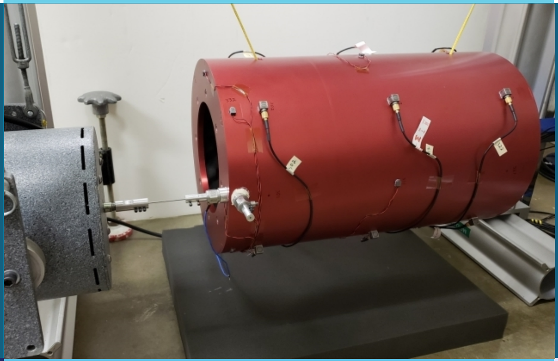
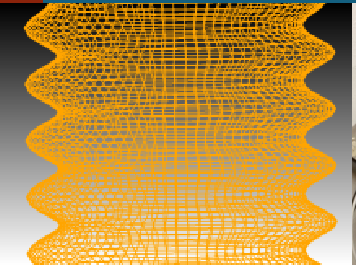
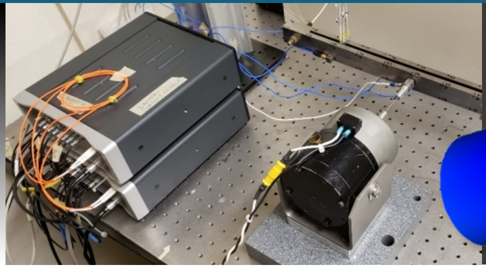
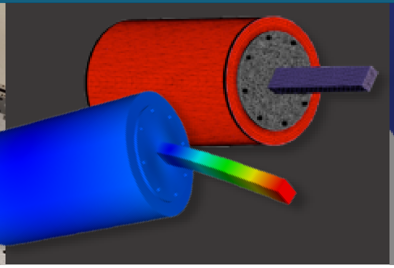
SAND2023-11543C

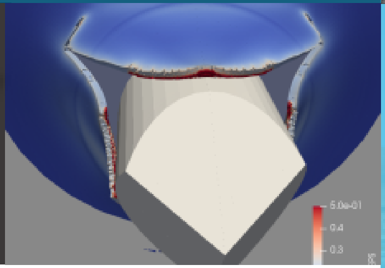
Layered Plate Damping Systems











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February 16, 2023

NSC-614-4725 08/2022 Unclassified Unlimited Release
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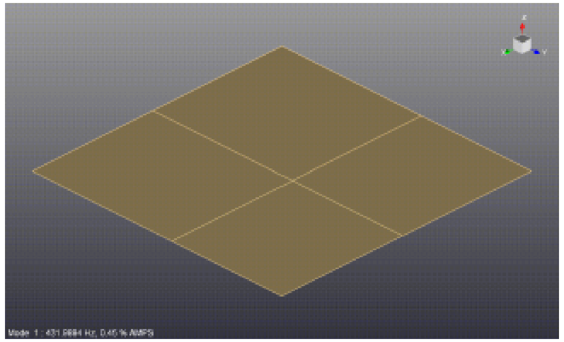
SAND2022-XXX

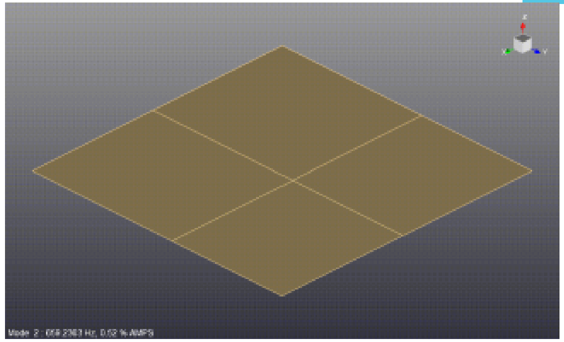
Introduction

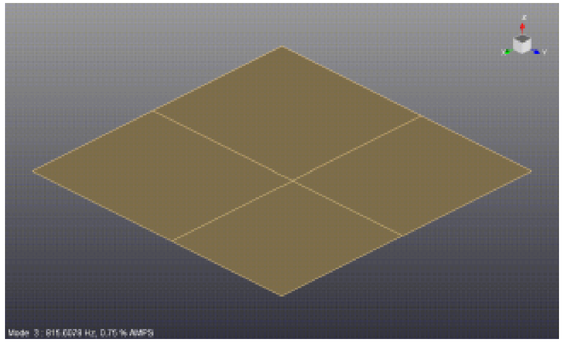
<u>Objective:</u> Determine the critical factors and their effects on layered plates joined by bolts

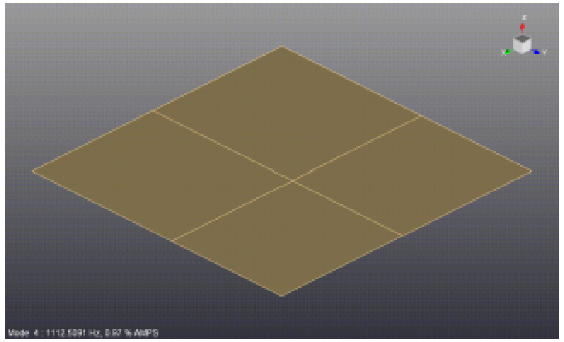
<u>Method:</u> Experimental modal analysis using a full factorial experimental design

<u>Motivation:</u> Bolted plates and joints are omnipresent. Understanding the dynamic response of bolted plate systems are critical to their use.



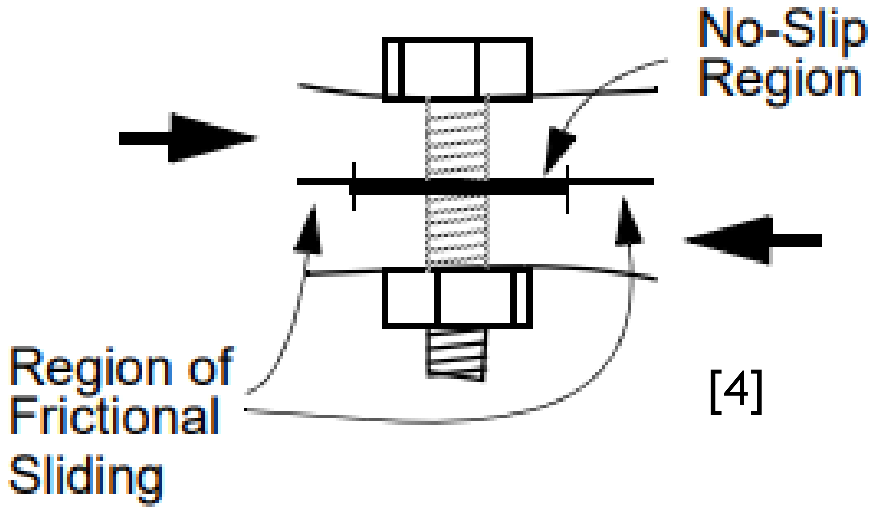






Critical Factors

- Damping is dominated by microslip
  - Microslip- the localized slip between two bolted plates - can be described by dry Coulomb friction
  - Upon excitation, the plate areas furthest from bolts will slip
  - The interface can also separate depending on direction of excitation (also known as slap)
- 5 factors across 2 levels (along w/ 32 unique configurations) selected to assess their relationship with two dynamic properties

