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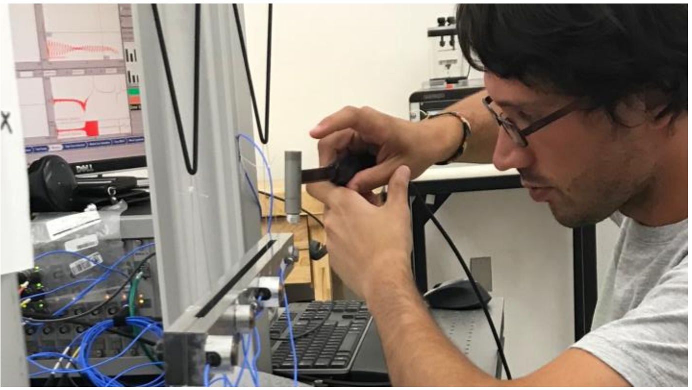

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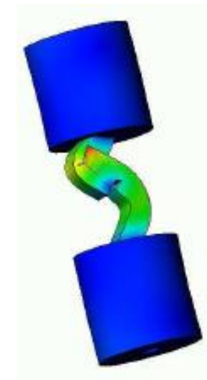

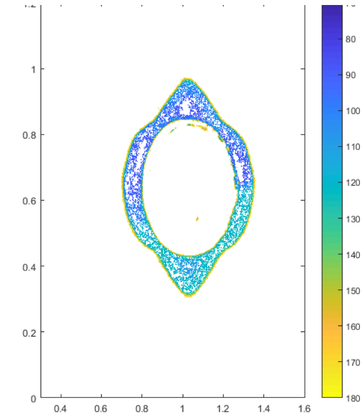

A Priori Methods to Assess the Strength of Nonlinearities for Design Applications

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Agenda

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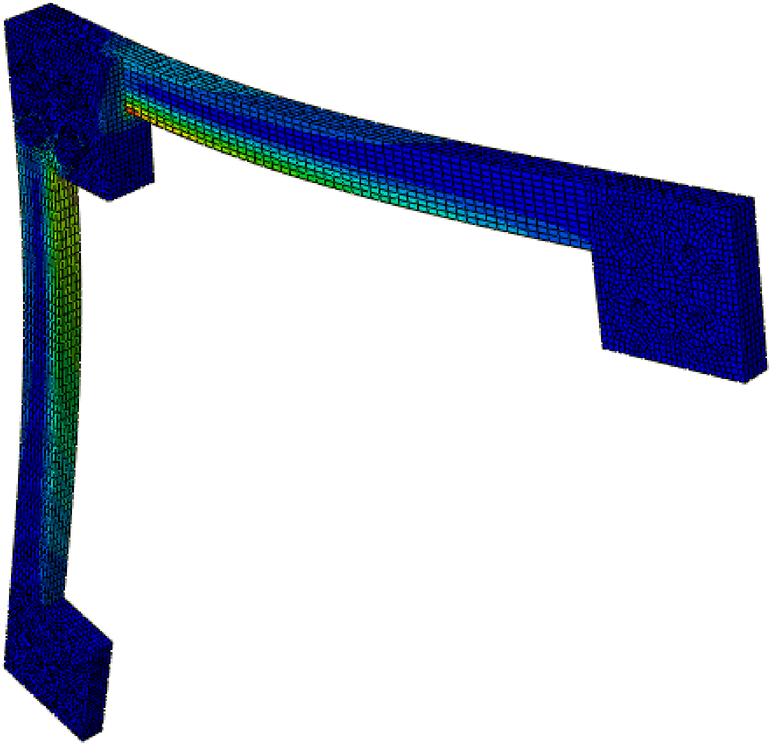
Project Overview

- It is hypothesized that the strength of a nonlinearity (SNL) in a jointed system can be predicted by quantifying the **magnitude and uniformity of contact pressure** within an interface and by assessing the **modal excitation of an interface**.

- Numerical Methods:

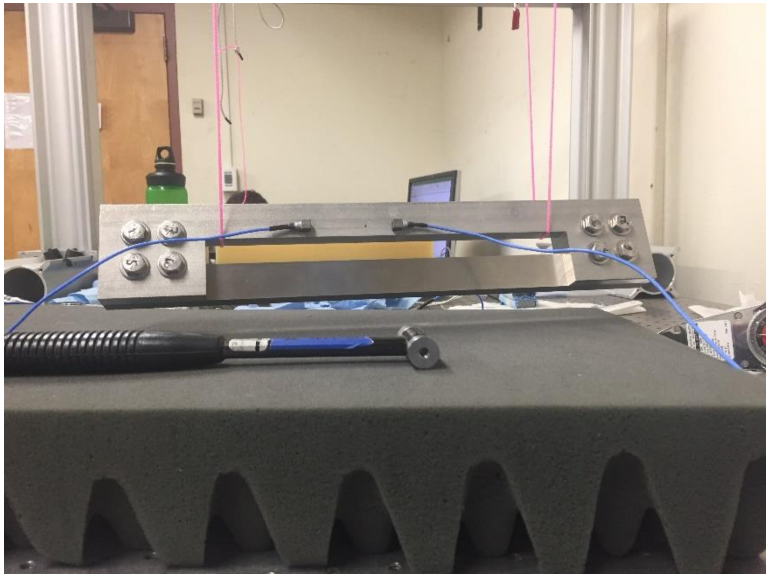
  Using Abaqus, we calculated a variety of statistics regarding contact pressure and modal strain to utilize in developing a metric to predict strength of nonlinearity.

