ARIZONA STATE UNIVERSITY

SAND2017-6690PE

Nonlinear Dynamics of Multi-Joint Structures

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April 29th, 2016

M.S. Mechanical Engineering Thesis Defense

Committee:

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Member – Dr. Matt Brake

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Motivation

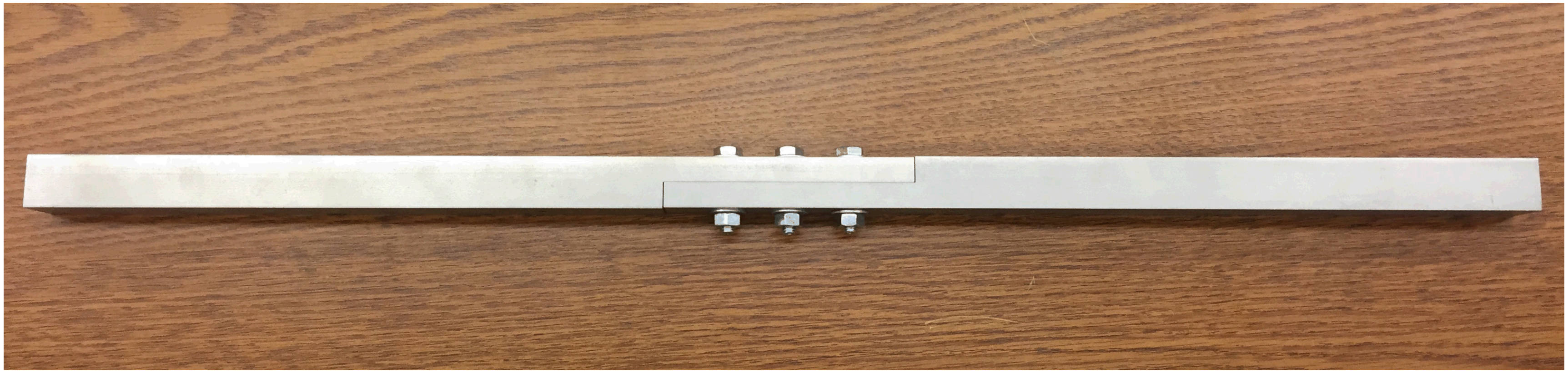
- Nonlinearities in jointed structures can largely change the dynamics of a system
- When structures contain only a few joints, the nonlinearities may not affect computations much, but when they contain hundreds or thousands of joints, the effort increases drastically

- Want to be able to determine when fully nonlinear models are necessary and when some linearization will suffice

Aleatoric vs. Epistemic Uncertainty

- Joints have intrinsically variable properties, from one nominally identical joint to another (aleatoric uncertainty)
- Joint *models* introduce epistemic uncertainty as they approximate the physics
- It is suggested that if a joint model is somewhat simplified, the increase in epistemic uncertainty can be present, as long as its effects remain small with respect to those of its aleatoric counterpart
- Will explore the simplification of a stochastic multi-joint model to observe if the increased epistemic uncertainty will be noticeable compared to the existing variability in the response

Core Test Article: Brake-Reuss Beam



- Brake-Reuss (BR) Beam – 3 Bolt Lap Joint
- Used as baseline model for nonlinear dynamics research
- Impact experiments were performed during Nonlinear Mechanics and Dynamics Institute 2015 (NOMAD)

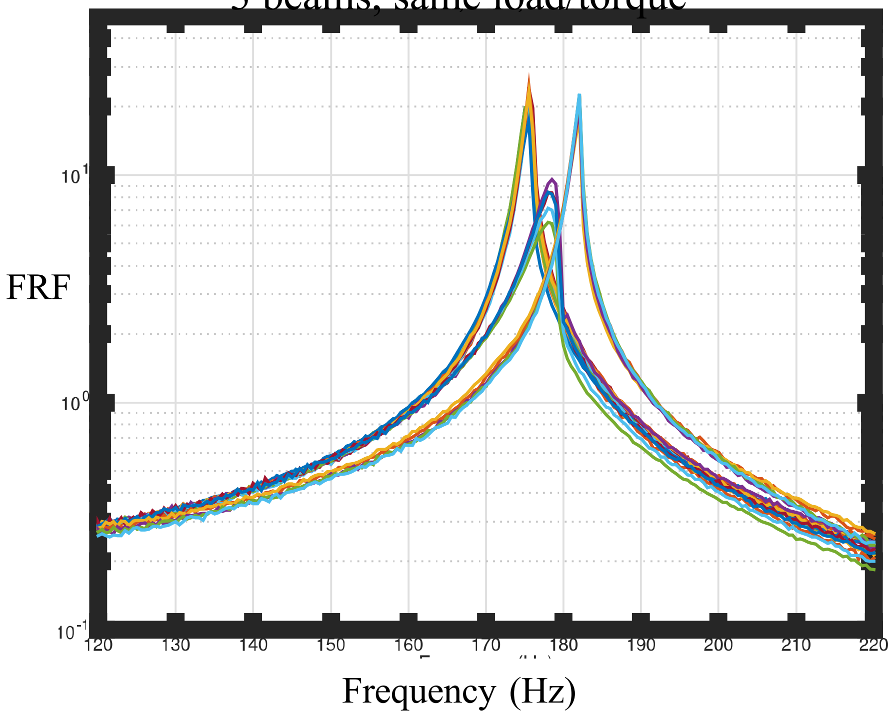
Research Goals

- BR Beam:
  - Obtain experimental data
  - Create reduced order model (ROM) of BR beam that allows a nonlinear interface/joint model
  - Find parameters of joint model that replicate frequency shift found experimentally
  - Make correlations between impact level and frequency shift/damping ratio increase
- Multi-Joint Frame:
  - Design frame which contains multiple BR beams, create ROM, and implement into solver (Romulis)
  - Relate impact level/location and joint activity
  - Determine if certain joints can be modeled linearly when aleatoric uncertainty is present

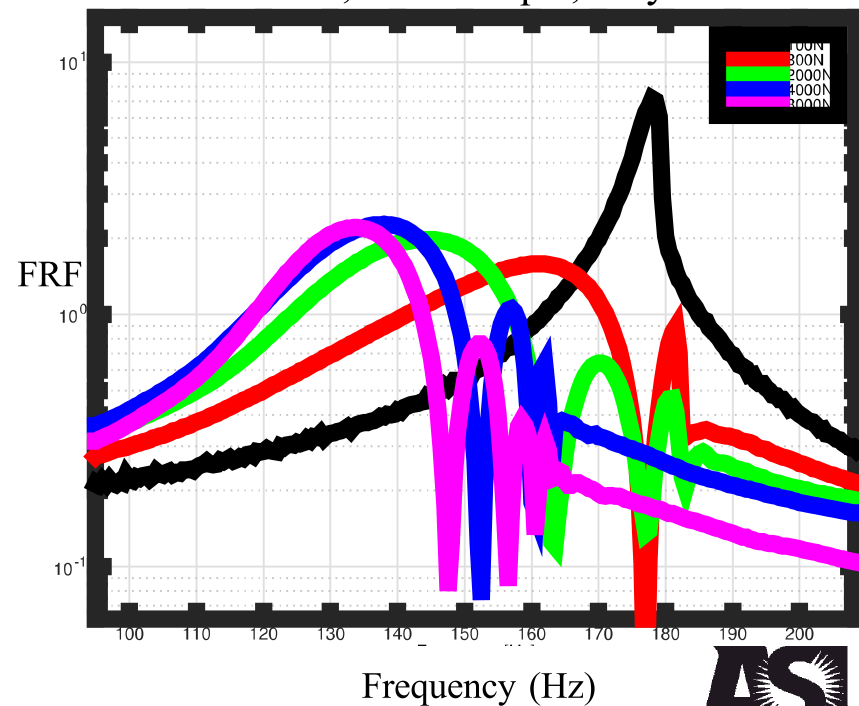
Impact Hammer Experiments – BR Beam

- Support beam by bungee cords (free-free)
- Vary interface, torque, load level
- Large data set was collected

