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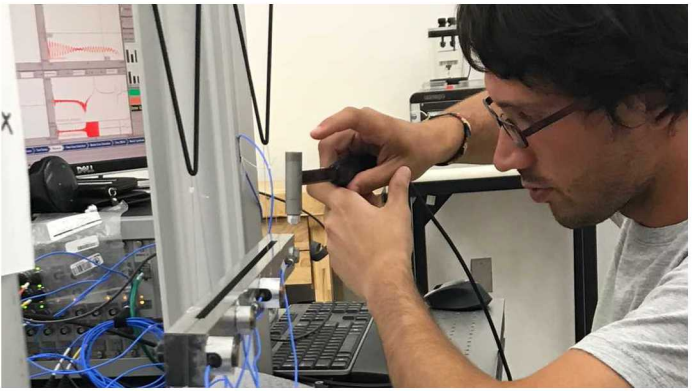


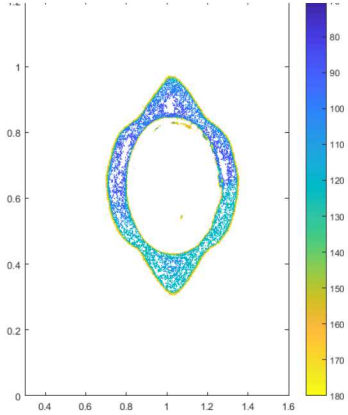


# A Priori Methods to Assess the Strength of Nonlinearities for Design Applications

Craig Broadman, She'ifa Punla-Green, Edward Rojas

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SAND2017-7813 C

# Agenda

1. Introduction
2. Project Overview
3. Numerical Methodology
4. Experimental Methodology
5. Characterization of Strength of Nonlinearity
6. Conclusion

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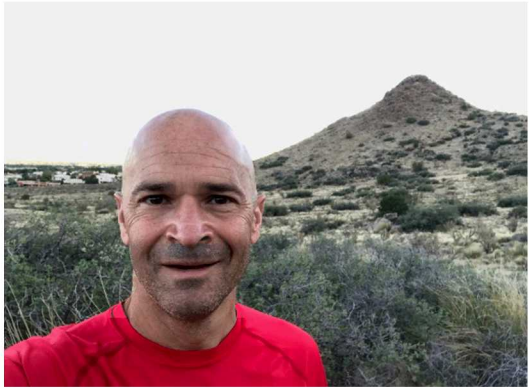

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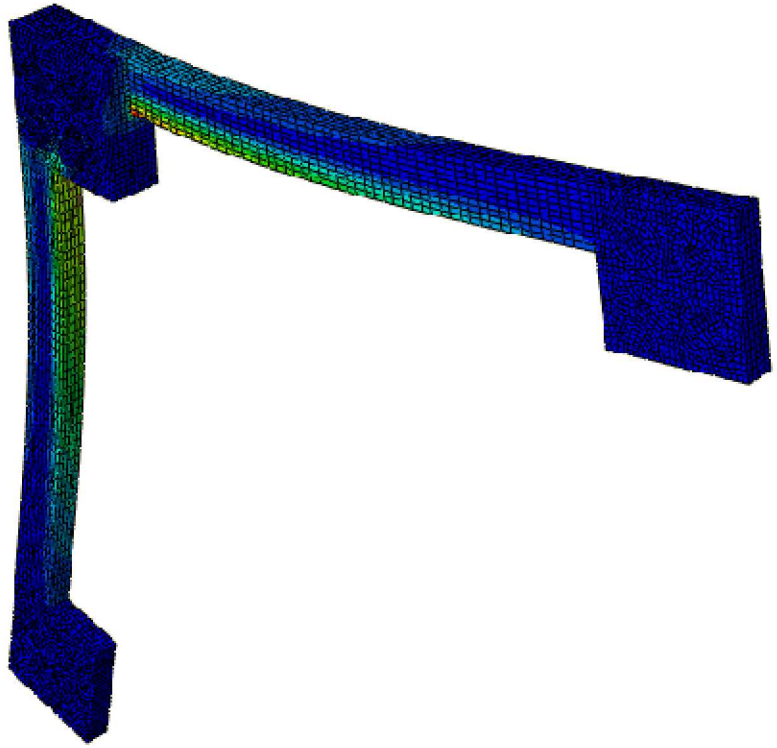
# Project Overview

- 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:

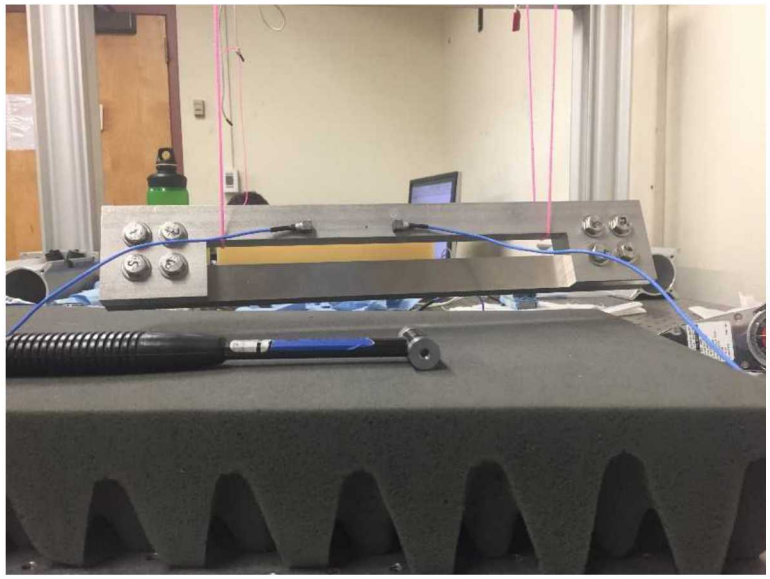
  Using Abaqus, we calculated a variety of statistics regarding contact pressure and modal strain to utilize in developing a metric to predict strength of nonlinearity.

