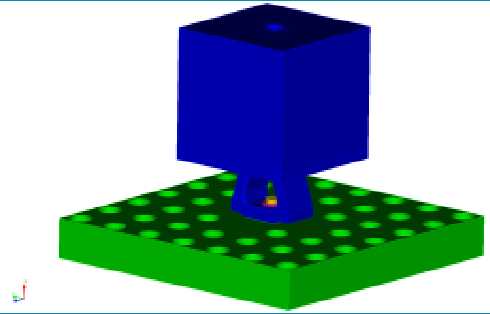
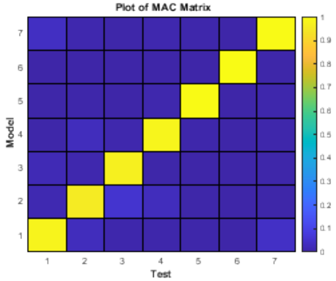
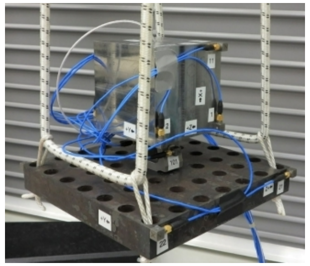
Sandia National Laboratories

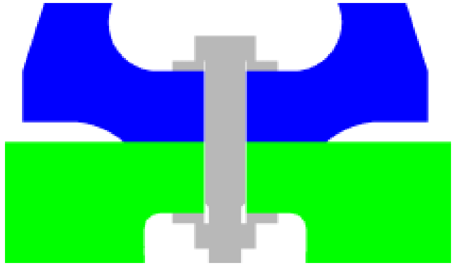
SAND2020-13875C

Evaluation of Joint Modeling Techniques Using Calibration and Fatigue Assessment of a Bolted Structure









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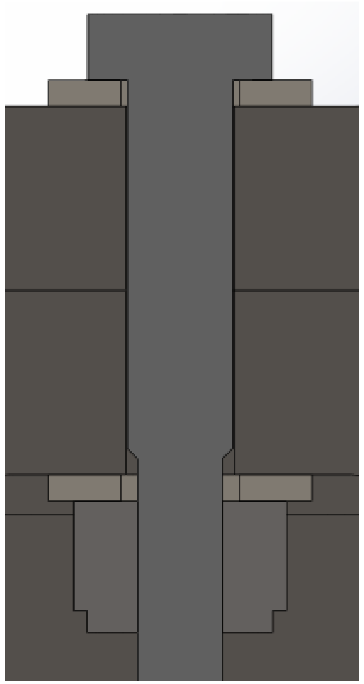
Outline

Abstract

- Calibrating a finite element model to test data is often required to accurately characterize a joint, predict its dynamic behavior, and determine fastener fatigue life
- In this work, modal testing, model calibration, and fatigue analysis are performed for a bolted structure and various joint modeling techniques are compared
  - Structure is designed to test a single bolt to fatigue failure using a modal shaker to axially force the bolted joint at resonance
  - Modal testing is done to obtain the dynamic properties, evaluate joint modeling techniques, and determine viability of the structure to perform fatigue testing of bolts
- Results show that common joint models can be inaccurate
  - Over-predicting bolt stiffness and load, even when updated using modal test data
  - Simple linear models alone may be insufficient in evaluating fatigue

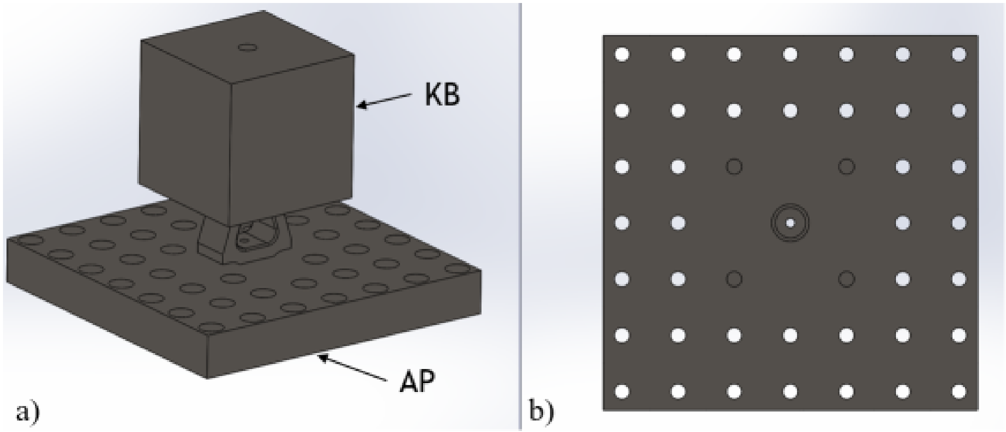
Introduction

- Bolted joints are a common assembly approach but are still a source of error in analytical structural models
  - Joint modeling technique depends on the application and QOI
- For dynamic loading cases, typically concerned with modal parameters, frequency response, and fatigue
  - Predicting failure requires accurate representation of bolt loading
- Experimental structure designed to fail a bolt in fatigue and with the following goals:
  - **Evaluate and improve joint modeling techniques**
  - **Enhance fatigue analysis**
  - **Advance testing capabilities**
- Testing and analysis performed to accomplish the above goals
  - Several joint models evaluated
  - Model updating and calibration to test data
  - Compared to analytical calculations from literature

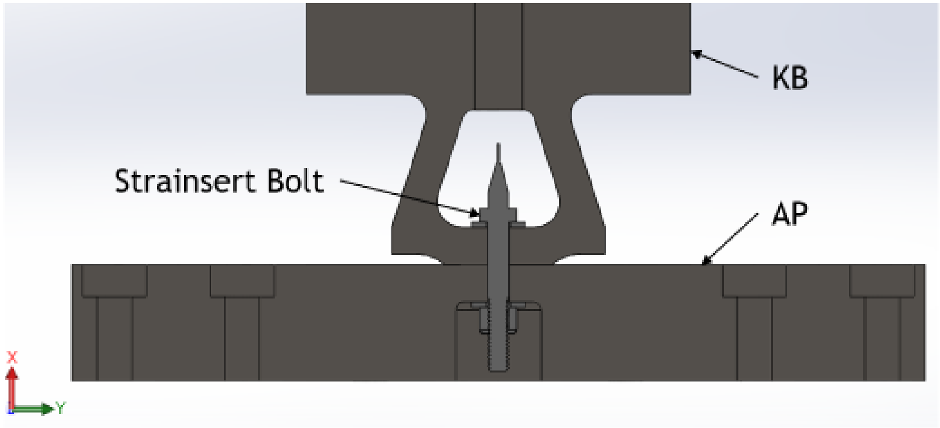


Hardware Description

- Two-part bolted structure is designed for use in model calibration and fatigue testing for a ¼ inch bolt
  - Kettlebell (KB), directly attaches to the Adapter Plate (AP), which has bolt pattern to attach to a seismic mass
  - Designed such that its axial mode imparts a large force on the bolt when driven with a modal shaker, ideally resulting in the bolt failing in fatigue

