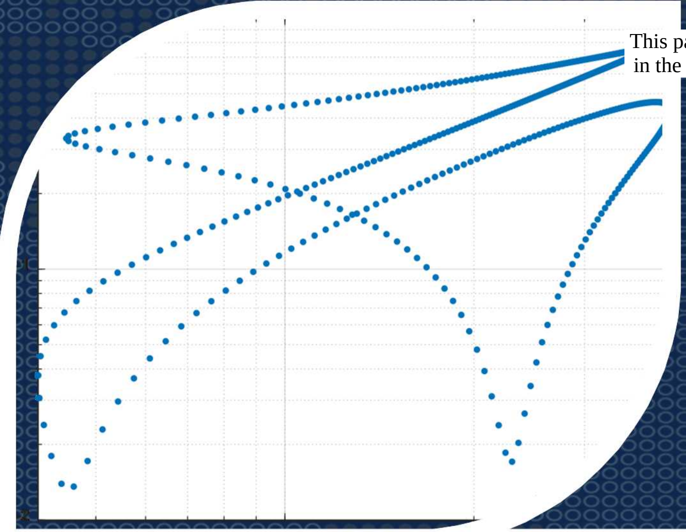

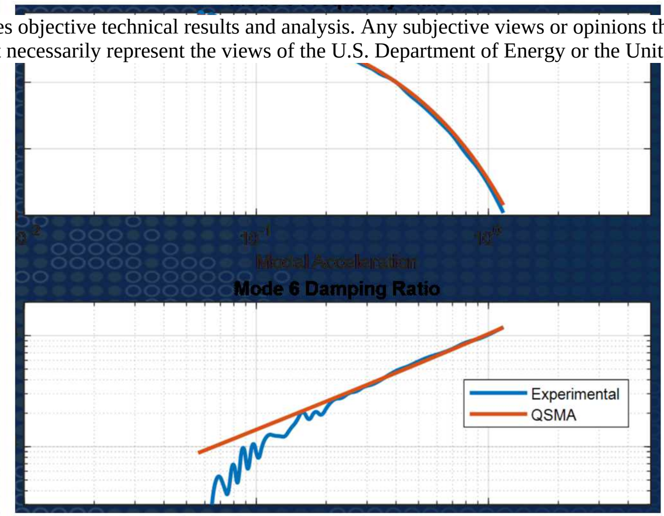


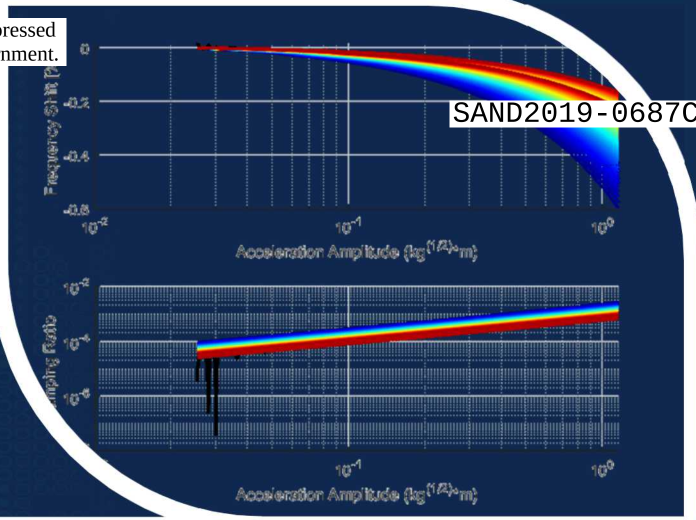

SAND2019-0687C

# Spider Configurations for Models with Discrete Iwan Elements

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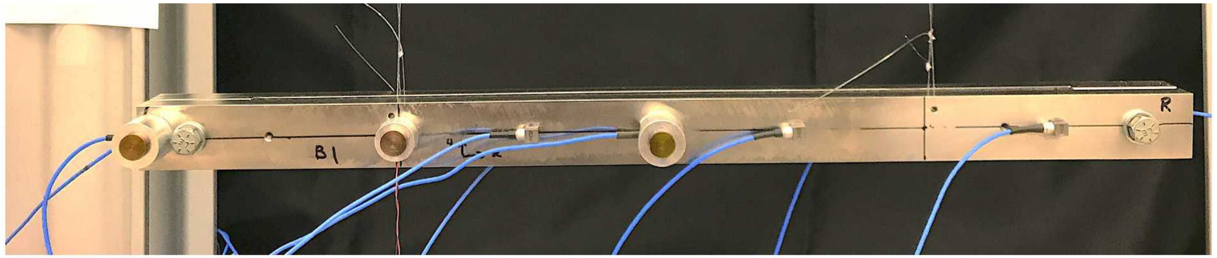
Matthew S. Allen (UW – Madison)

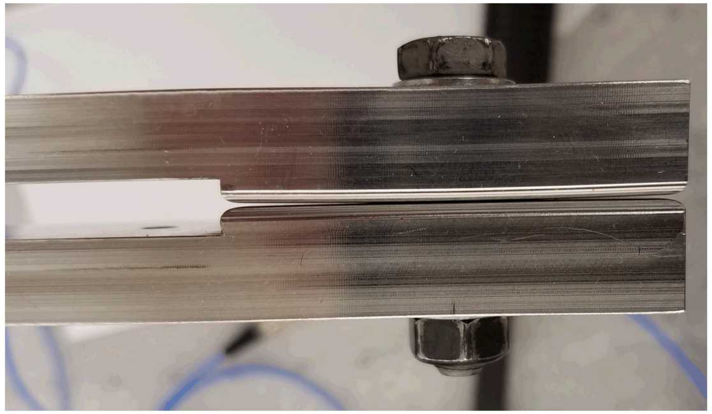
Robert J. Kuether (SNL*)

International Modal Analysis Conference XXXVII

*Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & 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. SAND2019-???? C

# Overview





I. Introduction to Bolted Joints
   i. Whole Joint Models
   ii. Quasi-static Modal Analysis (QSMA)

II. S4B Experimental Structure

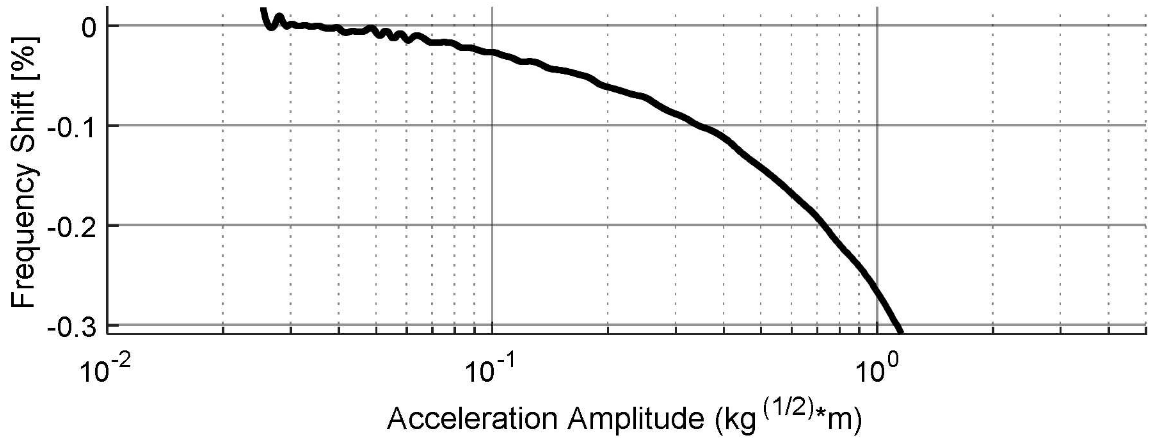
III. Results of Model Updating

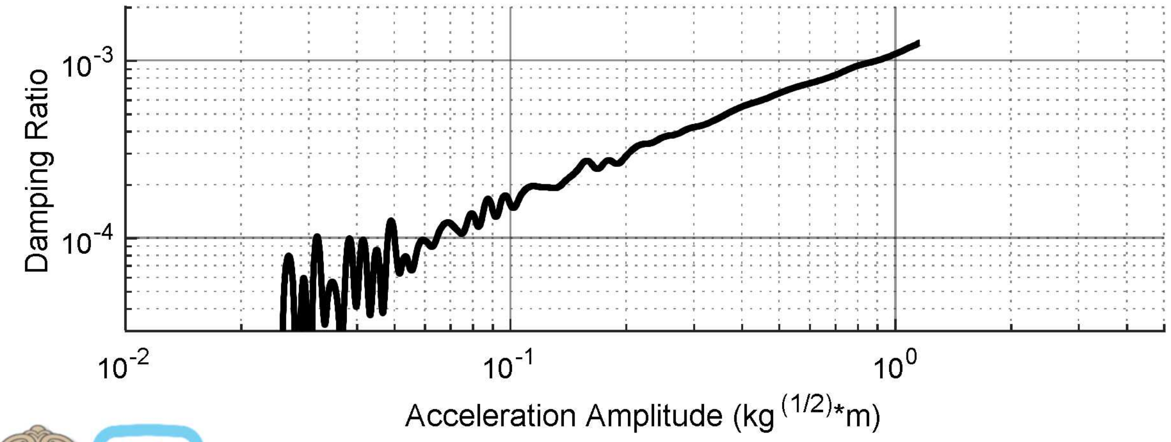
IV. Parameter Study

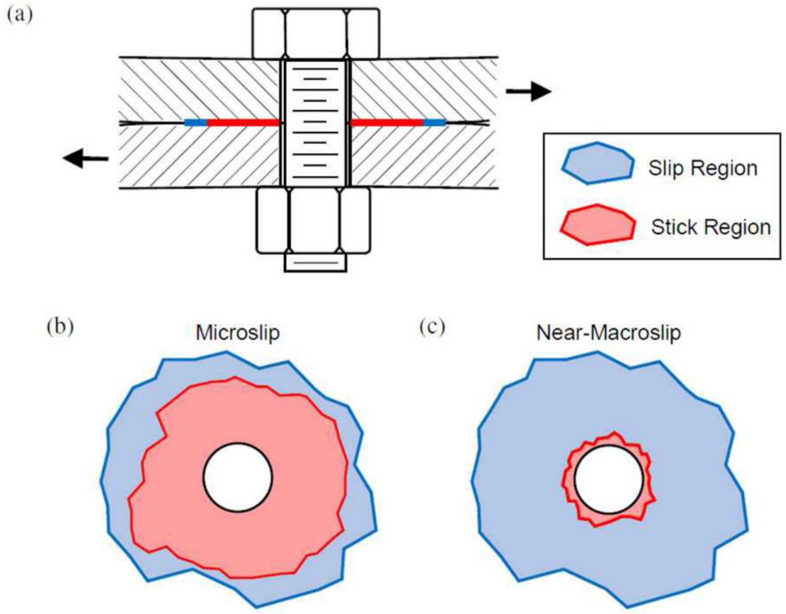
V. Concluding Remarks

# Importance of Bolted Joint Modeling

- Bolted joints are ubiquitous in assembled structures, yet they are poorly understood and difficult to model.
  - Two regions: Microslip and Macroslip

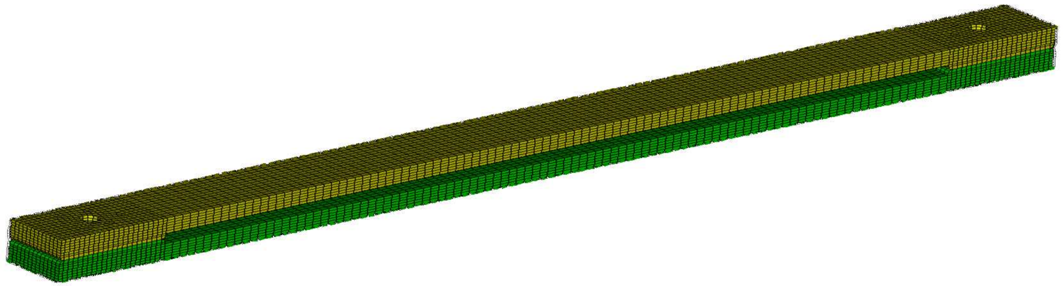


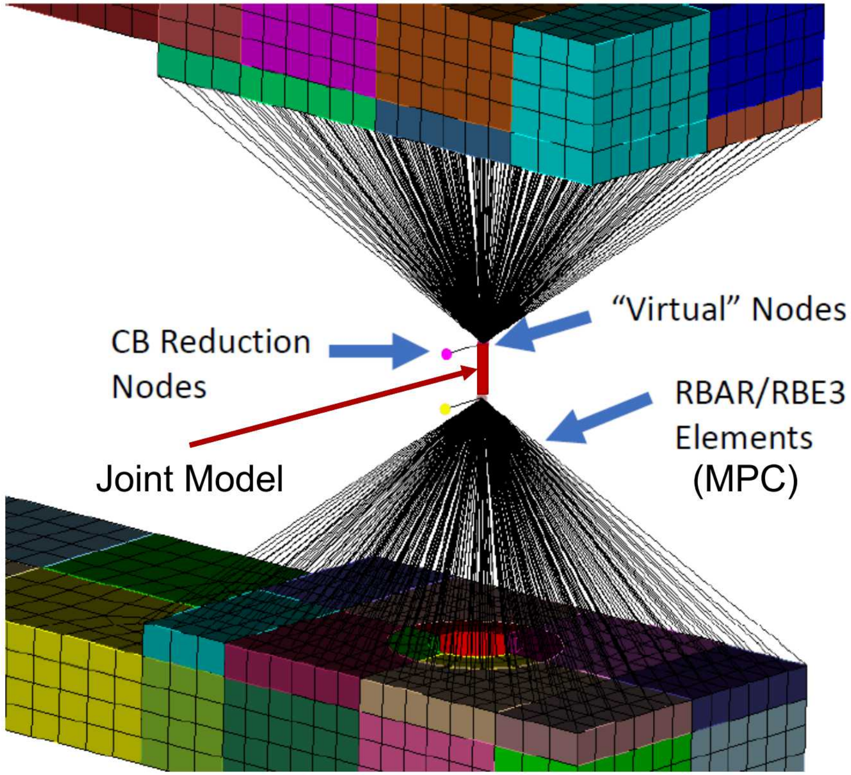

Well tightened bolts still exhibit regions of slip at the edge of contact

- Introduces nonlinearity: hysteresis and amplitude dependent frequency and damping
- Difficult to predict stiffness and damping at the interface