3 beams, same load/torque

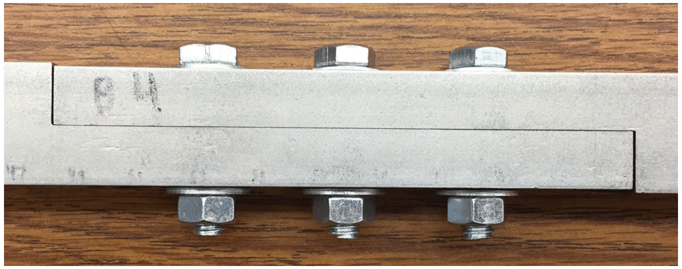


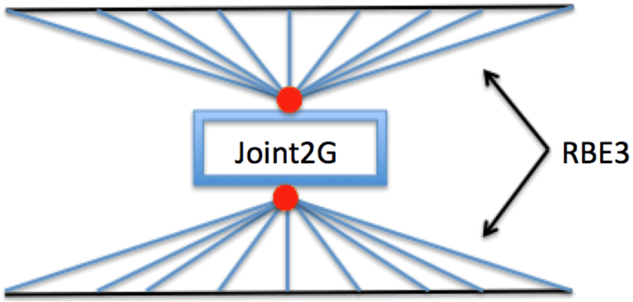
One beam, same torque, vary load

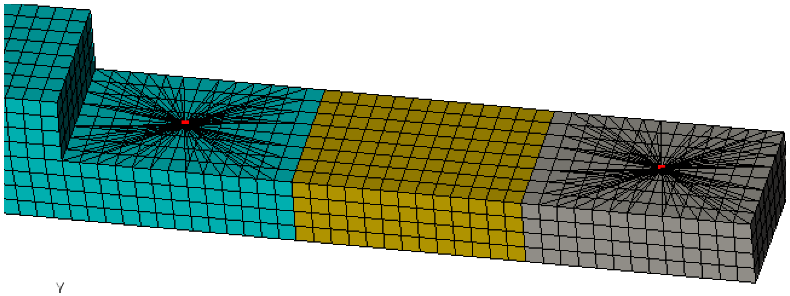


Modeling the BR Beam

- After discussion with modeling group at NOMAD (Stuttgart), the interface was cut into three equal sections
- The middle section completely tied, due to tightness of interface
- Outer sections are rigidly connected to single nodes, act as interface

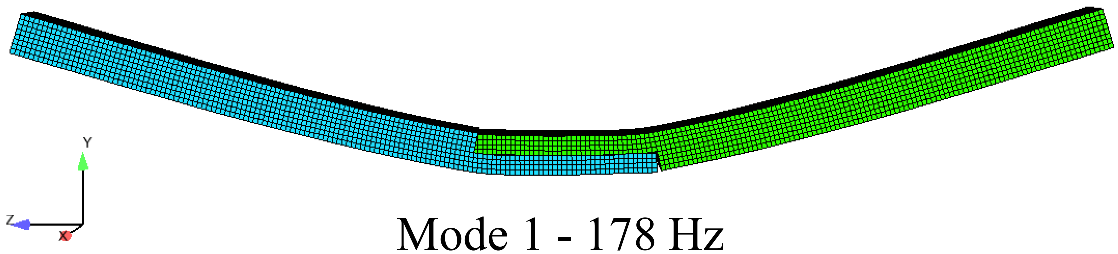




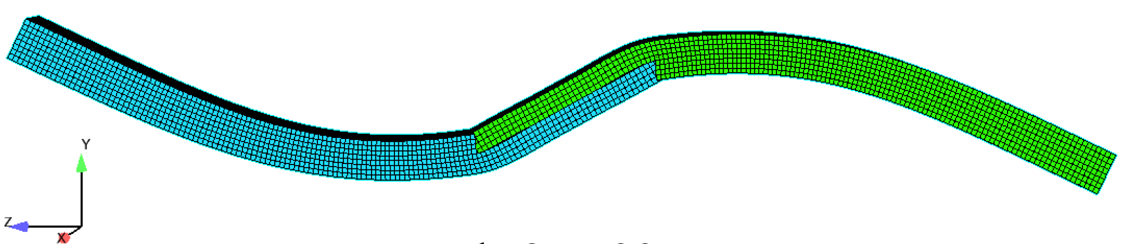


In-Plane Modes of BR Beam

- Able to match linear natural frequencies of first two in-plane modes using springs as interface elements



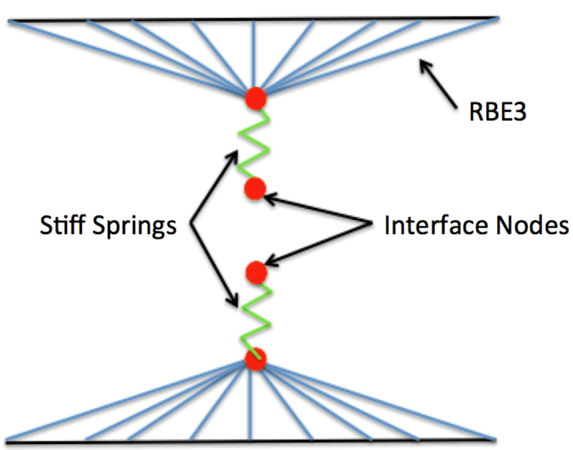
Mode 1 - 178 Hz



Mode 2 - 599 Hz

Craig-Bampton Reduced Order Model (ROM)

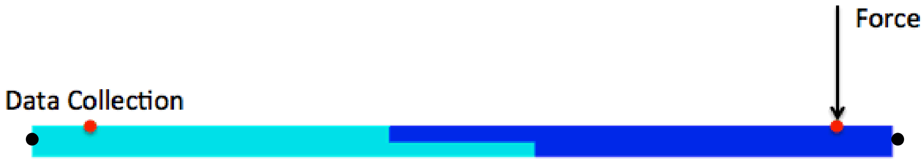
- Reduced number of degrees of freedom (d.o.f) is highly desirable for computational efficiency
- ROM is created by Craig-Bampton in Sierra by specifying the interface nodes and number of fixed interface modes
- 4 interface nodes (3 d.o.f each), 13 fixed interface modes = **25 d.o.f total**

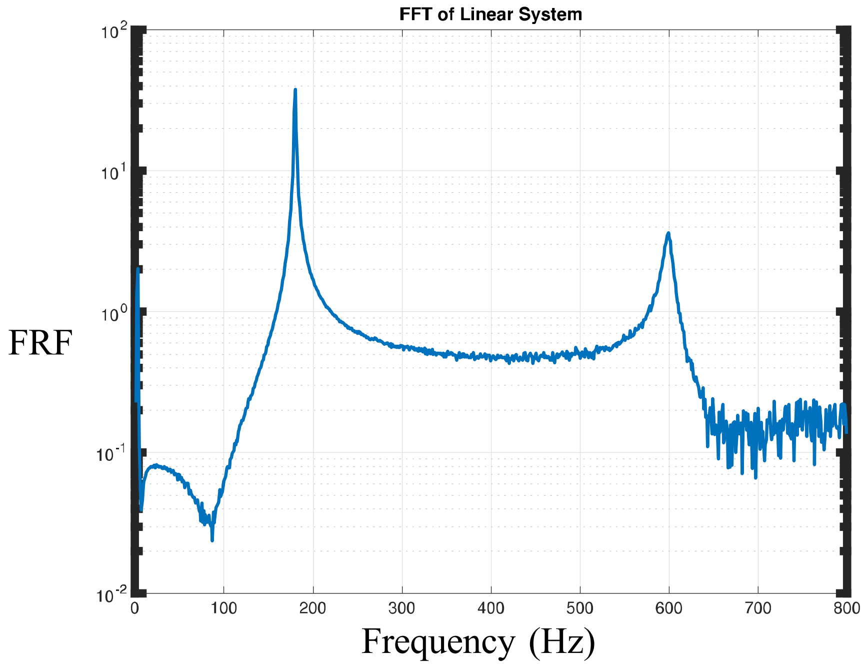


- Issues arise with direct RBE3 connections, solved with stiff springs

Linear Analysis of BR Beam

- Using Romulis, an impact hammer simulation is performed on the beam
- Linear interface elements are used to verify ROM is performing correctly
- Frequencies of first two modes confirmed – 178 Hz, 599 Hz