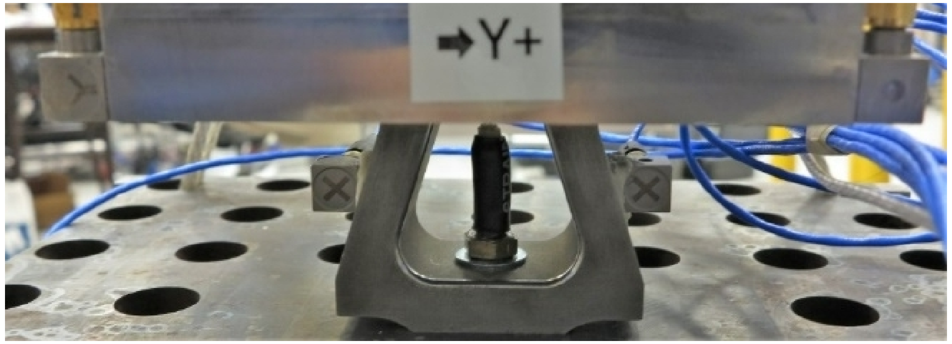


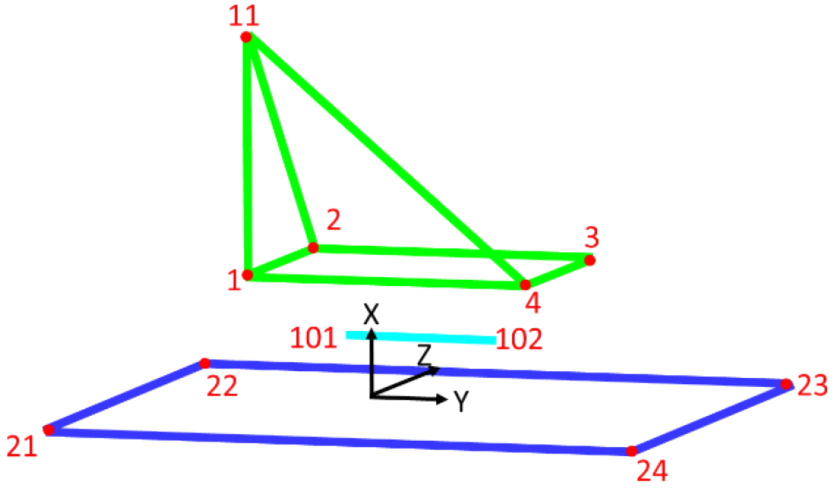
- Hardware
  - KB- 4340 Steel, 4.5" x 4.5" x 6.5", 26 lb_f
  - AP- 4340 Steel, 10" x 10" x 1.4", 35 lb_f
    - 0.875" grip length, equally split between KB and AP
  - ¼"-20 UNC Strainsert force-sensing bolt with strain gauge, 1.75" length and 0.875" shank
  - Standard SAE washers (0.65" diameter and 0.0625" thick)
  - Nylon-insert locknut



Experimental Data and Analysis

- Free-free and fixed base modal testing was done for the structure
  - Instrumented with 11 triaxial accelerometers
  - Strainsert bolt used to recorded preload and response data
- Test data used to characterize the structure and bolted joint
  - Used for calibrating the finite element model
  - Results compared with various joint modeling techniques





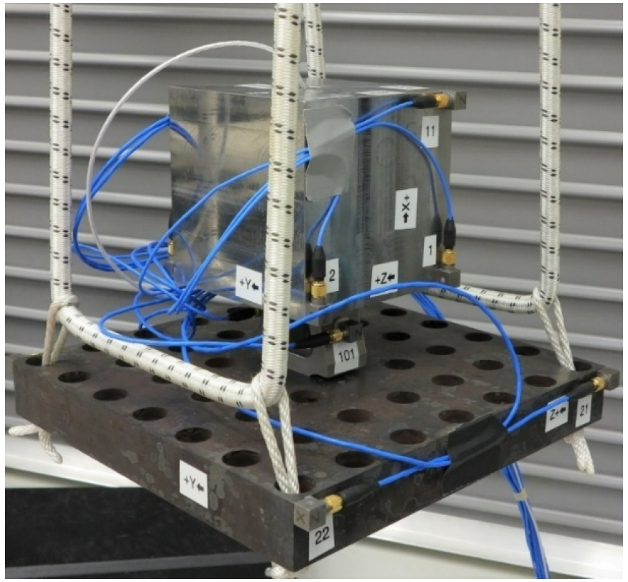
Instrumentation Locations (in.)

Accel Label	X	Y	Z
1	2.2	-2.45	-2.05
2	2.2	-2.45	2.05
3	2.2	2.45	2.05
4	2.2	2.45	-2.05
11	6.3	-2.45	-2.05
21	-0.2	-5.2	-4.8
22	-0.2	-5.2	4.8
23	-0.2	5.2	4.8
24	-0.2	5.2	-4.8
101	1	-1.3	0
102	1	1.3	0

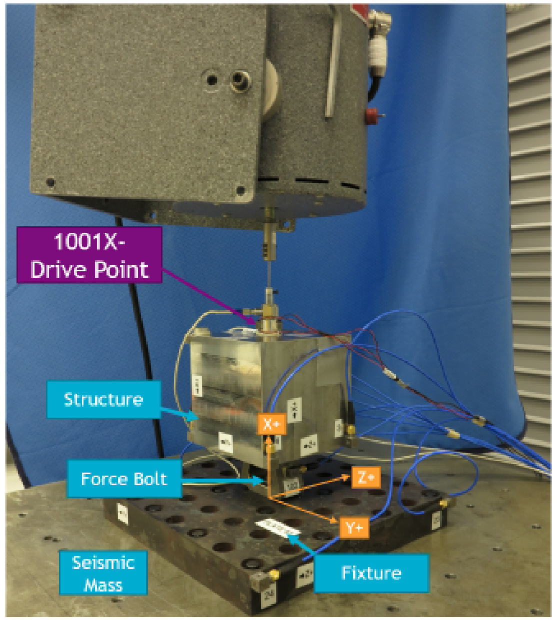
Modal Results

- Free-Free Testing
  - Initial testing was performed with a hammer input
    - Strainsert bolt preloaded to 144 in·lb_f (SAE grade 8 value)
  - Second set of free-free data was obtained with modal shaker
    - Strainsert bolt preloaded to 100 in·lb_f due to sensor limit
- Fixed-Base Testing
  - Assembly bolted to a seismic mass to approximate a fixed base BC
  - Strainsert bolt was preloaded to 100 in·lb_f

Free-Free Test Mode	Description	Frequency (Hz)	Damping (%)
1	1st Bending in Z	194	0.52
2	1st Bending in Y	356	0.40
3	Torsion about X	371	0.73
4	2nd Bending in Y	1202	0.06
5	Axial in X	1307	0.21
6	Plate Twist	1517	0.33
7	2nd Bending in Z	1566	0.16

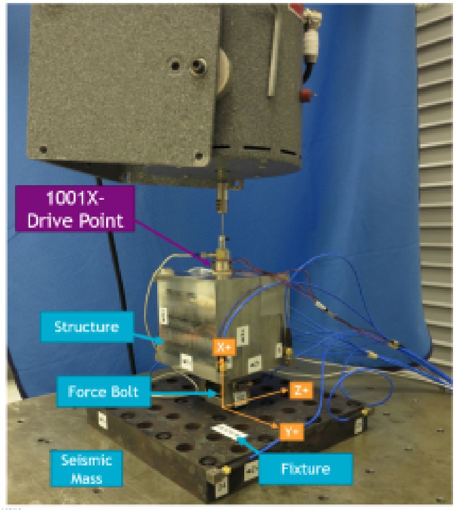


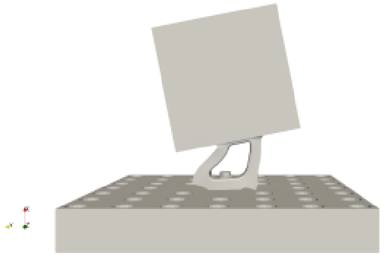
Fixed Base Test Mode	Description	Frequency (Hz)	Damping (%)
1	1st Bending in Z	101	8.61
2	1st Bending in Y	189	9.38
3	Torsion about X	339	0.12
4	2nd Bending in Y	1137	0.14
5	Axial in X	1254	2.42
6	2nd Bending in Z	1512	1.82