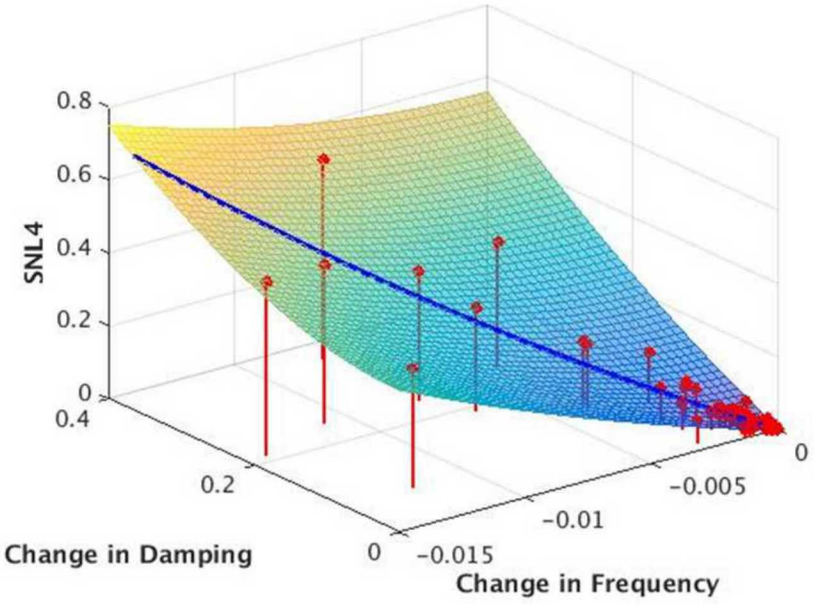


# Project Overview

- Experimental Methods:

  We obtained time response data for many beam configurations.



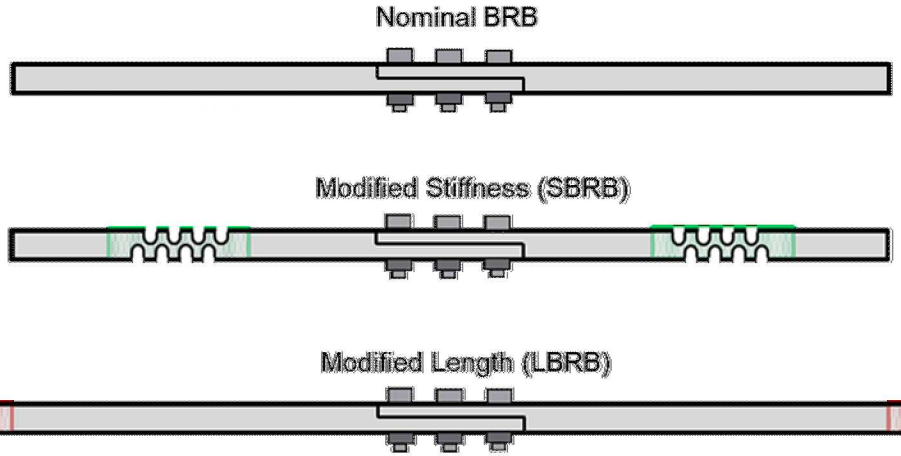


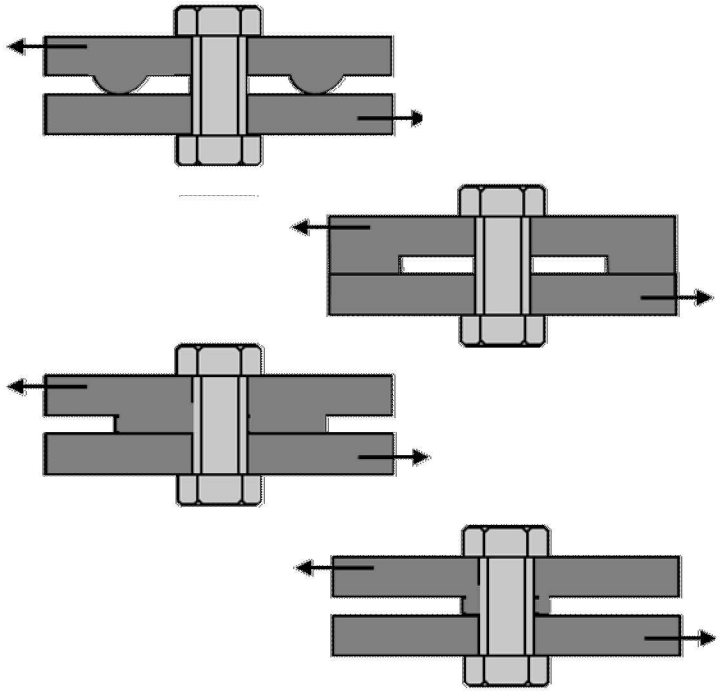

- Analysis:

  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

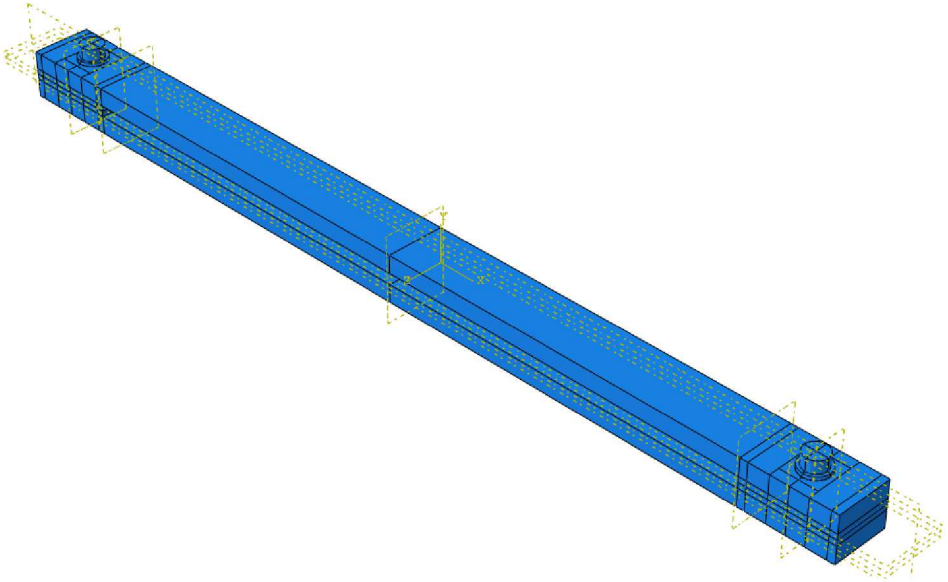
- BRB
- Spring (SBRB)
- Long (LBRB)
- Hertzian Contact (HZ)
- Reverse Pad Contact (RPD)
- Large Pad Contact (LPD)
- Small Pad Contact (SPD)

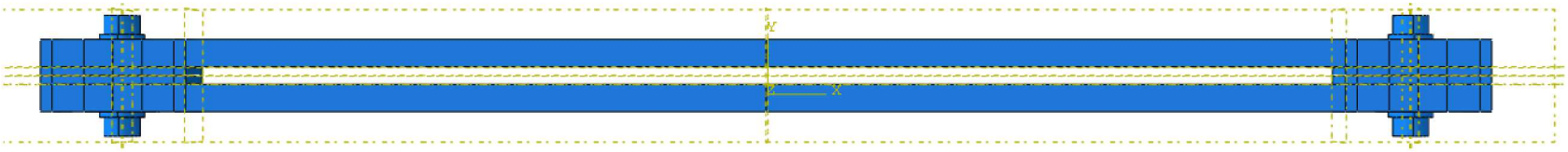


# Configurations – C-Beam

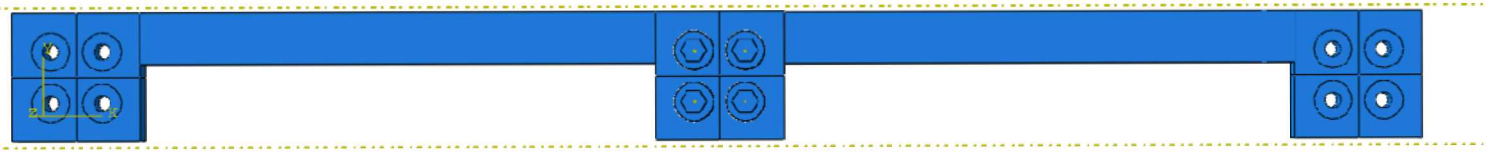
- CBM (also known as the S4 or Sandwich beam)





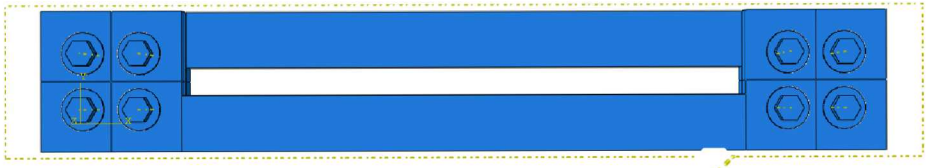
# Configurations – 4-Bolt Beam

- 4LS



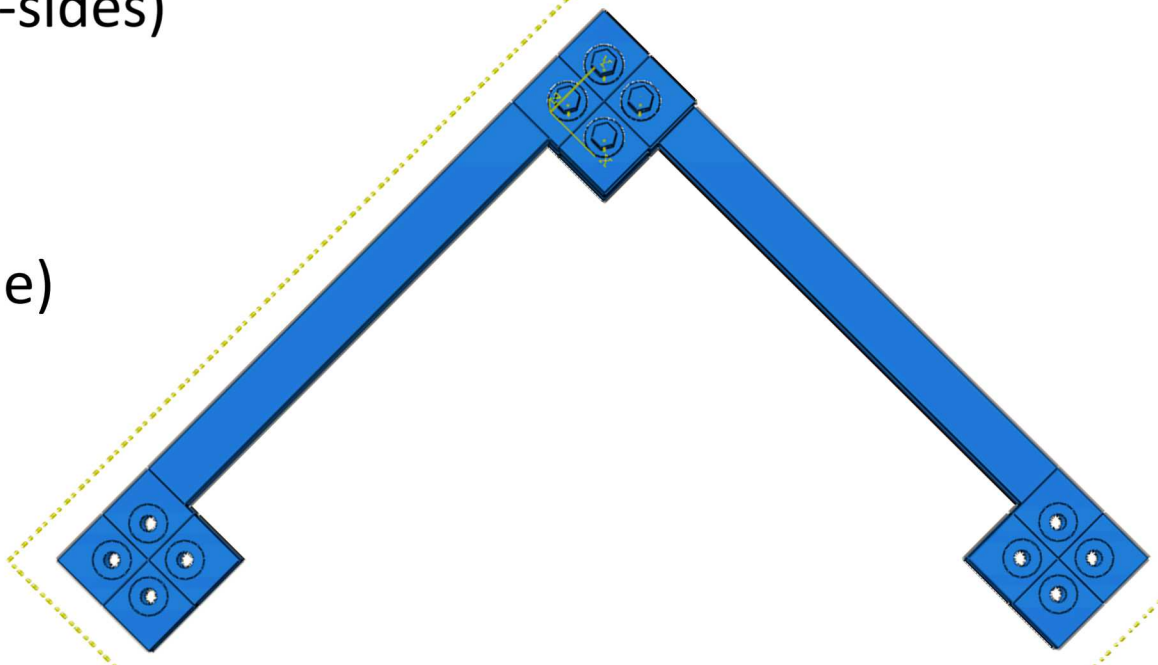
(**4**-bolt **L**ong **S**ame-side)