# Modeling through Whole Joint Models

- **Whole Joint Models**
  - Reduce the DOFs for the interface nodes down to a single node using Multi – Point – Constraints (MPCs)
    - Only 6 DOF (3 translation, 3 rotation)
  - Apply a single elastoplastic model to predict the hysteretic behavior of the joint

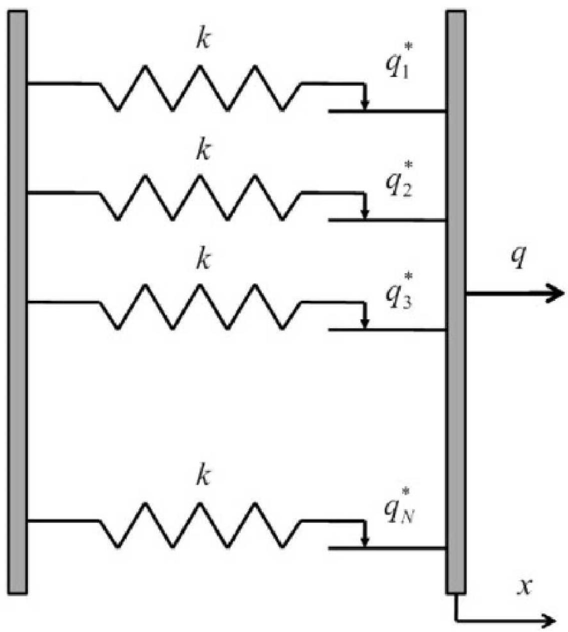



- **Multi – Point Constraints (MPCs)**
  - Constraint equations applied to the stiffness matrix
  1. **RBar:** rigid beam with infinite stiffness
  2. **RBE3:** ties the average displacement and rotation of the surface to a single point

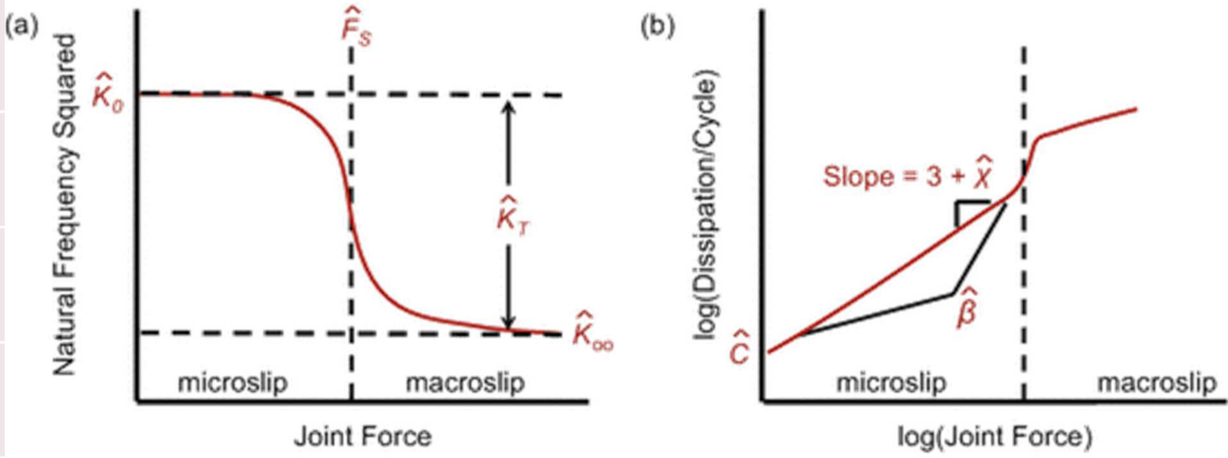
- **Issues with MPCs**
  - Not sure what the best contact area size and MPC type is
  - Different types and contact area sizes yield different results

# Whole Joint Models – Iwan Model

- A whole joint model that uses **four parameters** to characterize the amplitude dependent behavior
- Multiple Jenkin's slider elements in parallel




| | |
|---|---|
| $F_S$ | The force necessary to cause macroslip |
| $K_T$ | The tangential stiffness of the Jenkins elements (i.e. the joint stiffness when no slip occurs) |
| $\chi$ | The exponent that describes the slope of the energy dissipation curve |
| $\beta$ | The ratio of the number of Jenkins elements that slip before micro-slip and then at macroslip |

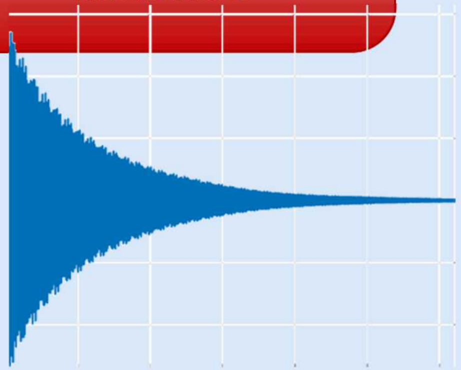



D. J. Segalman, "A Four-Parameter Iwan Model for Lap-Type Joints," *Journal of Applied Mechanics*, vol. 72, no. 5, pp. 752–760, Sep. 2005.

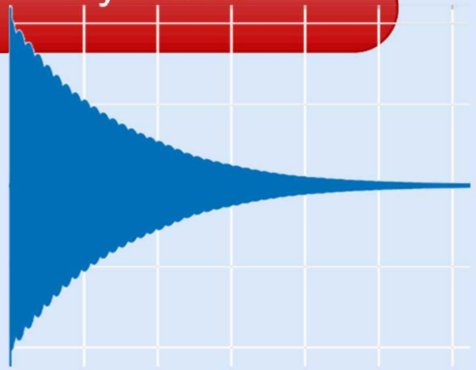
# Dynamic and Quasi-Static Analysis of Structures with Joints

EXPERIMENTAL

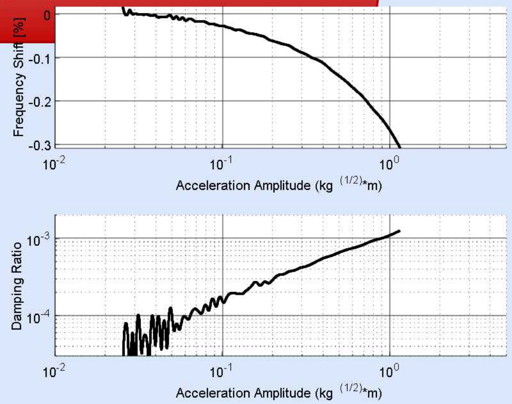
Impulse Test → Ringdown time histories



Modal Filter to obtain SDOF systems

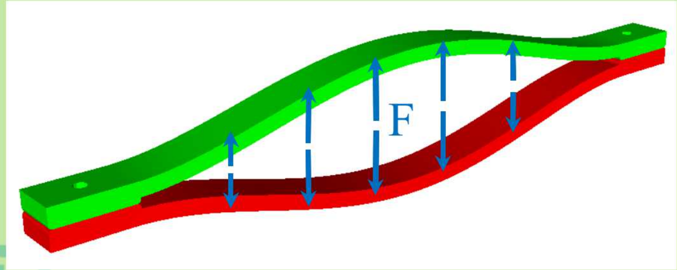


Hilbert Analysis to get amplitude dependent curves

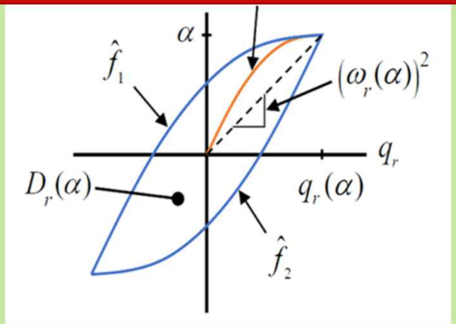


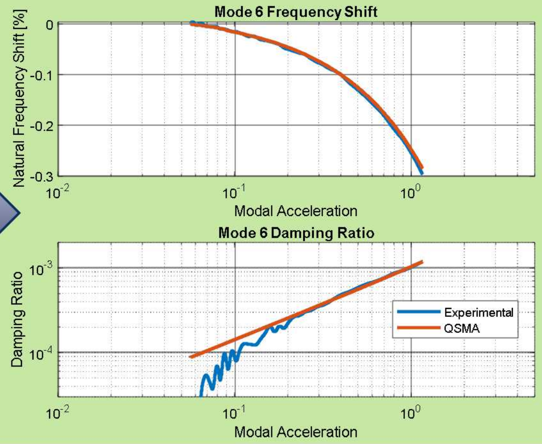

NUMERICAL

Quasi – Static Load in the Shape of a Mode



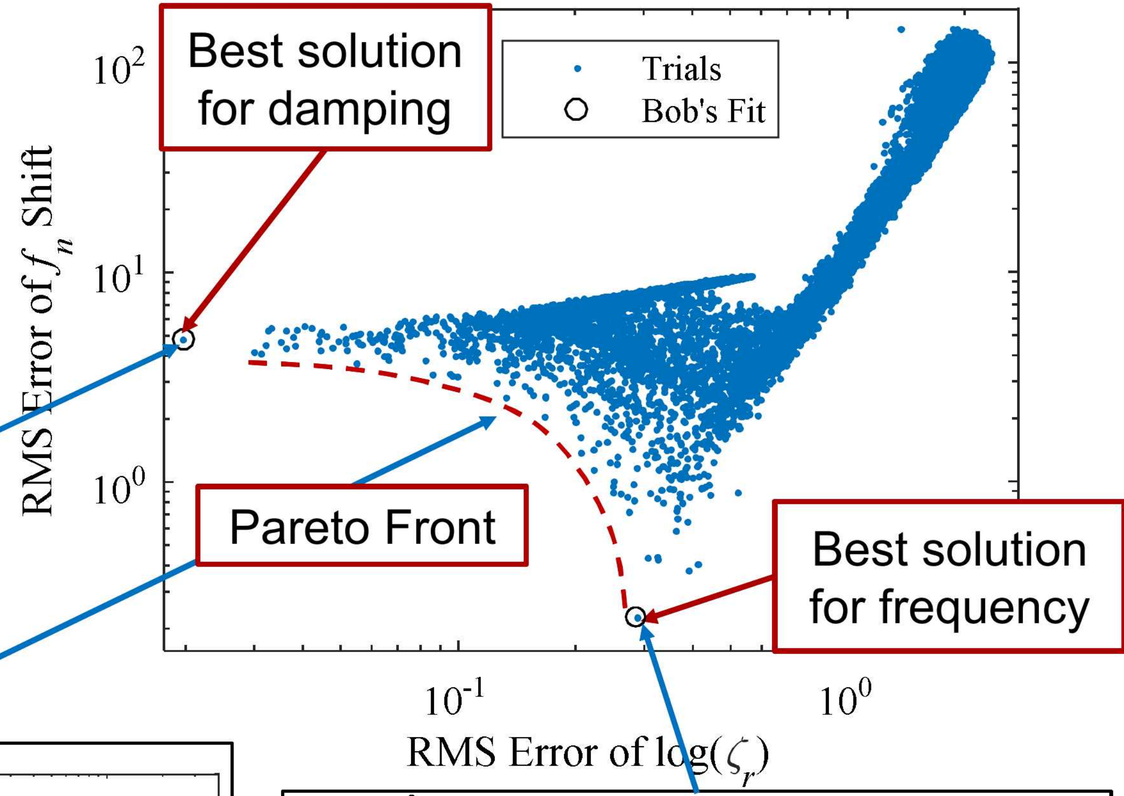

Force Displacement Curve

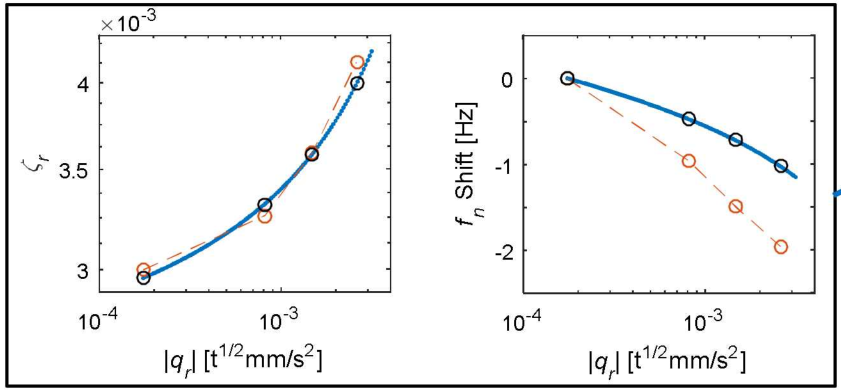


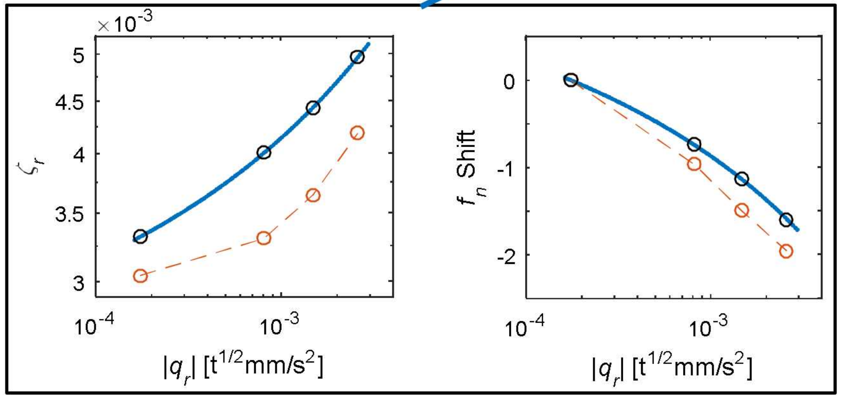



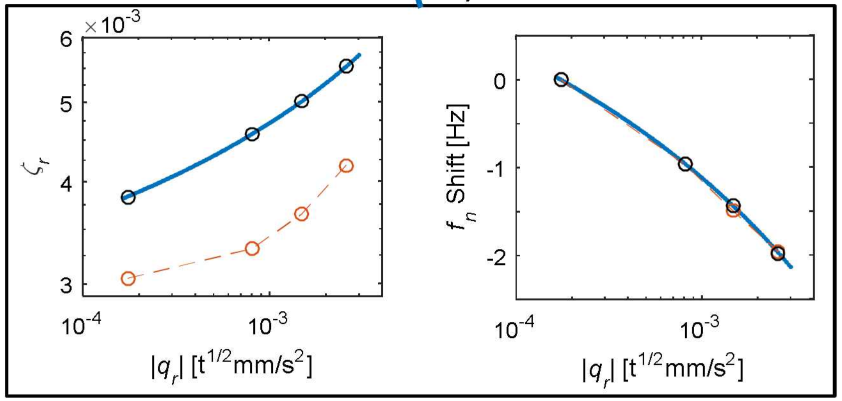
# A certain model can capture frequency or damping but not both

- Various studies that have sought to optimize the Iwan parameters to capture QSMA curves have found a Pareto front
- This is thought to arise due to a limitation in the way the joints are spidered and is explored here.



