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N=O=MAD

Predictive Structural Dynamics Modeling of Bolted Interfaces

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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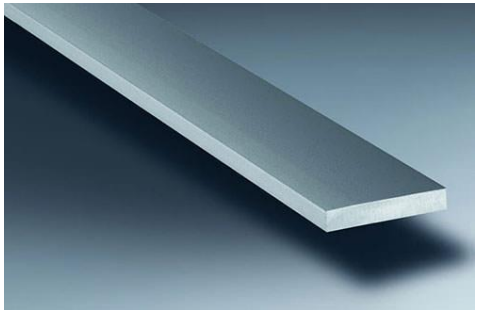
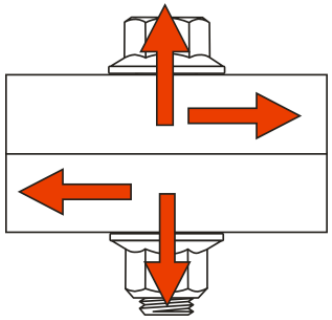
Structural dynamics on a single structure provide accurate results

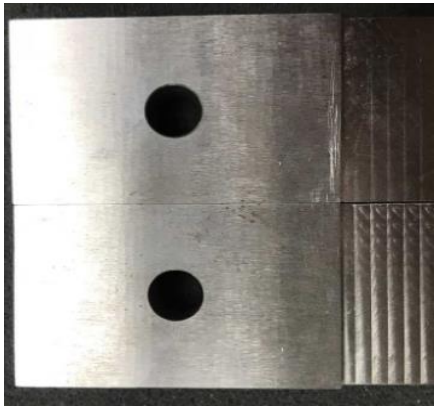


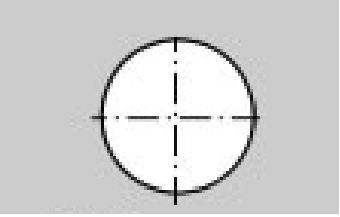
Single Structures

Many mechanical structures use bolted joints



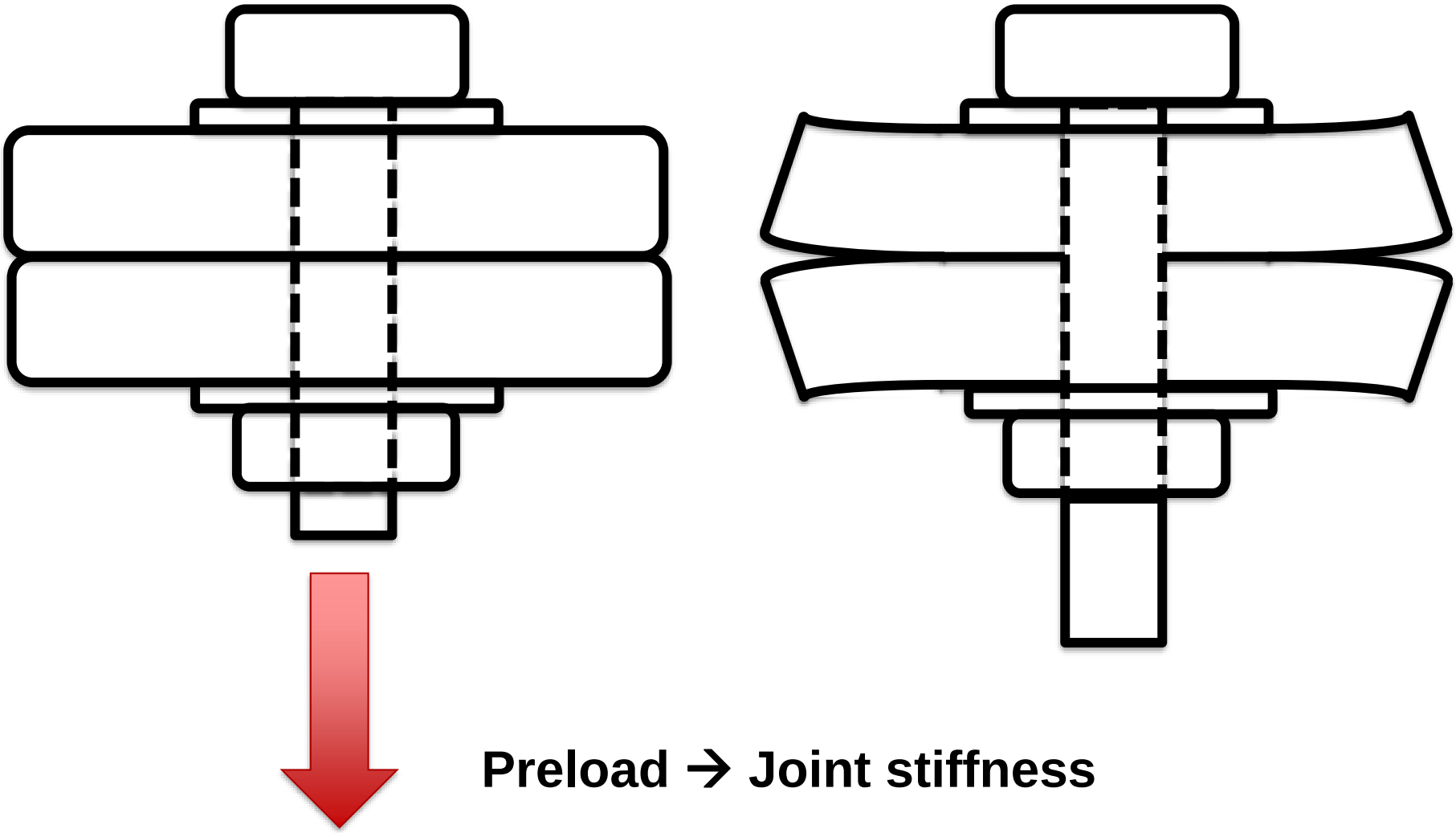
Model of study



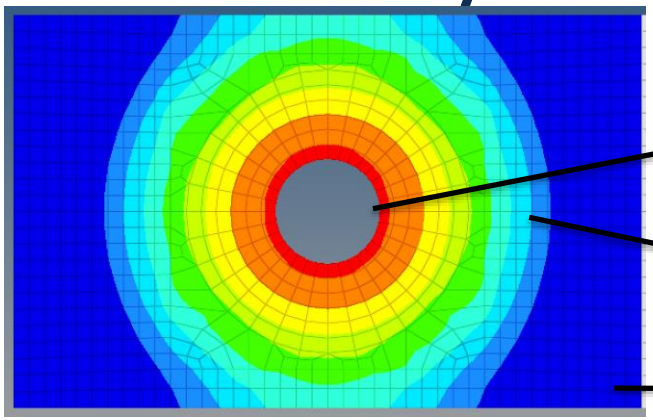


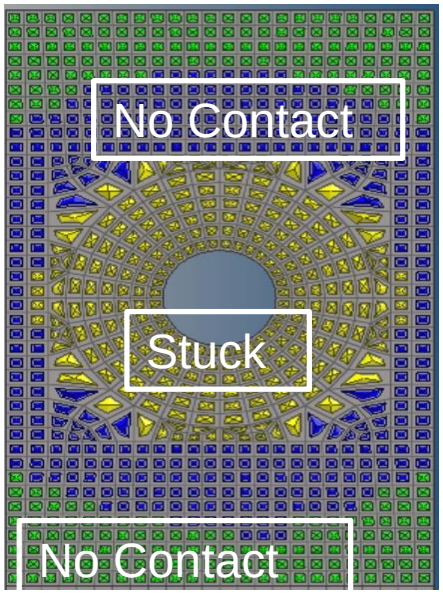
Greatest uncertainty arises from the interface

