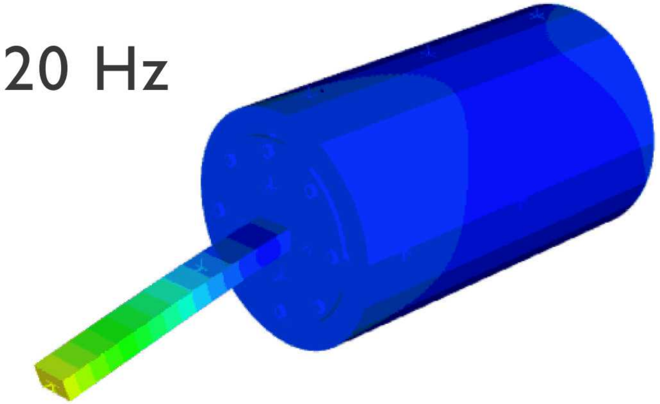
Experimental procedure to nonlinear system identification

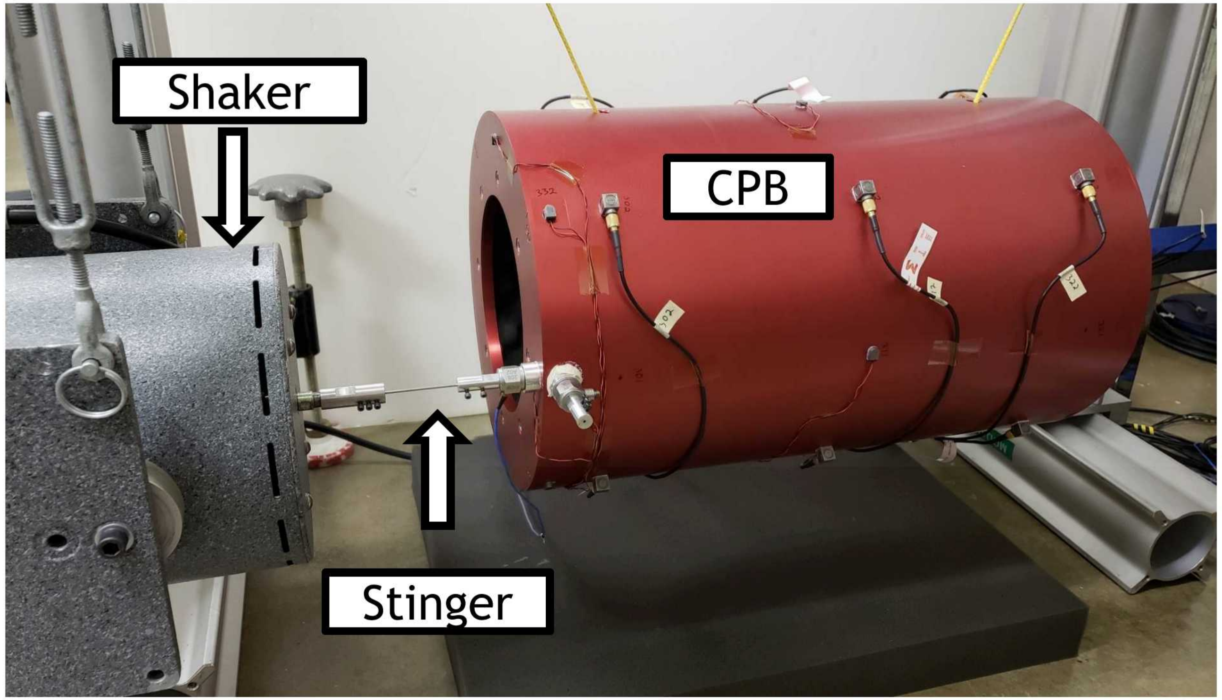


Measured frequency and damping data on cylinder-plate-beam (NOMAD)