- 4SO



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

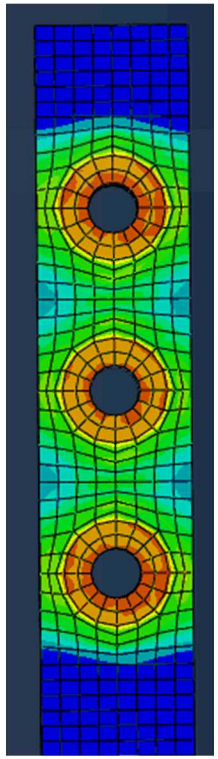
- 4VO

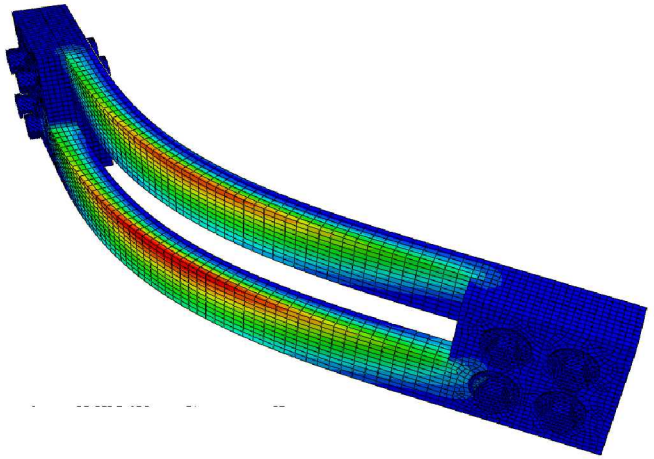


(**4**-bolt **V**-shape **O**utside)

# Numerical Methodology

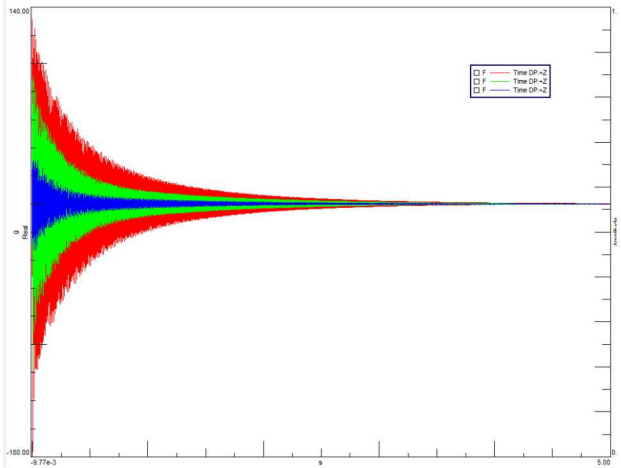
- To develop the metric, we sought easy-to-access data from an FEA model: modal strain and contact pressure.
- A nonlinear frictionless interface implicit solver was used to determine contact pressure.
- A linearized eigen analysis was used to find mode shapes and strain.
- Various statistics were calculated 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