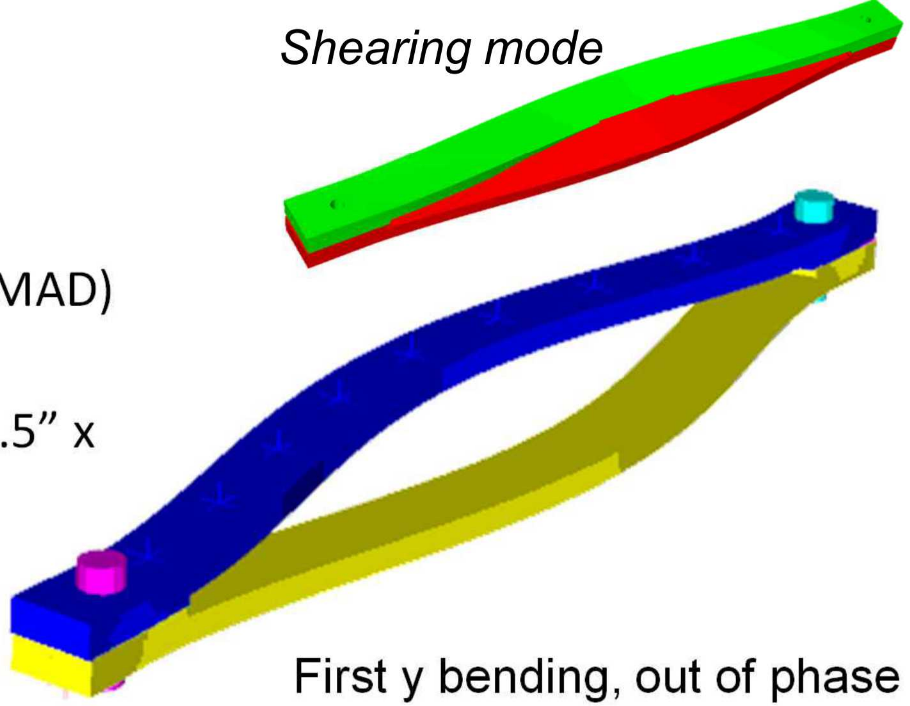




R. M. Lacayo and M. S. Allen, "Updating Structural Models Containing Nonlinear Iwan Joints Using Quasi-Static Modal Analysis," *Mechanical Systems and Signal Processing*, vol 118, pp. 133-157, 2019.

# Experimental Structure – S4 Beam (S4B)

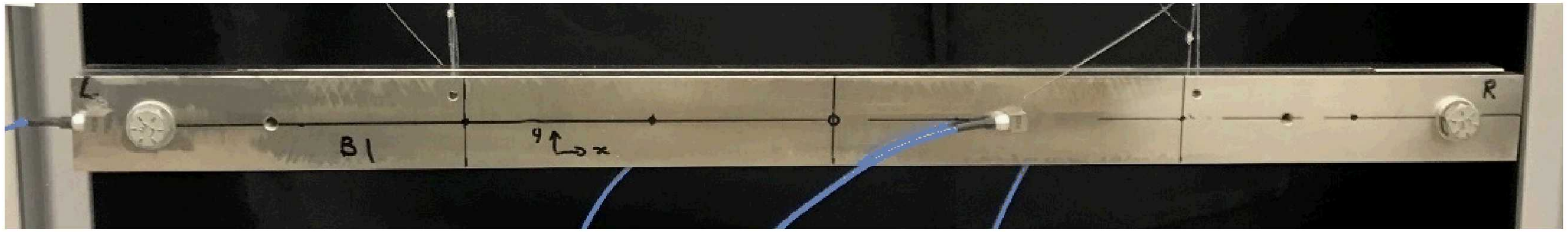
*Shearing mode*

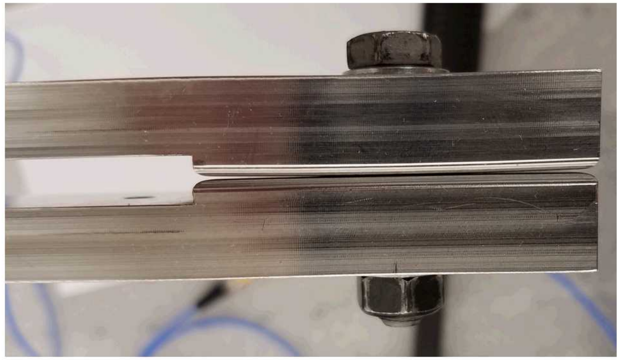


First y bending, out of phase

- Characterized in Sandia’s 2017 Nonlinear Mechanics and Dynamics (NOMAD) Institute
- Two C shaped beams with nominally flat interfaces are used to from a 1.5” x 1.0” x 20” structure
- Two Bolted regions (4 interfaces)
- 6 modes of vibration within 1 kHz

- **For this presentation, we will examine Mode 6 forced at 100 N with a bolt torque of 25.1 Nm.**
- **Reduced Model: Place a Z Rotation Iwan element to capture the slip**

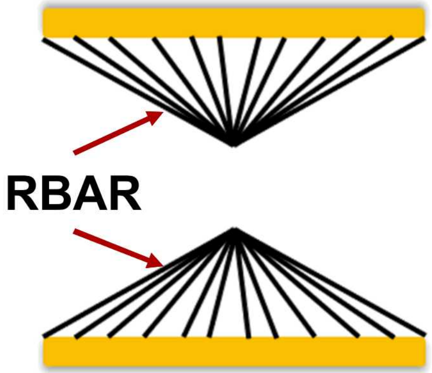




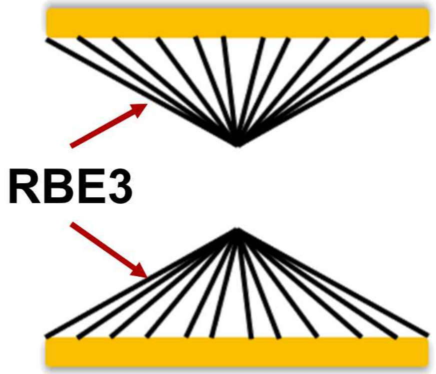
A. Singh *et al.*, “Experimental Characterization of a new Benchmark Structure for Prediction of Damping Nonlinearity,” presented at the 36th International Modal Analysis Conference (IMAC XXXVI), Orlando, Florida, 2018.

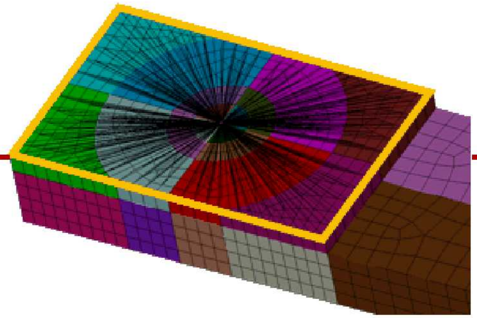
# Modeling the S4 Beam

**a.) Full Interface RBAR**

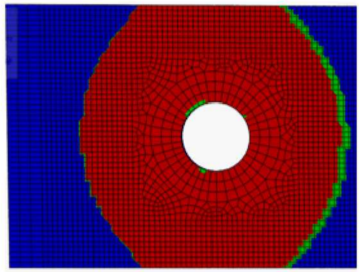



**b.) Full Interface RBE3**

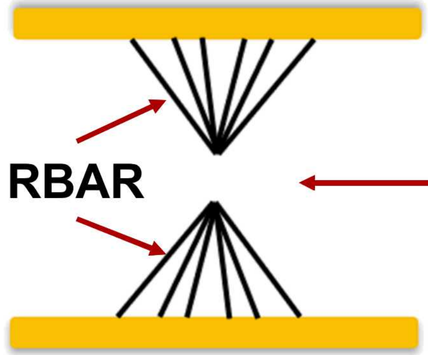


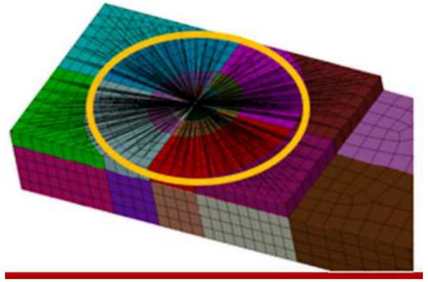



Contact area from nonlinear contact simulation

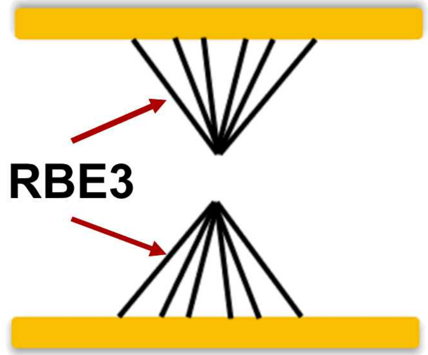


**c.) Reduced Interface RBAR**



**d.) Reduced Interface RBE3**



# Test Cases

1) Obtain all parameters $F_s, K_t, \chi,$ and $\beta$ from Monte Carlo Updating. (Following Lacayo et al. [1])

| Monte Carlo $K_t$ (Linear), $F_s, \chi, \beta$ | 1st Optimization | 2nd Optimization |
|---|---|---|

2) Obtain $F_s, \chi,$ and $\beta$ from Monte Carlo Updating and update $K_t$ through a range (Pareto fronts)

| Monte Carlo $F_s, \chi, \beta$ | 1st Optimization $K_t$ | 2nd Optimization |
|---|---|---|

3) Run secondary optimization loop to iterate on $F_s$ and $K_t$. $\chi$ and $\beta$ remain at nominal values (3D Pareto fronts)

| Monte Carlo $\chi, \beta$ | 1st Optimization $F_s$ | 2nd Optimization $K_t$ |
|---|---|---|

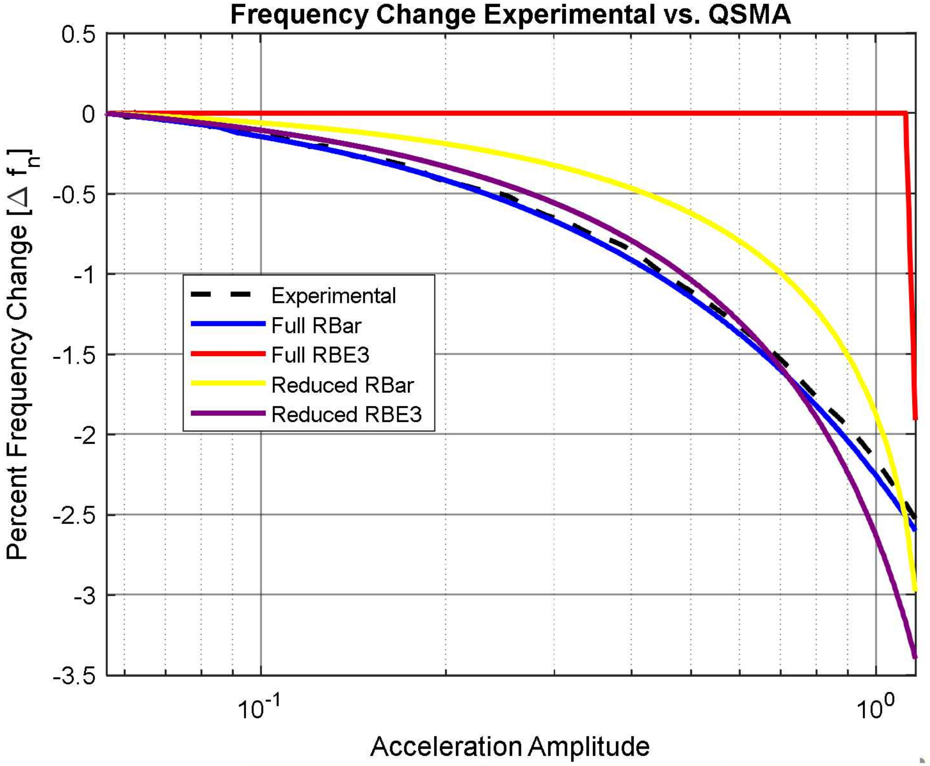
R. M. Lacayo and M. S. Allen, "Updating Structural Models Containing Nonlinear Iwan Joints Using Quasi-Static Modal Analysis," *Mechanical Systems and Signal Processing*, vol 118, pp. 133-157, 2019.