Nonlinear Joint Model: 4-Parameter Iwan

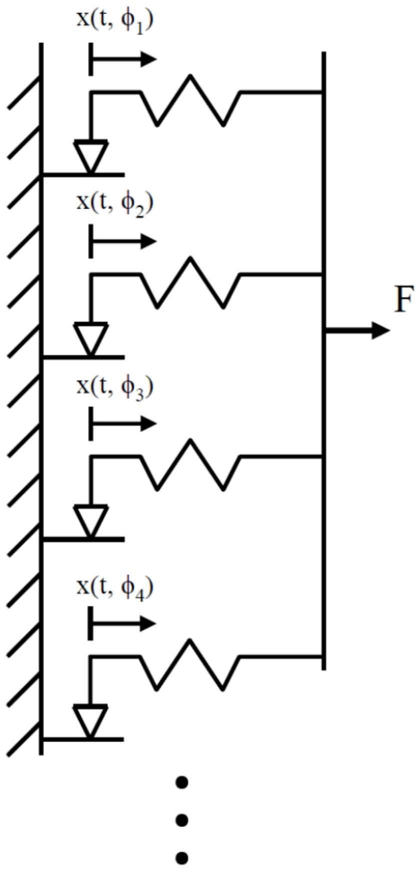
- Phenomenological model with likely epistemic uncertainty
- The Iwan is a distribution of Jenkins elements, allowing microslip/macroslip across an interface
- Depends on 4 parameters:

F_S : force at which macroslip occurs

K_T : tangential stiffness at no slip

χ : strength of singularity at 0 (dimensionless)

β : ratio of joint stiffness (dimensionless)

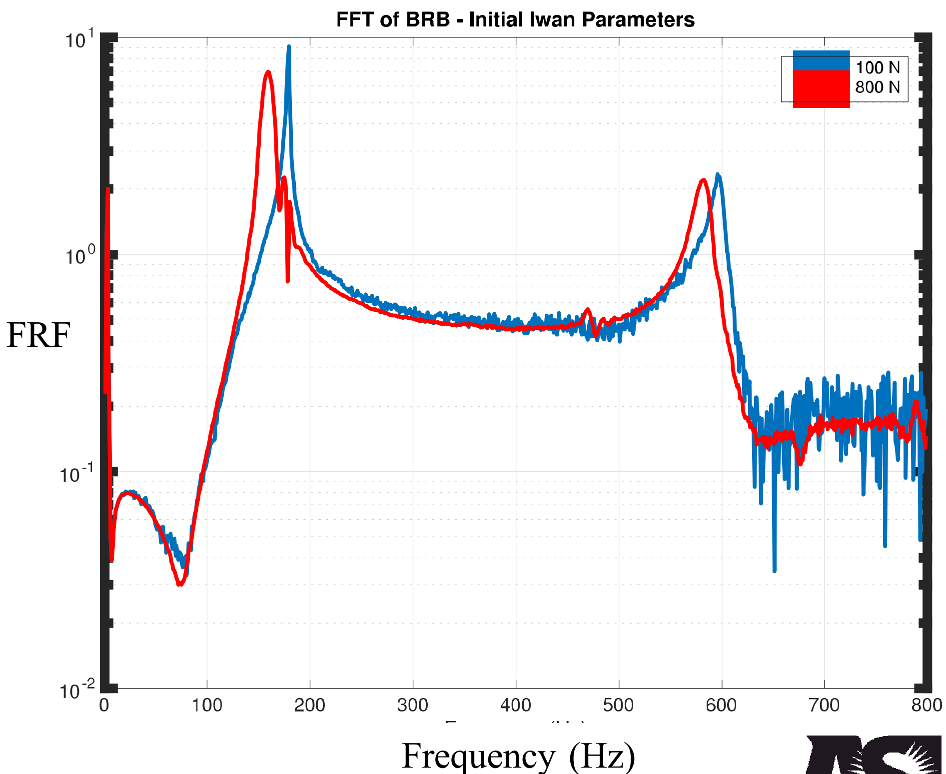


Identification of Iwan Parameters

- Attempting to match the mode 1 frequency shift between 100 N and 800 N impacts, Iwan parameters were approximated as:

  $F_S = 200$, $K_T = 1e10$, $\chi = -0.5$, and $\beta = 0.5$

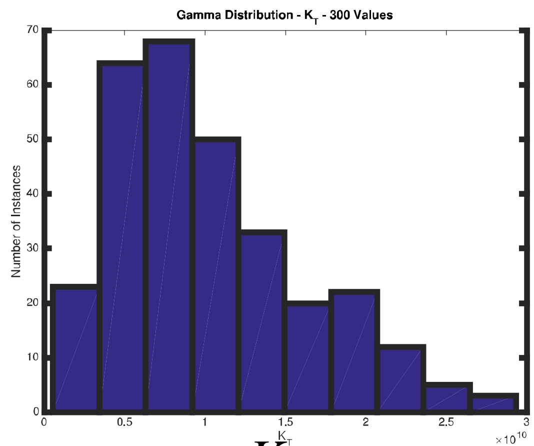
Mode	Frequency-100 N	Frequency-800 N
1	178 Hz	160 Hz



Introducing Uncertainty into Iwan Model

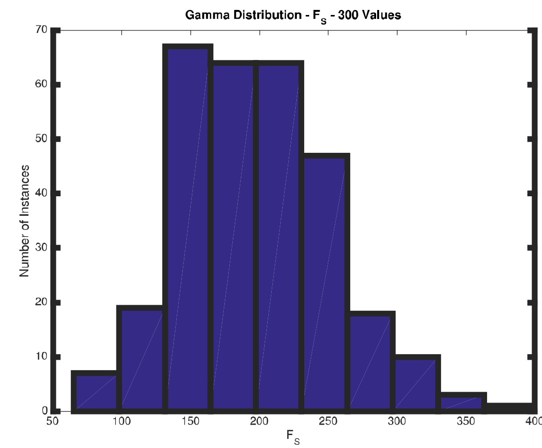
- Gamma distributions created to maximize entropy