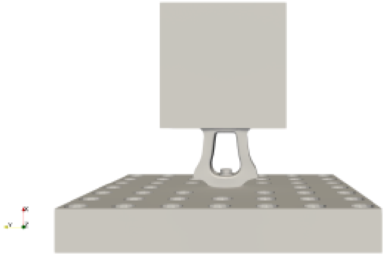
Additional Fixed Base Testing and Analysis

- One objective is to fail a bolt in fatigue by dwelling the axial mode
  - Expect frequency to shift due to joint nonlinearities
  - Additional fixed base testing done to study axial mode
- Preliminary characterization was conducted using a series of band-limited random excitation for fixed base BC
  - Excitation Bandwidth: 850 Hz to 1650 Hz
  - RMS force levels applied: 0.14 to 17.99 lbf RMS
- Imaginary drive point FRF studied
  - As force level increased, axial mode near 1250 Hz shifte to the 2nd bending mode in Y near 1130 Hz
  - Damping initially increased with higher excitation then decreased around 5 lbf RMS
    - Atypical joint behavior
    - Reduction in damping results in a nearly 500% peak increase
- Potential mode coupling at the high force levels
  - Energy composition of modes used for further study

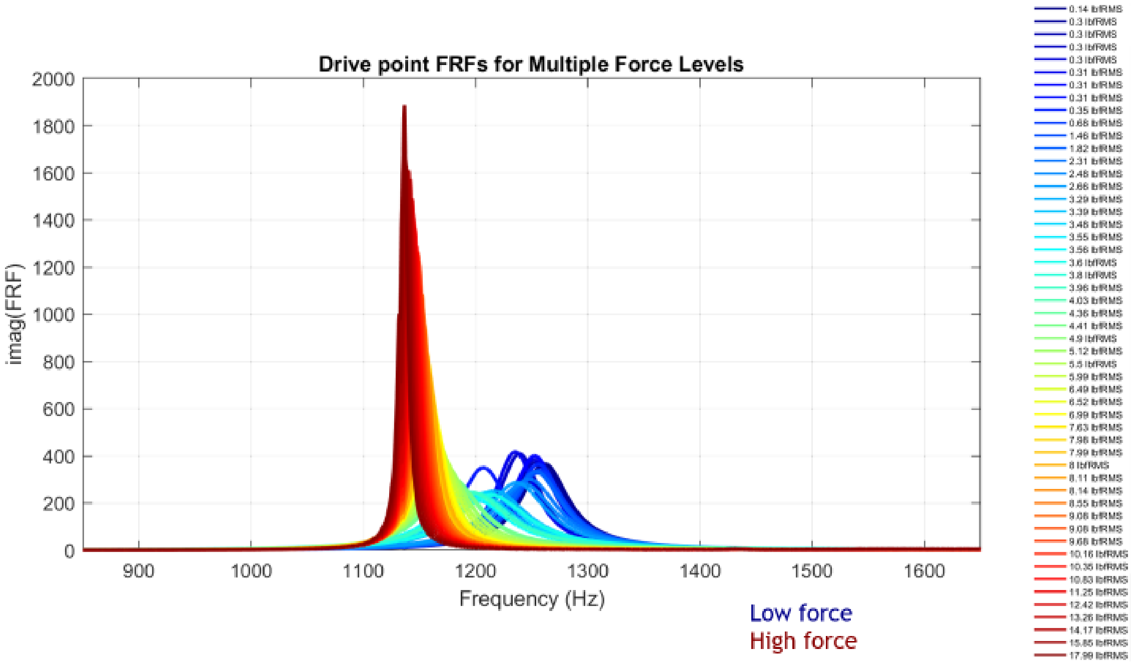




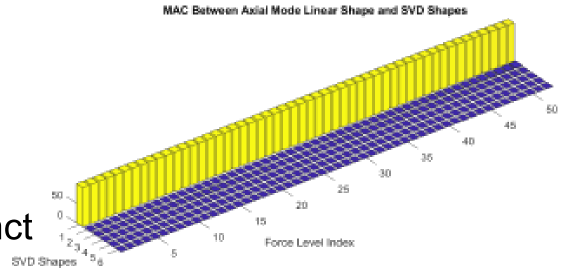
2nd Bending Mode

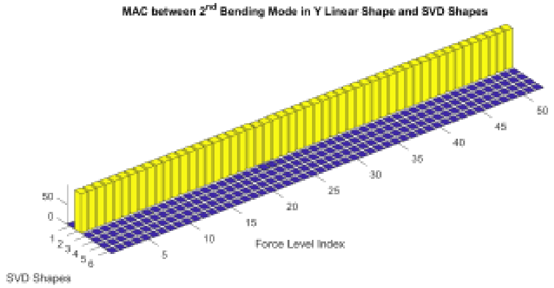


Axial Mode

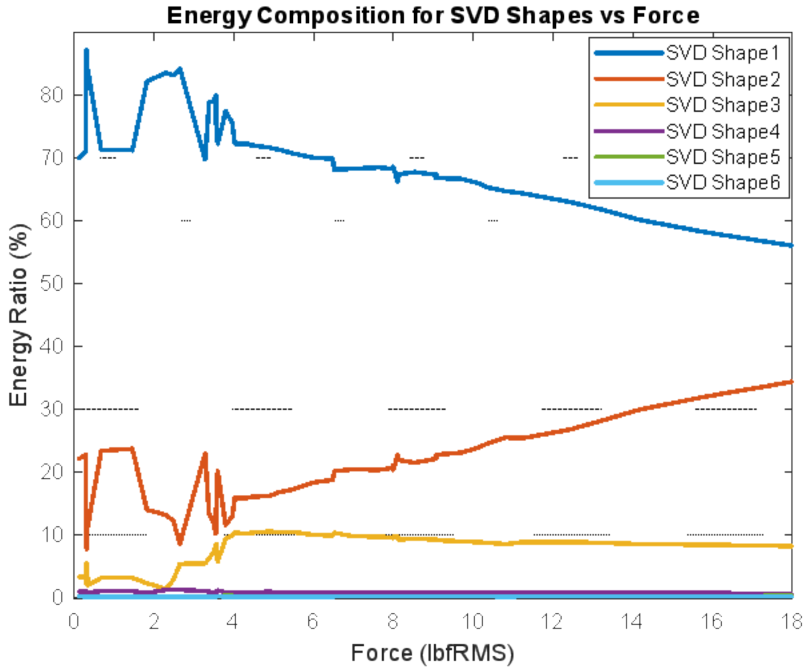


Additional Fixed Base Testing and Analysis





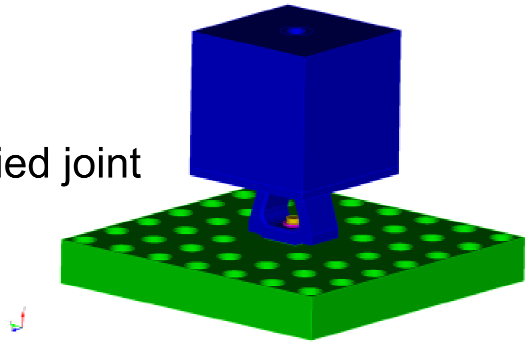
- Singular value decomposition (SVD) analysis was performed to evaluate modal coupling
  - Decomposed the measured FRFs, H, at each force level
  - SVD Shapes calculated: High MAC, two singular values remain distinct
- Energy contribution using SVD at each force level
  - Energy ratios r_i, defined for each singular value, σ_i
  - At low force levels, 75% of total due to axial mode and 15% 2nd bending mode in Y
  - As excitation force rises, 2nd bending mode increases to 35%, axial mode decreases to 55%
- Nonlinearity introduced by the bolted joint results in modal coupling
  - Decreased damping, increased excitation of the 2nd bending mode in Y
  - As the axial mode softens, the 2nd bending mode in Y is further excited and contributes more to the overall response
- Implications for fatigue testing
  - Multiaxial load with high lateral motion at increased force levels
  - Limits the viability of the structure to consistently test bolts to failure
  - There may be experimental methods to reduce lateral motion, but further research is needed