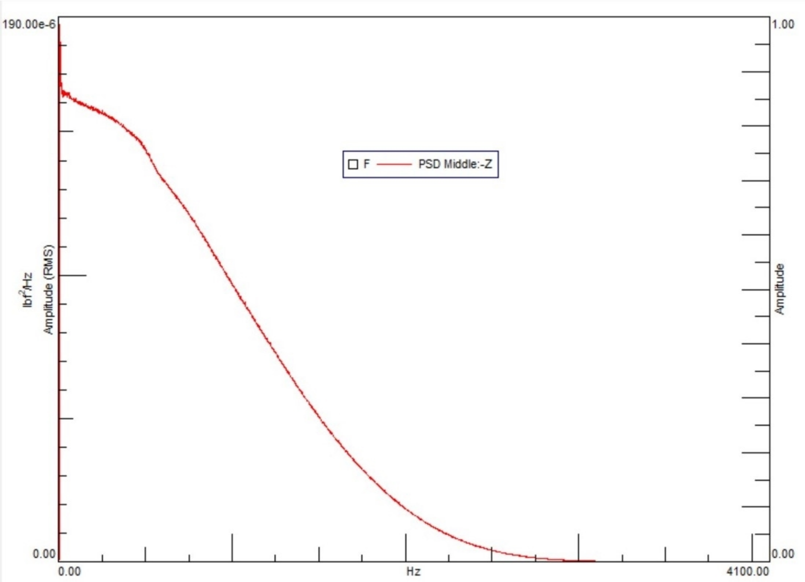


[4]

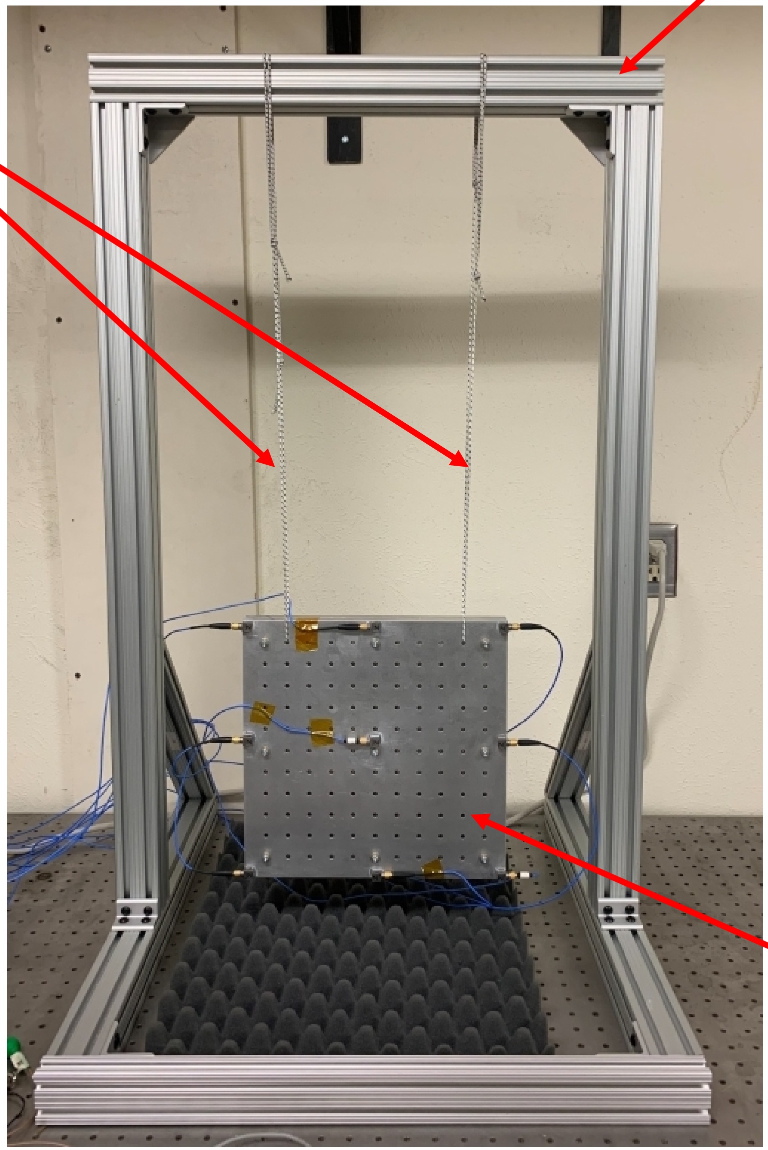
	Low	High	Expected Relationship with Frequency	Expected Relationship with Damping
Bolt Preload (in-lb)	25	50	Direct [2]	Inverse [2]
Bolt Spacing (in)	2	7.1	Unknown	Direct [3]
Total Thickness (in)	0.75	1.0	Direct	None (Minimal)
Number of Interfaces	1	2	Inverse	Direct
Impact Amplitude (lbf)	20-30	60-70	Direct	Direct [4]

Experimental Test Set-up

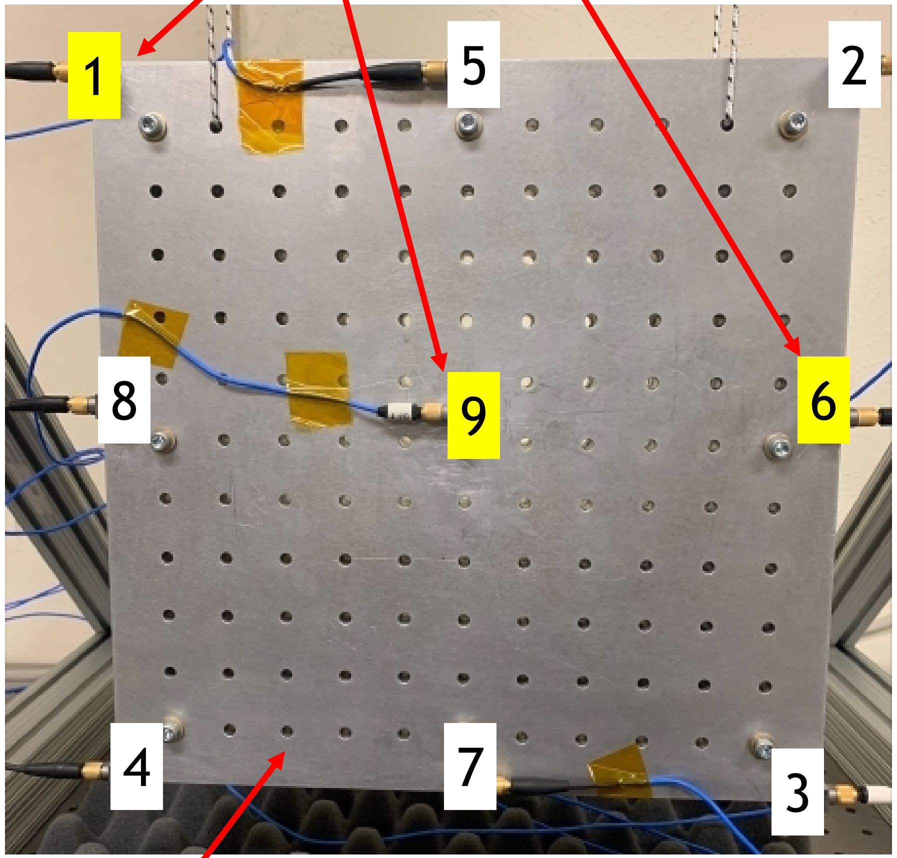
- Free boundary conditions supported by bungee cords
- Accelerometer placement based on mode shapes of interest
- White plastic impact tip (084B04 PCB) inputs content in frequency range of interest