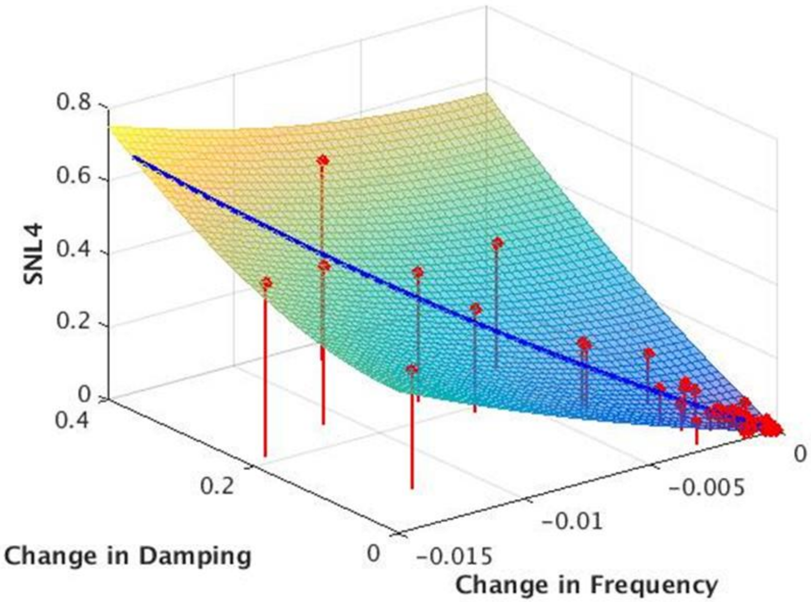


Project Overview

- Experimental Methods:

  We obtained time response data for many beam configurations.



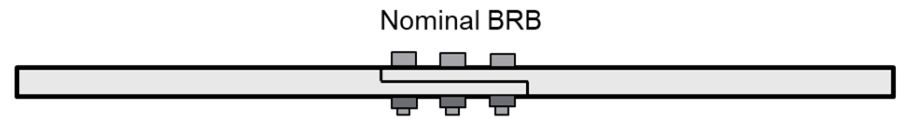


- Analysis:

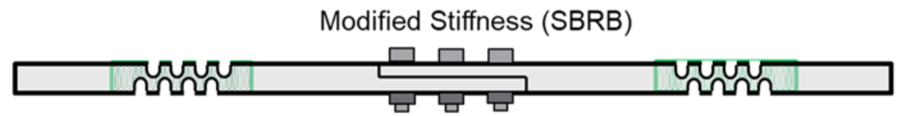
  We developed a definition for SNL based on change in damping ratio and change in frequency. Using machine learning, we assessed the importance of various statistics in predicting SNL and finalized a metric.

Configurations – Brake-Reuß Beam

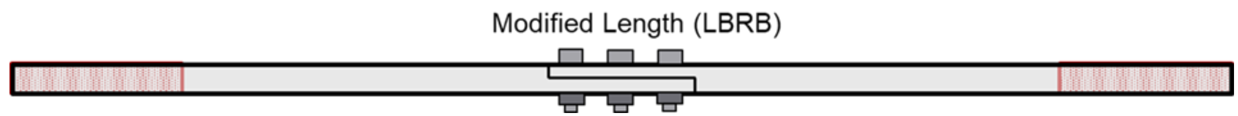
- BRB



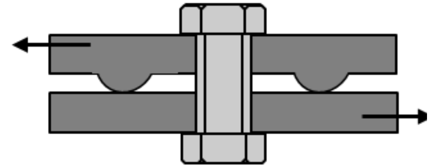
- Spring (SBRB)



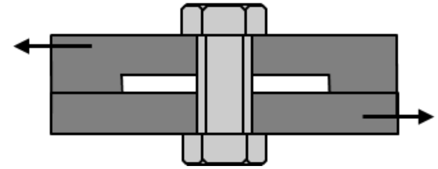
- Long (LBRB)



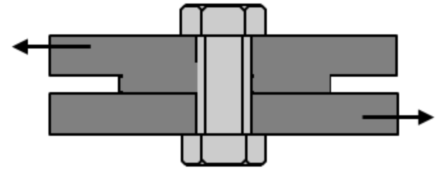
- Hertzian Contact (HZ)



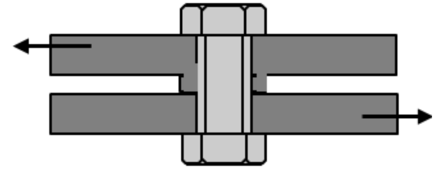
- Reverse Pad Contact (RPD)



- Large Pad Contact (LPD)

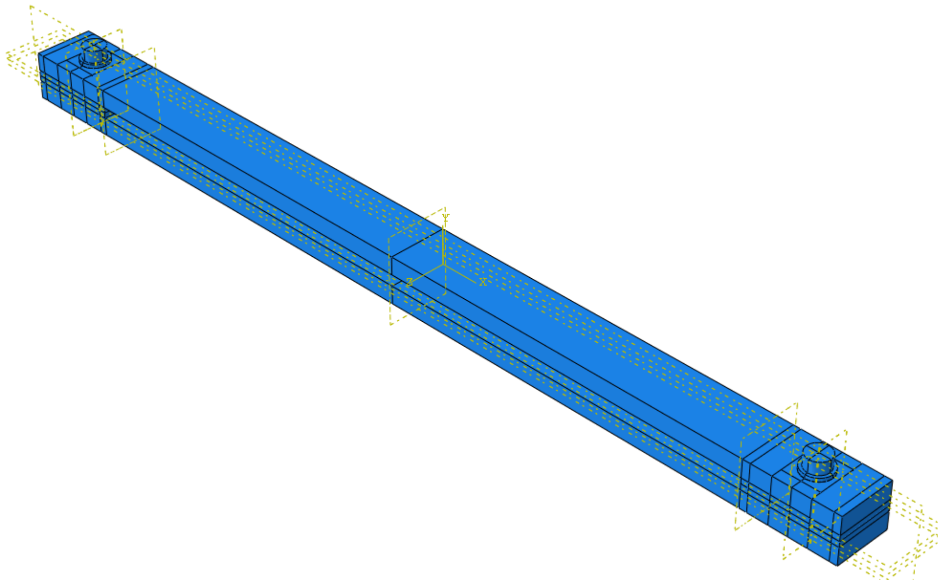


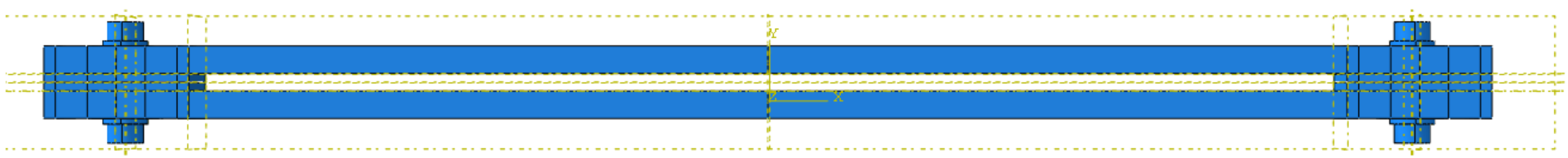
- Small Pad Contact (SPD)