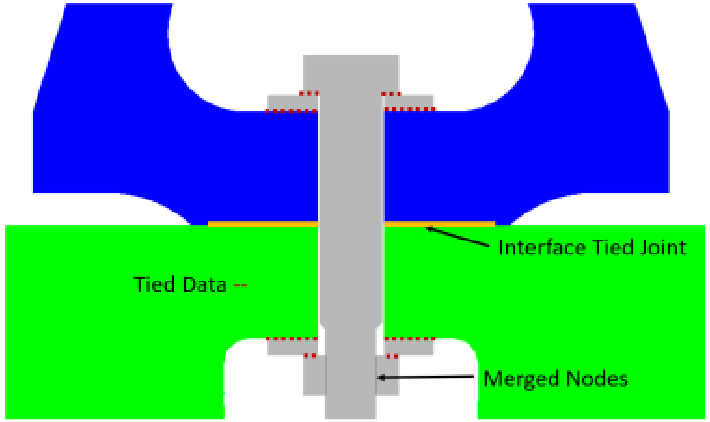


$$r_i = \frac{\sigma_i}{\sum_{i=1}^{N} \sigma_i}$$

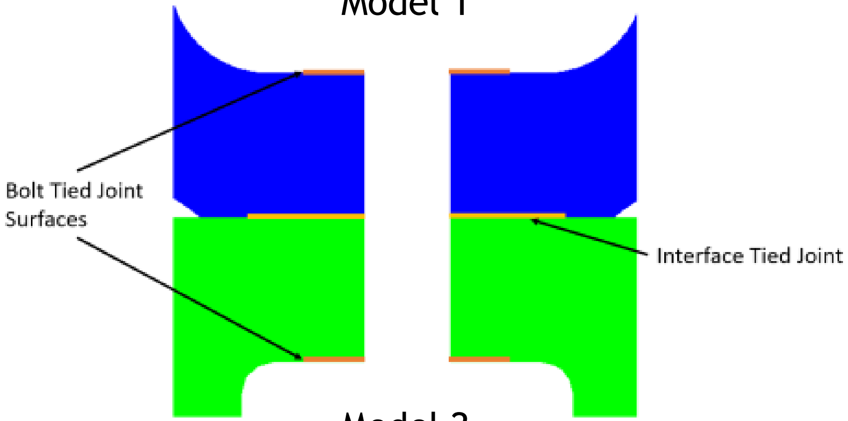
Structural Dynamic Modeling

- Four linear FE models created for the bolted joint
  - Varying fidelity meshes were created using CUBIT software
  - Preload is not included- spring elements used for bolt and member stiffness
- Model 1: Solid Bolt and Tied Joint Interface
  - Solid bolt with washers and a nut
  - Tied Data constraints for incident parts
  - Tied Joint virtual spring element
- Model 2: Tied Joint Bolt Interface
  - Replaced all solid bolt elements with additional tied joint
- Model 3: Single Tied Joint
  - Single Tied joint for entire joint
- Model 4: Tied Data
  - No bolt, only tied data for surfaces
- Models are typical for linear structural dynamics
  - Lack of frictional contact and preload, plus artificial rigidity at the interface
  - Spring elements only roughly approximate member and joint stiffness
  - Future work is needed to fully study preload effects

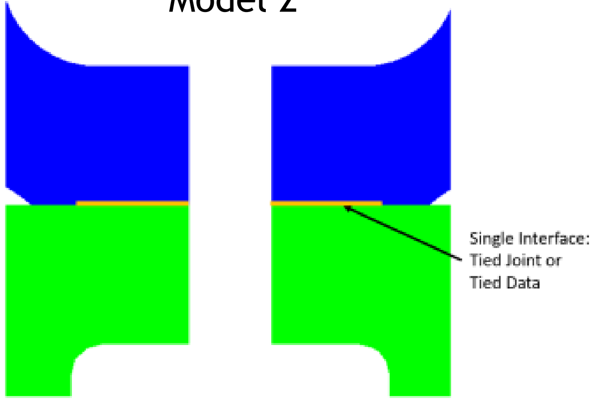




Model 1



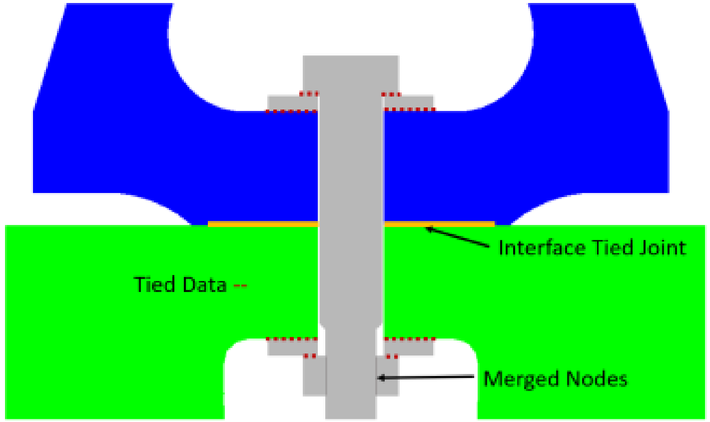
Model 2



Models 3, 4

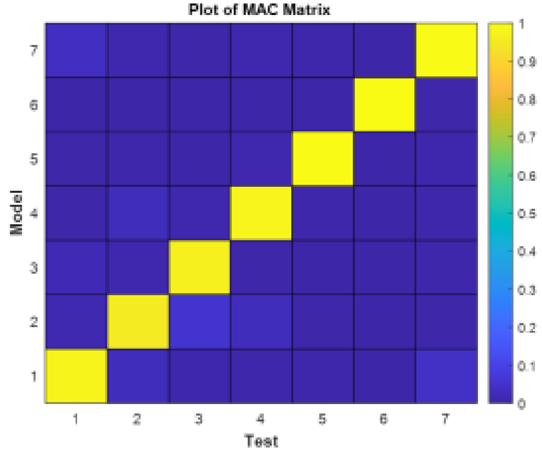
Model Updating

- Model calibration and updating done using test data and SIERRA/SD linear structural dynamics code
- After initial study, 1st set of free-free data used for the calibration
  - Adjusted interface diameter and joint stiffness
- Results matched well with the test
  - Lowest MAC value 0.96
  - Largest frequency error of 4.2%
- Fixed base mode shapes similar, except that the plate twisting mode 6 is not present since the AP is bolted to a seismic mass
- Future calibration efforts could include orthogonality checks