Test Frame



Drive-points near 1, 9, and 6 chosen to excite first 4 modes

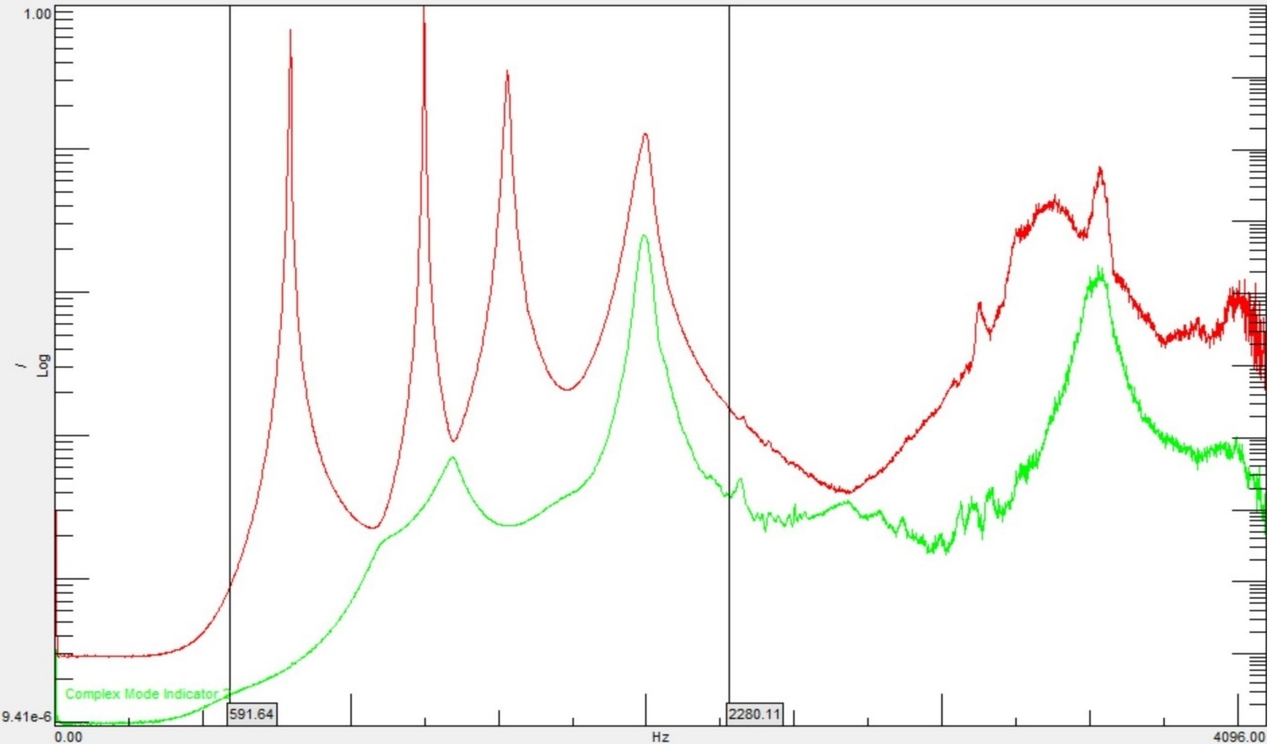


Test Specimen

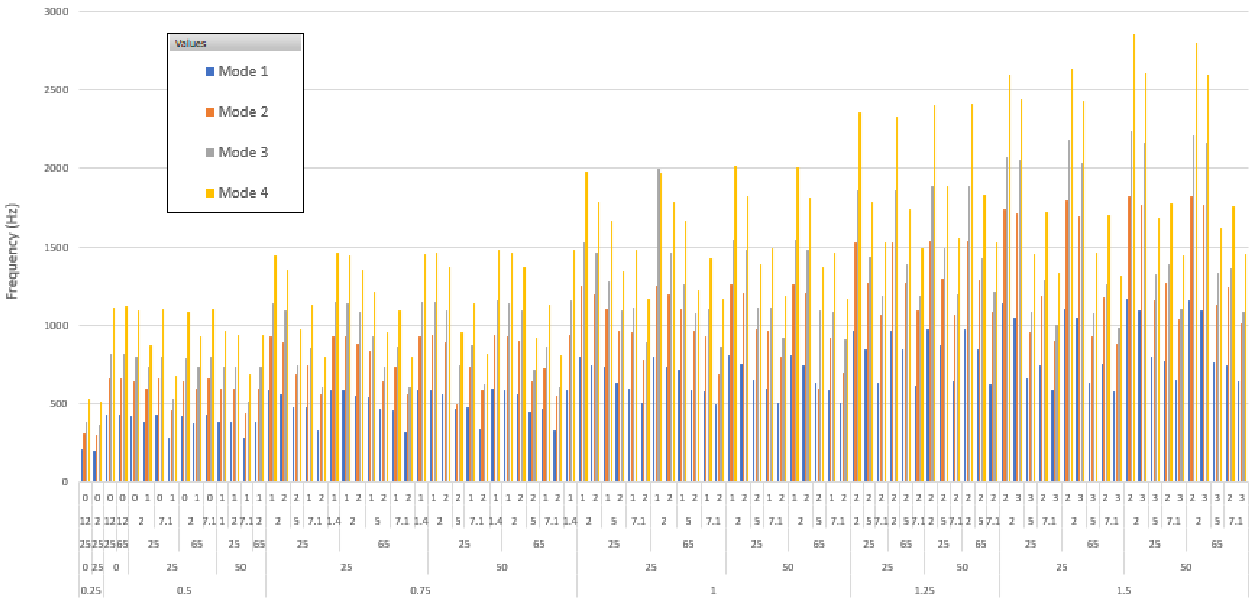
Experimental Metrics and Evaluation

- Siemens LMS used to acquire data and extract natural frequencies, mode shapes, and modal damping via curve fitting
  - FRFs averaged over three impacts at each drive point (9 impacts) from measurements at each accelerometer
- Excel and Minitab used for data organization and visualization
  - Factor importance and effects on natural frequency and modal damping

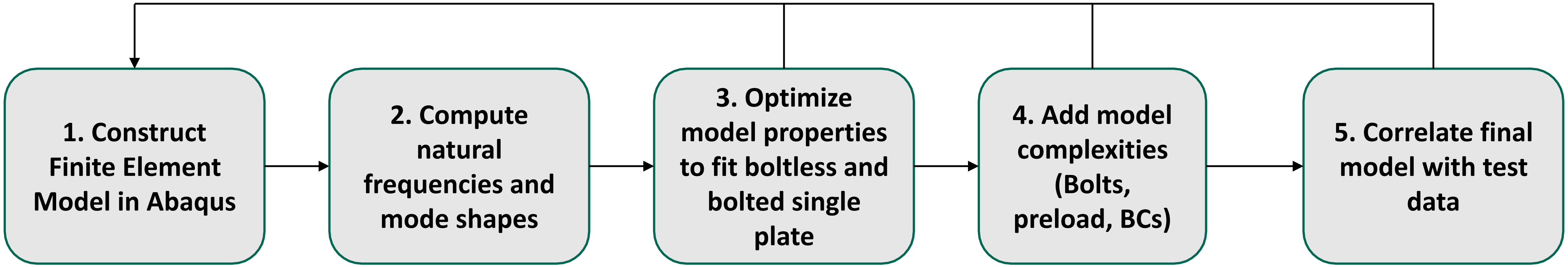
Averaged Frequency Response Function (FRF)
(Configuration 5, Bolt Pattern 3, 25 in-lb Bolt Preload, Low Impact Amplitude)