Configurations – C-Beam

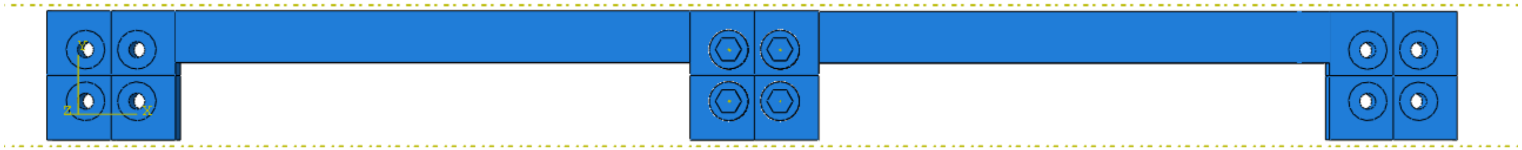
- CBM (also known as the S4 or Sandwich beam)





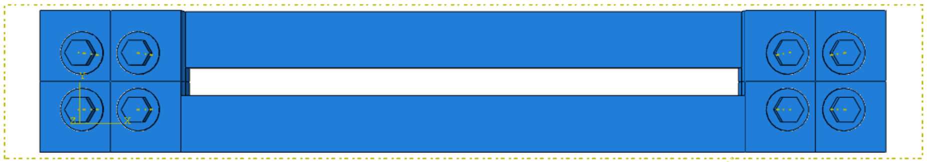
Configurations – 4-Bolt Beam

- 4LS



(**4**-bolt **L**ong **S**ame-side)

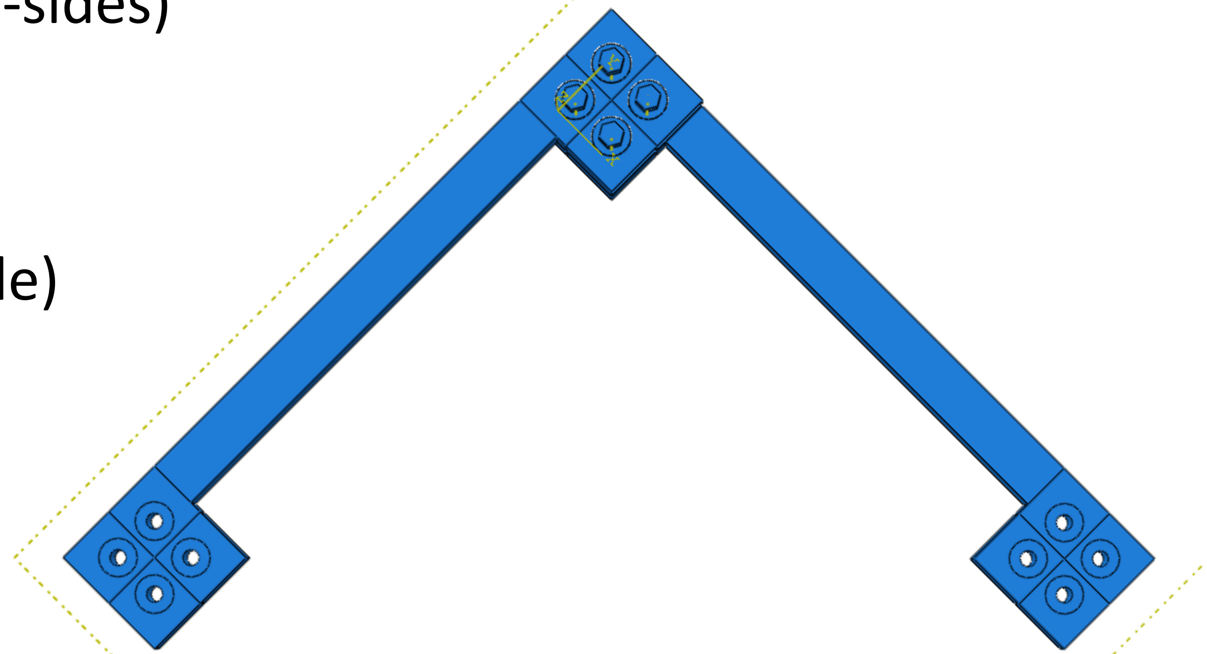
- 4SO



(**4**-bolt **S**hort **O**pposite-sides)

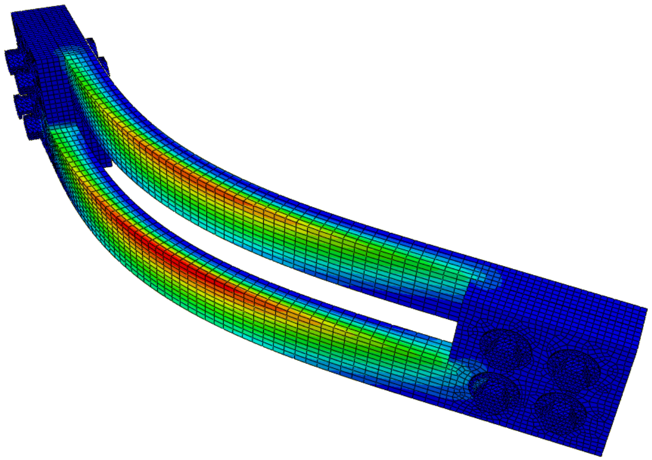
- 4VO

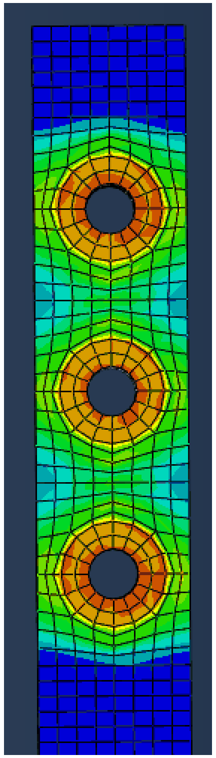
(**4**-bolt **V**-shape **O**utside)