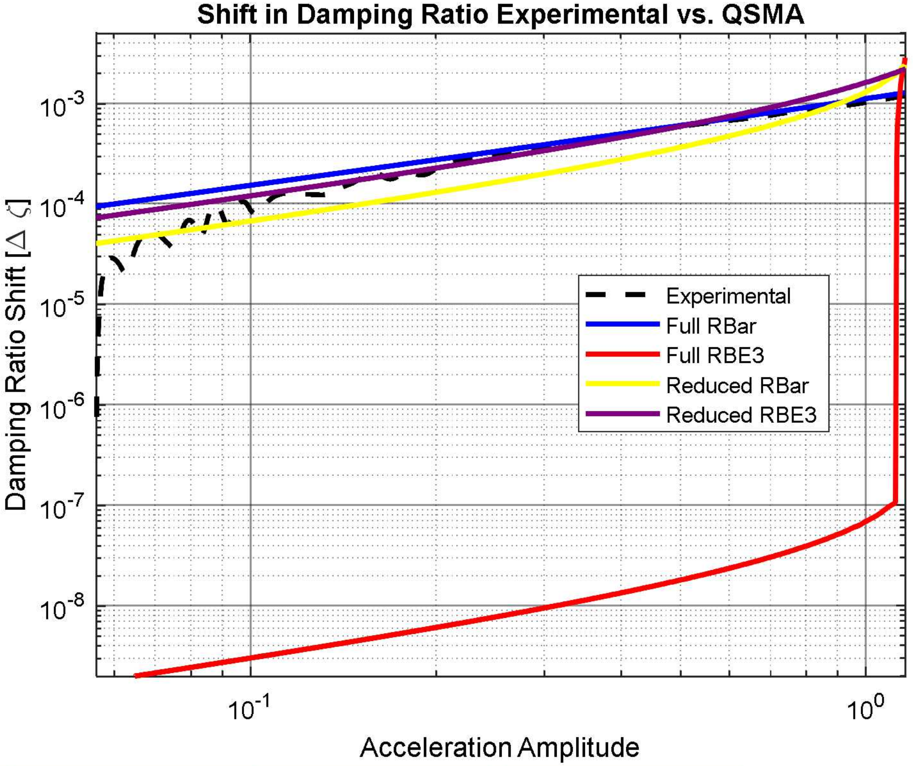
# Mode 6 Optimization

**Monte Carlo**
$F_s, K_t(Linear), \chi, \beta$

**1st Optimization**
$K_t$

**2nd Optimization**

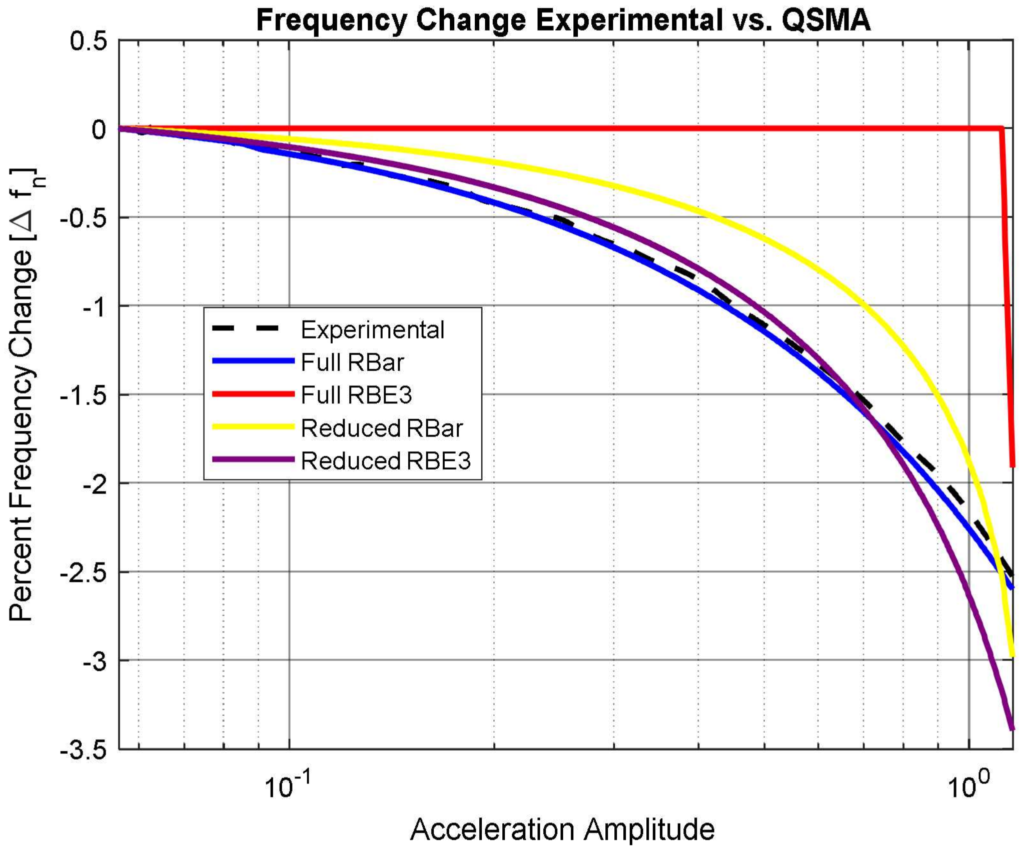


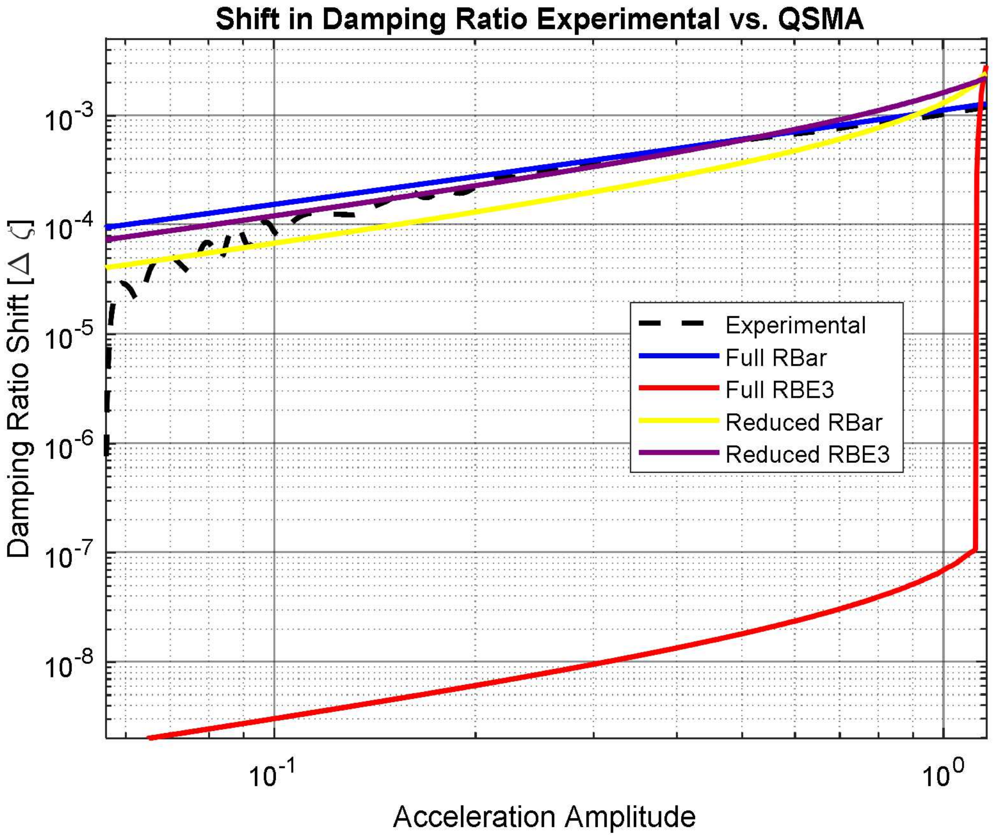




| Interface | MPC | $F_s$ | $K_t$ | $\chi$ | $\beta$ |
|---|---|---|---|---|---|
| Full | RBar | 0.4472 | 2.0773e6 | -0.1697 | 2.3521 |
| | RBE3 | 0.0945 | 7.7204e11 | -0.112 | 0.00307 |
| Reduced | RBar | 0.0971 | 4.1480e7 | -0.1833 | 7.589e-5 |
| | RBE3 | 0.1207 | 1.8246e7 | -0.1905 | 0.000951 |

- Most models are relatively accurate to predict the amplitude dependency of frequency and damping
- However, the Reduced RBar/RBE3 models are on the verge of macroslip
- As expected, the type of spider employed DOES have a significant effect on the model.
- Most accurate model: **Full RBar –** Counter Intuitive

# Goal: Improve nonlinear models while minimizing linear frequency error

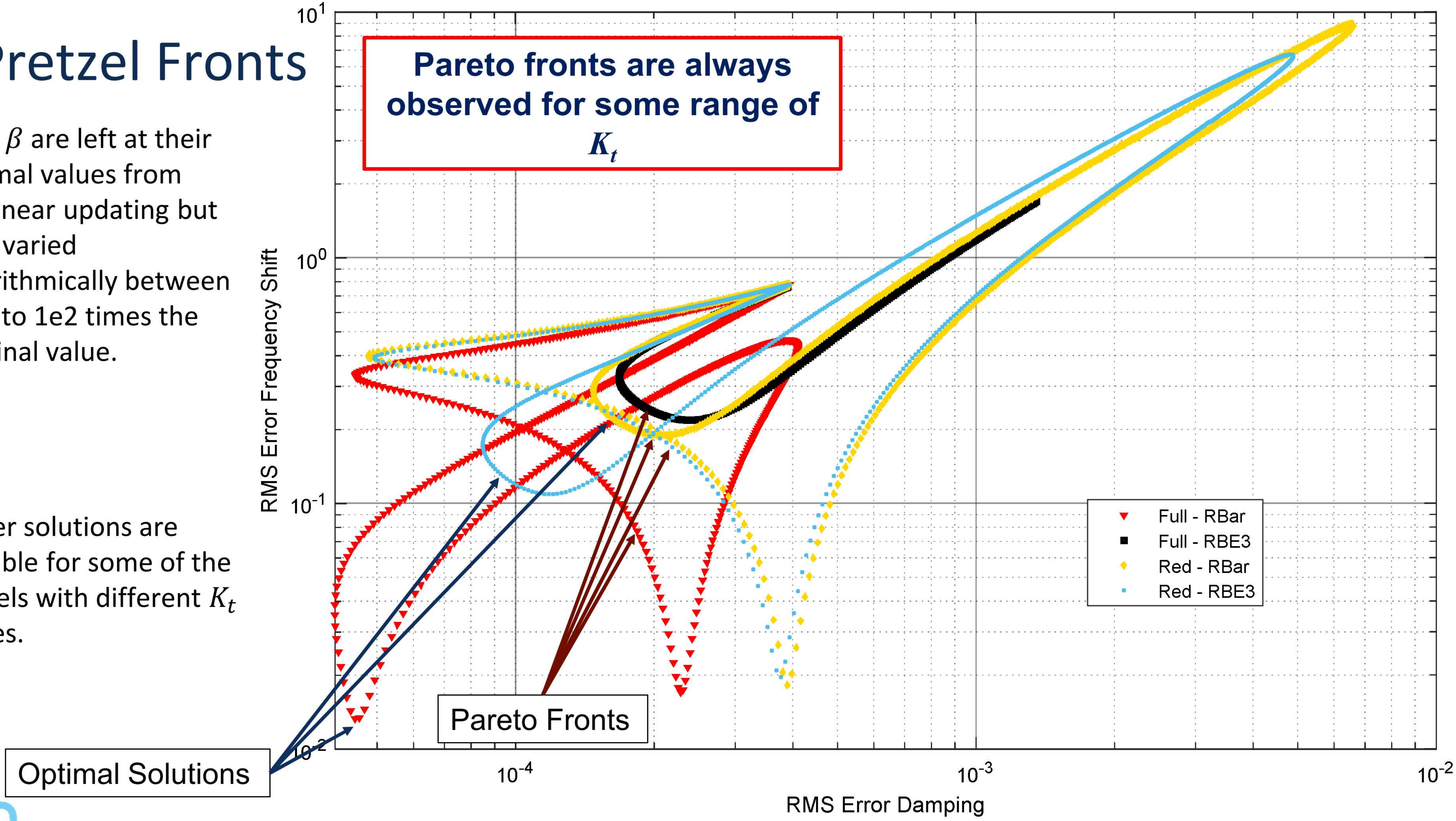



- The RBE3 MPCs require a larger joint stiffness to stiffen the joint to the same caliber as the RBar MPCs.
- **What if we vary the stiffness of the joint?**
  - Uncertainty from linear optimization that we have a global minimum solution

# Pretzel Fronts

- $F_s, \chi, \beta$ are left at their optimal values from nonlinear updating but $K_t$ is varied logarithmically between 1e-5 to 1e2 times the nominal value.
- Better solutions are possible for some of the models with different $K_t$ values.