Natural Frequencies over all 32 tests for 1st four modes plotted on a PivotChart in Excel



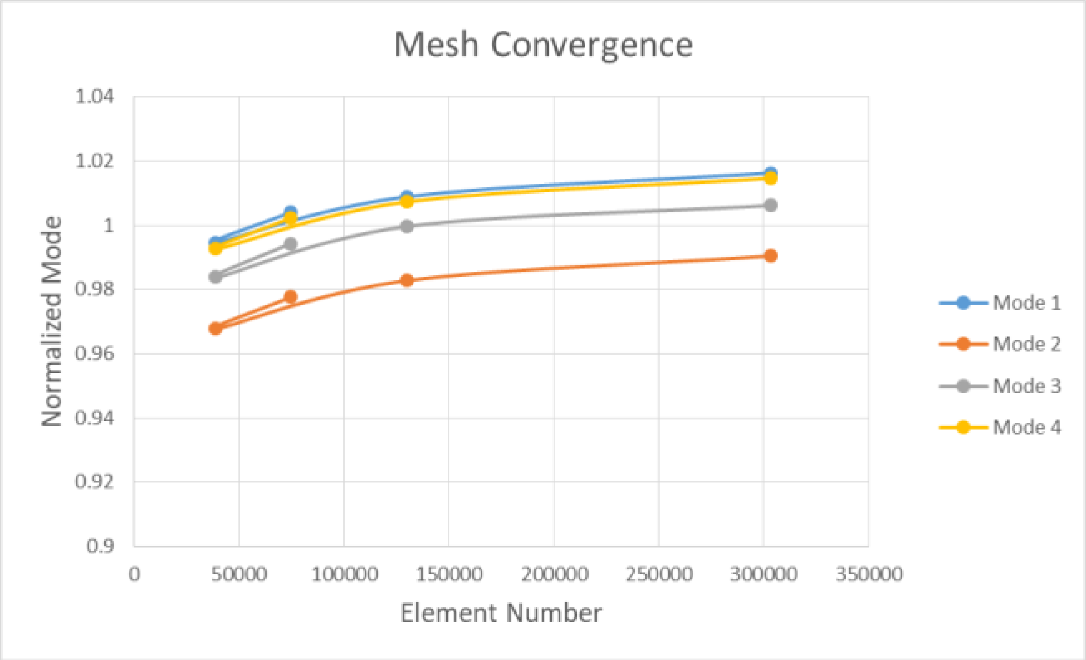
Finite Element (FE) Modeling Process



- Bolted plate system modeled in Abaqus
- Frequency and Modal Dynamics steps in Abaqus Standard used during analysis
- Material property values reflect model properties after Step 3

	Aluminum (Plate)	Steel (Bolts)
Elastic Modulus $\left(\frac{lb}{in^2}\right)$	10^7	$2.8 * 10^7$
Density $\left(\frac{lb}{in^3}\right)$	0.093	0.28
Poisson’s Ratio	0.33	0.29

- Convergence study resulted in use of 300k elements (0.1 global mesh size)

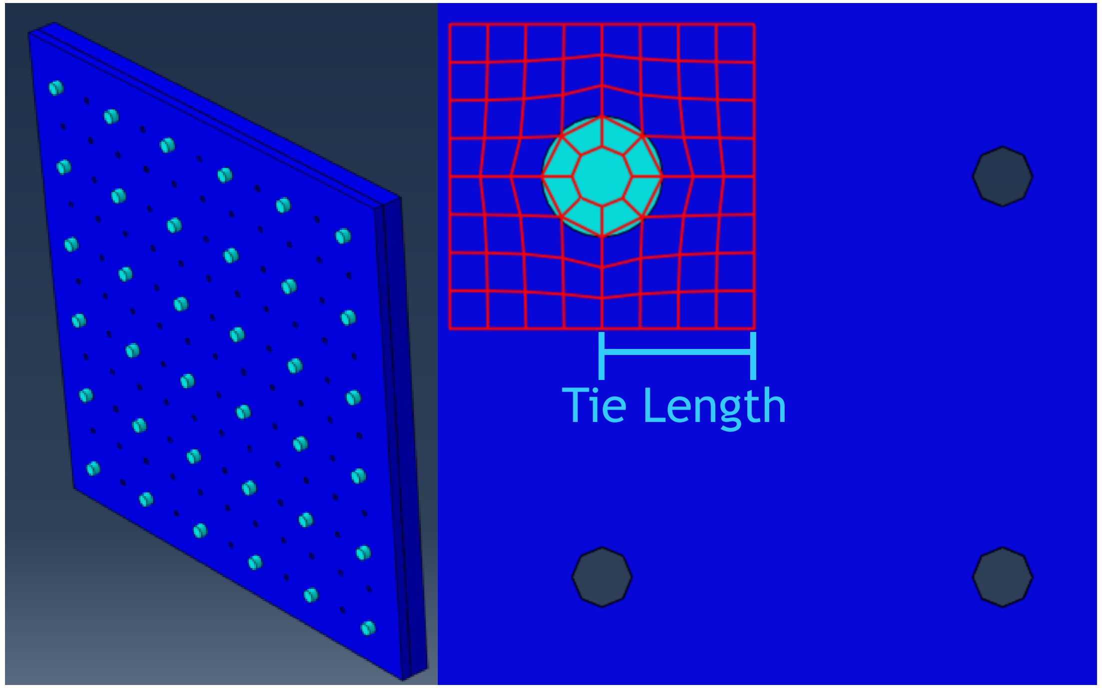


Bolt Constraints and Connections

Tie constraints

- Square partitions tie bolt heads to plate as well as adjacent plates together
- Tie area varied between configurations to assure frequency match