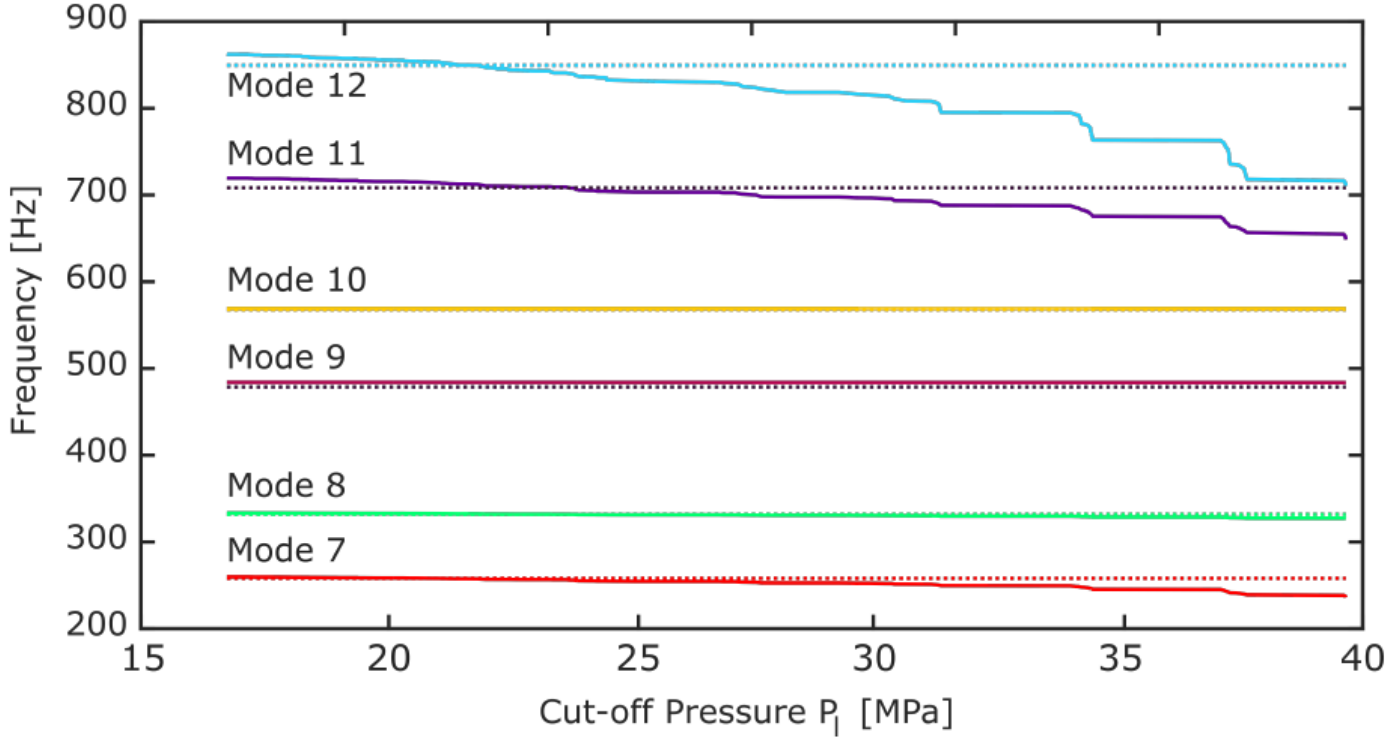
Introduction



Prior study: NOMAD 2017





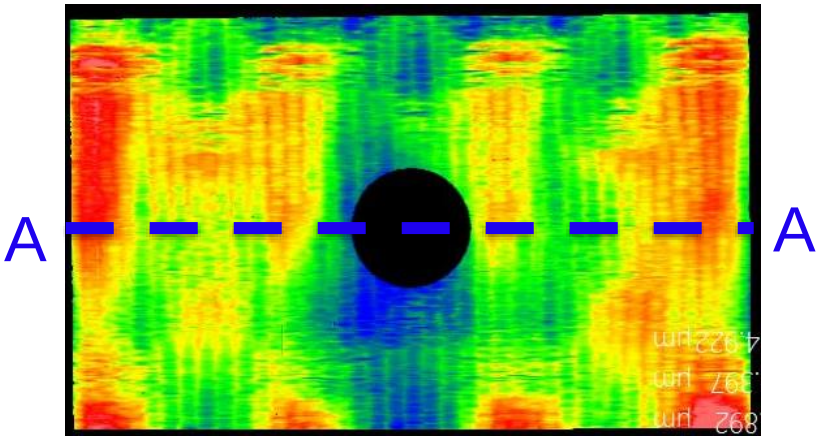


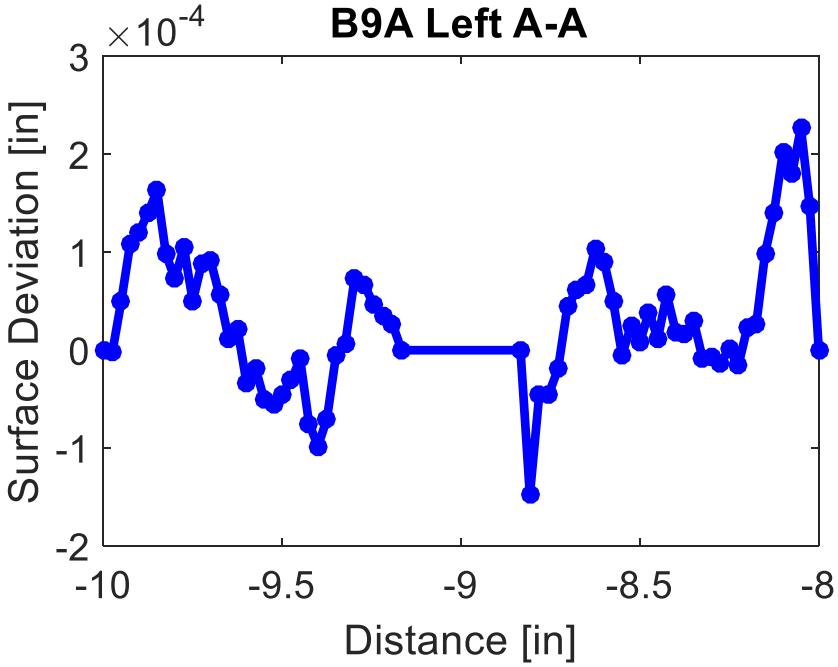
Case study

- Shigley's static stiffness of interface
  - $k = \left[\left(k_{fastener}\right)^{-1} + \left(k_{members}\right)^{-1}\right]^{-1}$
  - $\delta = \frac{P}{k}$
- Example:
  - Two 0.5 in steel plates with 5/16"-24 steel bolt, nut, and washers
  - Bolt preload: 90% yield
  - Max interface deflection: $\delta \cong 0.0015$ in