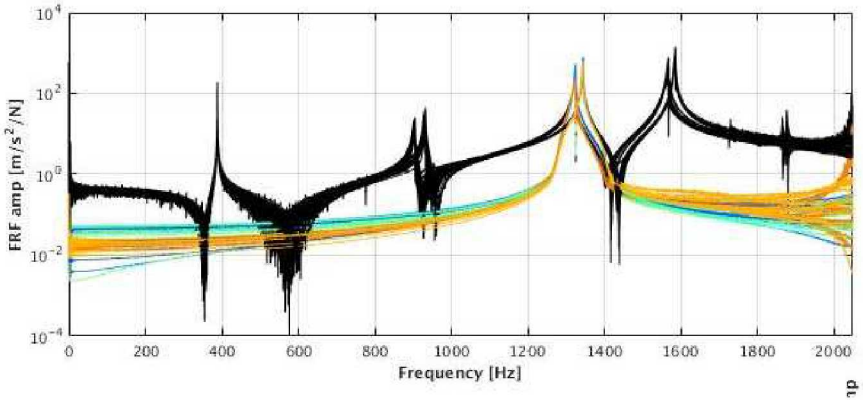


# Experimental Methodology

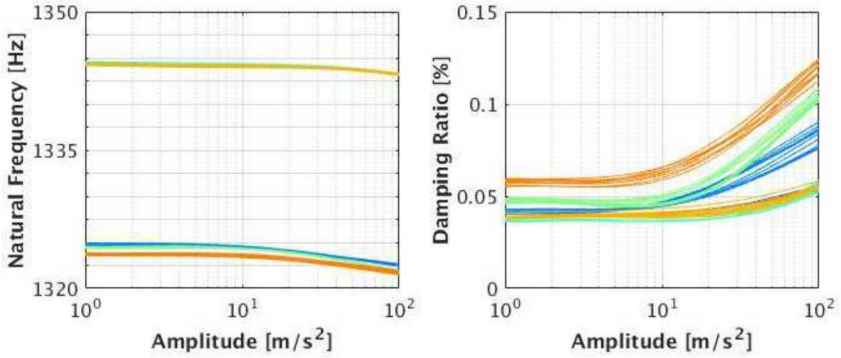
- Impact Testing



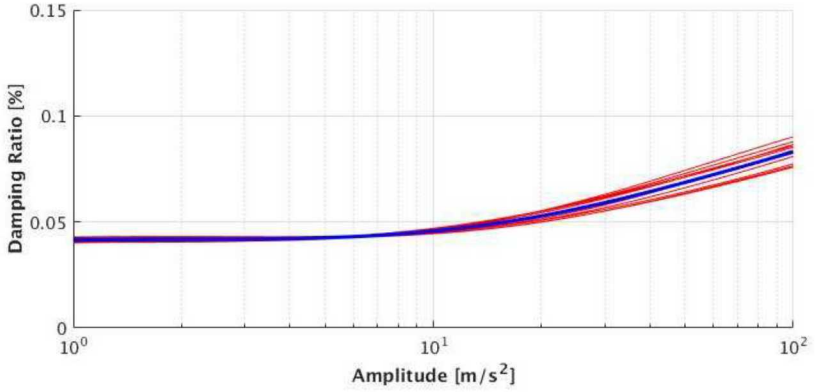
- Bandpass Filtering and Hilbert Transform