Configuration	3	4	5	6
Tie Length (in)	0.38	0.4	0.8	1

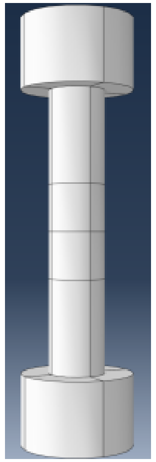


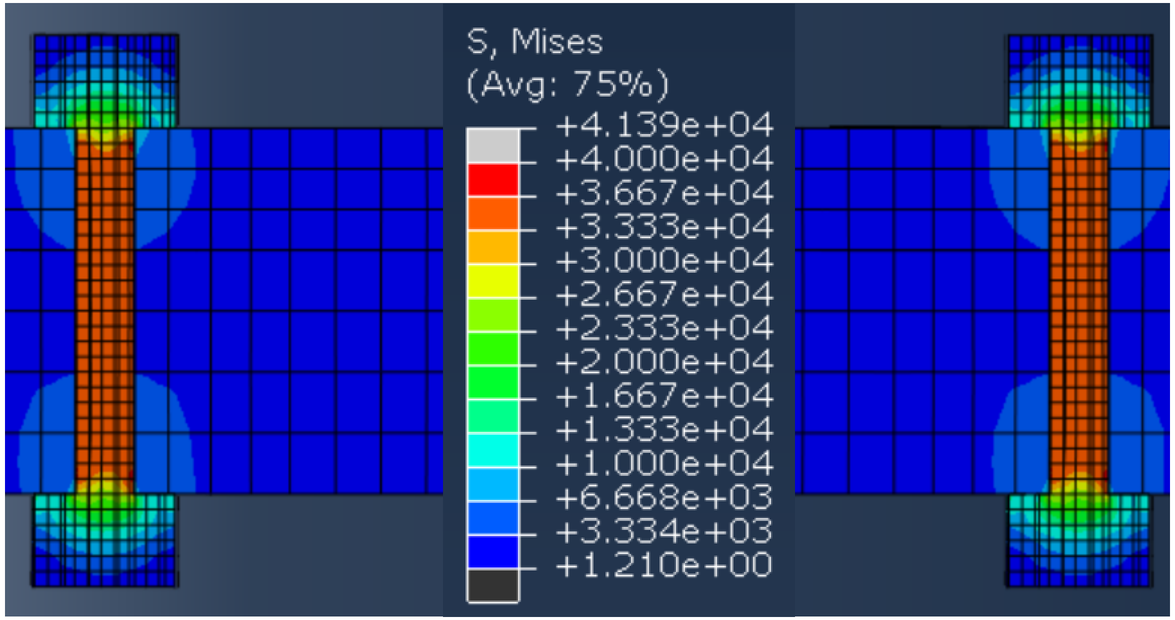
Bolted Connections:

- Simplified, symmetric bolt used in analysis
- Preload (T) related to clamping force (F) via:

$$F = \frac{T}{K_i * d} \quad [5]$$

- Preload validation:
  - Symmetric stress profile obtained in FEA consistent with above formula after translation to force



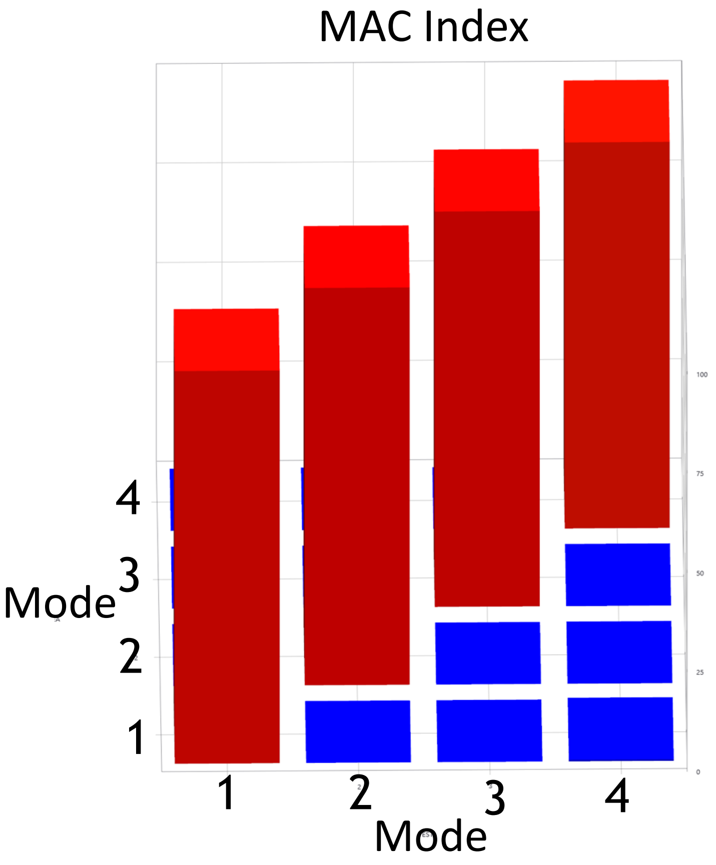


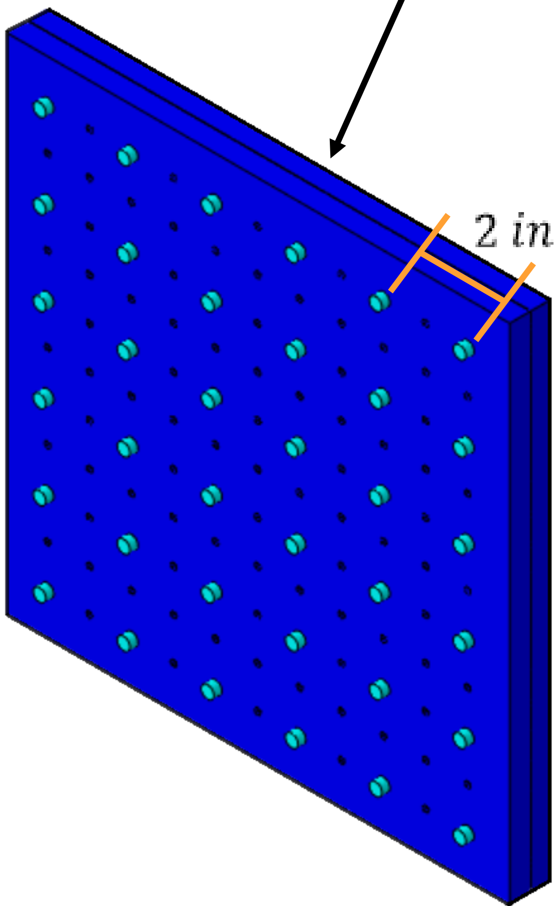
Modal Comparison between FE and Experimental

Configuration	Thickness (in)	Number of Interfaces
3	0.5	0
4	0.75	2
5	1	1
6	0.75	1