Introduction

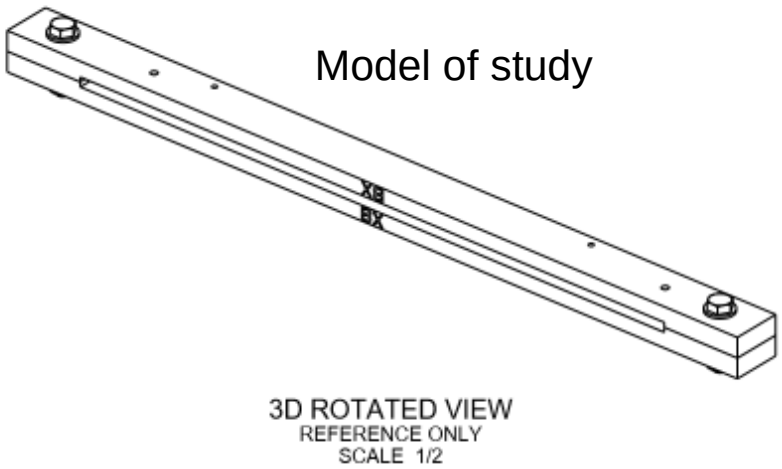
- To what extent do surface irregularities in an interface effect the dynamic properties of a joint?



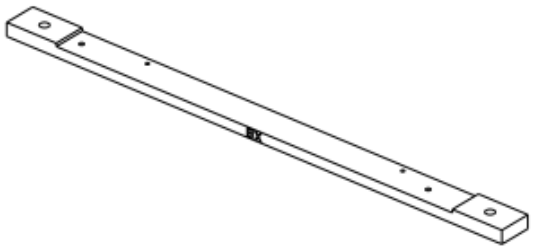


Agenda

1. System Description
2. Single Beam Structure
    1. Experimental Modal Analysis
    2. Model Updating
        1. Young's Modulus
        2. Density
        3. Surface geometry
3. Assembled Beam Structure
    1. Experimental Modal Analysis
    2. Computational Analysis
    3. Validation
4. Conclusions

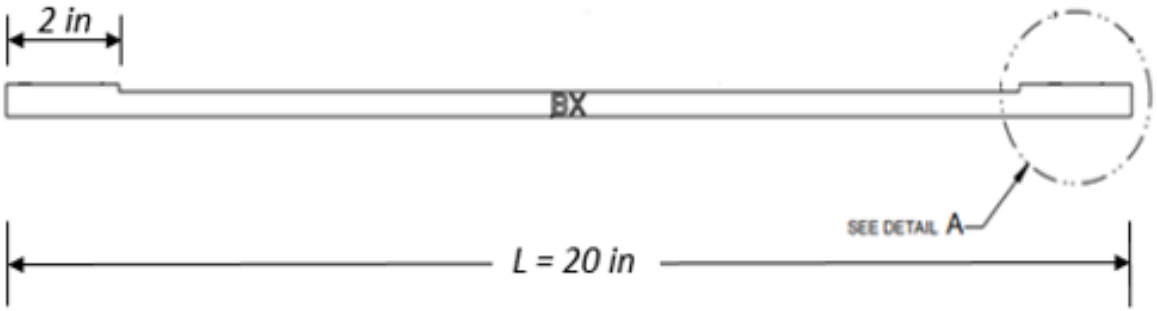


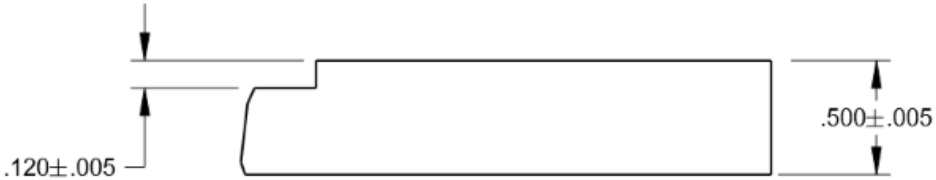
System description



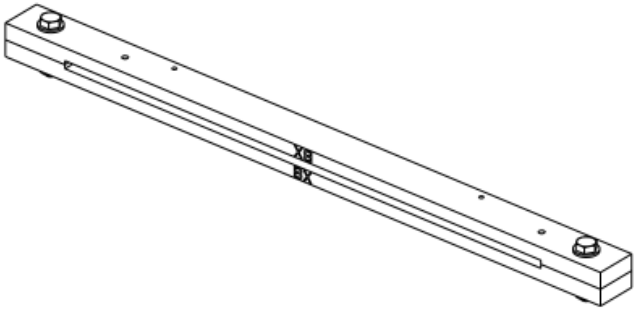
3D ROTATED VIEW
REFERENCE ONLY
SCALE 3/8