Numerical Methodology

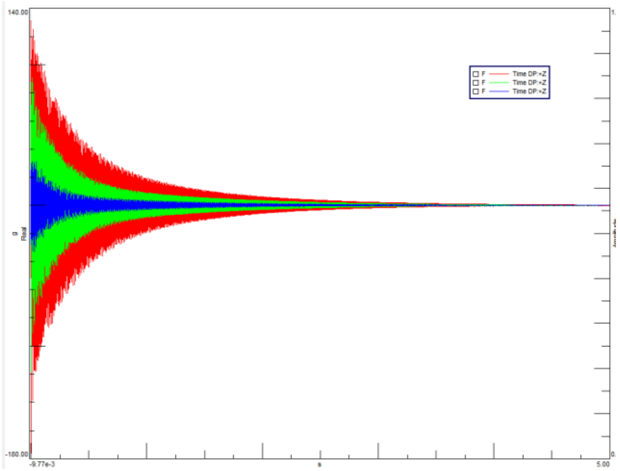
- To develop the metric, we sought easy-to-access data from an FEA model: modal strain and contact pressure.
- A nonlinear frictionless interface implicit solver was used to determine contact pressure.
- A linearized eigen analysis was used to find mode shapes and strain.
- Various statistics were calculated based on the data:
  - Mean (Contact Pressure and Strain)
  - Max (Contact Pressure and Strain)
  - Standard Deviation (Contact Pressure and Strain)
  - Skew (Contact Pressure and Strain)
  - Kurtosis (Contact Pressure and Strain)
  - Contact Area



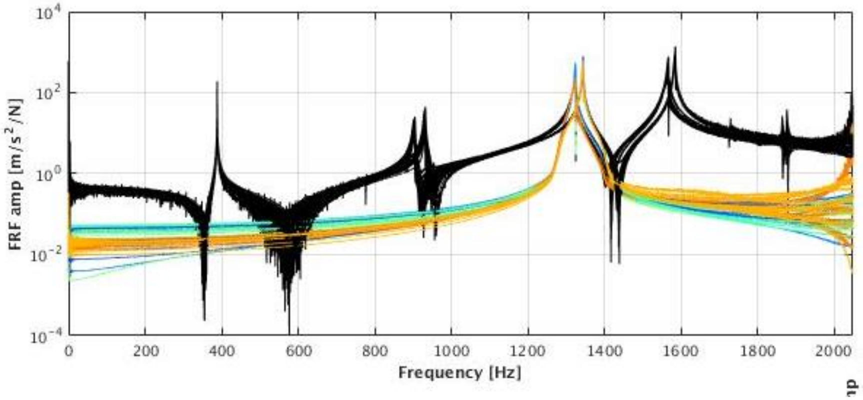


Experimental Methodology

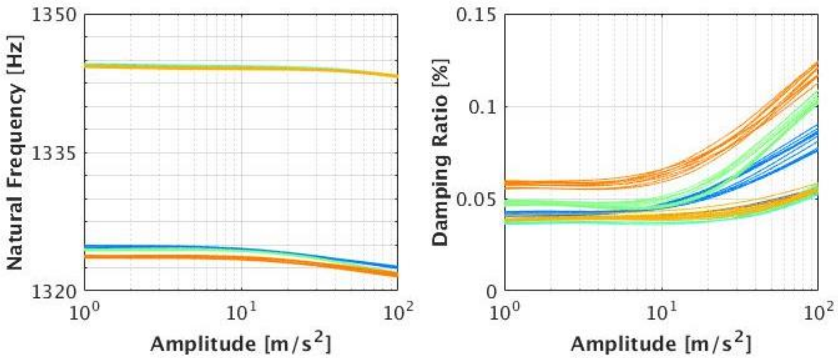
- Impact Testing



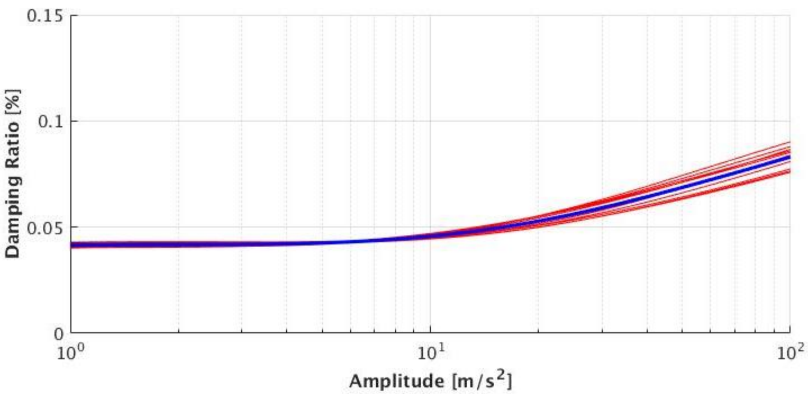
- Bandpass Filtering and Hilbert Transform