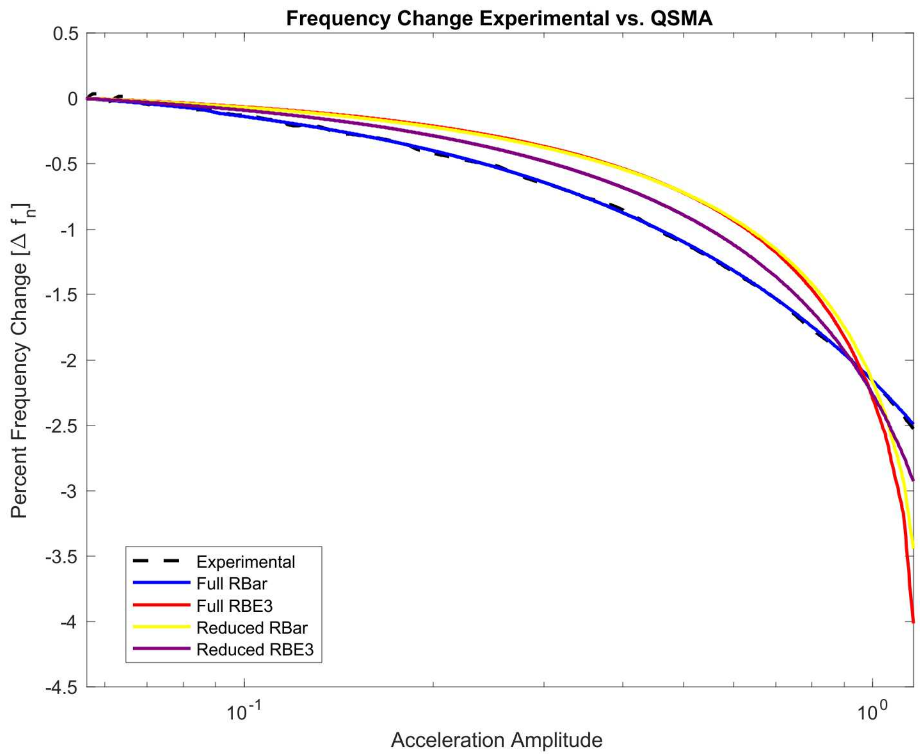


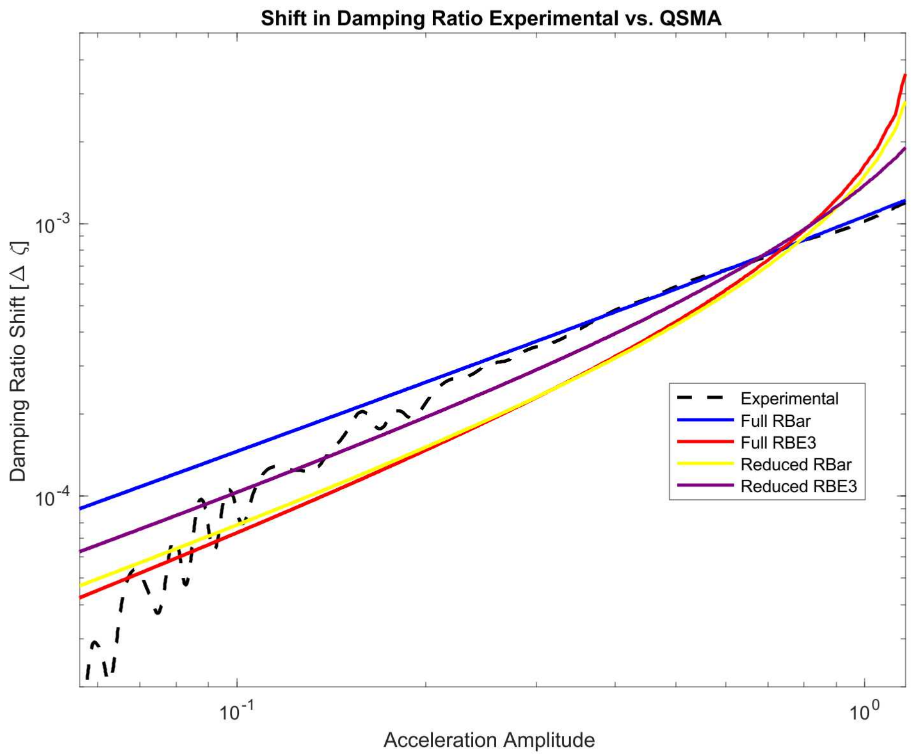
# Solution with optimal $K_t$

Monte Carlo $F_s, \chi, \beta$

1st Optimization $K_t$

2nd Optimization

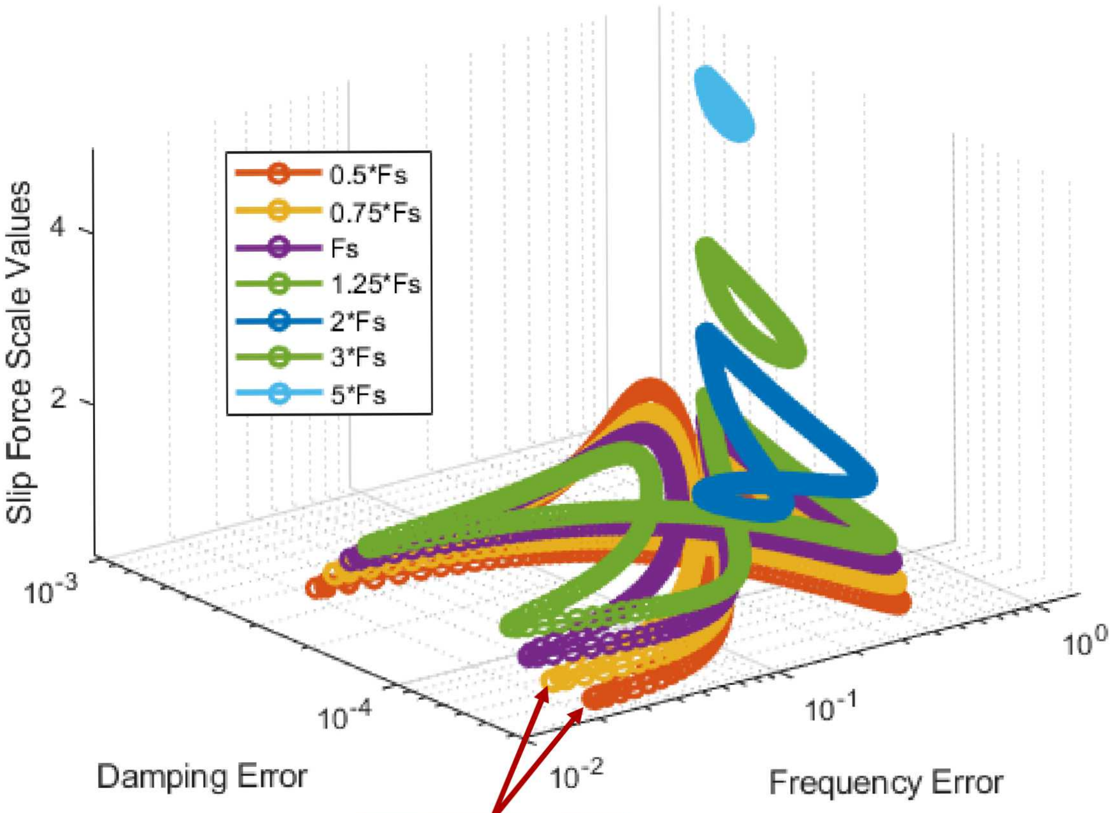


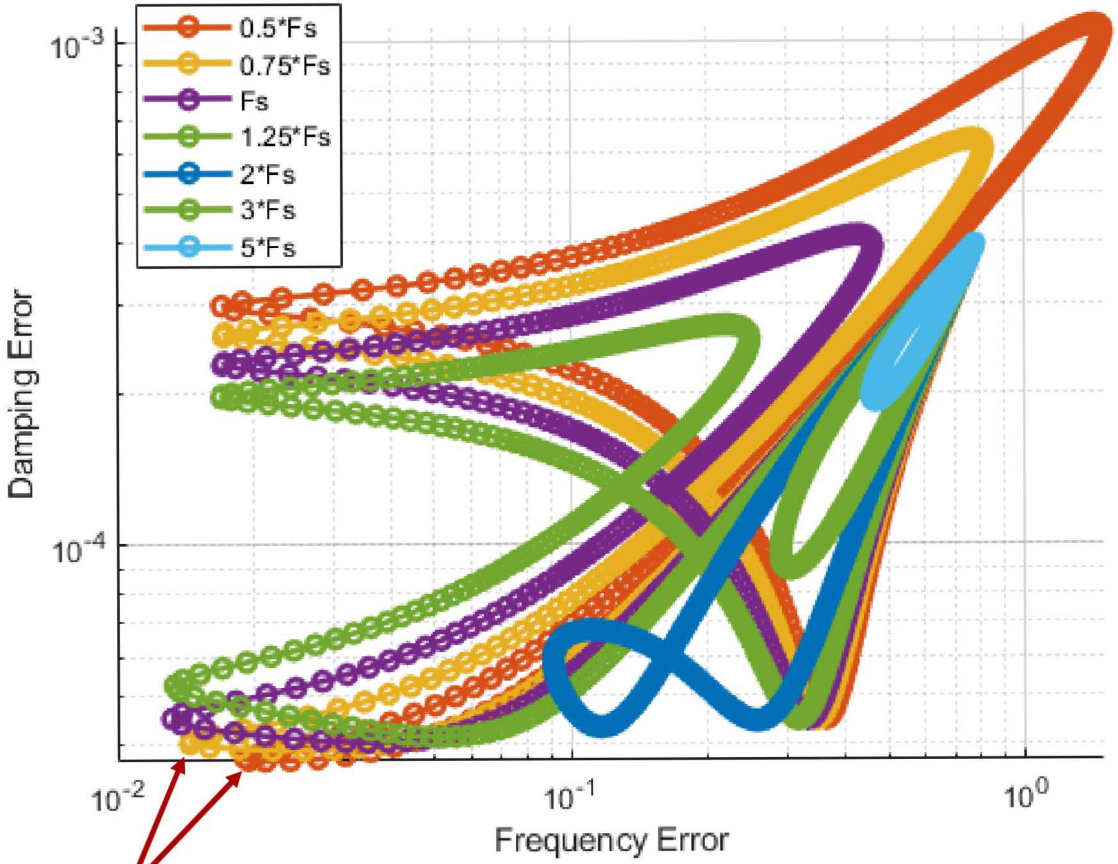

- No models clearly depict macroslip, but all models other than Full RBar are on the verge of macroslip
- This implies that we might not have the correct slip force from a Monte – Carlo Simulation
- Most accurate model: **Full RBar**

| Interface | MPC | $F_s$ | $K_t$ | $\chi$ | $\beta$ |
|---|---|---|---|---|---|
| Full | RBar | 0.4472 | 2.2211e6 | -0.1697 | 2.3521 |
| | RBE3 | 0.0945 | 3.1147e7 | -0.112 | 0.00307 |
| Reduced | RBar | 0.0971 | 3.5646e7 | -0.1833 | 7.589e-5 |
| | RBE3 | 0.1207 | 2.1344e7 | -0.1905 | 0.000951 |