Mode 1 @ 120 Hz





Overview of Structural Dynamics of Mechanical Joints

Nonlinear reduced order models with mechanical interfaces

- Whole joint modeling
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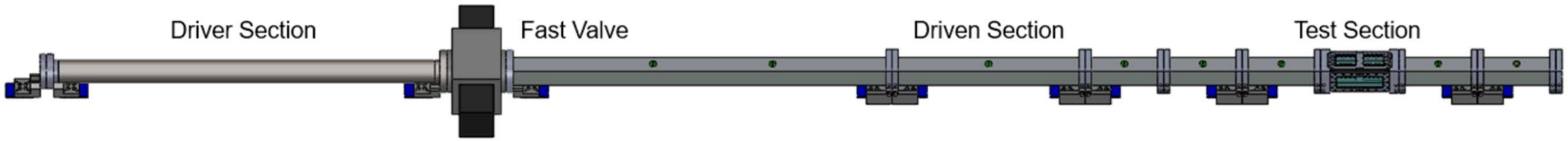
Experimental methods to measure nonlinear frequency and damping characteristics

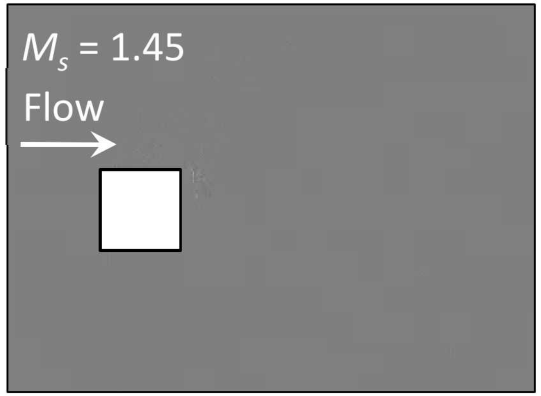
Comparison of various dissipation models to model jointed structures

Motivations

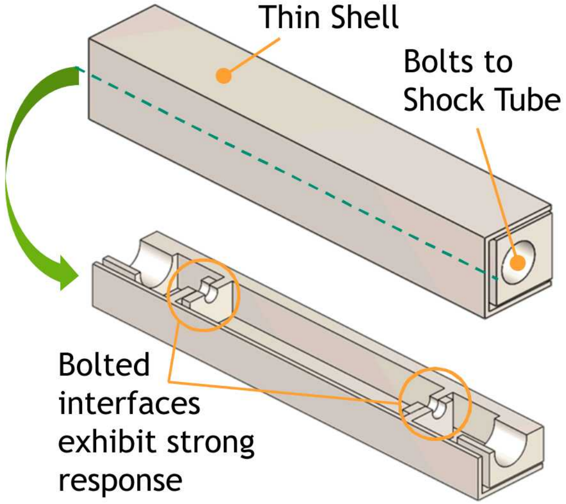
Predicting transfer of energy from a flowfield to structures is challenging, and is often based on semi-empirical models and simple modal testing, with large uncertainties



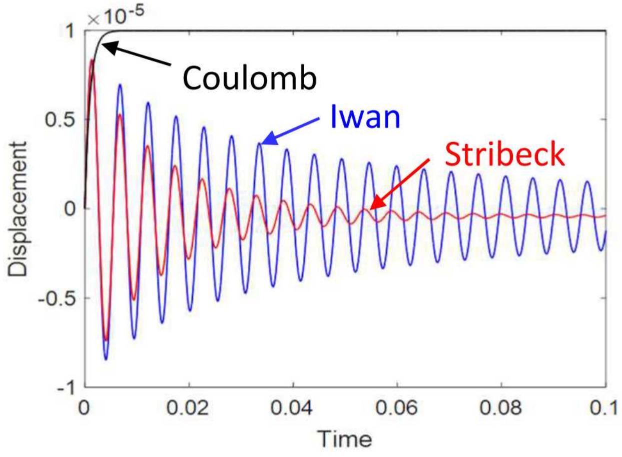
Shock tube creates impulsive start and periodic vortex shedding loads



Loads a susceptible jointed structure



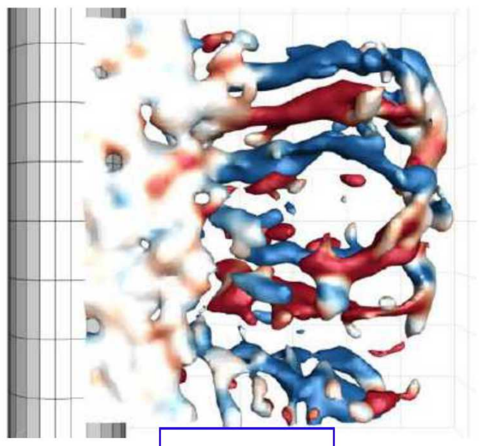
Evaluate response of structural joint models



Primary goal: measure the input loading and output structural response to test the predictivity of constitutive models on jointed structures under real fluid dynamic loading.