$$K_T = \bar{K_T} X_1$$



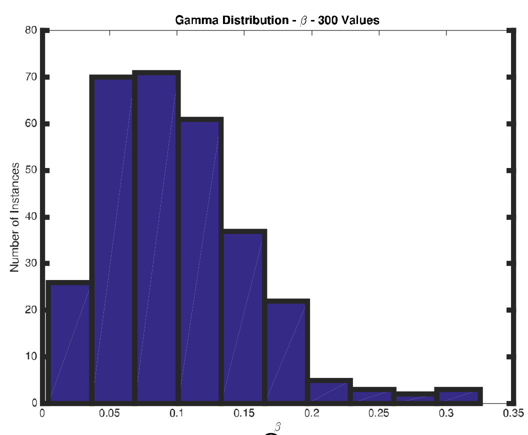
K_T

$$F_S = \bar{F_S} X_2$$



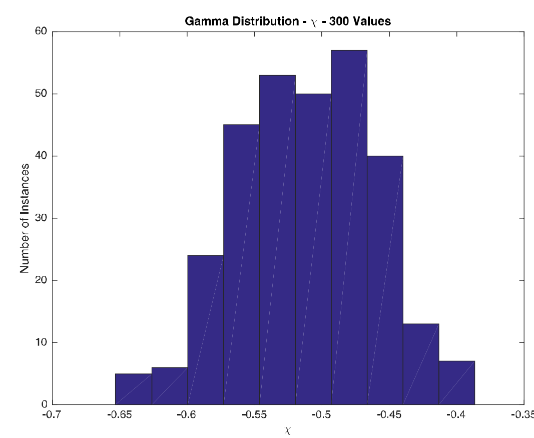
F_S

$$\beta = \bar{\beta} X_3$$



β

$$\chi = -\frac{1}{1 + \bar{\chi} X_4}$$

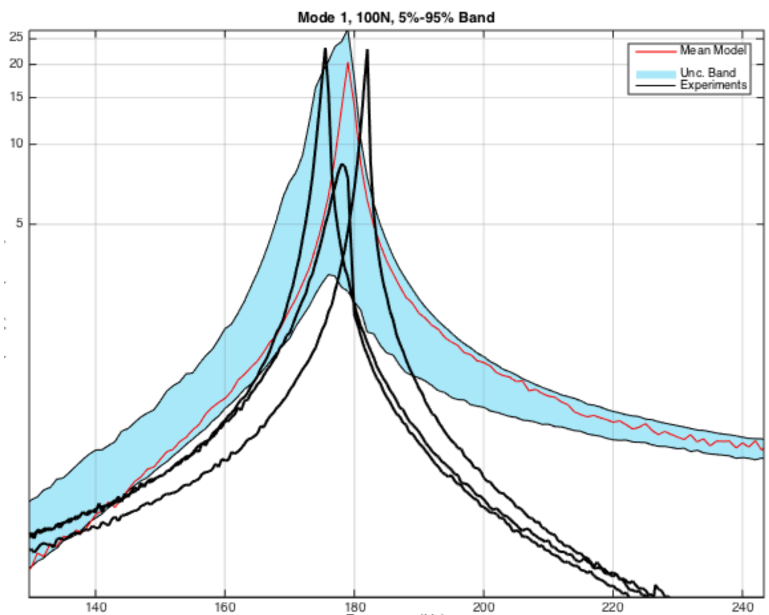


χ

Uncertainty Propagation – BR Beam

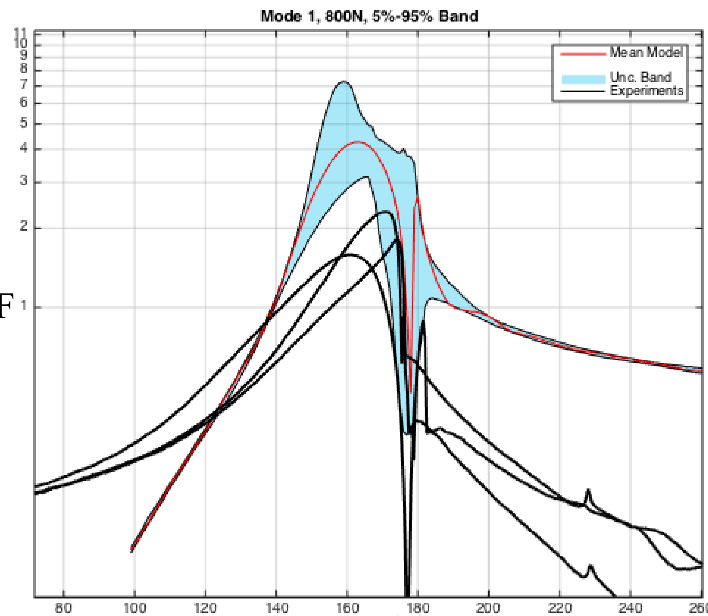
- Monte Carlo – 300 tests, each with different Iwan parameters
- Uncertainty Bands – 5th and 95th percentile
- 100 N bands fit somewhat nicely, but 800 N bands do not capture the same amount of dissipation as experiments

FRF



Frequency (Hz)

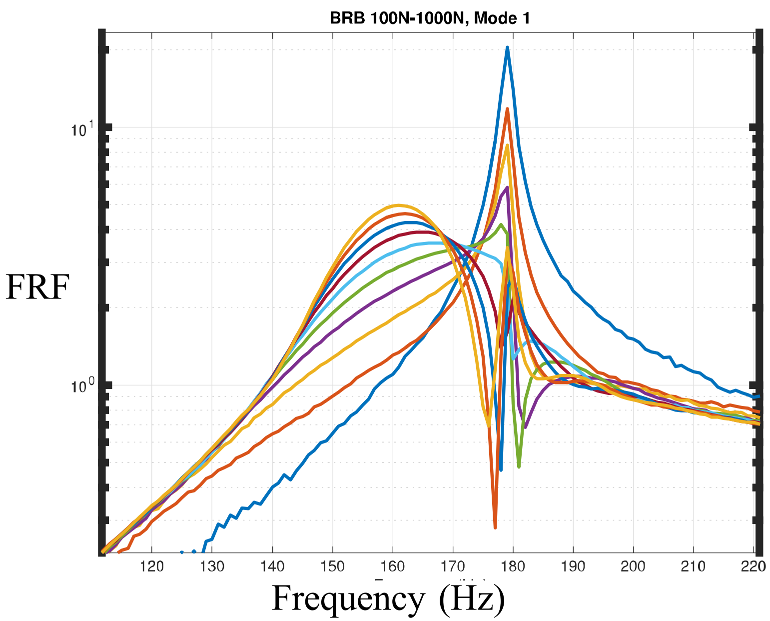
FRF

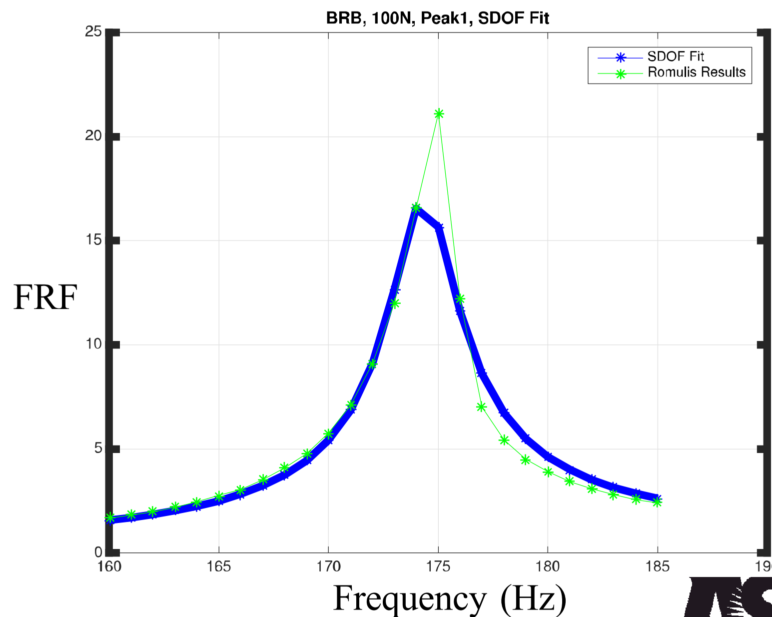


Frequency (Hz)