# Influence of the Slip Force On the Pretzel Front (Full-RBar)

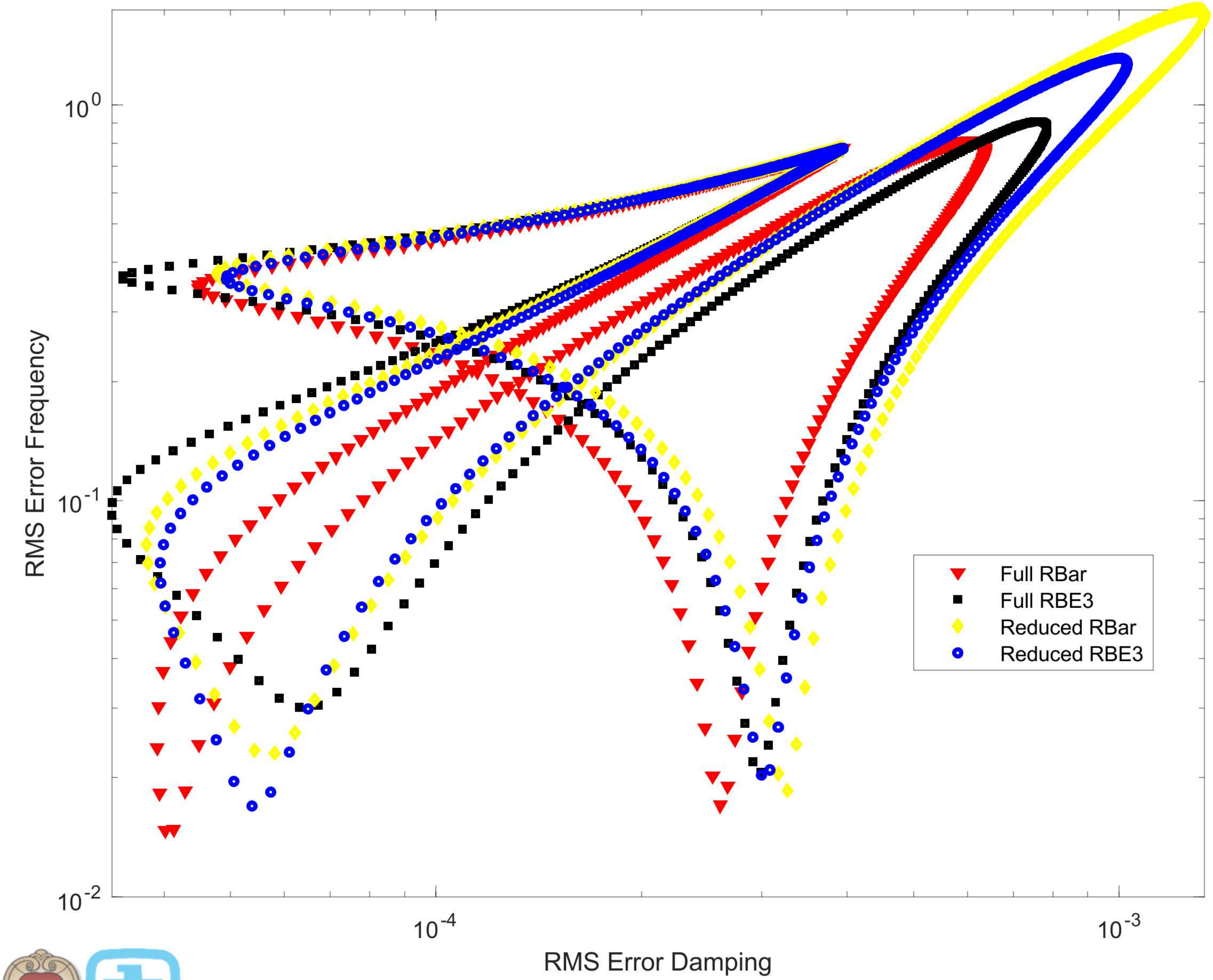



Potential Optimal Solutions




Potential Optimal Solutions

# Optimal Pretzels from $F_S$ and $K_t$ Parameter Sweep



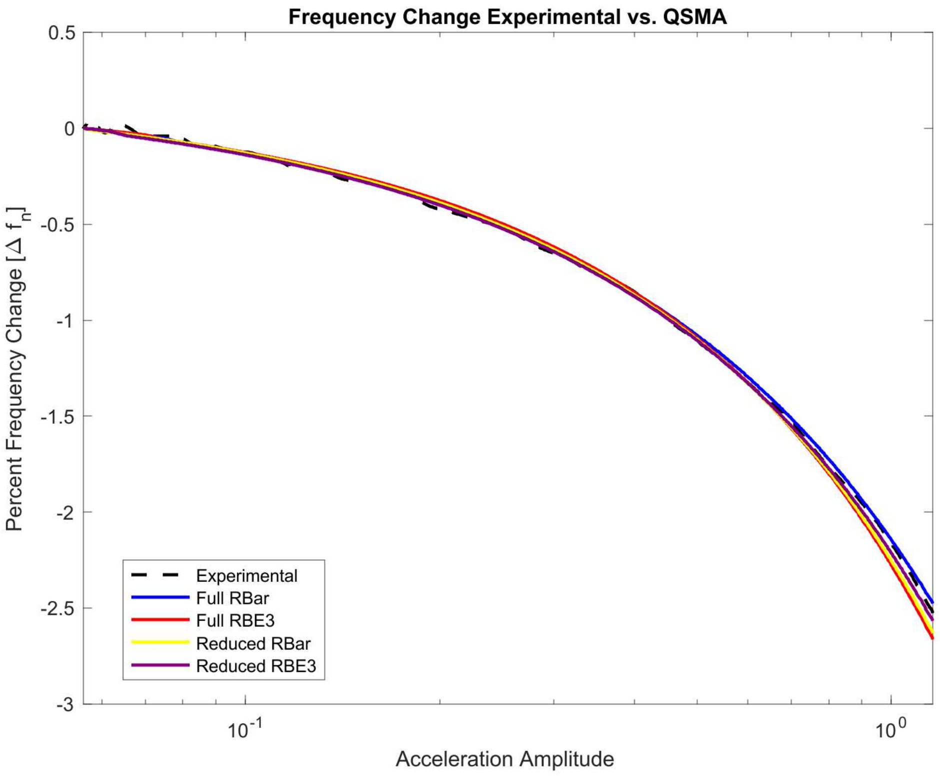

- All four models depict large tongues past the pareto front
- Nonetheless, the Full RBar Model shows the largest tongue that extends to the lowest errors
- How does this sweep impact the amplitude dependent curves?

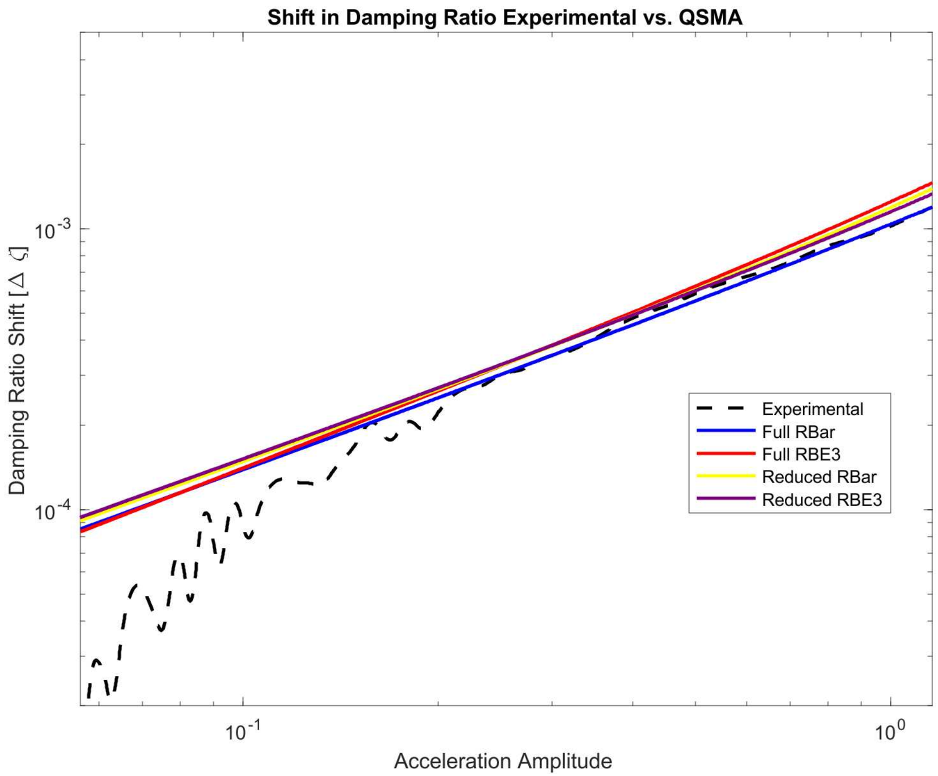
# QSMA Results: Case 3

**Monte Carlo** $\chi, \beta$

**1st Optimization** $F_s$

**2nd Optimization** $K_t$




- All models are nearly identical and very accurate in capturing the nonlinear amplitude dependency
- The only variance is due to the different $\chi$ values from the Monte - Carlo updating
- $F_s$ and $K_t$ have roughly the same magnitudes for each of the models respectively
- Most accurate model for Case 3: **All models**

| Interface | MPC | $F_s$ | $K_t$ | $\chi$ | $\beta$ |
|---|---|---|---|---|---|
| Full | RBar | 0.3354 | 3.245e6 | -0.1697 | 2.3521 |
| | RBE3 | 0.4725 | 3.061e6 | -0.112 | 0.00307 |
| Reduced | RBar | 0.3884 | 5.089e6 | -0.1833 | 7.589e-5 |
| | RBE3 | 0.4828 | 3.957e6 | -0.1905 | 0.000951 |

# The effect of the updated stiffness on the natural frequencies

| Mode | Experimental Frequency [Hz] | Linear Model Frequency Error [%] | | | | Updated Model Frequency Error [%] | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Model | Full RBar | Full RBE3 | Red RBAR | Red RBE3 | Full RBar | Full RBE3 | Red RBAR | Red RBE3 |
| Mode 1 | 258.01 | 0.60 | 0.43 | 0.63 | 0.29 | 0.60 | 0.43 | 0.63 | 0.29 |
| Mode 2 | 331.73 | 0.37 | -1.65 | -0.47 | -2.12 | 0.37 | -1.65 | -0.47 | -2.12 |
| Mode 3 | 478.55 | -0.78 | -0.98 | -0.87 | -0.99 | -0.78 | -0.98 | -0.87 | -0.99 |
| Mode 4 | 567.69 | -2.20 | -2.24 | -2.22 | -2.23 | -2.20 | -2.24 | -2.22 | -2.23 |
| Mode 5 | 708.29 | -0.78 | -0.05 | -0.25 | -0.12 | -0.78 | -0.05 | -0.25 | -0.12 |
| Mode 6 | 851.54 | -0.34 | 0.33 | 0.16 | 0.12 | 2.83 | -4.99 | -2.81 | -3.12 |

UNCHANGED

**Only this model gave a highly accurate linear natural frequency and nonlinear characteristics.**

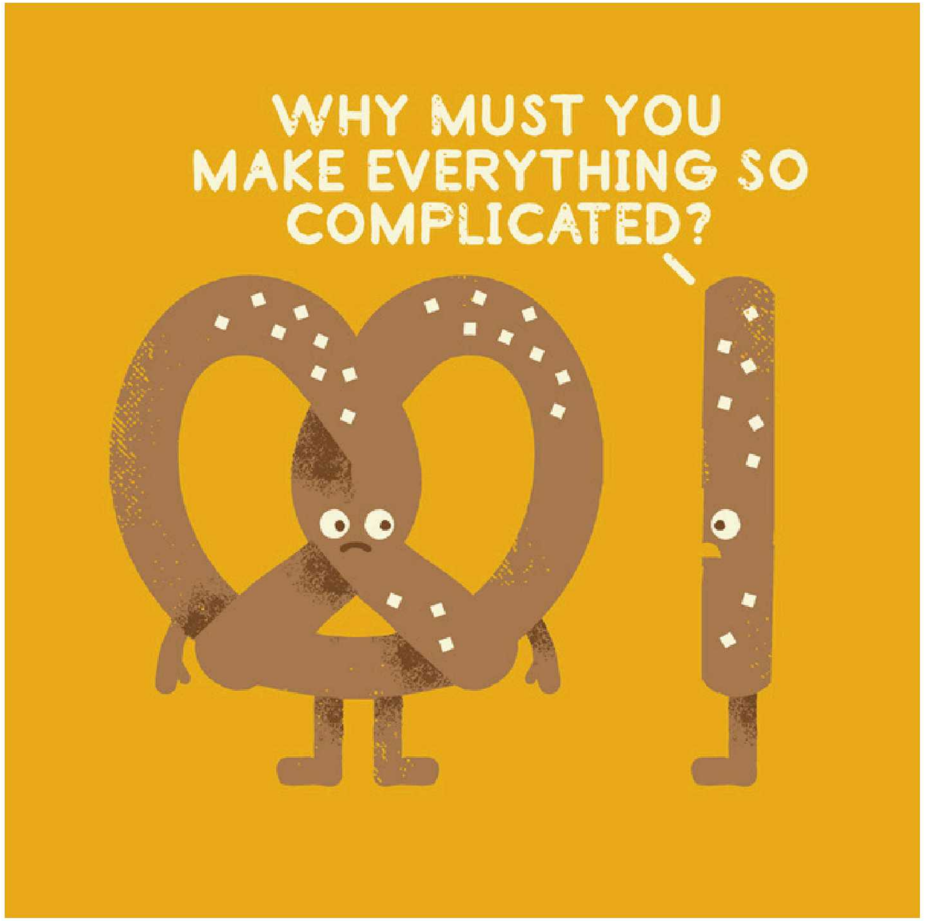
# Summary

- The parameters of a model with Iwan joints have a coupled and complicated effect on the frequency and damping of a mode in question.

- The type of spider used to represent the interface and its spatial extent can affect the ability of the model to capture measurements. The spider method that gave the best results in this study was counter-intuitive.

- While prior works had good success using linear updating to determine the linear parameters, and nonlinear updating to account for nonlinearity, this work shows that the linear stiffness must be carefully chosen or a Pareto front (pretzel shape) may be observed in which it is not possible to obtain an adequate solution.

- Fortunately, QSMA speeds up simulations so that the parameter space can be explored:
  - Monte – Carlo Optimization (random parameters): 100,000 iterations at ~15 minutes
  - Optimization loop (use nominal parameters from above as seeds): $1\ F_s \times 50000\ K_t\ Values$ at ~2.8 minutes
    - Joint stiffnesses are scaled from 1e-5 to 1e2 times the nominal stiffness from linear updating




# Thank You

Questions?

# Works Cited


[1] "Abaqus analysis user's guide." Simulia, 2014.

[2] E. Jewell, M. S. Allen, and R. Lacayo, "Predicting damping of a cantilever beam with a bolted joint using quasi-static modal analysis," presented at the Proceedings of the ASME 2017 International Design Engineering Technical Conference & 13th International Conference on Multibody Systems, Nonlinear Dynamics, and Control IDETC/ MSNDC 2017, 2017.

[3] D. J. Segalman, "A Four-Parameter Iwan Model for Lap-Type Joints," *Journal of Applied Mechanics*, vol. 72, no. 5, pp. 752–760, Sep. 2005.

[4] M. Feldman, "Non-linear system vibration analysis using Hilbert transform--I. Free vibration analysis method 'Freevib,'" *Mechanical Systems and Signal Processing*, vol. 8, no. 2, pp. 119–127, 1994.

[5] H. Festjens, G. Chevallier, and J.-L. Dion, "A numerical quasi-static method for the identification of frictional dissipation in bolted joints," presented at the ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE 2012, August 12, 2012 - August 12, 2012, 2012, vol. 1, pp. 353–358.

[6] R. M. Lacayo and M. S. Allen, "Updating Structural Models Containing Nonlinear Iwan Joints Using Quasi-Static Modal Analysis," *Mechanical Systems and Signal Processing*, vol 118, pp. 133-157, 2019.

[7] A. Singh *et al.*, "Experimental Characterization of a new Benchmark Structure for Prediction of Damping Nonlinearity," presented at the 36th International Modal Analysis Conference (IMAC XXXVI), Orlando, Florida, 2018.

[8] R. J. Kuether, P. B. Coffin, and A. R. Brink, "ON HURTY/CRAIG-BAMPTON SUBSTRUCTURING WITH INTERFACE REDUCTION ON CONTACTING SURFACES," in *International Design Engineering Technical Conferences*, Cleveland, Ohio, 2017.