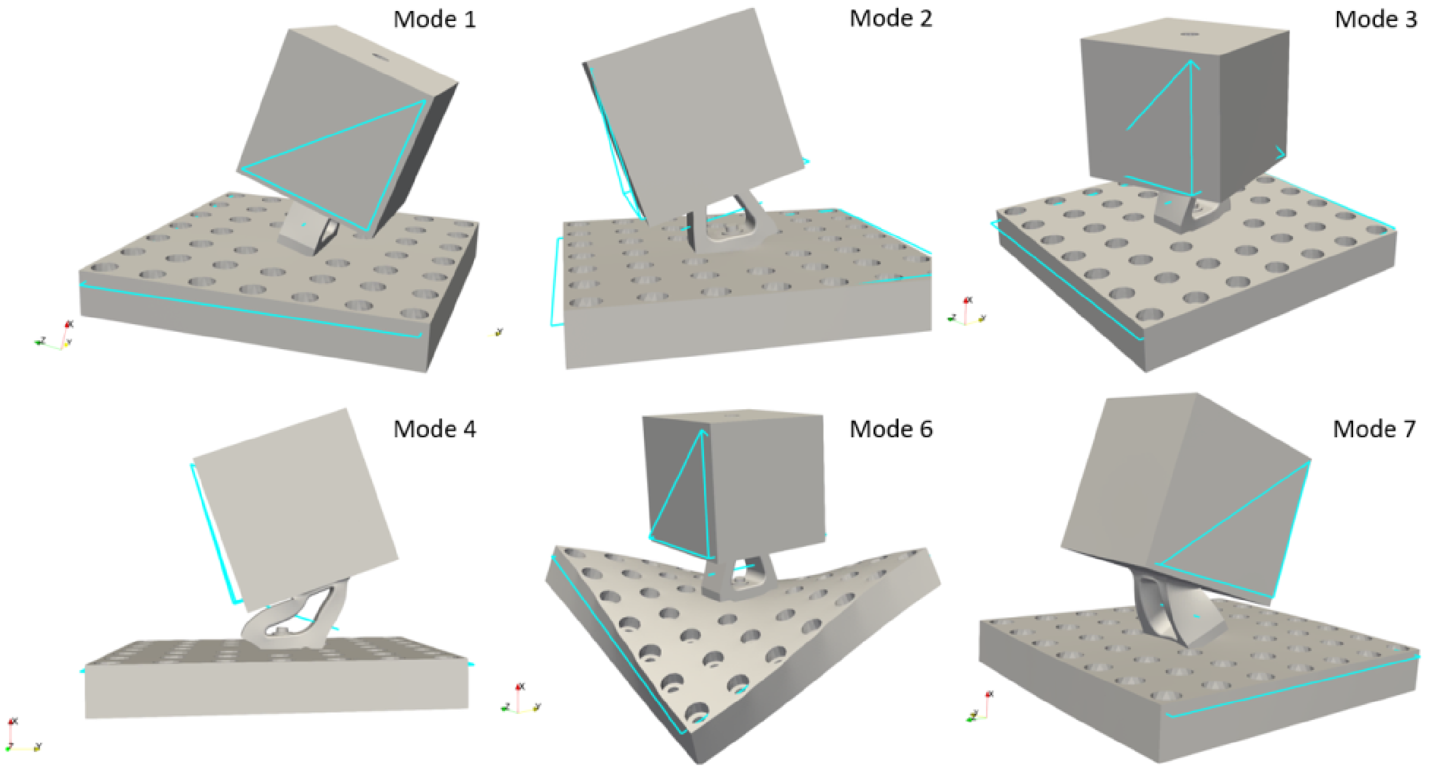
Model 1

Parameter	Initial Model 1a	Modified Model 1b	Units
k_x	6.13e6	5.00e7	lb_f/in
k_y	1.00e6	9.50e6	lb_f/in
k_z	1.00e6	9.50e6	lb_f/in
k_{rx}	1.00e7	5.0e6	in·lb_f/rad
k_{ry}	1.00e7	1.40e6	in·lb_f/rad
k_{rz}	1.00e7	1.00e8	in·lb_f/rad
Interface Contact Size	Full Surface (1.25 x 1.25)	1.125 (diameter)	in

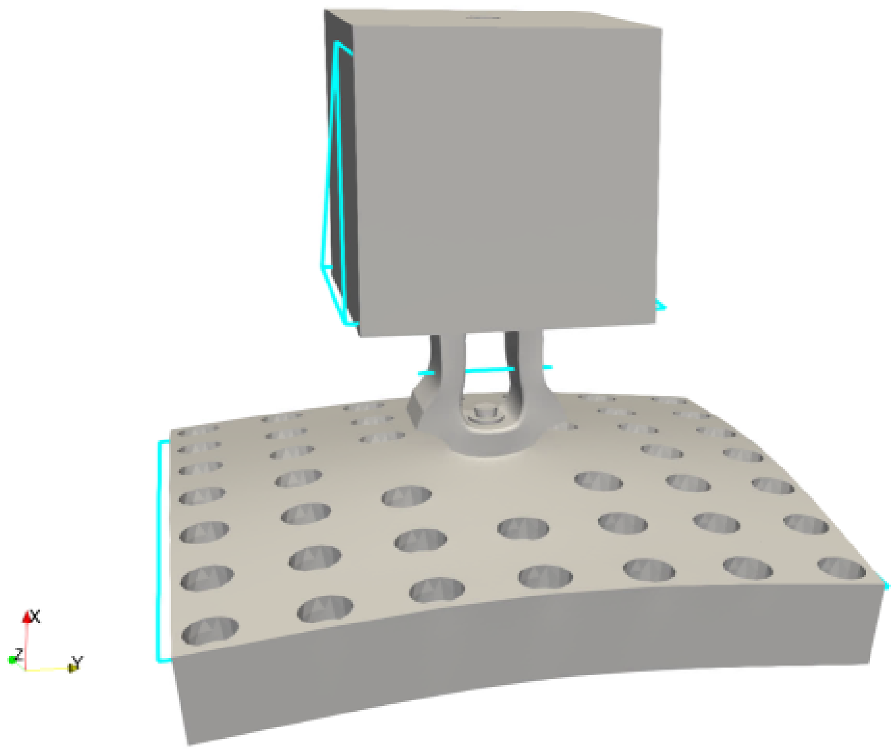


Test 1 Mode	Test 1 Freq (Hz)	Model 1b Mode	Model 1b Freq (Hz)	Freq Err %	MAC
1	193.6	1	201.5	4.1	0.982
2	356.4	2	371.0	4.1	0.958
3	371.2	3	382.4	3.0	0.972
4	1201.5	4	1183.3	-1.5	0.983
5	1307.3	5	1346.5	3.0	0.998
6	1517.2	6	1496.8	-1.3	0.999
7	1565.8	7	1500.4	-4.2	0.997