Linear Fit of BR Beam

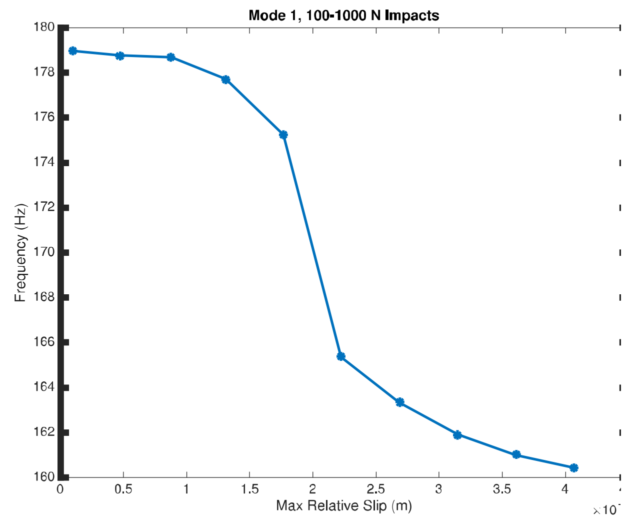
- Mean model analyzed for impacts of 100 to 1000 N to observe relationships between impact level, frequency, and damping ratio
- Fit frequency and damping ratio to linear, single degree of freedom (SDOF) system

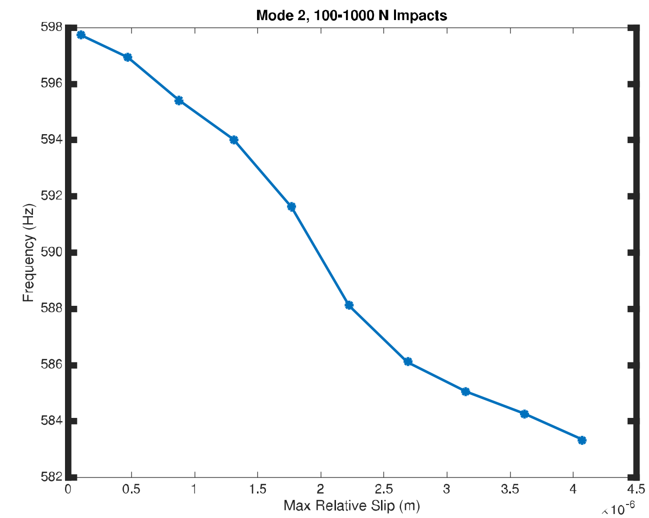




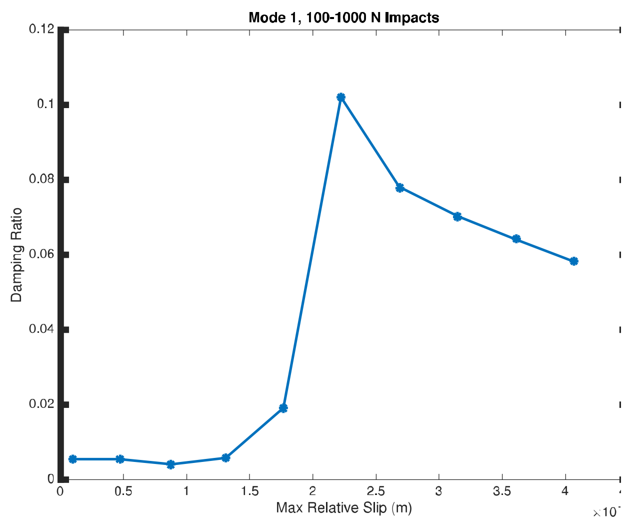
Linear Correlations

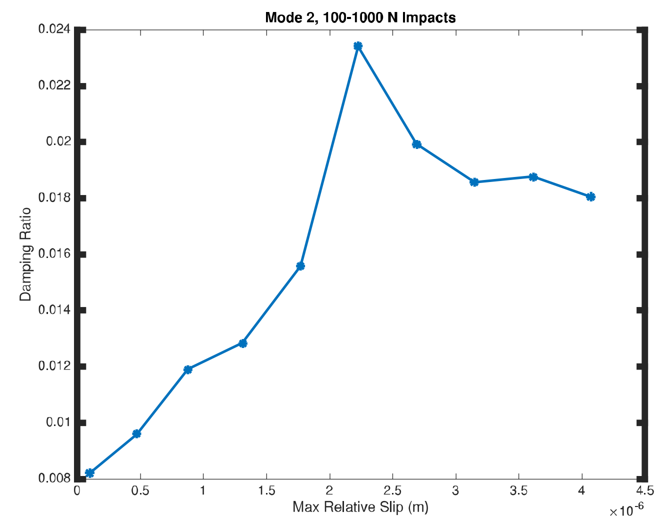
- Frequency (Hz) vs. Relative Slip (m)





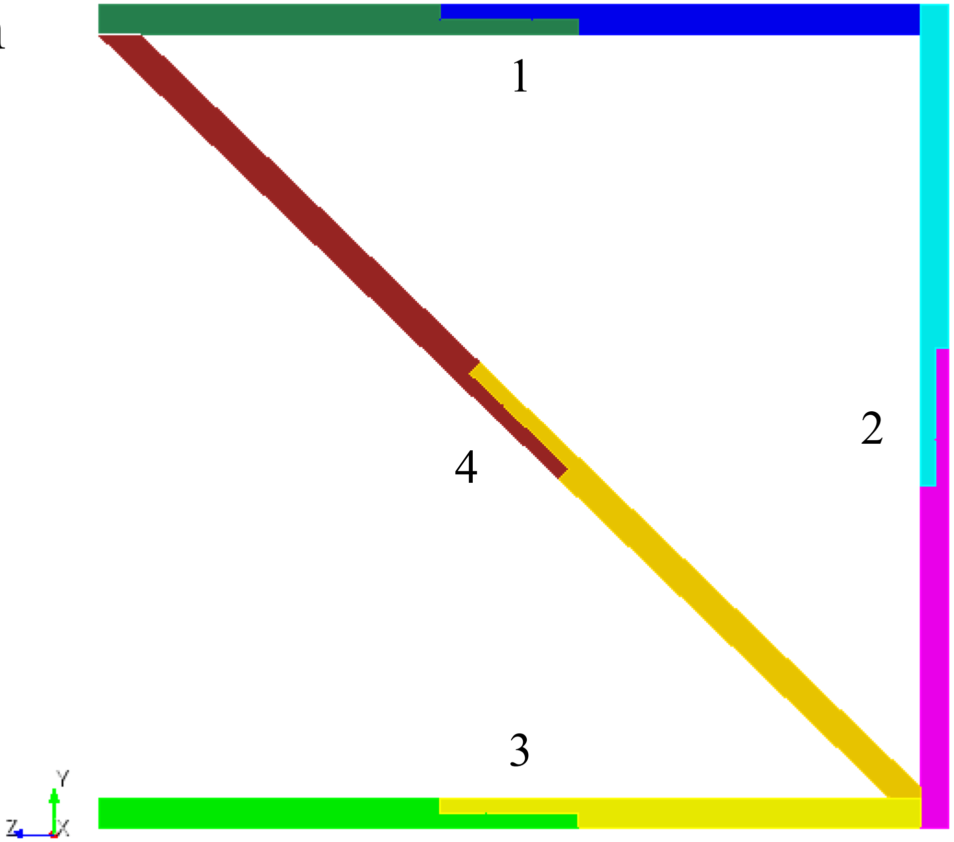
- Damping Ratio vs. Relative Slip (m)





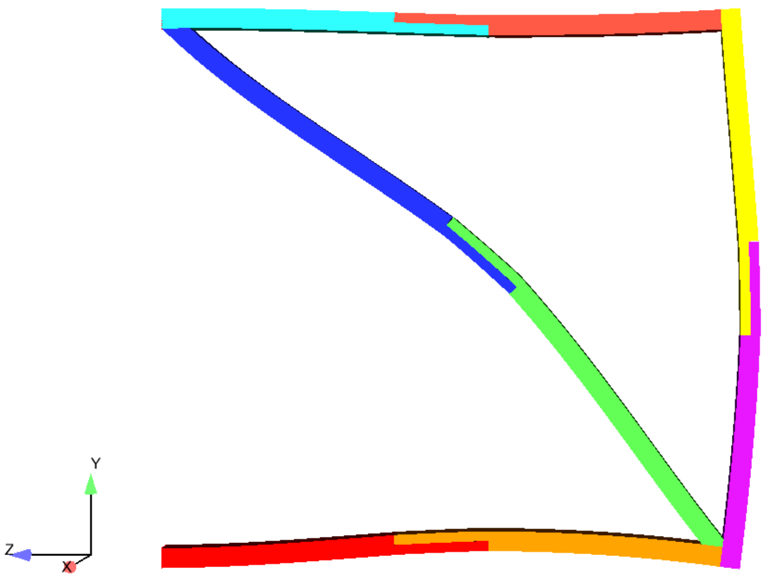
Multi-Joint Frame

- Introduce multiple joints in one structure
- Designed frame with 4 BR beams
- Same interface modeling techniques as BR beam