- Frequency and Damping vs Amplitude

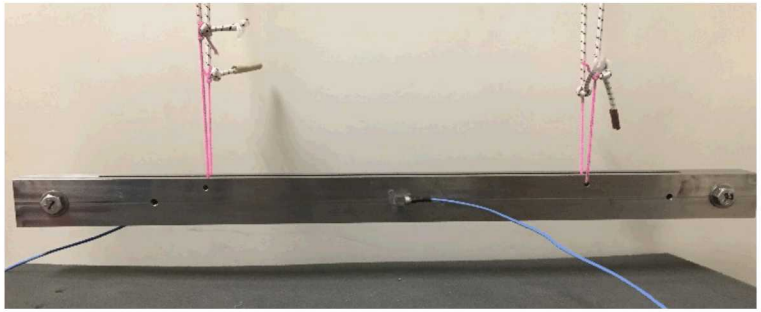



- Smooth and Average Curves

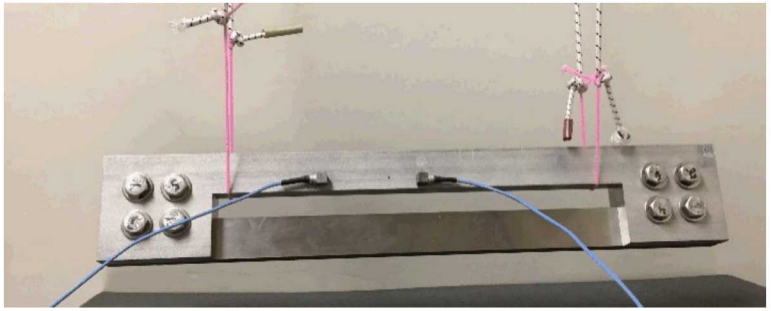


# Experimental Methodology

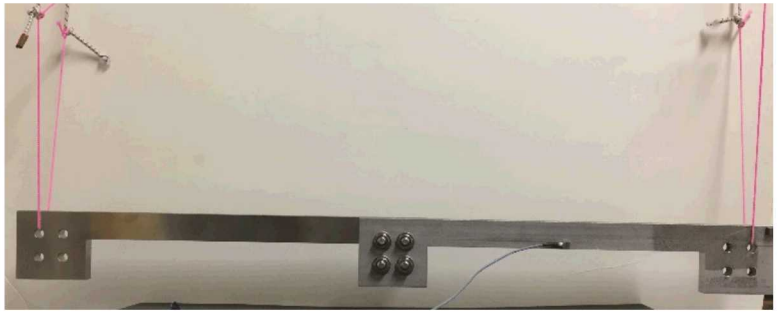
- CBM



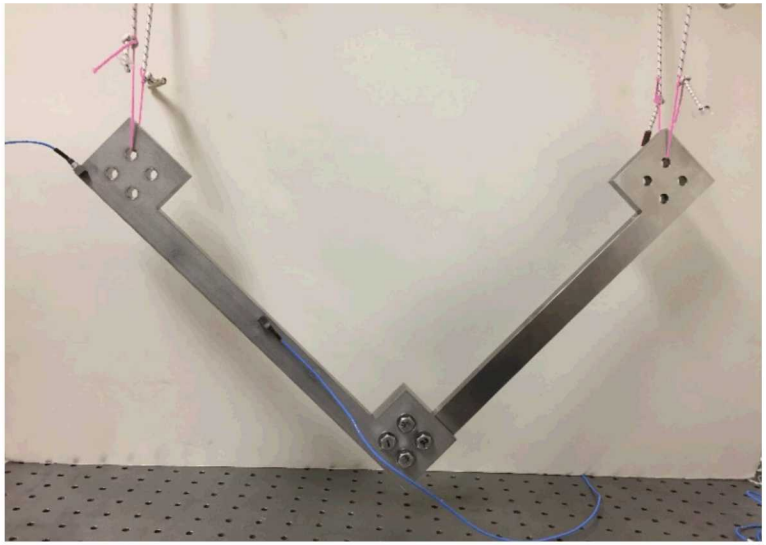
- 4SO



- 4LS

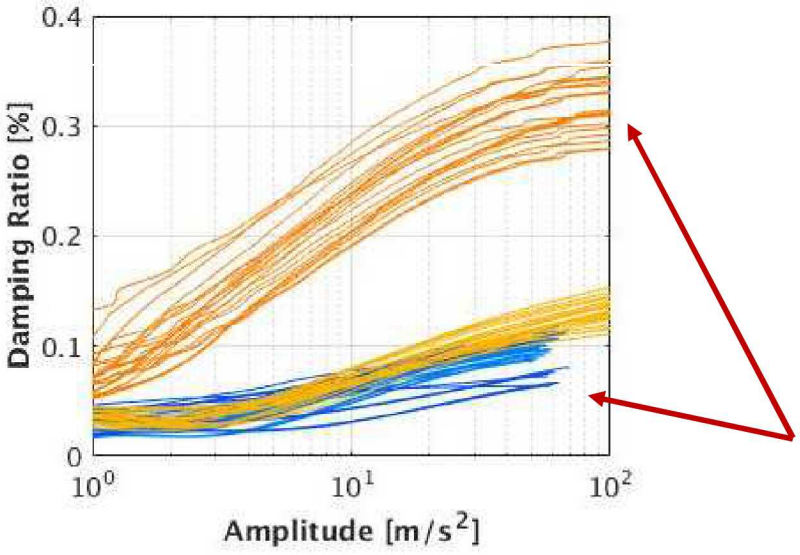


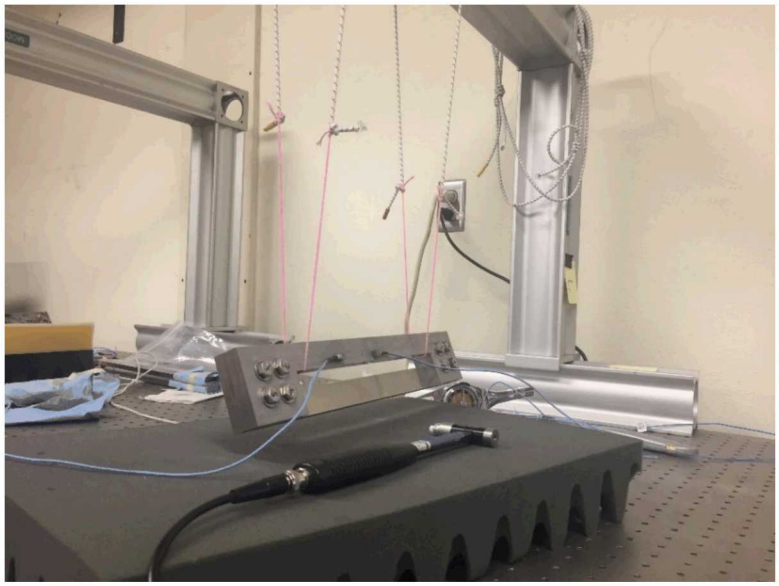
- 4VO



# 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

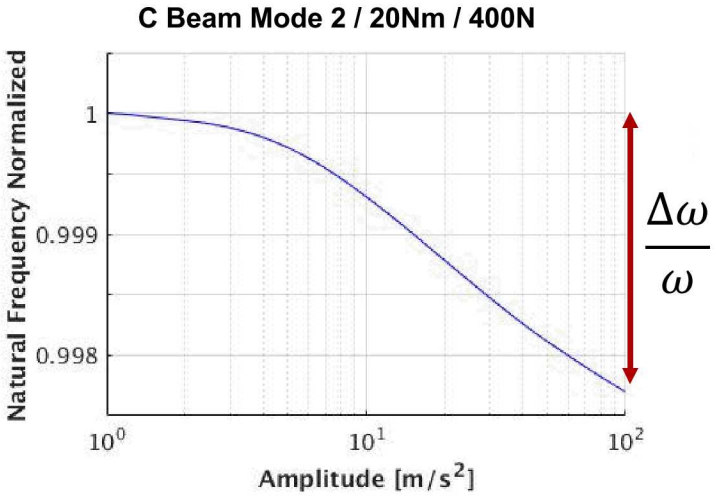


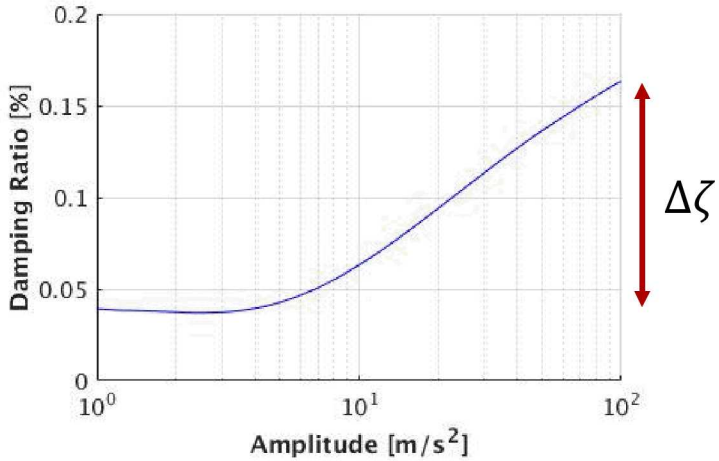



C Beam Mode 2: Extreme Modal Coupling

# Defining Strength of Nonlinearity (SNL)

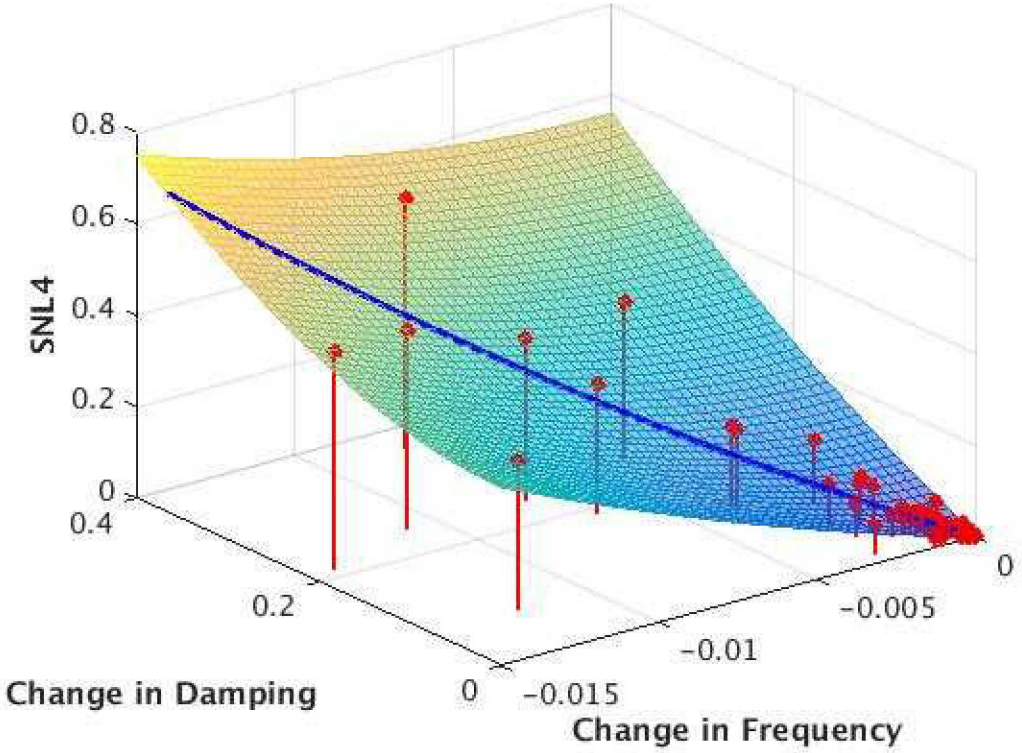
- Magnitude of shift in natural frequency and damping as the response amplitude of a structure is varied between two fixed bounds.