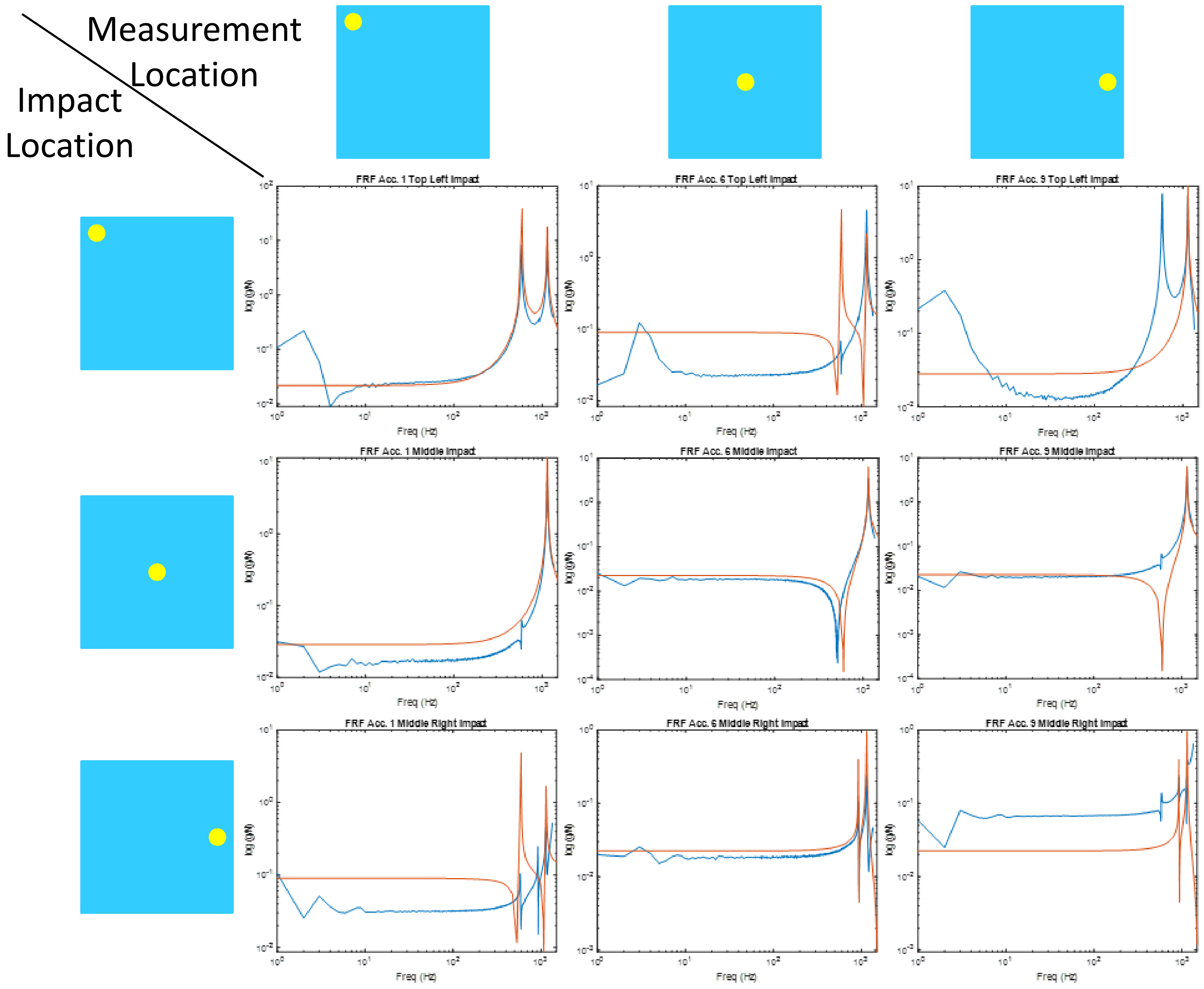
- Requisite change in density from $0.098\frac{lb}{in^3}$ to $0.093\frac{lb}{in^3}$ (-5.1%)
- Configuration used for material property calibration
- Modal Assurance Criterion (MAC) values suffers dramatically at degenerate mode

Configuration	Mode	Percent Difference (%) FE vs Exp Natural Frequency	MAC (%)
3	1	0.464	99.5
4	1	1.95	99.7
5	1	-0.81	98.7
6	1	1.13	99.1
3	2	-2.239	99.9
4	2	1.13	99.9
5	2	-2.08	100
6	2	-1.21	99.8
3	3	-0.564	99.4
4	3	1.08	99.7
5	3	-1.14	99.5
6	3	0.07	99.6
3	4	0.228	12.8
4	4	1.45	63.3
5	4	-1.9	84.5





Frequency Response Functions (FRFs)