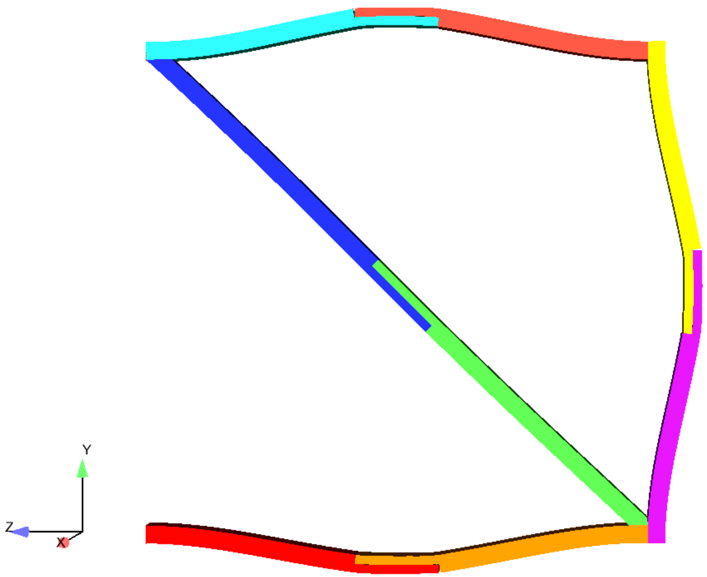


Modal Joint Activity

- Only interested in in-plane modes
- Asymmetry allows certain modes to have some joints active and some joints not as active



Mode 1

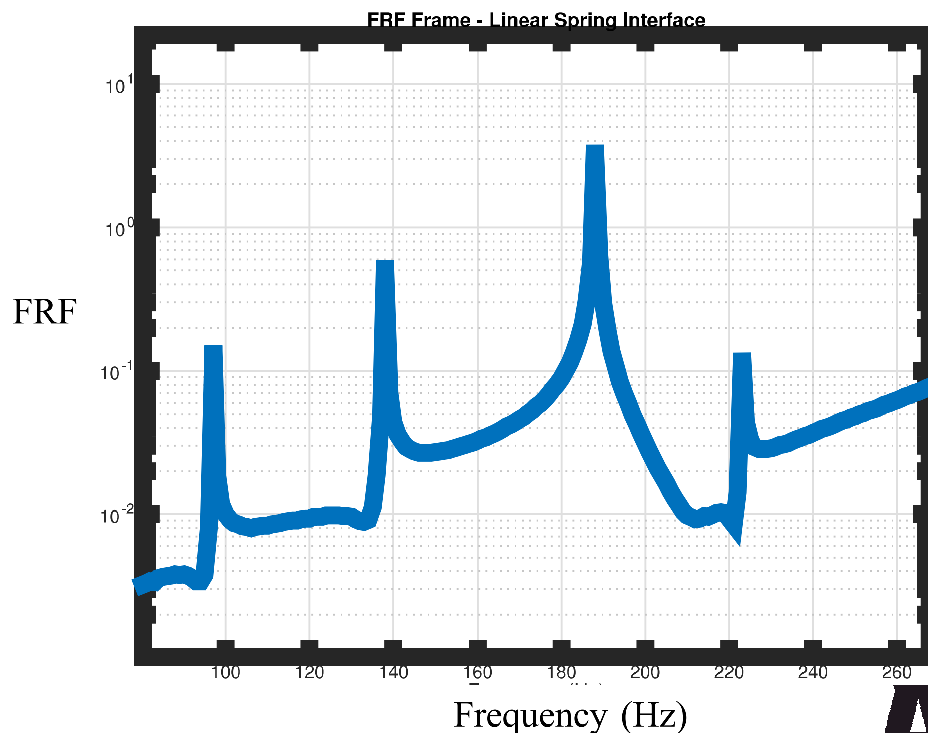


Mode 4

Impact Hammer Simulation

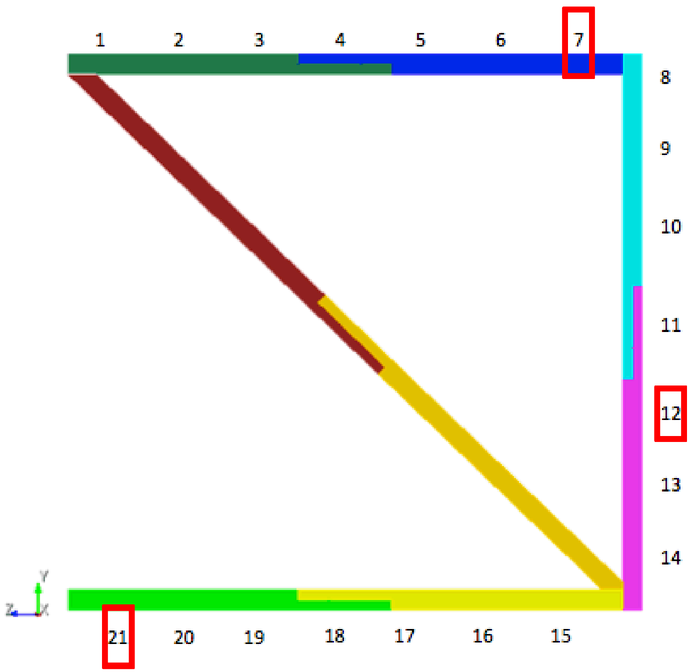
- Create Craig-Bampton ROM with same methods as BR beam
- Test setup created for Romulis to simulate impact hammer test
- ROM is verified with linear interface models first

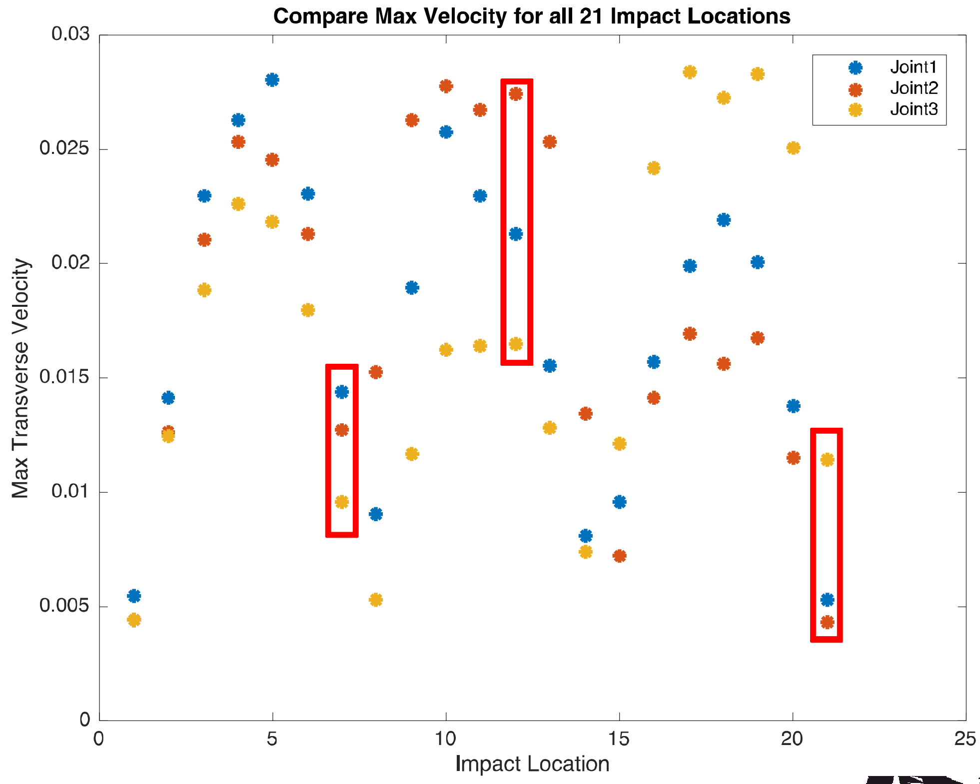
Mode	Frequency
1	97.19 Hz
2	138.12 Hz
3	188.27 Hz
4	223.21 Hz