Single beam





DETAIL A
SCALE 2/1

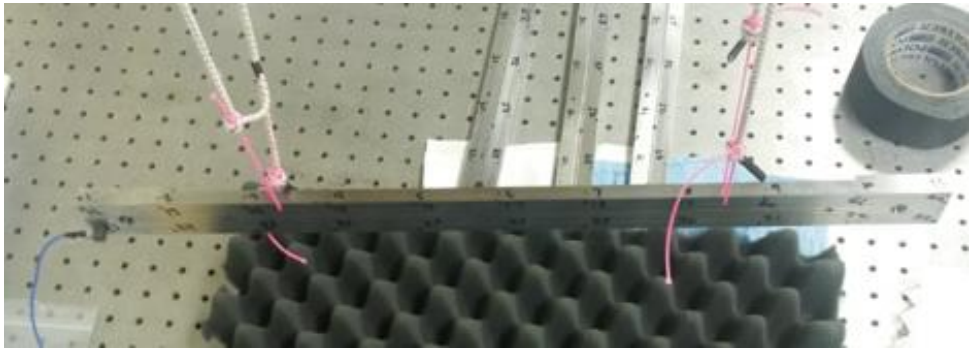


3D ROTATED VIEW
REFERENCE ONLY
SCALE 1/2

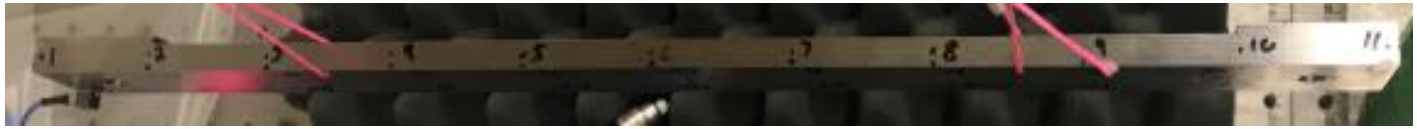
Beam assembly

Single Beam Structure: Experimental Modal Analysis

Impact Hammer



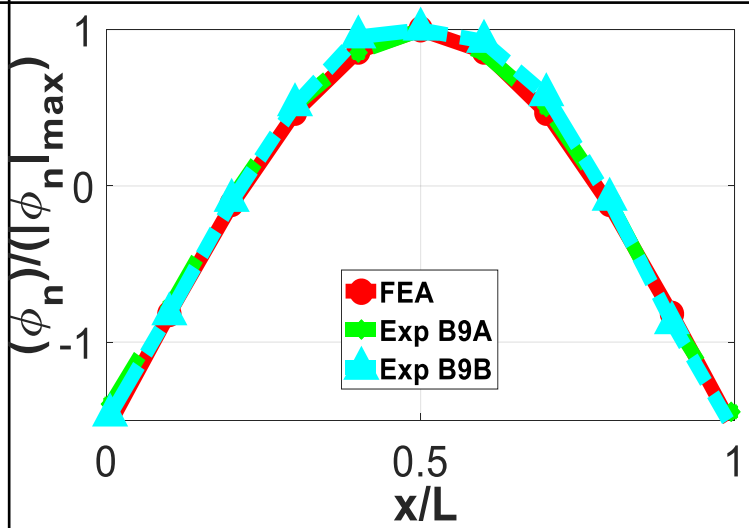
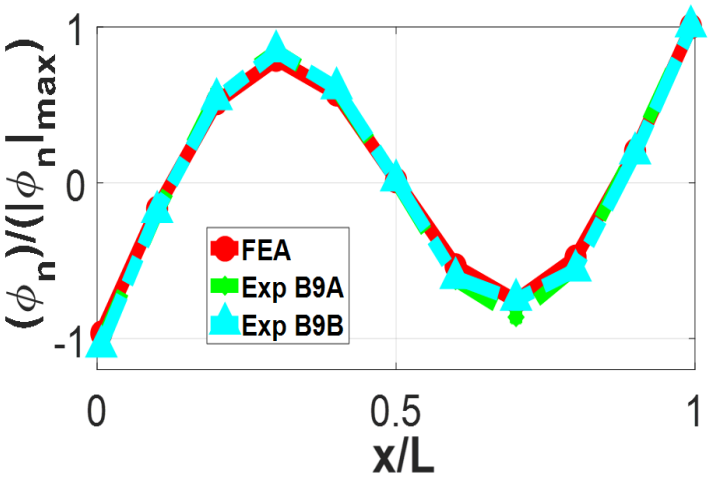
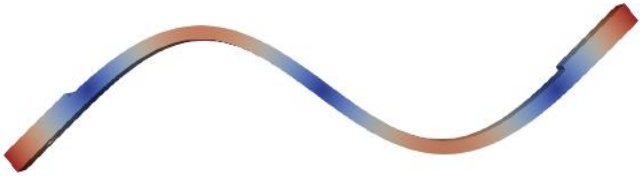
"Free-Free BC"