[9] R. R. J. Craig and M. C. C. Bampton, "Coupling of Substructures for Dynamic Analysis," *AIAA Journal*, vol. 6, no. 7, pp. 1313–1319, 1968.

[10] D. Krattiger *et al.*, "Interface Reduction for Hurty/Craig-Bampton Substructured Models: Review and Improvement," *Mechanical Systems and Signal Processing*, vol. Submitted April., 2017.

[11] "Sierra/SD - Theory Manual." Sandia National Laboratories, 2018.

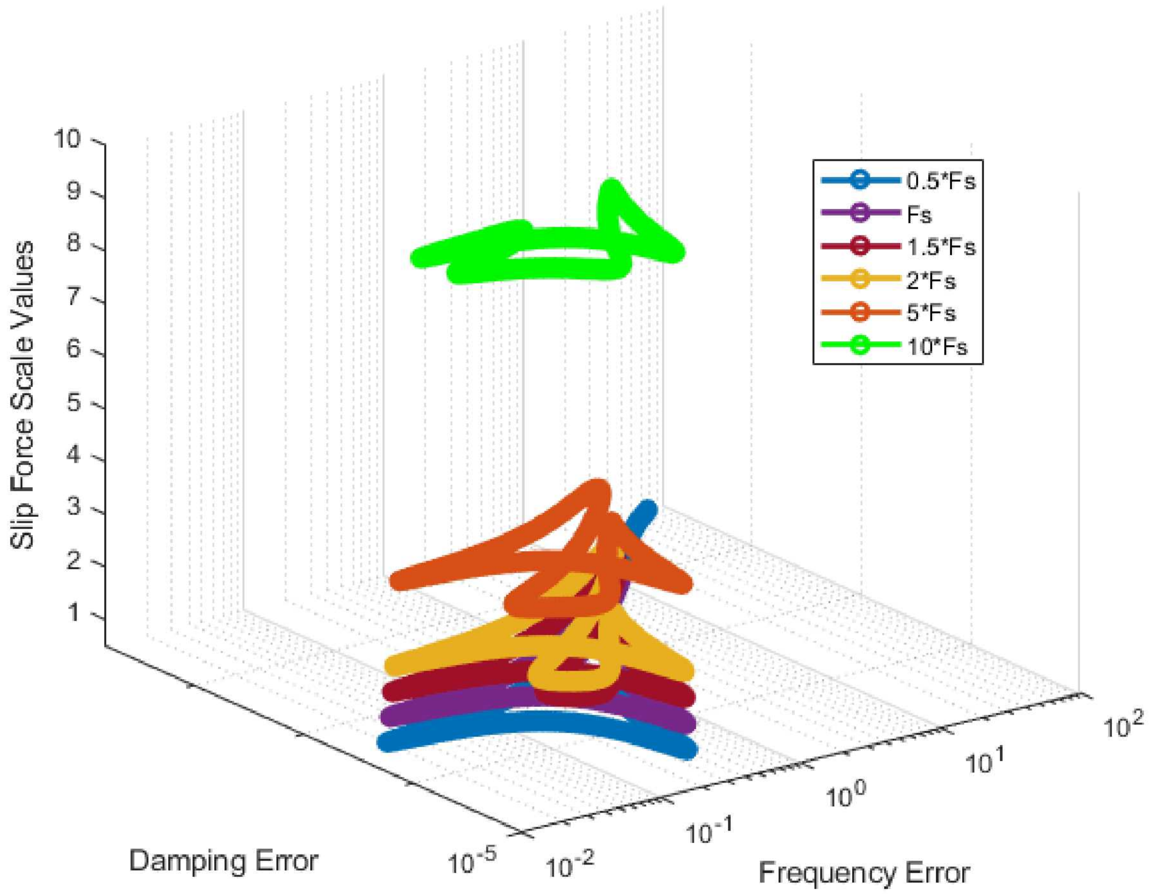
[12] D. J. Segalman *et al.*, "Handbook on Dynamics of Jointed Structures," Sandia National Laboratories, Albuquerque, NM 87185, 2009.

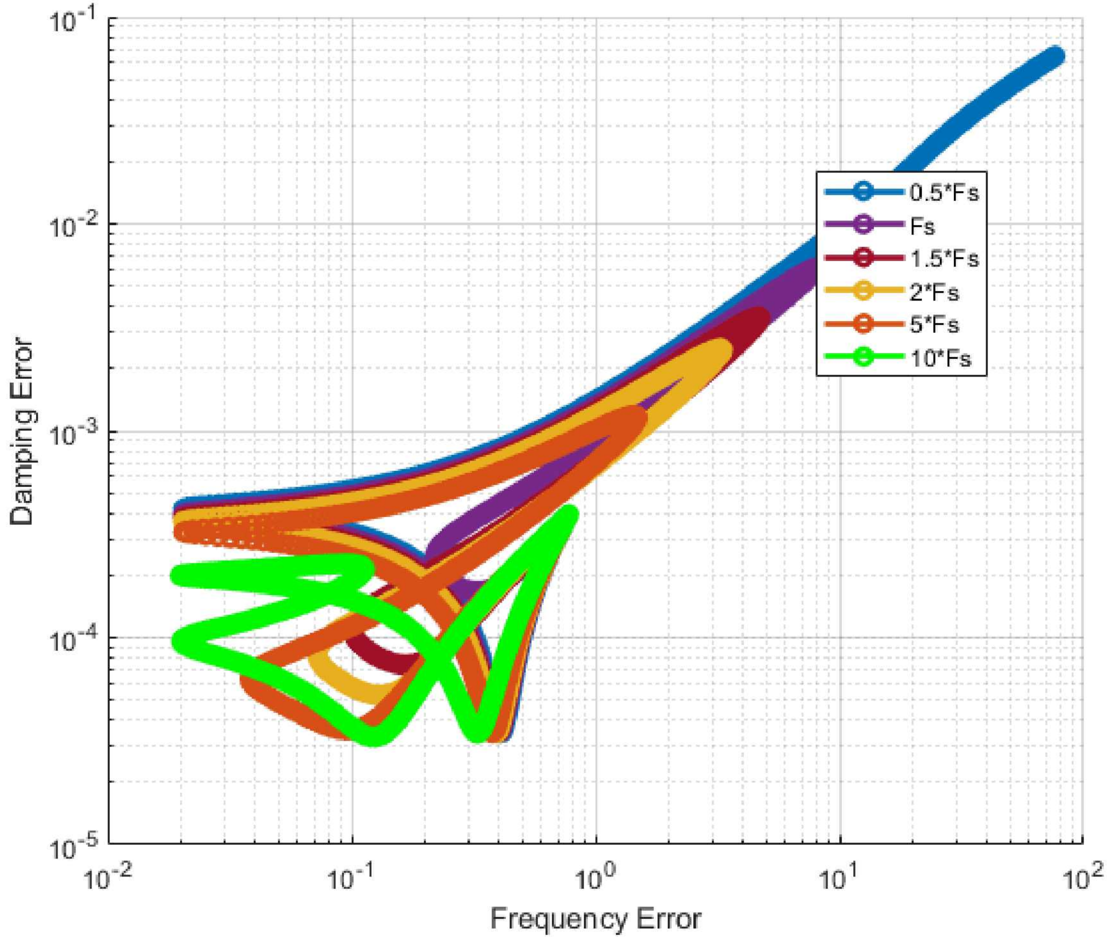
[13] B. Deaner, "Modeling the Nonlinear Damping of Jointed Structures Using Modal Models," University of Wisconsin-Madison, Madison, WI, 2013.

[14] M. Fronk *et al.*, "Inverse Methods for Characterization of Contact Areas in Mechanical Systems," presented at the 36th International Modal Analysis Conference (IMAC XXXVI), 2018.

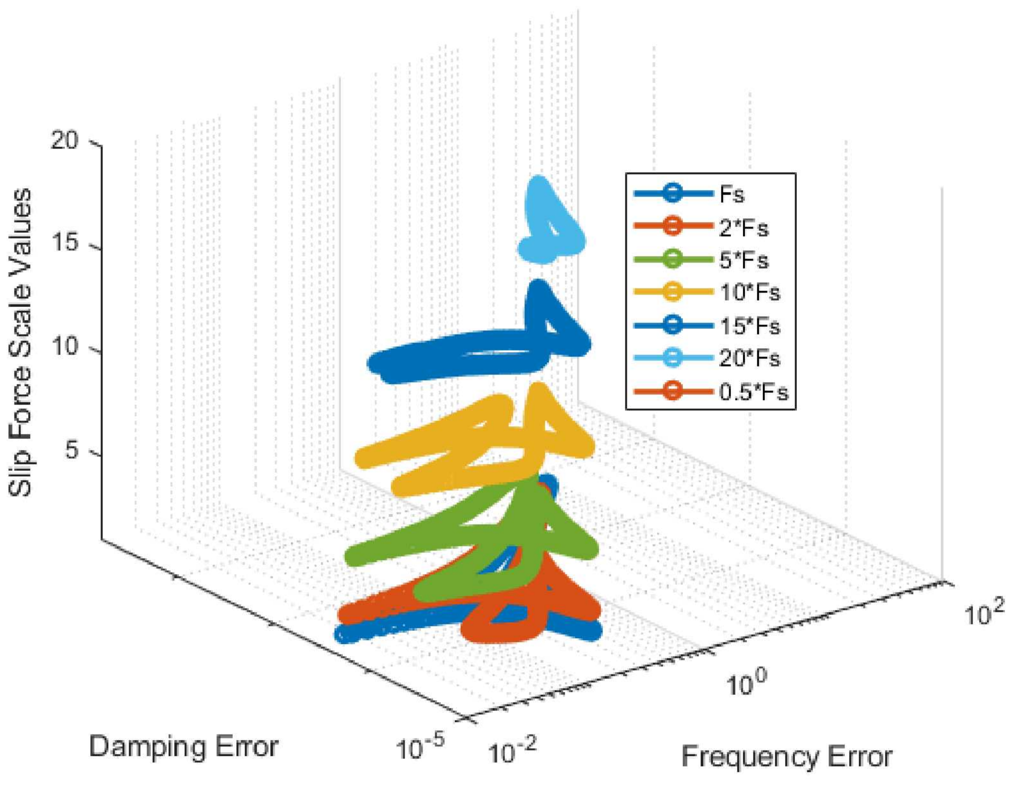
# Additional Slides

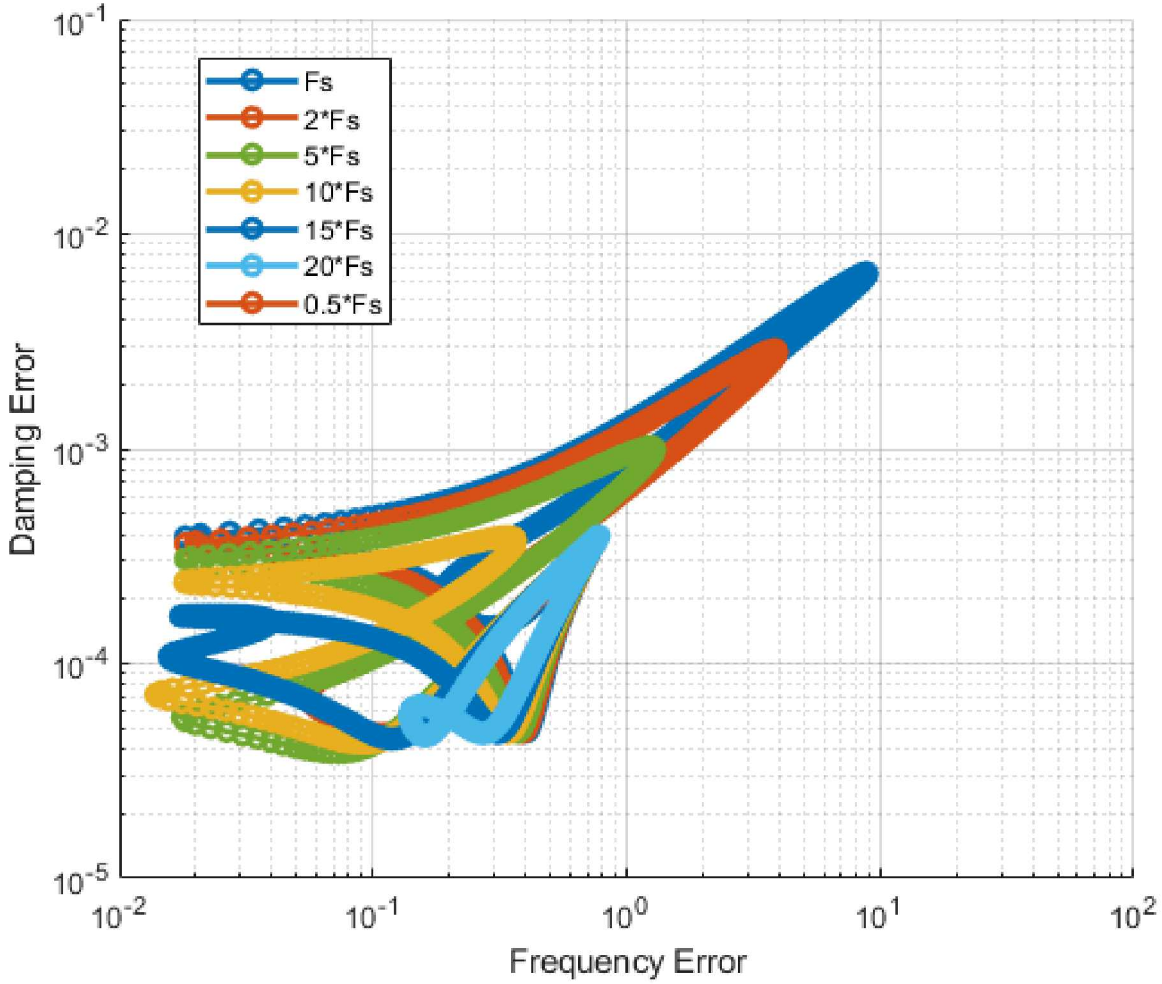
# Influence of the Slip Force On the Pretzel Front (Full-RBE3)