Impact Location Determination

- 21 impacts performed on linear system – 100N
- Max velocity at joints 1, 2, and 3 recorded
- Three interesting cases chosen – 7, 12, 21





Linear Correlation to BR Beam

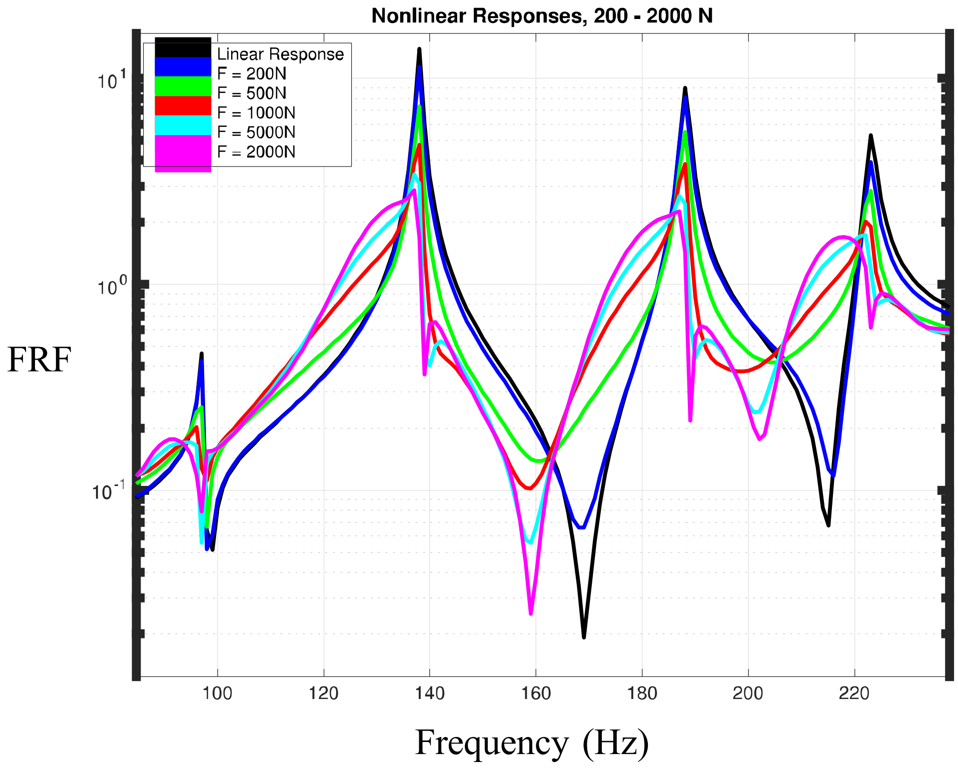
- Max relative displacements between interface nodes are recorded for 100 N and compared to the same metric of the single beam

100 N Impact	Max Relative Disp. (m)	Ratio to BR Beam
BR Beam	3.660e-8	1.00
Frame – Location 7	1.616e-8	0.4415
Frame – Location 12	2.520e-8	0.6885
Frame – Location 21	1.230e-8	0.3361

Impact Location	100 N Equiv.	200 N Equiv.	300 N Equiv.	400 N Equiv.
7	225	450	675	900
12	150	300	450	600
21	300	600	900	1200

Nonlinear Interface Models

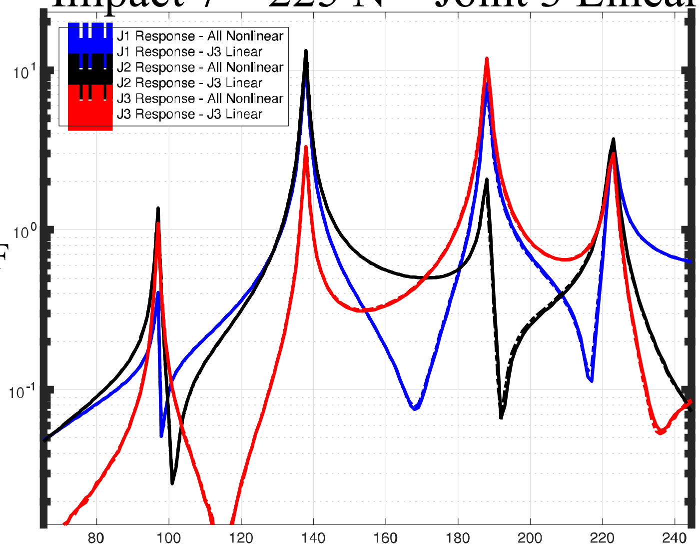
- Iwan elements are introduced at the joints (along beam direction only) with same mean parameters used for the beam
- Several impact simulations are performed at different levels to observe how mean model responds



Approximate Nonlinear Models

- Initial thought is that given a certain impact location, the least active joint (lowest velocity) can be linearized without affecting the dissipation
- At low levels, this is true, but at higher levels when more slip becomes apparent, the approximate models do not capture the correct damping

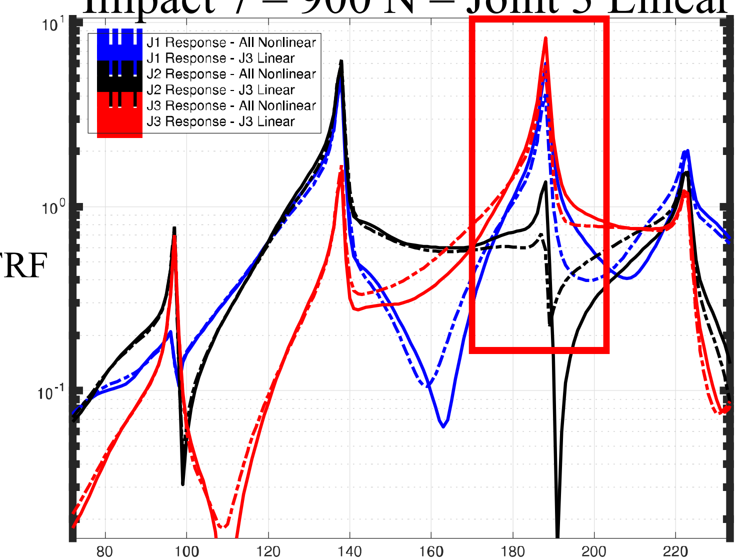
Impact 7 – 225 N – Joint 3 Linear



FRF

Frequency (Hz)