Diagnostic Approach

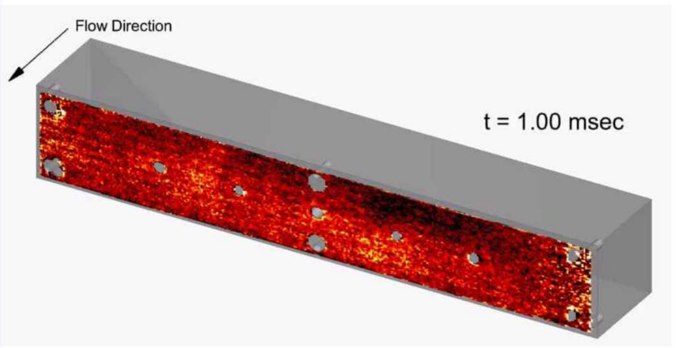
High-Speed Tomographic-PIV[1]



Source

- **Measure the flow-field responsible for pressure loading in a time-resolved fashion over a volume**

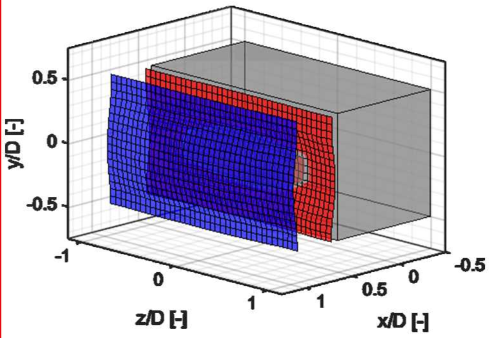
High-Speed PSP



Input

- **Obtain the pressure field on the body surface responsible for the loading. This is used directly as the input in simulations.**

High-Speed DIC



Output

- **Measure the output using DIC. Directly compare simulations to these measurements.**

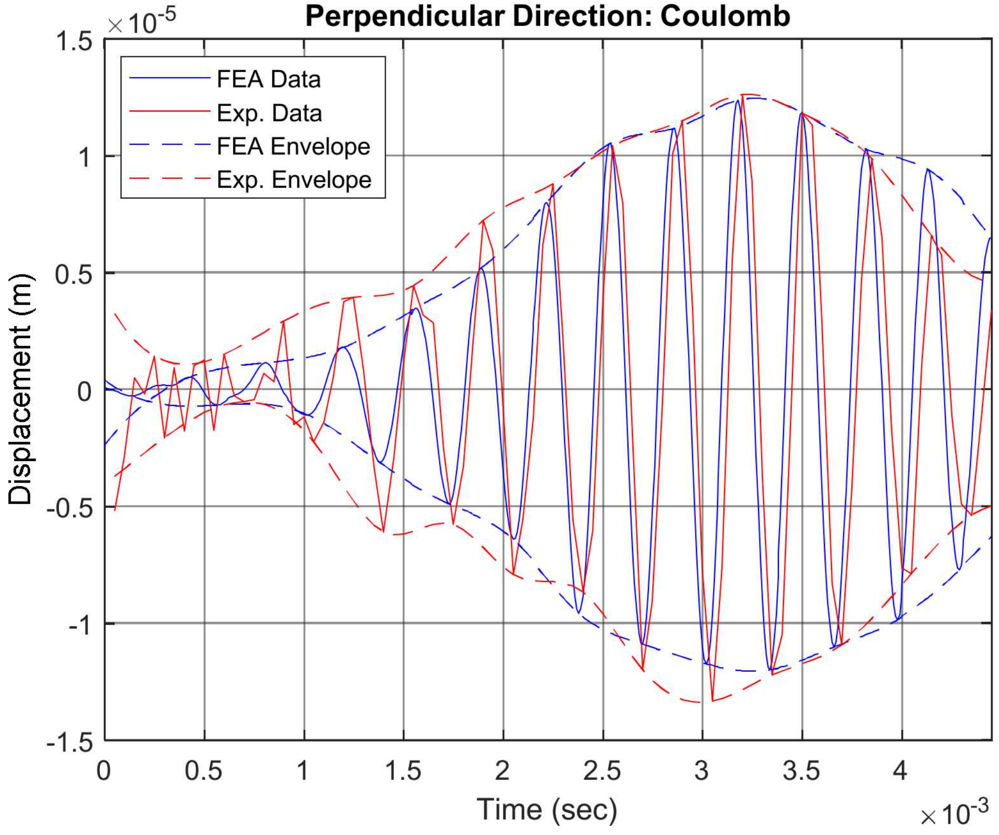
This work: perform high-speed PSP and DIC *simultaneously*