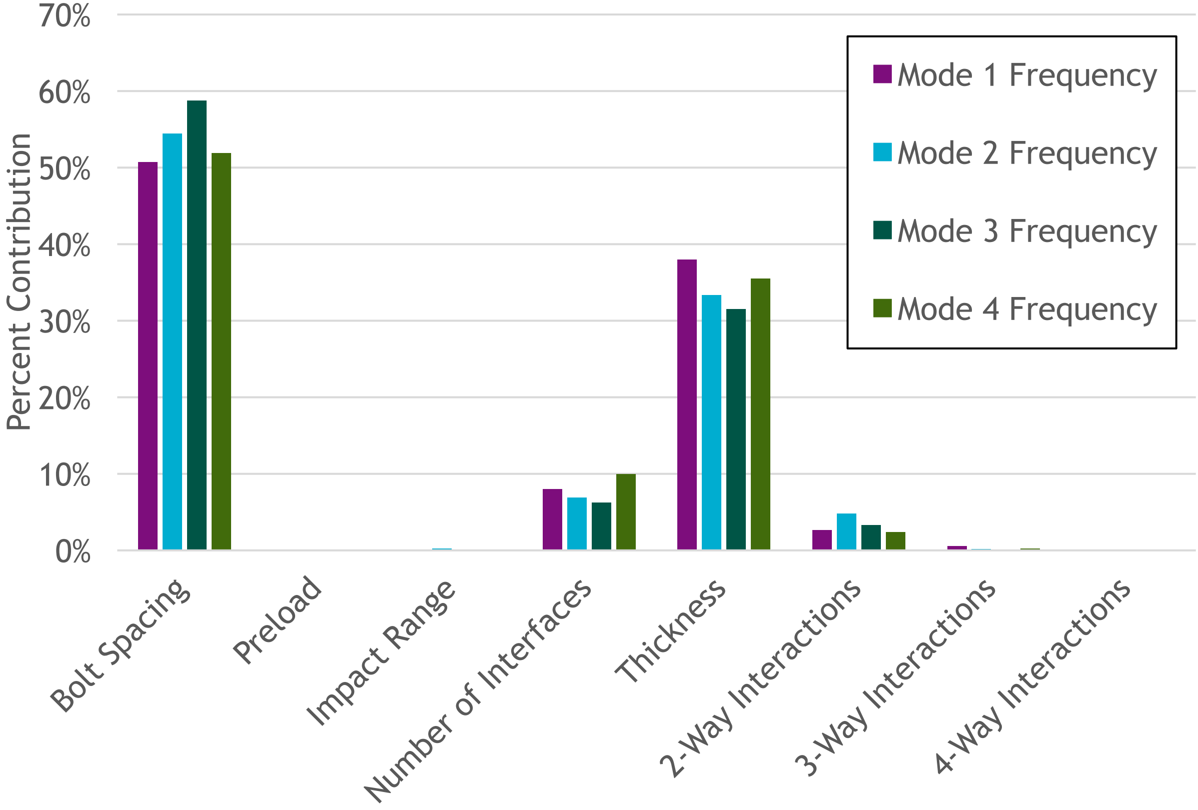


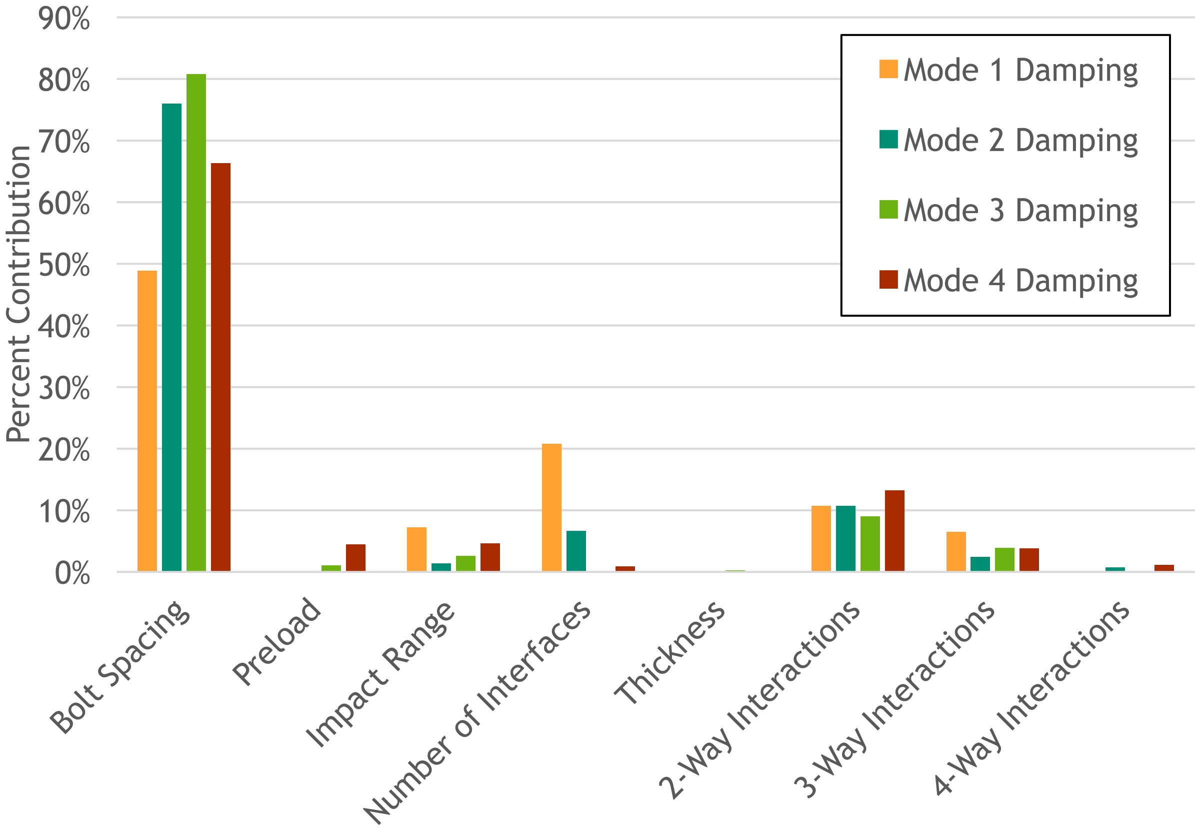
- Drive-point experimental FRFs matched in finite element by adjusting tie length on the bolt constraints
- Good agreement at natural frequencies
- Low fidelity at frequencies approaching zero (DC) as result of experimental set-up

Factor Importance

- Bolt preload and impact amplitude has negligible effect on frequency
- Thickness has minimal effect on damping
- Factor interactions much higher for damping than for frequency
- 2-way factor interactions not negligible for either indicator

	Frequency	Damping
Top Factors	Bolt Spacing	Bolt Spacing
	Thickness	Number of Interfaces
	Number of Interfaces	Bolt Preload

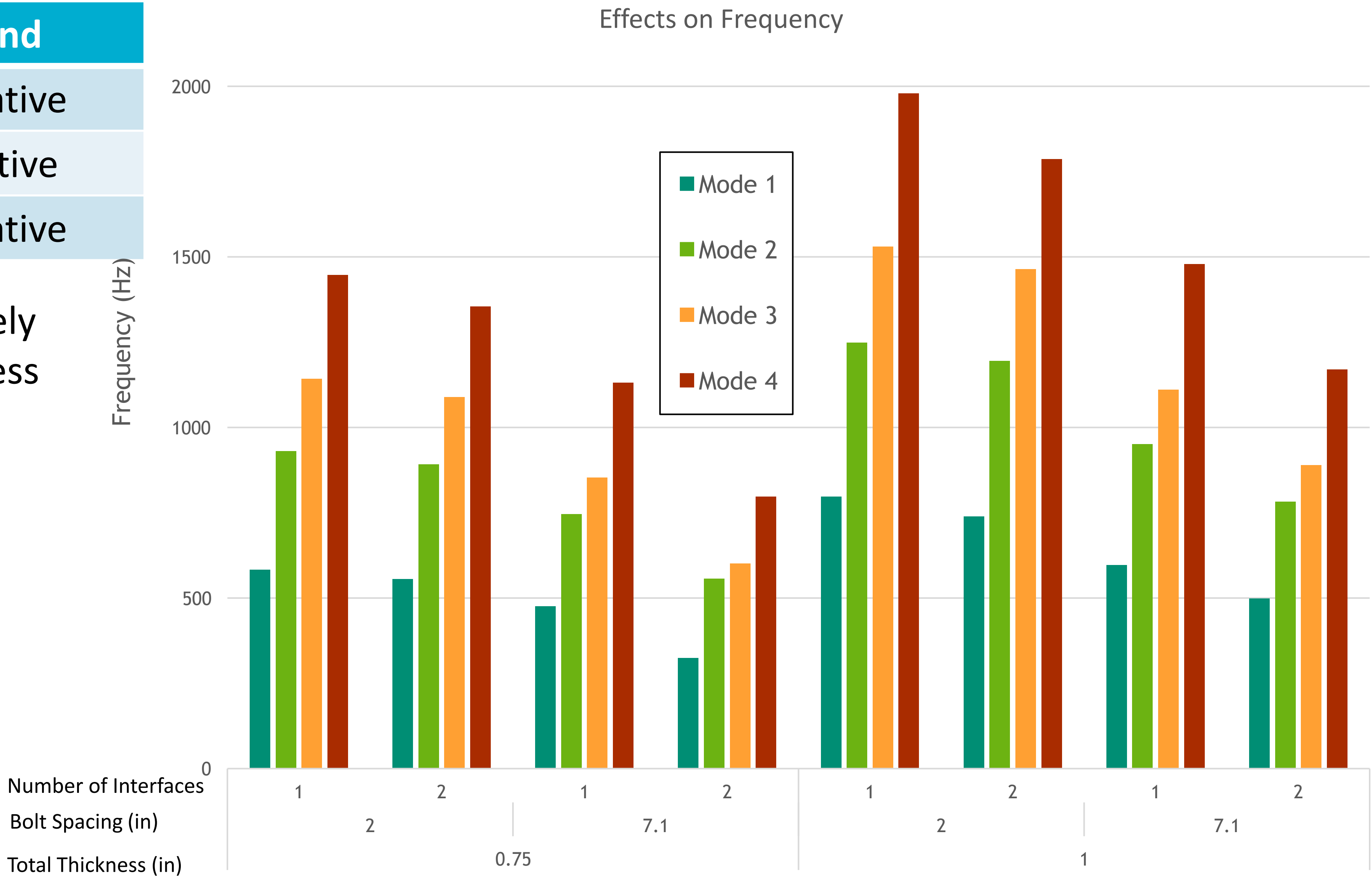




Factor Effects on Frequency

Factor	Trend
Bolt Spacing	Negative
Thickness	Positive
Number of Interfaces	Negative