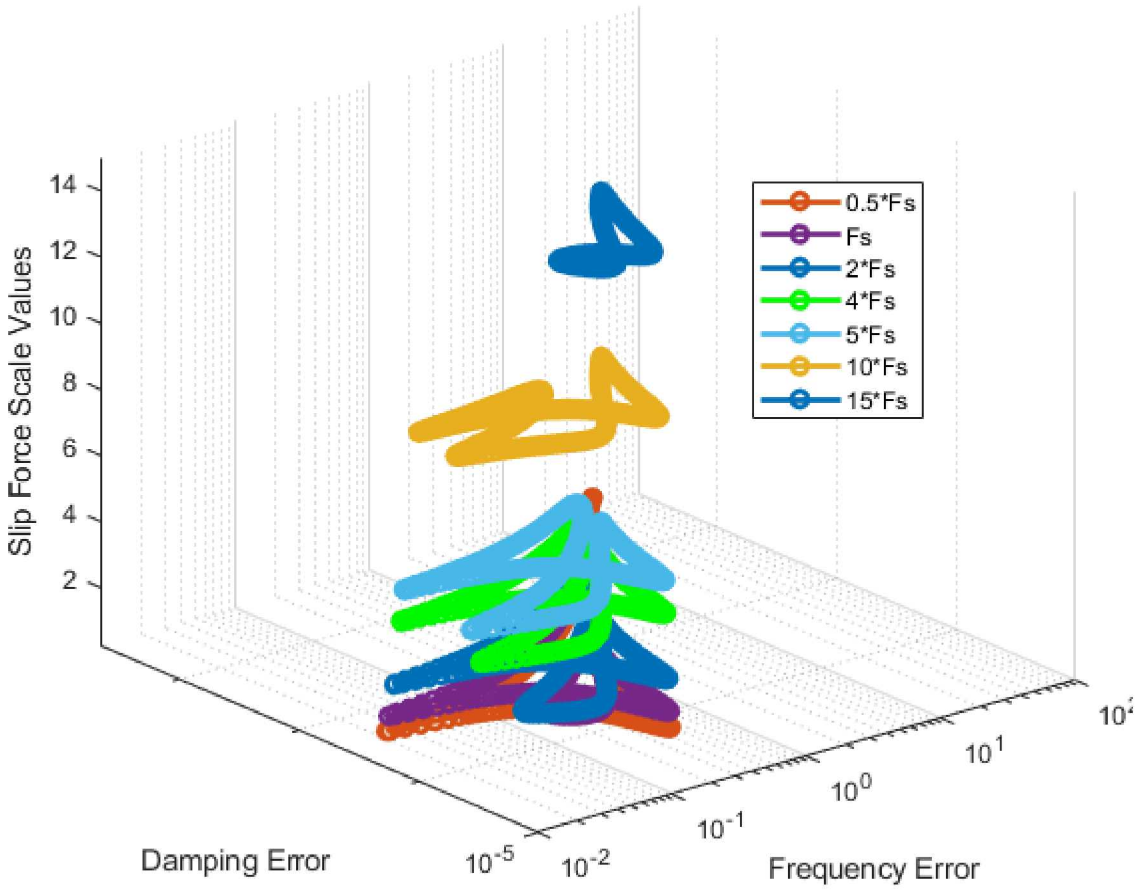



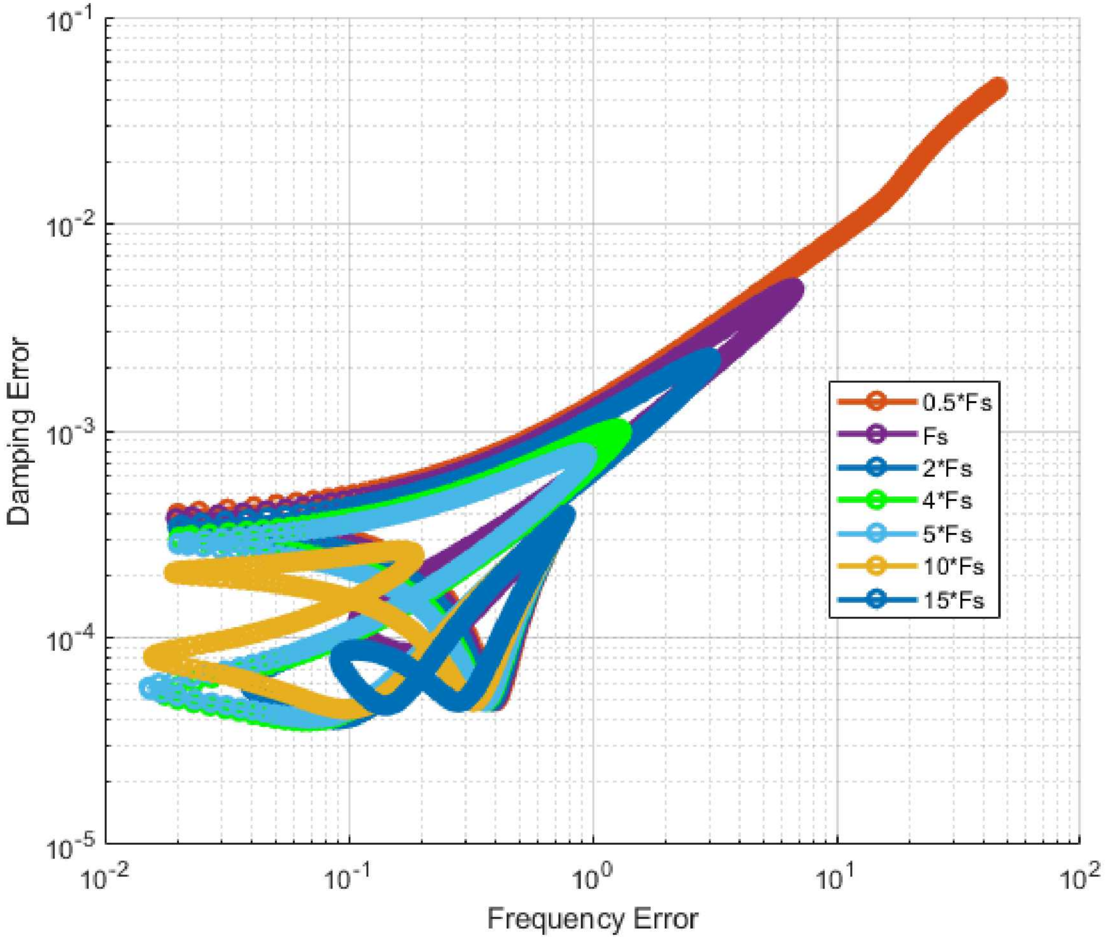
# Influence of the Slip Force On the Pretzel Front (Red-RBar)



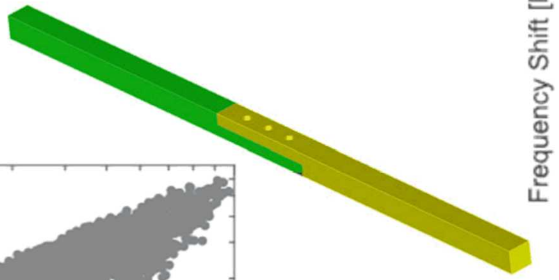



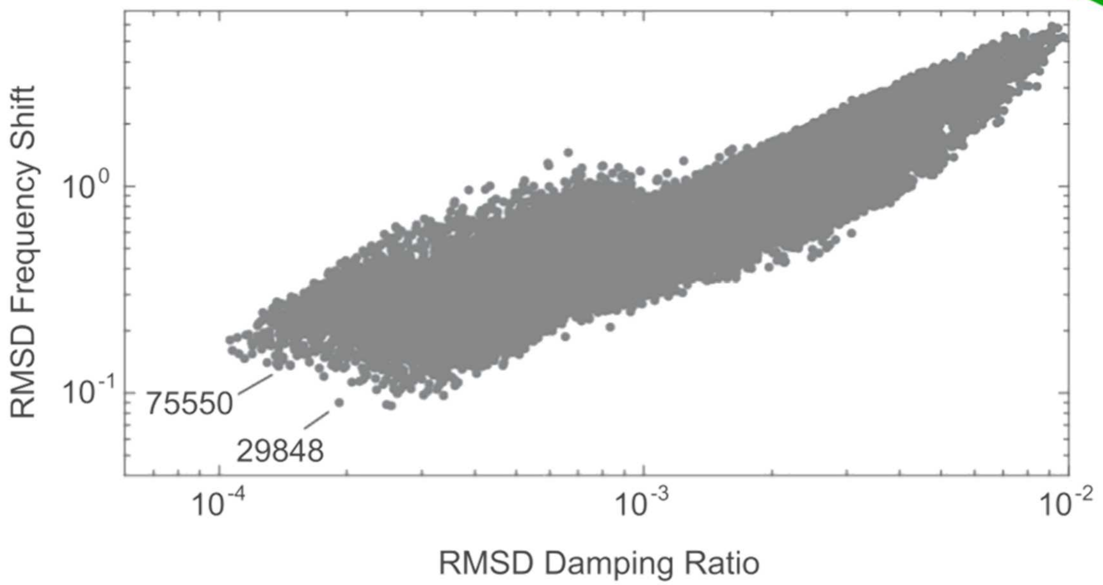
# Influence of the Slip Force On the Pretzel Front (Red-RBE3)

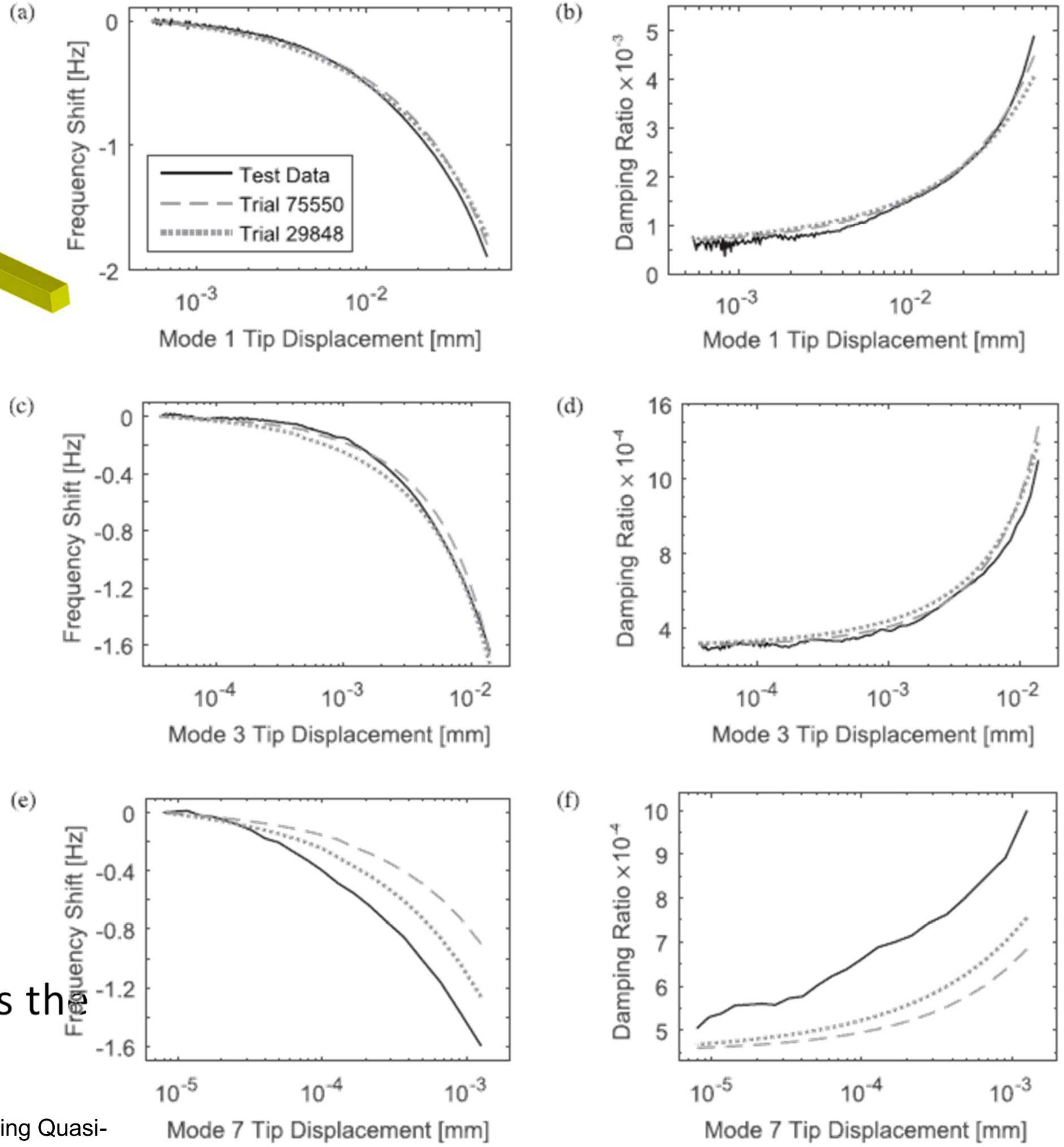


# Key finding from Lacayo for the Brake Reuss Beam (BRB)






- Lacayo et. al., found that we can accurately capture
  - amplitude dependent damping behavior
  - OR amplitude dependent frequency shift
  - BUT not both for a single parameter set
- There exists a Pareto front in the error plot that constrains the optimal nonlinear solution

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