- Frequency and Damping vs Amplitude

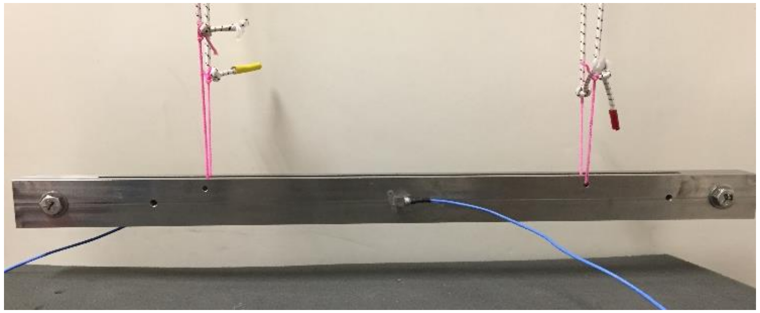


- Smooth and Average Curves

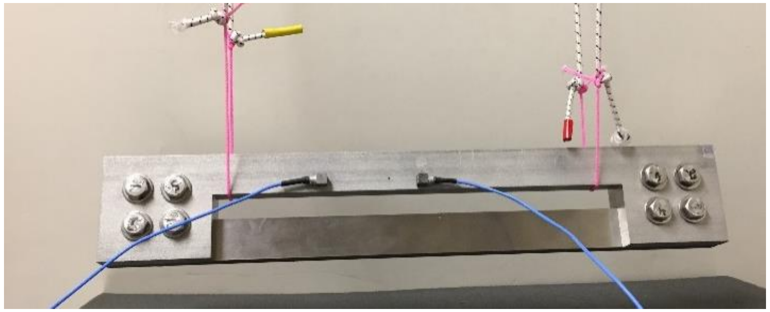


Experimental Methodology

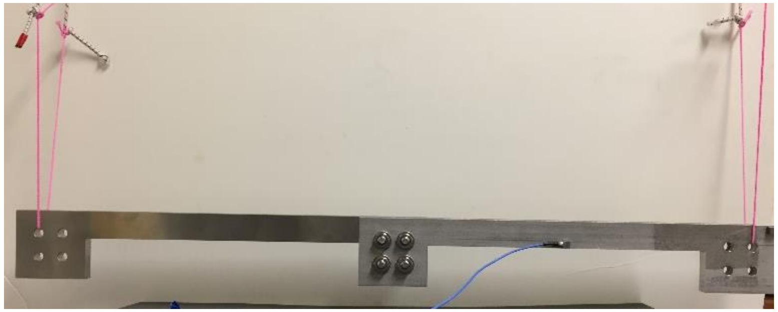
- CBM



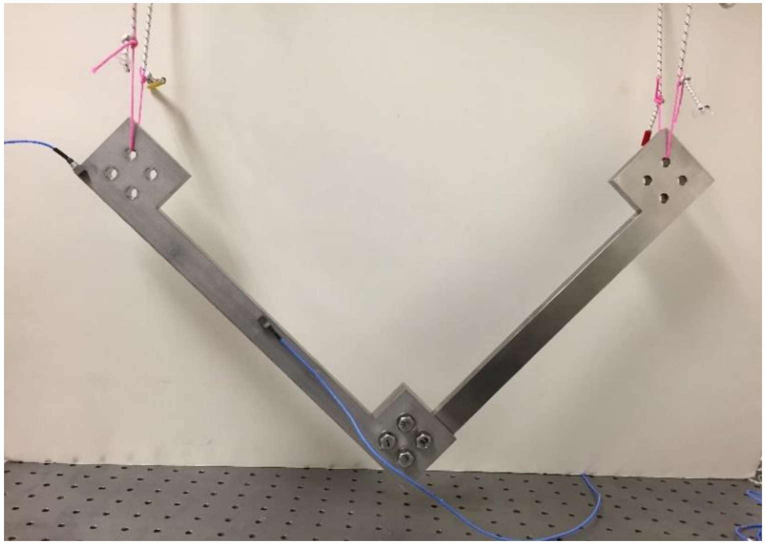
- 4SO



- 4LS

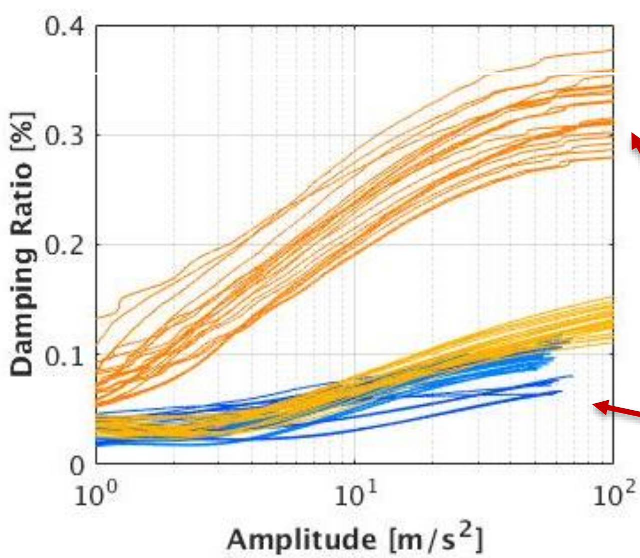


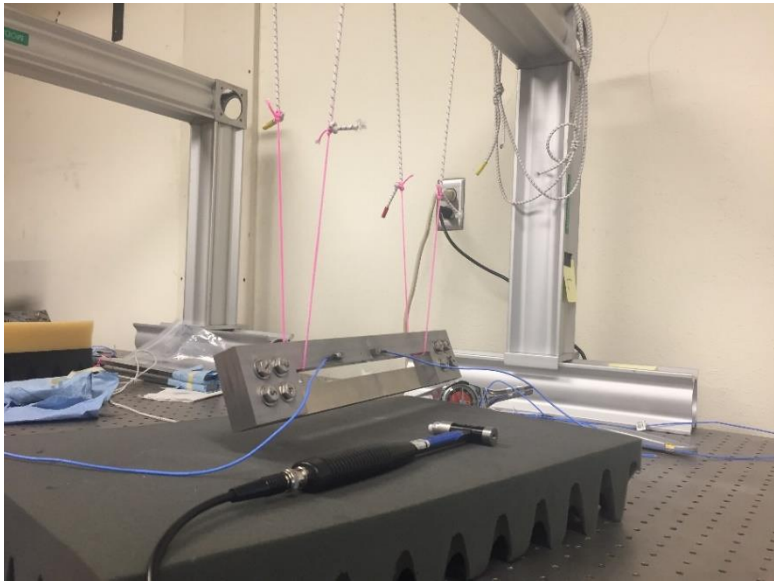
- 4VO



Experimental Methodology

- Impact hammer testing using free-free boundary condition
- Bolt torques range from 5Nm → 20Nm
  - What is the effect of changing contact pressure within beam configurations?
- Impact Levels ranging from 60N to 900N
  - What is the effect of modal coupling?
  - How do we normalize force?
- Standardize by max mode shape