- $SNL = \alpha \frac{\Delta\omega}{\omega} + \beta \Delta\zeta$



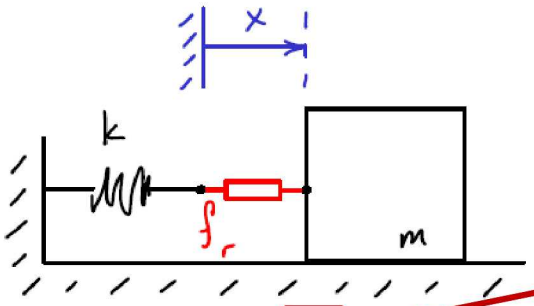
# Defining SNL

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

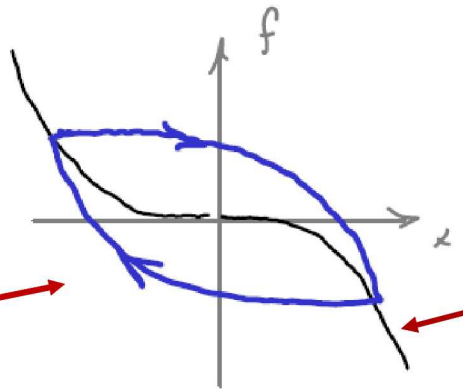


# Defining SNL: Perturbations Approach

- Based off of a mass-spring-damper system




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




Monotonic Loading

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

- General form of equivalent frequency and damping

Interface properties

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

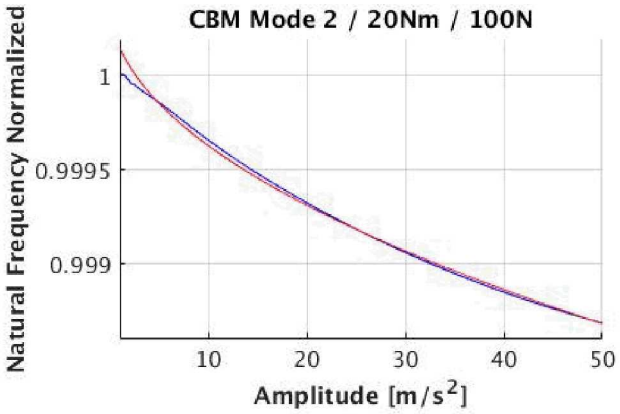
$$\zeta = C_3 + C_2 A^{n-1}$$

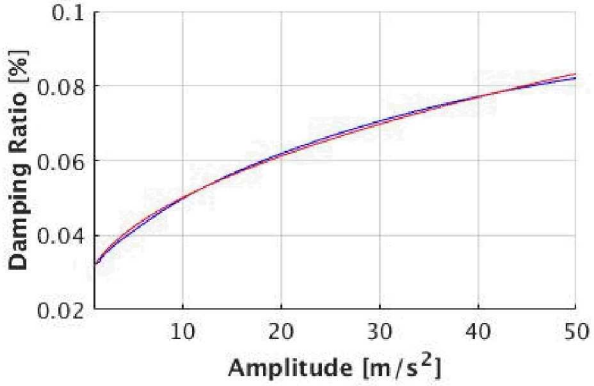
Linear Damping

Linear Frequency (Normalized)