Test-Model Shape Comparison



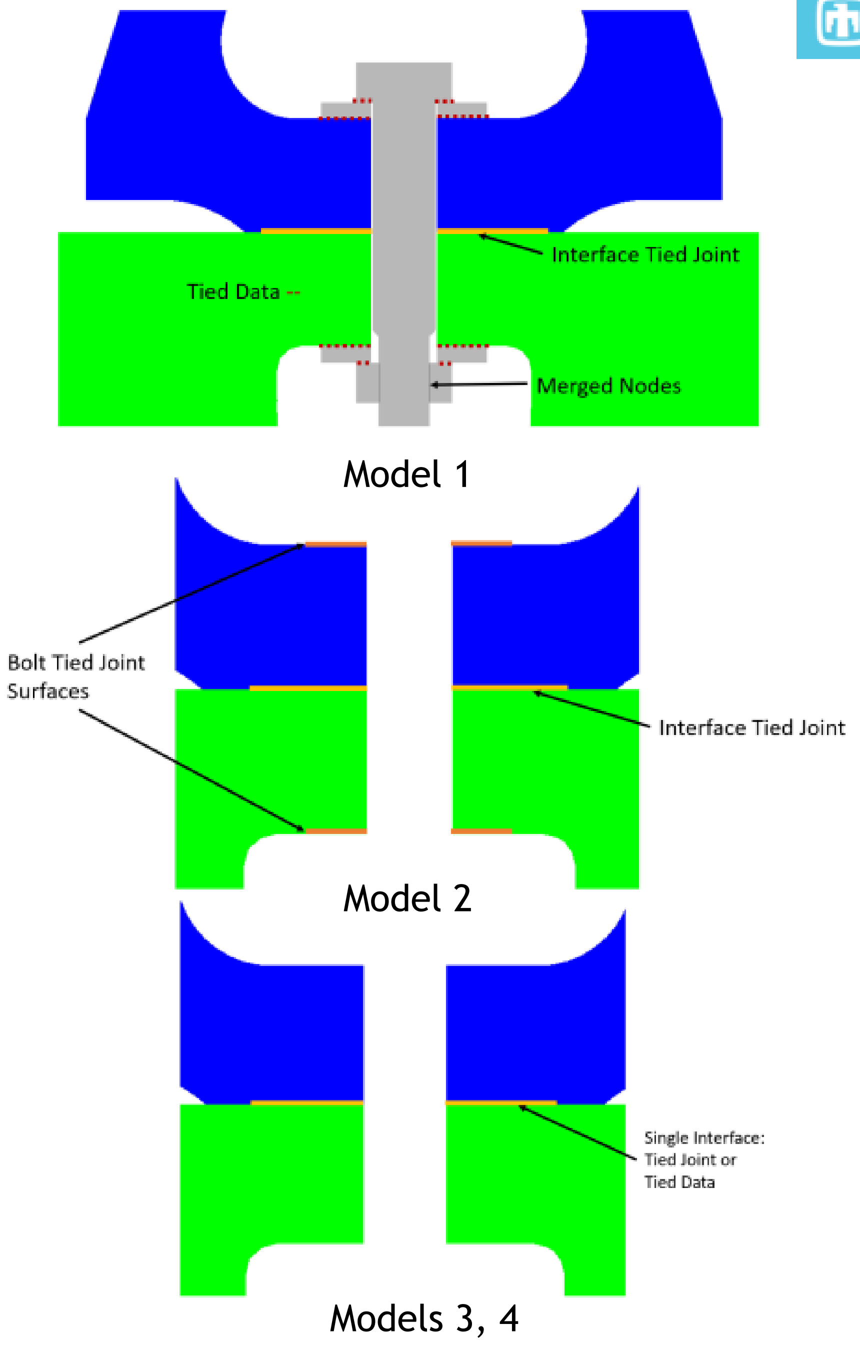
Mode 5- Axial



Model Updating

- Used free-free modal data and calibrated model to compare all joint models
  - Model 2b and 4b had larger error in modes 1 and 3
  - Model 3b matched best with the calibrated Model 1b and the test
- Results from the calibration study
  - Model 3 was almost identical to Model 1
  - Model 2 does not provide any additional advantages.
  - Model 4 is the least accurate in terms of frequency and lacks bolt
- **Single Tied Joint (Model 3) model is low-fidelity but accurate**
  - **Near identical dynamic behavior to detailed bolted joint, Model 1**
- Similar trends for fixed base comparisons
- Might expect this result since member stiffness dominates in typical joints
  - In cases where bolt force is important, such as vibration or fatigue analyses, these joint models may not be accurate

Model 1b			Model 2b			Model 3b			Model 4b		
Freq (Hz)	% Diff	MAC	Freq (Hz)	% Diff	MAC	Freq (Hz)	% Diff	MAC	Freq (Hz)	% Diff	MAC
201.5	4.1	0.982	221.3	14.3	0.981	201.3	4.0	0.982	255.5	32.0	0.978
371.0	4.1	0.958	373.7	4.9	0.958	370.7	4.1	0.958	362.2	1.6	0.957
382.4	3.0	0.972	401.9	8.3	0.971	382.2	3.0	0.972	427.8	15.2	0.970
1183.3	-1.5	0.983	1189.2	-1.0	0.983	1183.1	-1.5	0.983	1212.9	1.0	0.982
1346.5	3.0	0.998	1354.6	3.6	0.998	1343.4	3.0	0.998	1314.6	0.6	0.997
1496.8	-1.3	0.999	1496.9	-1.3	0.999	1496.8	-1.3	0.999	1491.8	-1.7	0.999
1500.4	-4.2	0.997	1529.4	-2.3	0.996	1500.0	-4.2	0.997	1675.6	7.0	0.986



Fatigue

- A calibrated joint model can be used for further analysis such as fatigue
  - Joint stiffness is important to accurately calculate bolt load
- For constant amplitude cyclic loading in time domain, simple guideline is to compare endurance strength, S_e
  - Literature for the bolt gives S_e^b values under 10% of S_{ut}
  - To obtain S_e^S For the structure, modification factors can be applied
- Can calculate safety fatigue safety factors using literature
- For axial loading, the external force is shared between the bolt and joint members
  - Need **Joint Stiffness Constant, C,** which indicates the portion of the load taken by the bolt
- An accurate value for C is needed to determine the bolt factor of safety for cyclic loading
  - This parameter is important and the next section demonstrates how different FE joint modeling techniques can affect this stiffness constant

$$\sigma_m = \frac{C(P_{max} + P_{min})}{2A_t} + \frac{F_i}{A_t}$$

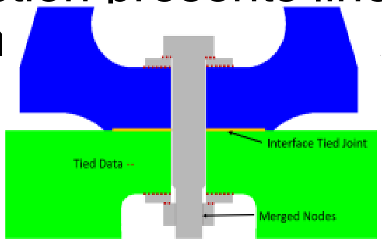
$$\sigma_a = \frac{C(P_{max} - P_{min})}{2A_t}$$

$$n_{f,bolt} = \frac{S_e^b(S_{ut}^b - \sigma_i)}{S_{ut}^b\sigma_a^f + S_e^b(\sigma_m^b - \sigma_i)}$$

$$n_{f,structure} = \left(\frac{\sigma_a^S}{S_e^S} + \frac{\sigma_m^S}{S_{ut}^S}\right)^{-1}$$

Joint Stiffness Analysis

- Analytical calculations from literature done to show how this stiffness factor C can vary depending on the joint model
- Additional linear structural analysis is done
  - Compare the natural frequencies using the calibrated and analytical joint stiffness
  - Stiffness values are calculated using literature
- The bolt stiffness can be calculated using a series of springs representing the shank and threaded portion
  - Bolt consists of series of springs (threaded and shank portion)
  - Members based on pressure cone/frustum approach
- The next section presents linear analysis of the bolted joint and con iffness constant and mode frequencies



Model 1

$$k_b = \frac{A_d A_t E}{A_d l_t + A_t l_d}$$

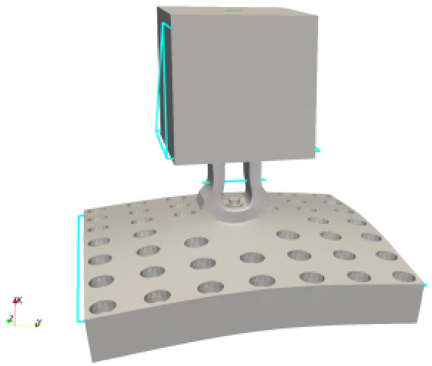
$$k_m = \frac{\pi E d \tan\alpha}{2\ln\left[\frac{(l\tan\alpha + d_w - d)(d_w + d)}{(l\tan\alpha + d_w + d)(d_w - d)}\right]}$$

$$C = \frac{k_b}{k_m + k_b}$$

Configuration	Joint Dimensions	Bolt Stiffness (lb_f/in)	Member Stiffness (lb_f/in)	Calculated Stiffness Constant, C
Partially Threaded Bolt	l_d = 0.875", l_t = 0.125"	1.33e6	6.13e6	0.179
Full Solid Shank	l_d = 0.875", l_d = 0	1.63e6	6.41e6	0.202

Joint Stiffness Analysis with SIERRA/SD

- Additional free-free modal analysis was performed on Model 1b
  - Updated Tied Joint stiffness
  - Evaluated change in axial mode frequency
  - Resulting change in C value
- Calibrated model had 10x larger stiffness than analytical calculations
  - Frequency 200 Hz lower using analytical joint stiffness
  - Factor of 5 change
- Calibrated SD model does not imply fastener or load transfer in the joint is necessarily accurate
  - Correct value not apparent since the linear models do not account for important factors such as preload or contact
- Can further study joint stiffness with nonlinear analysis
  - Includes the effects of frictional contact and preload