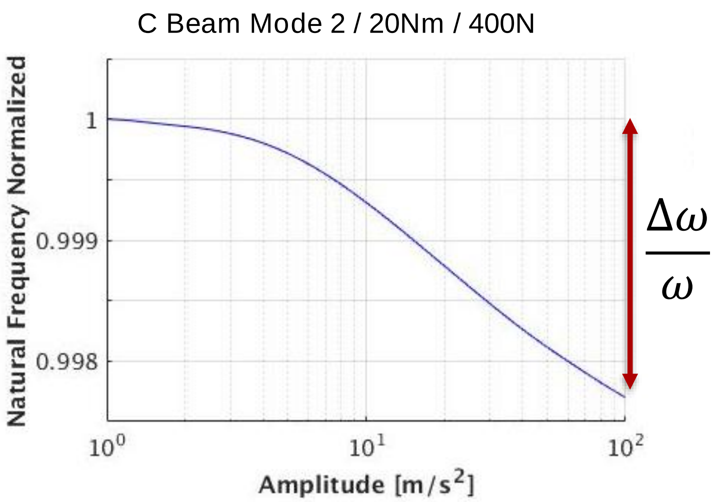


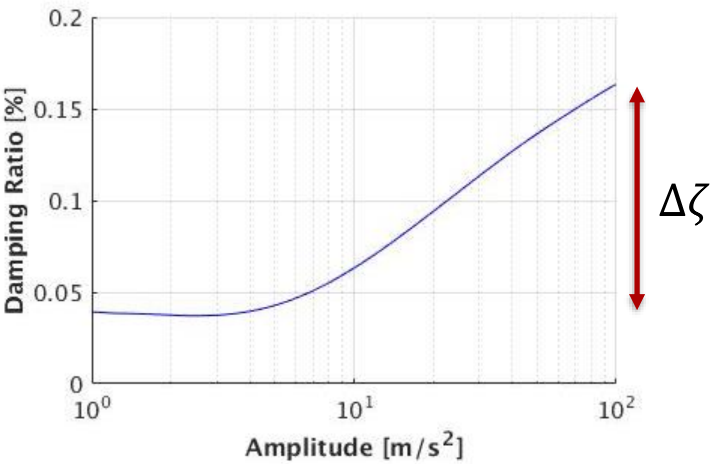


C Beam Mode 2: Extreme Modal Coupling

Defining Strength of Nonlinearity (SNL)

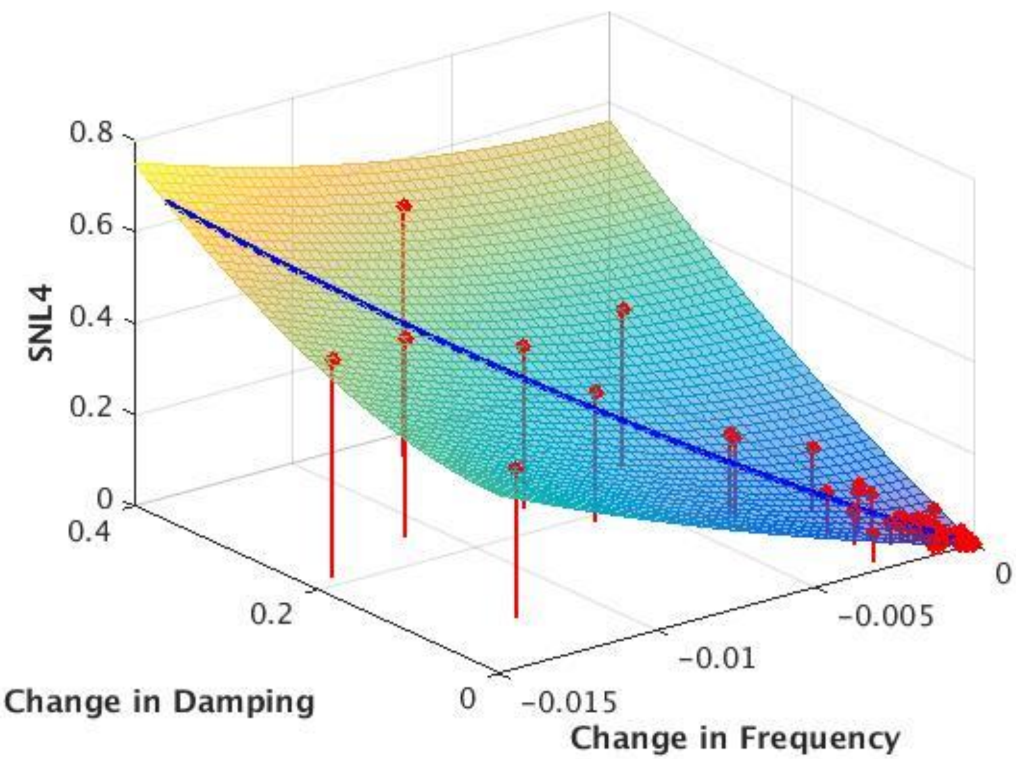
- Magnitude of shift in natural frequency and damping as the response amplitude of a structure is varied between two fixed bounds.
- $SNL = \alpha \frac{\Delta\omega}{\omega} + \beta\Delta\zeta$