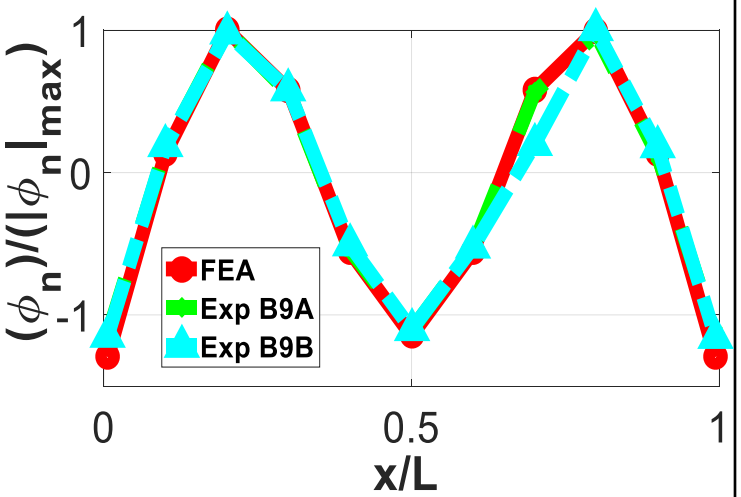
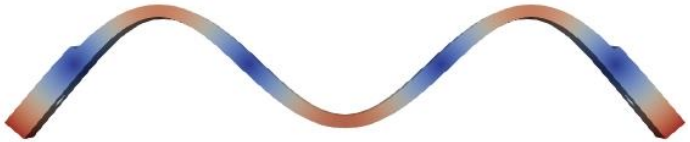
Top View

Front View

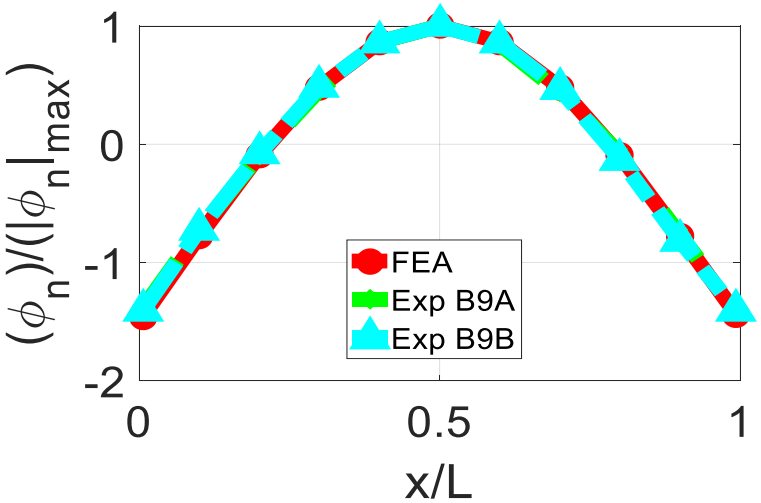
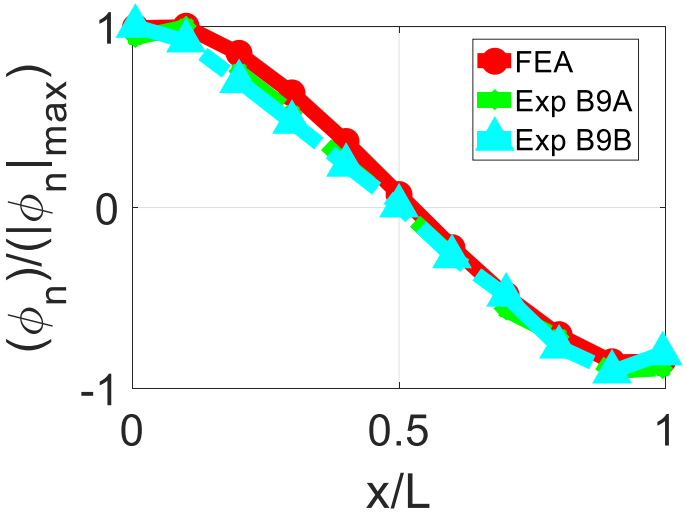
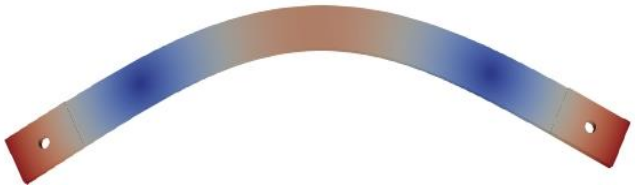
Single Beam Structure: Experimental Modal Analysis