Impact 7 – 900 N – Joint 3 Linear

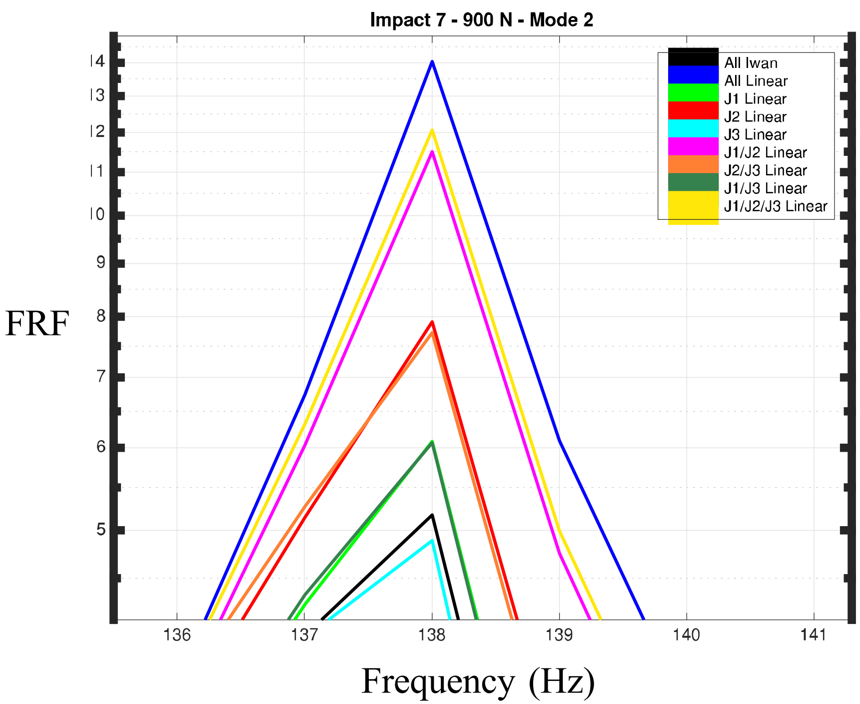


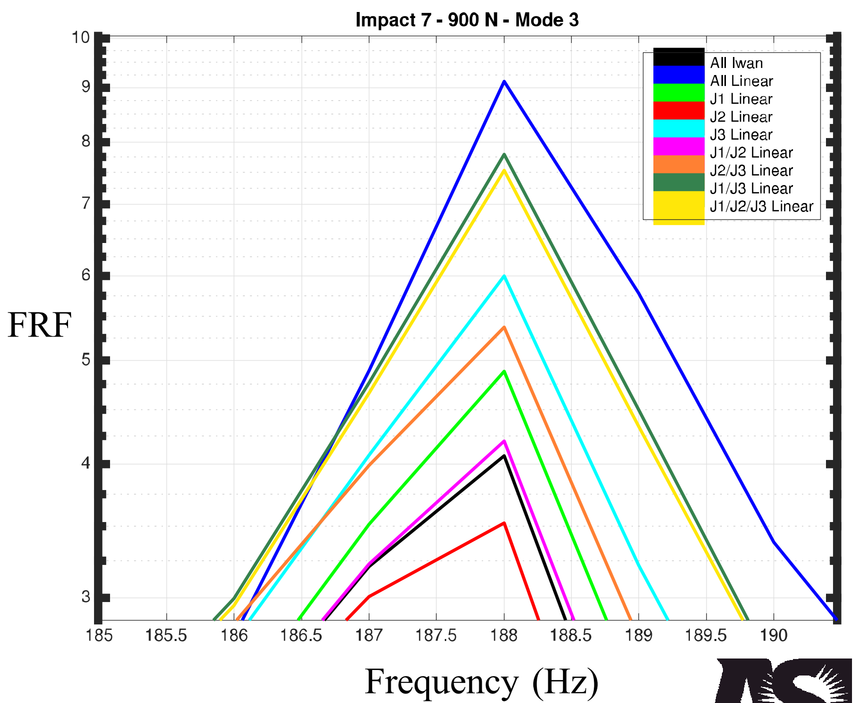
FRF

Frequency (Hz)

Approximate Nonlinear Models

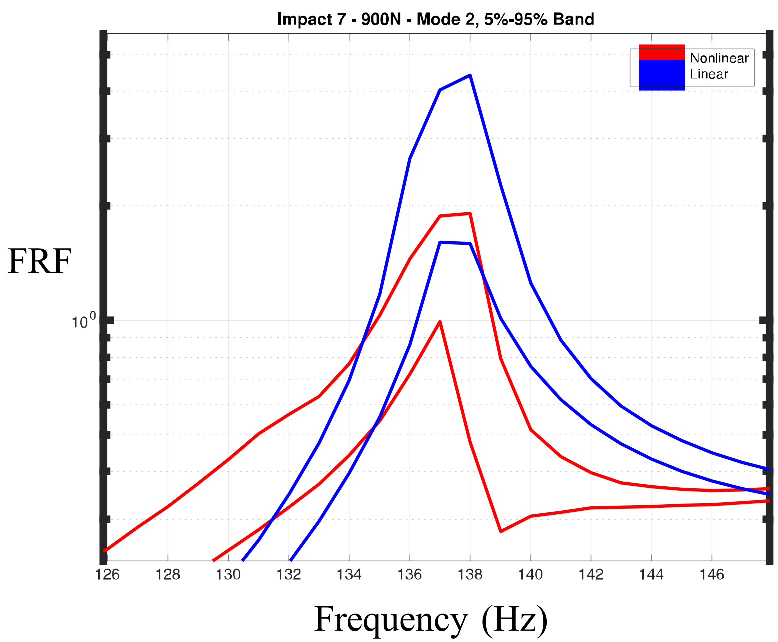
- It becomes more apparent, the joint activity is much more dependent on the mode than impact location
- For mode 2, joint 3 is the least active
- For mode 3, joint 2 is the least active

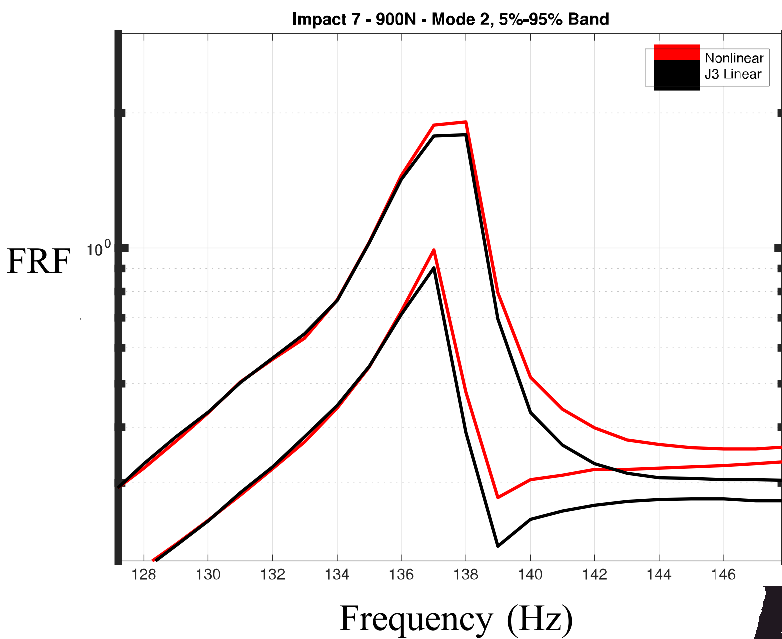




Introduce Uncertainty into Frame

- Same distributions as previously used with the BR beam
- 300 sample Monte Carlo test is performed
- Simplification of model does not outweigh the variability





Summary

- Single joint beam was tested, analyzed, and modeled
- Multi-joint frame was designed and analyzed using correlations from the single joint beam
- Comparisons were made for the multi-joint frame when using interface models that are nonlinear, linear, and combinations of both nonlinear and linear
- The computational model adopted for the frame is only required to provide a good estimate of an uncertainty band
- A relaxation of the model complexity (epistemic uncertainty) can be performed as long as it does not affect significantly the band of predictions
- For our model, it is found that the model simplification is often acceptable at lower excitation levels where microslip dominates

Acknowledgments

- Dr. Mignolet and Dr. Liu – Arizona State University

- Matt Brake – Sandia National Labs
  - Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporations, for the U.S. Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

- Thank you for your attention
- Questions??