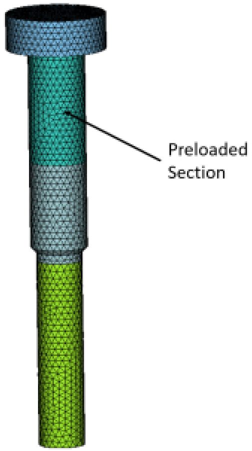
$$C = \frac{k_b}{k_m + k_b}$$

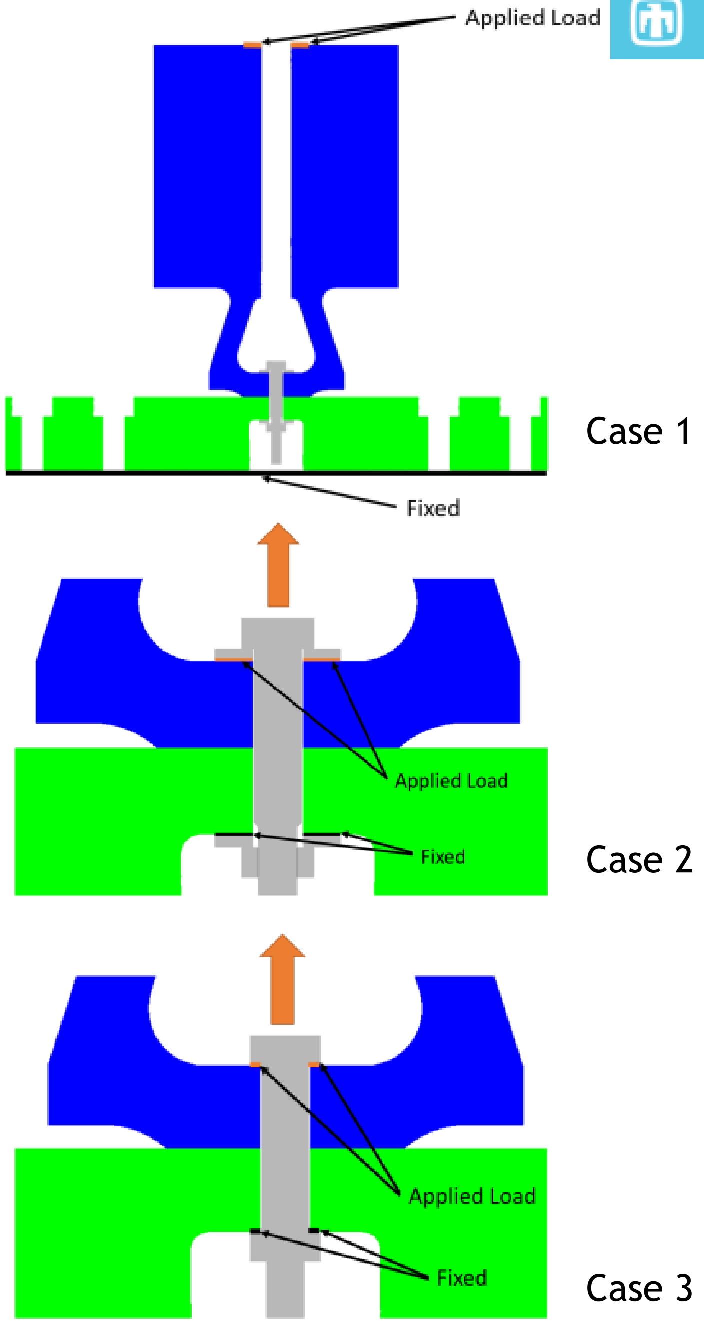
Configuration	Joint Dimensions	Bolt Stiffness (lb_f/in)	Member Stiffness (lb_f/in)	Calculated Stiffness Constant, C
Partially Threaded Bolt	l_d = 0.875", l_t = 0.125"	1.33e6	6.13e6	0.179
Full Solid Shank	l_d = 0.875", l_d = 0	1.63e6	6.41e6	0.202

Model	Tied Joint Axial Stiffness (lb_f/in)	Approximate Stiffness Constant, C	Free-Free Axial Mode Frequency (Hz)
Calibrated Model 1b	5.00e7	0.03	1346
Model 1b Adjusted with Analytical Stiffness	6.13e6	0.179	1165

Joint Stiffness Analysis with SIERRA/SM

- SIERRA/SM nonlinear FE code used to evaluate joint
  - Implicit quasi-static solid mechanics modeling
  - Can investigate the joint and examine the accuracy of the linear structural dynamic models
- Three separate loading cases to evaluate nonlinearity, effect of loading planes, loading distance from bolt axis, and washer face diameter
  - Case 1: similar to laboratory loading case in fixed base testing
  - Case 2: moved load to washer surfaces
  - Case 3: simplified joint with inward load
- Parameters
  - General normal contact with coulomb friction
    - Coefficient of friction of 0.3 was used
  - Preload was applied to a portion of the bolt shank using artificial strain
    - Torque for SAE Grade 5 results in 2027.25 lbf preload, which was applied
  - Distributed load was linearly ramped up from 0 to 3000 lb_f to achieve joint separation
  - The internal bolt force and the interface contact force throughout the analysis was calculated