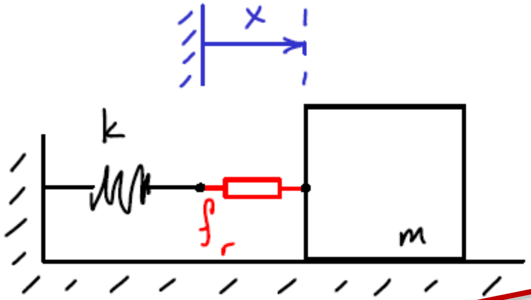
Defining SNL

$$SNL4 = \left(\left(\left(20 * \frac{\Delta\omega}{\omega}\right)^2 + (\Delta\zeta)^2\right)^{\frac{1}{2}} + \left(20 * \frac{\Delta\omega}{\omega}\right)^2 + (\Delta\zeta)^2\right)$$

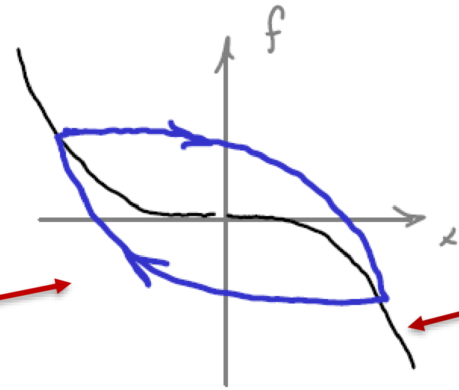


Defining SNL: Perturbations Approach

- Based off of a mass-spring-damper system



$$m\,\ddot{x} + c\,f_r + kx = 0$$



Monotonic Loading

$$f(x) = -sgn(x)\alpha x^n$$

- General form of equivalent frequency and damping

Interface properties

$$\boldsymbol{\omega = 1 + C_1 A^{n-1}}$$

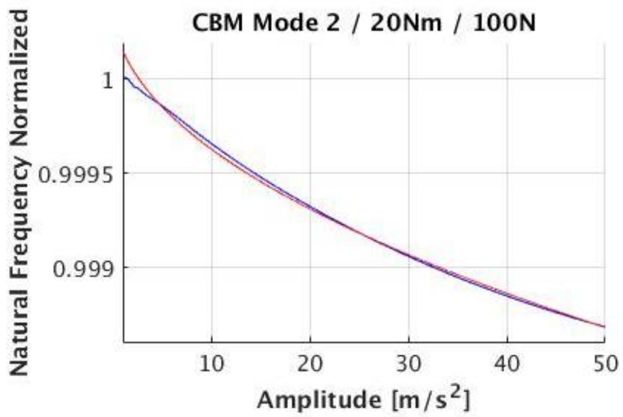
$$\boldsymbol{\zeta = C_3 + C_2 A^{n-1}}$$

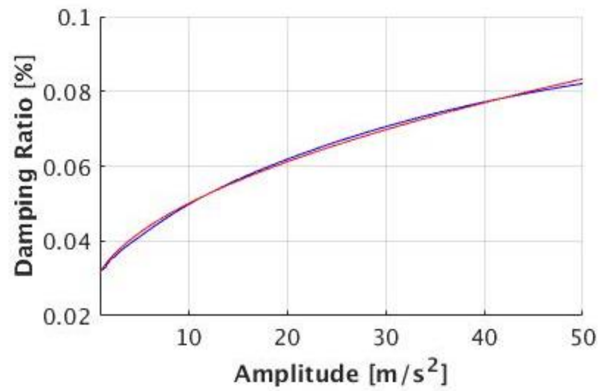
Linear Damping

Linear Frequency (Normalized)