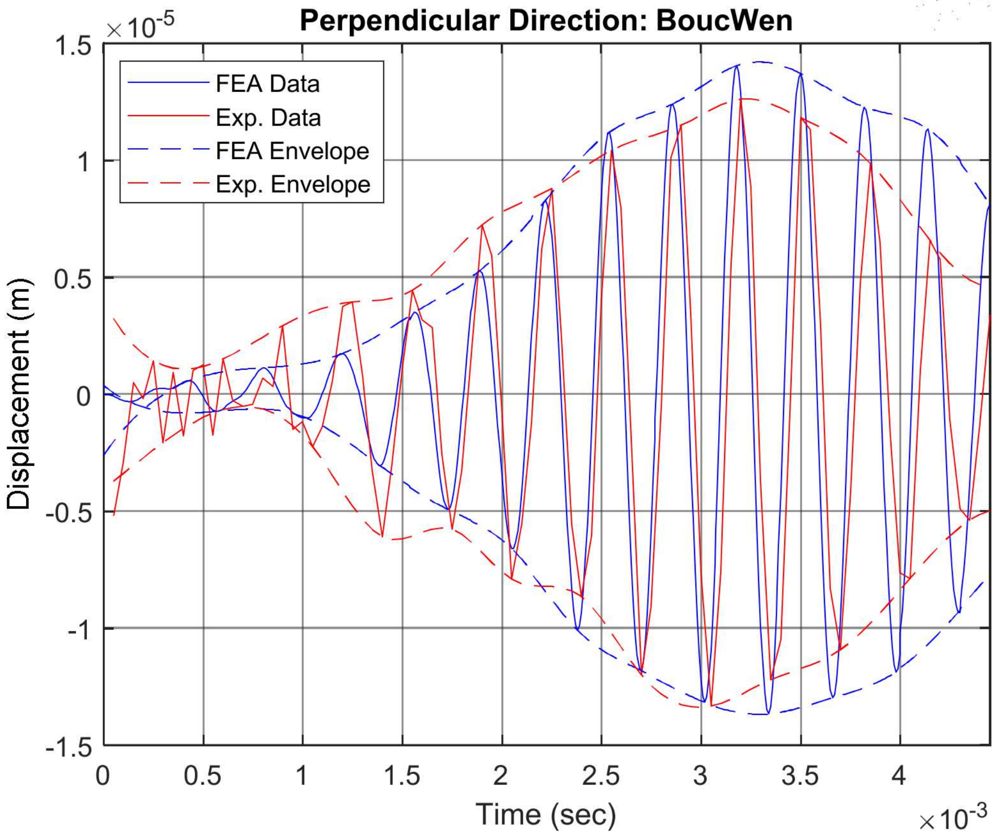
[1] Lynch and Wagner (2018) Time-resolved pulse-burst tomographic PIV of impulsively-started cylinder wakes in a shock tube. AIAA 2018-2038.

Comparison of friction models for jointed structure in shock tube

Coulomb friction and Bouc-Wen element appear to match test data well

- Rocking mode is main contribution to loading the joint





Concluding remarks

Joints in structural dynamics realize new challenges that make modeling and experiments challenging

- Linear theory no longer valid
- Excessive simulation times for models
- Issues with convergence, repeatability, etc..