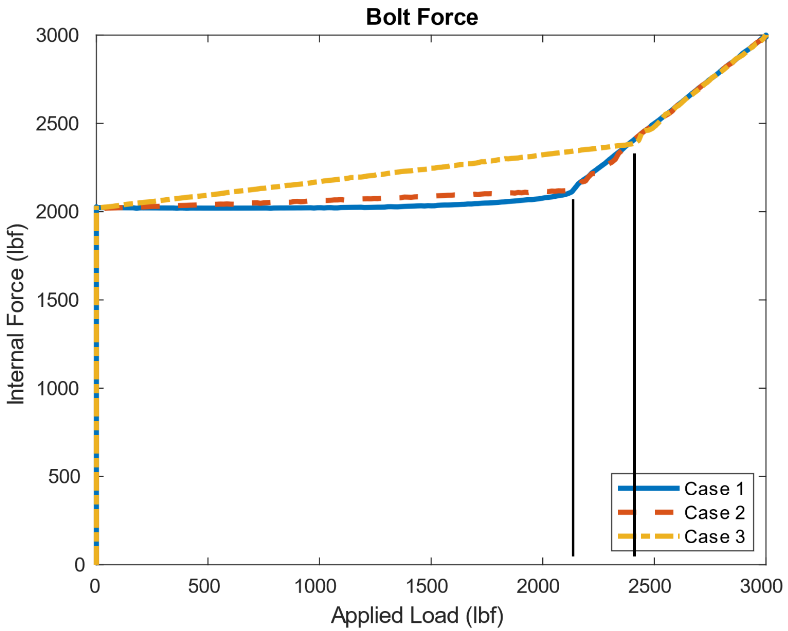
Joint Stiffness Analysis-SM

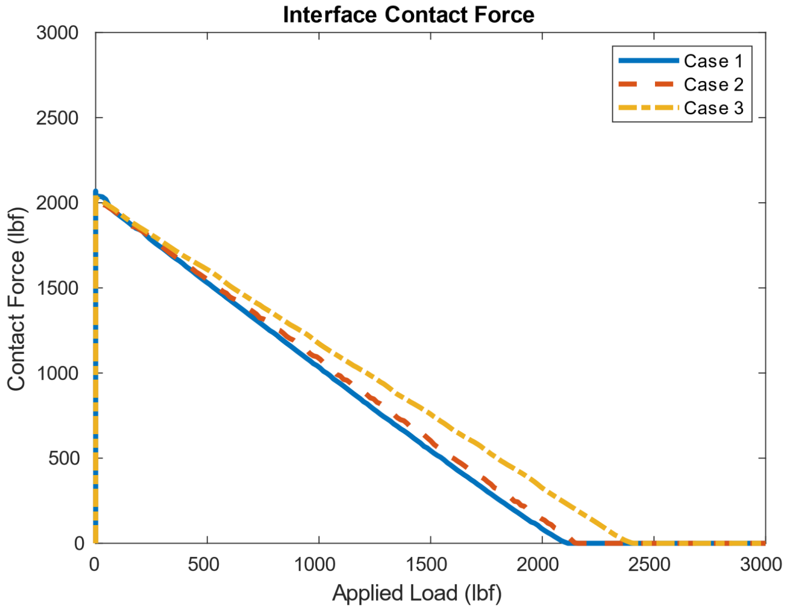
- Separation force, F_s, at the change in slope can be used to determine the equivalent stiffness and compare to theory
- Results show that stiffness constant can be highly variable, dependent on loading geometry
  - Case 1 has nearly constant bolt force until separation due to nonlinearity in joint gapping
  - Case 2,3 have linearly increasing bolt force before separation, but Case 2 has a lower slope
    - Washer face diameter has a large effect on the joint load behavior
- For basic fatigue calculations presented earlier, the stiffness constant and any stress calculations would not be accurate for this joint
- Even though the model was calibrated to modal test data, these results indicate that the fastener load behavior may not be properly represente
- Also effects joint design against separation
  - Could result in under-conservative calculations based on C and F_i

Model	Preload Value (lb_f)	Separation Load (lb_f)	Approximate Stiffness Constant, C
Case 1	2023	2103	0.038*
Case 2	2016	2135	0.056*
Shigley, (α = 30°)	2028	2470*	0.179
Shigley, (α = 33°)	2028	2435*	0.167
Case 3 (no washers)	2021	2403	0.159*
Shigley, no washers (α = 30°)	2028	2541*	0.202
Shigley, no washers (α = 33°)	2028	2503*	0.190

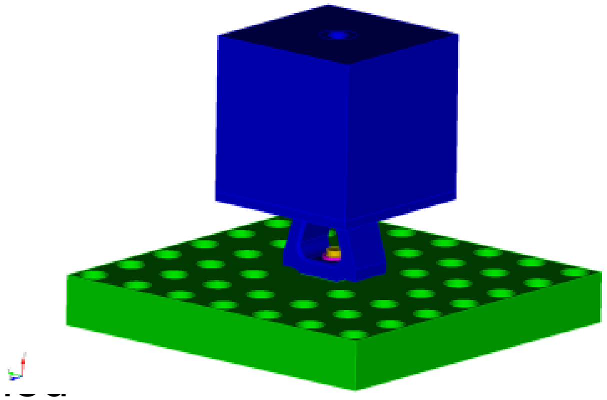
$$C = 1 - \frac{F_i}{F_s}$$

$$F_s = \frac{F_i}{1 - C}$$





Conclusion



- An experimental structure was designed with the following objectives:
  - Evaluate and improve joint modeling techniques
  - Enhance fatigue analysis
  - Advance testing capabilities
- Modal testing was conducted, FE analyses, and model calibration was performed
  - Tied Joint spring model was found to accurately represent joint dynamics with low model fidelity
- A brief fatigue study was presented and analytical calculations for joint stiffness were compared to the calibrated model and results from nonlinear FE analysis
  - Nonlinear effects as the joint is loaded causes constant bolt load until separation
  - Traditional equations and linear modeling techniques (without preload) can be inaccurate for fastener stiffness and loading behavior
  - Resulting fatigue calculations for joint design can be affected
- Fatigue testing using the designed structure was considered, but there were issues
  - Effect of nonlinearity on joint stiffness
  - Coupling of bending and axial mode
- Future work can evaluate unit to unit variability, further joint characterization, testing, and calibration

Acknowledgements

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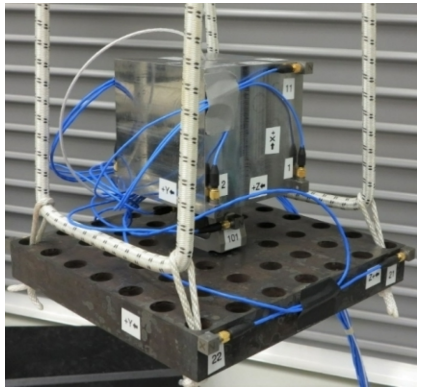
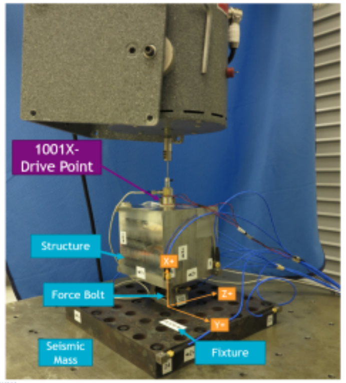
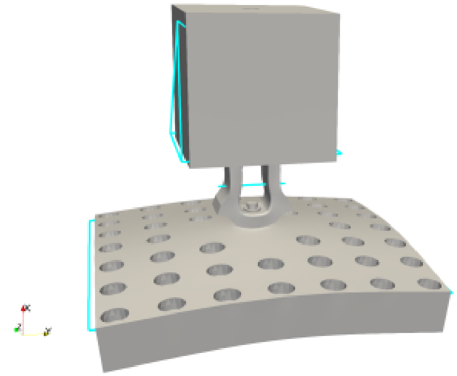
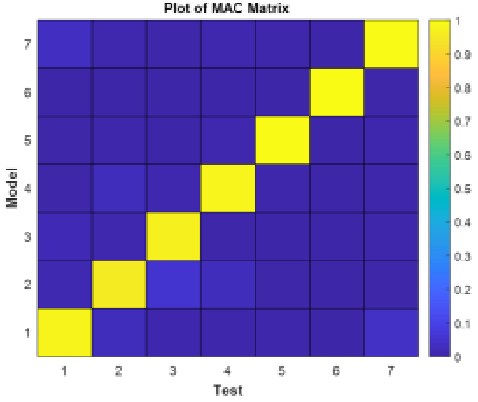
Summary

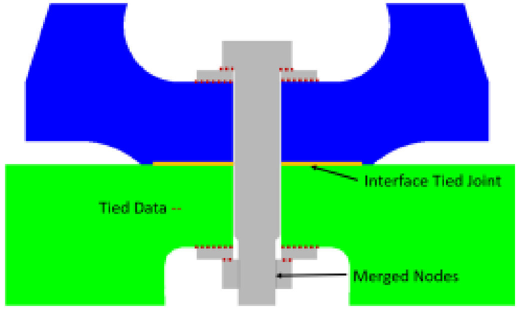
- An experimental structure was designed with the following objectives:
  - Evaluate and improve joint modeling techniques
  - Enhance fatigue analysis
  - Advance testing capabilities
- Modal testing was conducted, FE analyses, and model calibration was performed
  - Tied Joint spring model was found to accurately represent joint dynamics with low model fidelity
- A brief fatigue study was presented and analytical calculations for joint stiffness were compared to the calibrated model and results from nonlinear FE analysis
  - Nonlinear effects as the joint is loaded causes constant bolt load until separation
  - Traditional equations and linear modeling techniques can be inaccurate for fastener stiffness and loading behavior
  - Resulting fatigue calculations for joint design can be affected
- Fatigue testing using the designed structure was considered, but there were issues
  - Along with above points on joint stiffness and nonlinearity
  - Coupling of bending and axial mode
- Future work can evaluate unit to unit variability, further joint characterization, testing, and calibration











$$C = \frac{k_b}{k_m + k_b}$$