	1st Out of Plane Bending Mode	2nd Out of Plane Bending Mode
Beam 9A	187.5 Hz	526.3 Hz
Beam 9B	187.1 Hz	525.1 Hz
Nominal FEA	189.3 Hz	523.3 Hz
Mode Shape Experiments		
Mode Shapes FEA		

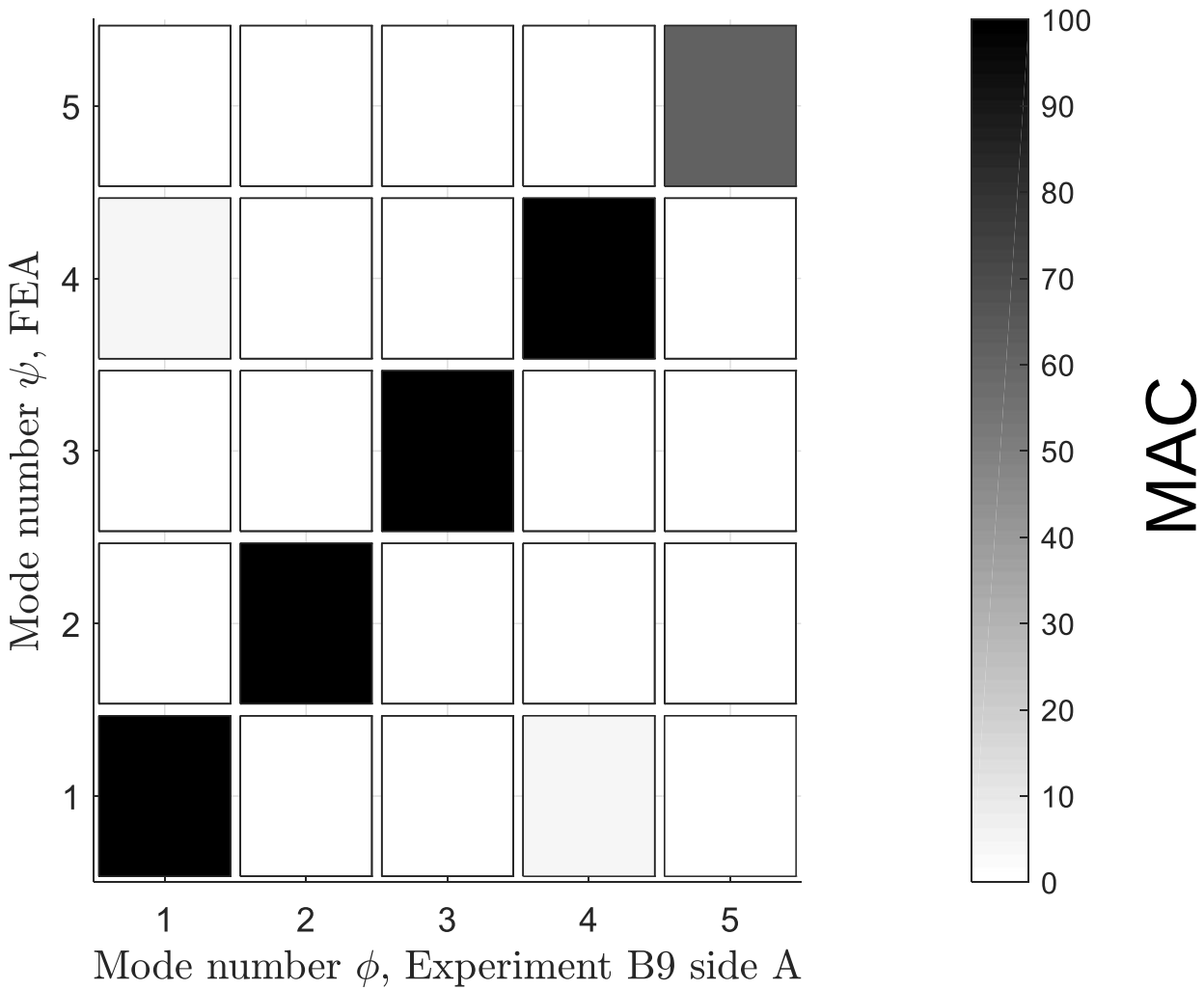
Single Beam Structure: Experimental Modal Analysis