Reduced order models provide a unique opportunity for model calibration

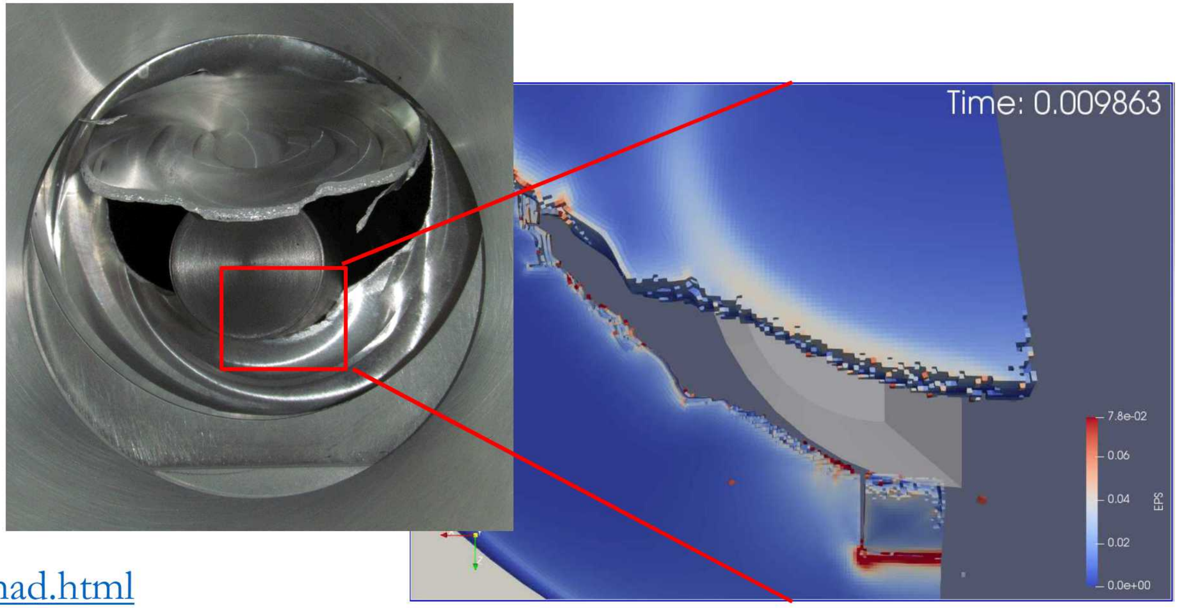
- System identification based on nonlinear frequency and damping
- Ability to quickly sample the model and understand joint behavior

Many options available for modeling friction: which one is correct?

- Small length scales beyond our macro-scale models
- Coulomb most widely available/used

Research collaboration opportunities for students and professors

- Hosted by Sandia National Laboratories and University of New Mexico
- Collaborative opportunity to work on research in topic areas across nonlinear mechanics and dynamics
- 7 week program held in Albuquerque, New Mexico; open to graduate and highly qualified undergraduate level students



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For more information, please visit:
http://www.sandia.gov/careers/students_postdocs/internships/institutes/nomad.html

Any questions?

Special thanks to my collaborators:

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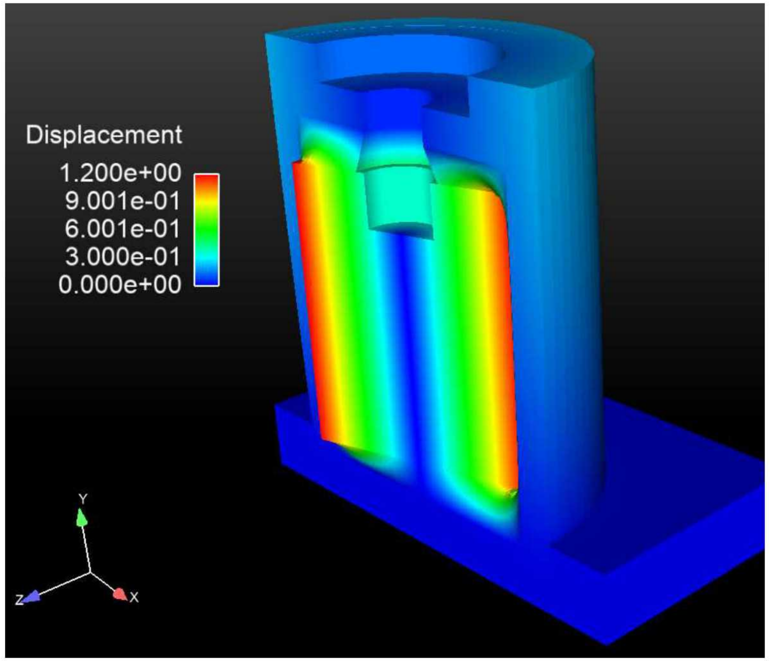

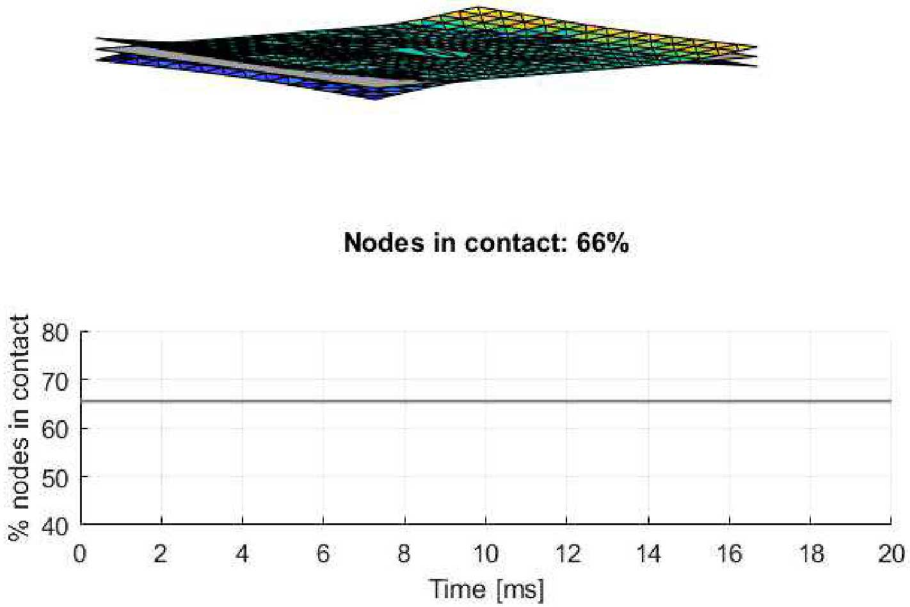

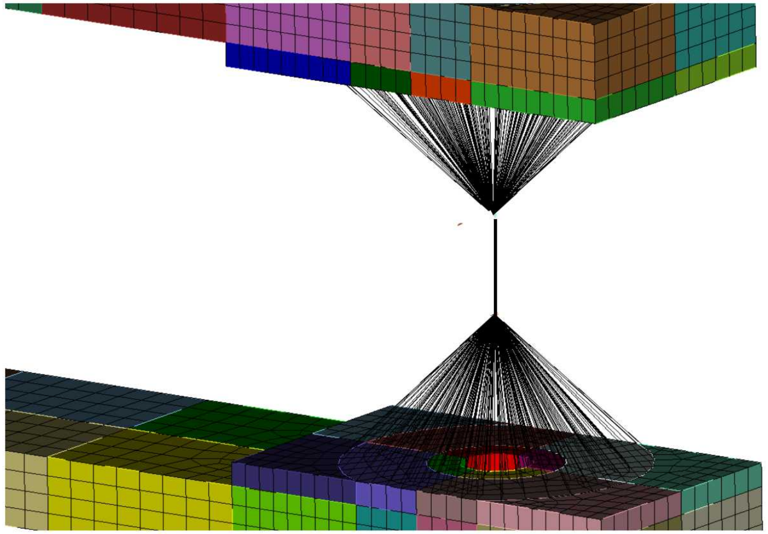

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