Influence of joint on structure

Defining SNL: Perturbations Approach



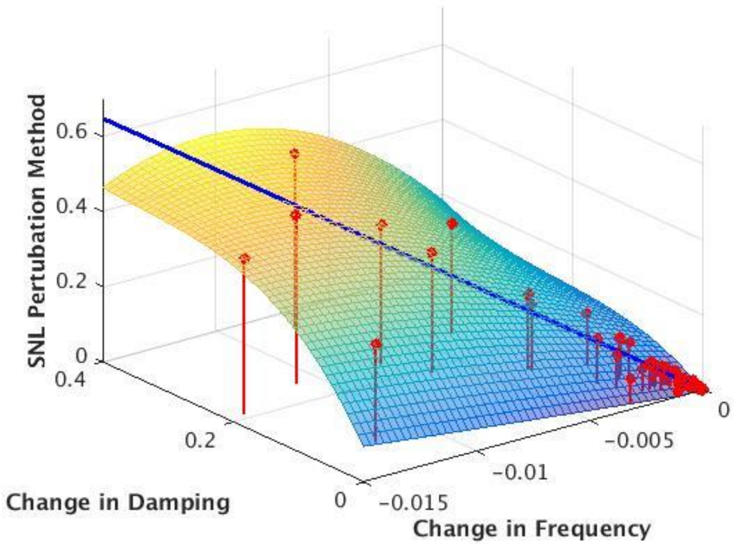


$$\zeta = -0.01 + \mathbf{0.0345}\, A^{0.25}$$

$$R^2 = 0.9931$$

$$\omega = 1.003 \mathbf{- 9.703 * 10^{-4}}\, A^{0.25}$$

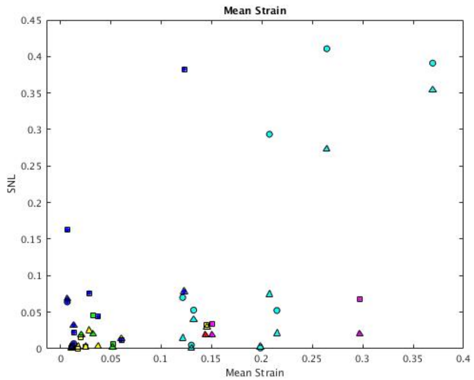
$$R^2 = 0.9757$$

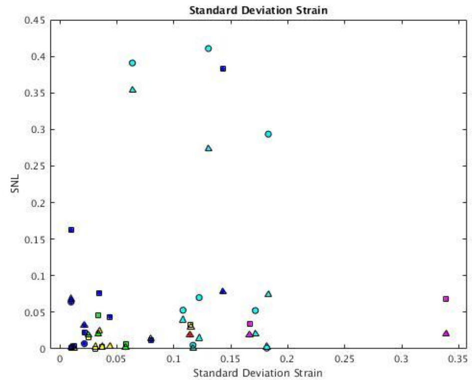


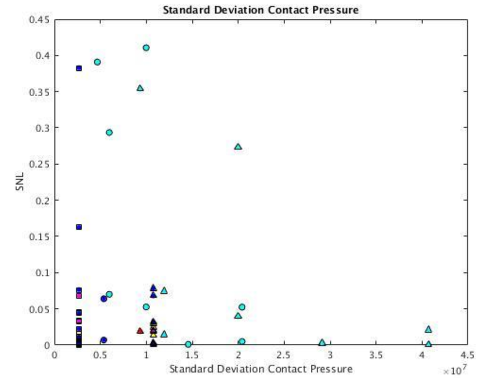
Overall:
Frequency $R^2 = 0.8434$
Damping $R^2 = 0.7841$

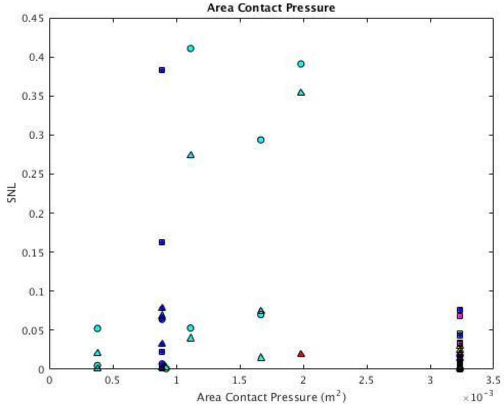
Machine Learning

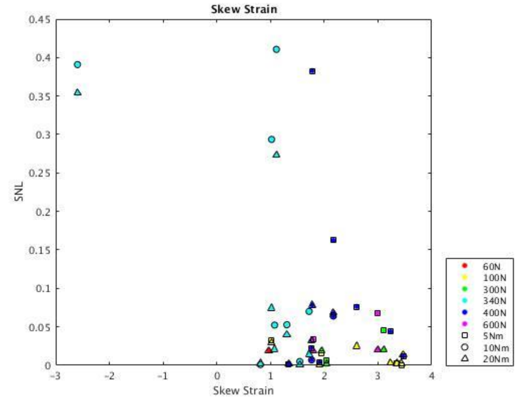
- Correlation of parameters to SNL and frequency-only-based SNL by visual inspection and ANOVA
  - **70% of variance explained by 5 variables**: Mean Strain, Standard Deviation Strain, Standard Deviation Contact Pressure, Contact Area, Skew Strain





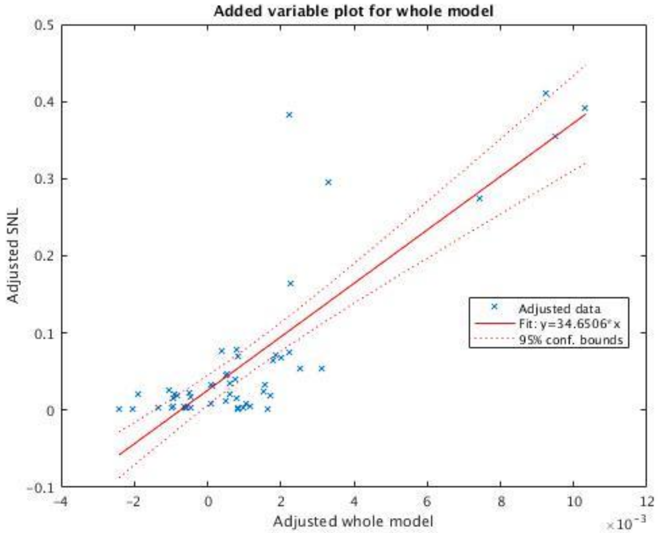






Machine Learning

- $SNL = .065802 + 1.7405MeanE - 1.3022STDE - 5.7476 * 10^{-9}STDCP - 41.301AreaCP + .041298SkewE$, p-value=1.17e-10, $R^2 = .696$
- MATLAB's built-in functions *fitlm, stepwiselm,* and *step* were utilized to create a linear regression model using the various statistics
  - *stepwiselm* automatically tests the importance of each statistic to create the optimal metric
  - *step* takes an existing model and checks whether additional terms should be added or existing terms should be removed
  - *fitlm* fits a model using the parameters specified



Whole Model Parameters (R^2=0.696, p-value=1.17e-10)	p-value	Frequency Parameters (R^2=0.833,p-value=1.49e-15)	p-value
MeanE	6.5816e-08	MeanE	6.6878e-12
STDE	1.499e-05	STDE	2.8118e-10
STDCP	4.1232e-05	SkewE	2.6391e-06
AreaCP	0.00032329	STDCP	9.671e-06
SkewE	0.01428	KurtosisE	0.000461
(KurtosisE)	(0.09601)	AreaCP	.026855

Conclusions

- We were not able to produce a metric that could accurately predict the SNL metric using only contact pressure and modal strain. A future metric could possibly be determined if additional interface properties were also included.
- We were able to identify the key variables that explain variance in our SNL metric
  - Strain: Mean, Standard Deviation and Skew
  - Contact Pressure: Standard Deviation and Area
- We were able to identify areas of improvement for future research
  - Using modal acceleration instead of absolute acceleration
  - Better understand how force levels activate modal coupling
  - Implement genetic algorithms for model predictions
  - Use surface properties to explain damping variance

Acknowledgments

- This research was conducted at the 2018 Nonlinear Mechanics and Dynamics Research Institute hosted by Sandia National Laboratories and the University of New Mexico.
- This research was assisted by the research of previous NOMAD teams and research ongoing at University of Wisconsin-Madison and Rice University.
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