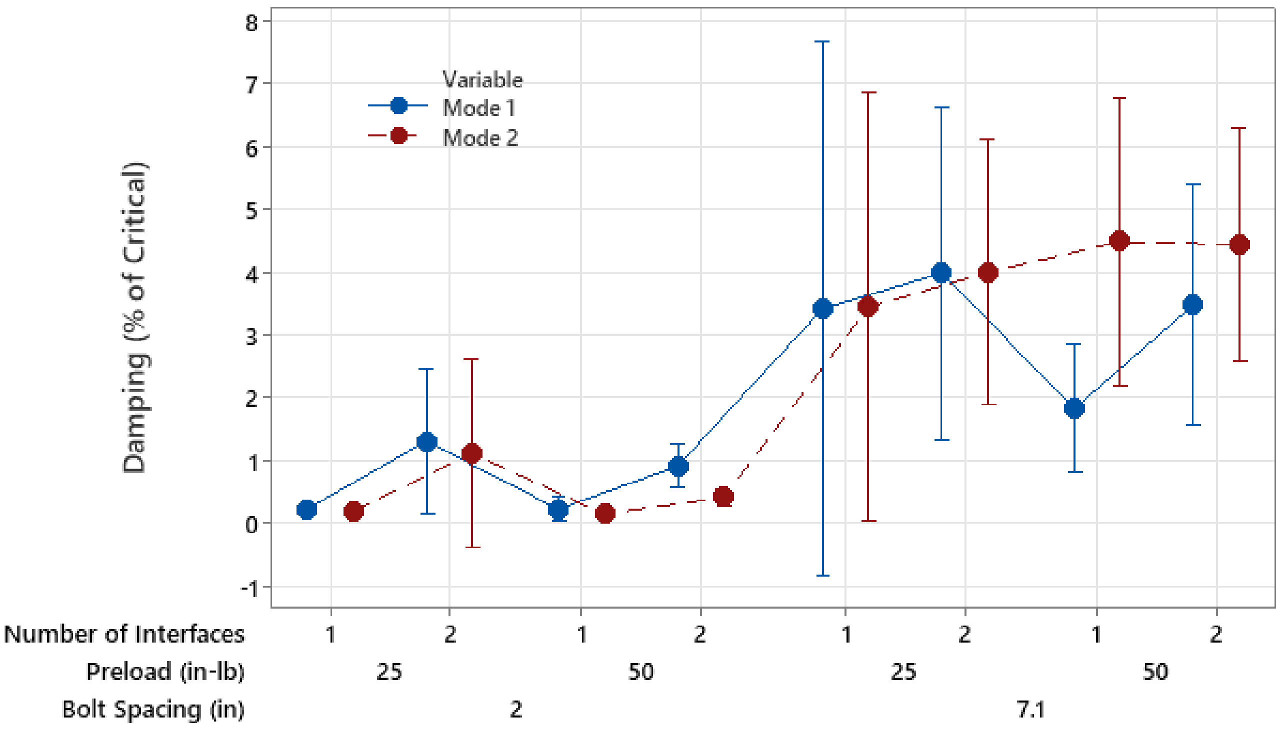
- Frequency shares approximately cubic relationship with thickness
- As bolt spacing increases, the bolted system becomes less coupled and less stiff
- More interfaces for the same thickness results in a less coupled system

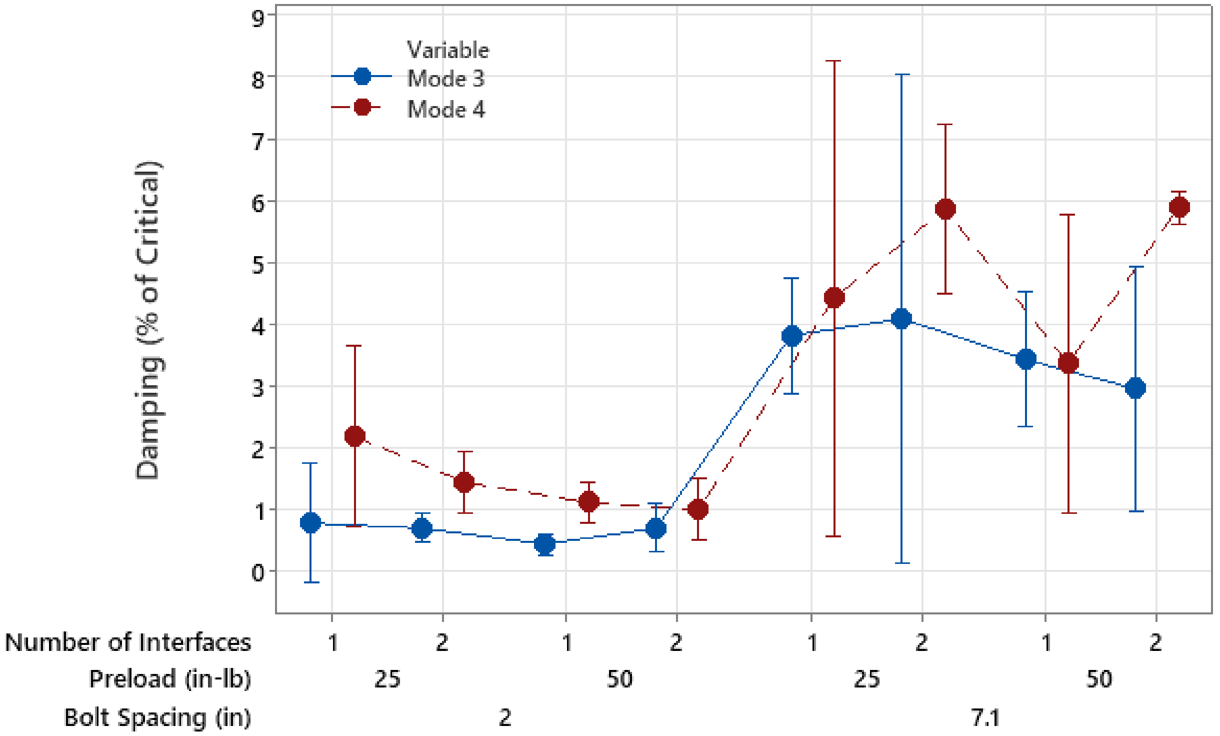


Factor Effects on Damping

- Variability in damping also correlates positively with bolt spacing
- Lack of clear trends indicate factor interactions likely play key role in damping
- Decreased coupling between plates introduces greater amounts of slip at the interfaces and thus greater damping

Factor	Trend
Bolt Spacing	Positive
Number of Interfaces	Positive
Bolt Preload	Negative





Summary

- Full factorial experimental design over 5 factors and 2 levels assessed the factor importance and effects on modal frequency and damping
- Bolt spacing is the most important factor in predicting both natural frequency and damping
- Factor interactions affect modal damping much more than it does the natural frequency
- Finite element and experimental mode shapes have good agreement for first three mode shapes using tie constraints as bolt connections but disagree at the first asymmetric mode

References

[1] W. Chen, X. Deng, Structural damping caused by micro-slip along frictional interfaces, International Journal of Mechanical Sciences, Volume 47, Issue 8, 2005, Pages 1191-1211, ISSN 0020-7403, https://doi.org/10.1016/j.ijmecsci.2005.04.005.

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[3] Ungar, Eric E., "Energy dissipation at structural joints; mechanisms and magnitudes", Technical Documentary Report No. FDL-TDR-64-98, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, 1964.

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Questions?