Influence of joint on structure

# Defining SNL: Perturbations Approach



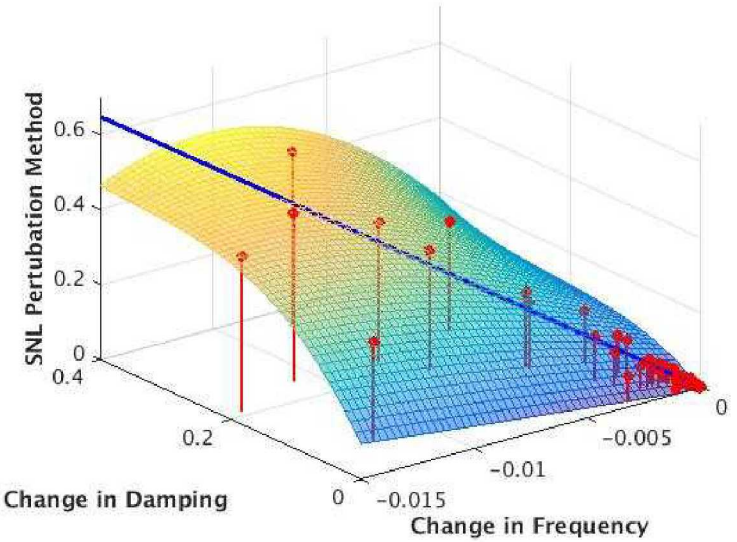




$$\zeta = -0.01 + \mathbf{0.0345}\, A^{0.25}$$

$$R^2 = 0.9931$$

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

$$R^2 = 0.9757$$



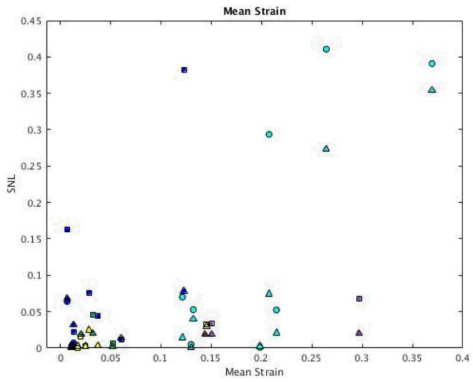

Overall:

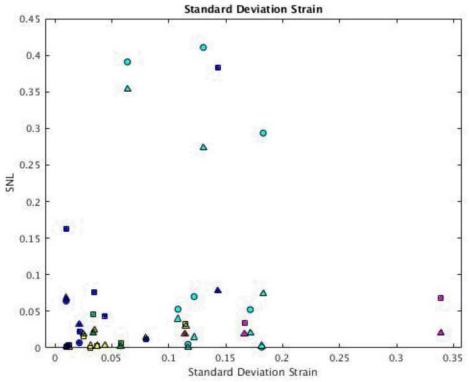
Frequency $R^2 = 0.8434$

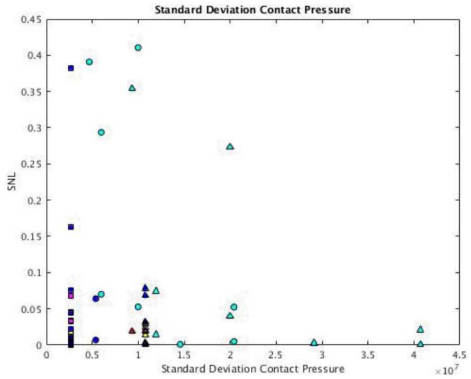
Damping $R^2 = 0.7841$

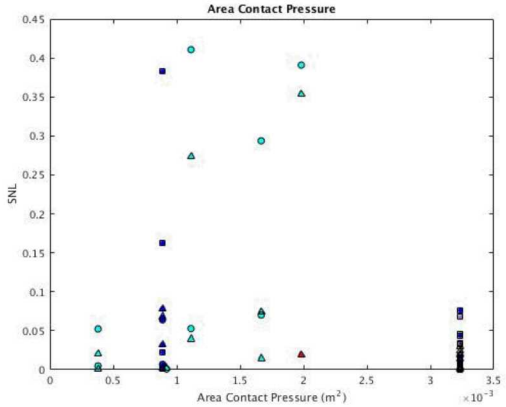
# Machine Learning

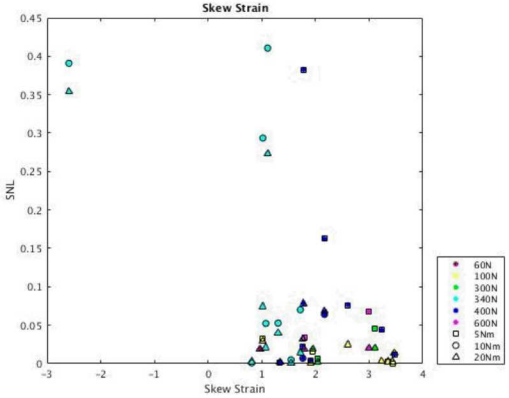
- Correlation of parameters to SNL and frequency-only-based SNL by visual inspection and ANOVA
  - **70% of variance explained by 5 variables**: Mean Strain, Standard Deviation Strain, Standard Deviation Contact Pressure, Contact Area, Skew Strain



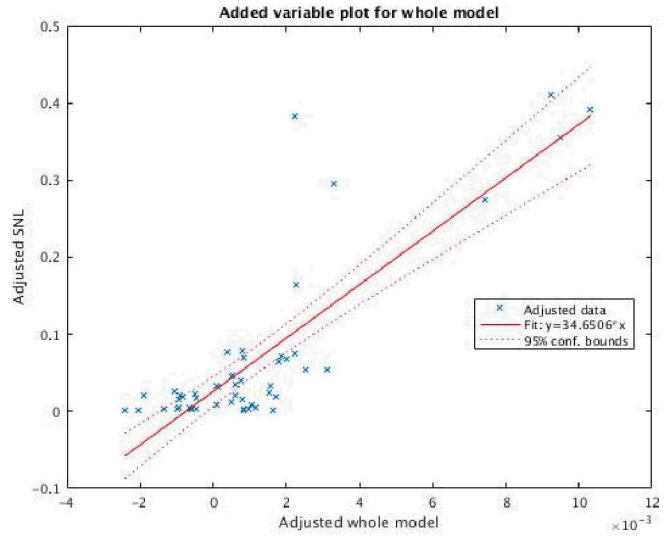



# Machine Learning

- $SNL = .065802 + 1.7405MeanE - 1.3022STDE - 5.7476 * 10^{-9}STDCP - 41.301AreaCP + .041298SkewE$, 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.
- Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.