	3rd Out of Plane Bending Mode
Beam 9A	610.8 Hz
Beam 9B	610.3 Hz
Nominal FEA	603.8 Hz
Mode Shape Experiments	
Mode Shapes FEA	

Single Beam Structure: Experimental Modal Analysis

	1st In-Plane Bending Mode	1st Torsional Mode
Beam 9A	1042.7 Hz	1545.5 Hz
Beam 9B	1042.8 Hz	1541.8 Hz
Nominal FEA	1037.9 Hz	1530.7 Hz
Mode Shape Experiments		
Mode Shape FEA		

Single Beam Structure: Experimental Modal Analysis



Single Beam Structure: Model Updating of Young's Modulus

Nominal Young's Modulus (Mpsi)	Updated Modulus (Mpsi) without Accelerometer	
	B9 Side A	B9 Side B
29.0	30.5	30.5

Nominal Young's Modulus (Mpsi)	Updated Modulus (Mpsi) with Accelerometer	
	B9 Side A	B9 Side B
29.0	30.9	30.5

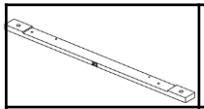
Natural Frequency (Hz) *B9A*			
Mode	**Experimental**	**Calibrated FEA with accelerometer**	**|% Error|**
1st Out of Plane Bending	187.5	187.7	***0.1***
2nd Out of Plane Bending	526.3	527.4	***0.2***
3rd Out of Plane Bending	610.8	608.1	***0.4***
1st In-Plane Bending Mode	1042.7	1046.5	***0.4***
1st Torsional	1545.6	1541.8	***0.2***

Natural Frequency (Hz) *B9B*			
Mode	**Experimental**	**Calibrated FEA with accelerometer**	**|% Error|**
1st Out of Plane Bending	187.1	187.3	***0.1***
2nd Out of Plane Bending	525.1	526.4	***0.2***
3rd Out of Plane Bending	610.2	606.9	***0.0***
1st In-Plane Bending Mode	1042.9	1044.5	***0.2***
1st Torsional	1541.8	1538.8	***0.2***

Single Beam Structure: Model Updating of Density

Serialize components

4340 Alloy Steel Beams

	**B9A**	**B9B**
Mass (slug)	7.3E-03	7.3E-03
Density (slug/in^3)	**7.3E-04**	**7.4E-04**

Hex Head Screw, .3125-25 UNF-2B

	Bolt 1 (Right)	**Bolt 2 (Left)**
Mass (slug)	1.0E-04	1.0 E-04
Density (slug/in^3)	**6.7E-04**	**6.7E-04**

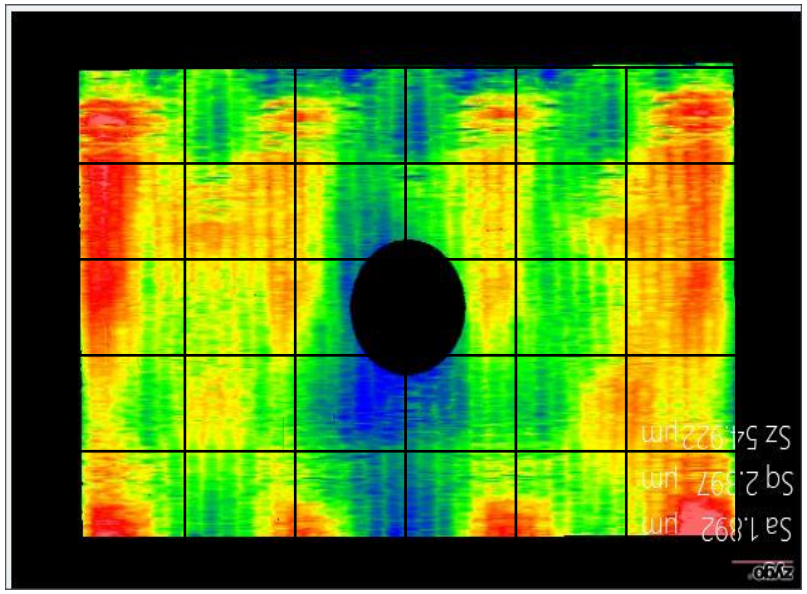
Washer .344ID, .688OD, .065 THK

	Washer 1 (Right)	**Washer 2 (Right)**	**Washer 3 (Left)**	**Washer 4 (Left)**
Mass (slug)	1.1E-05	1.2E-05	1.1E-05	1.2E-05
Density (slug/in^3)	**6.3E-04**	**6.4E-04**	**6.3E-04**	**6.4E-04**

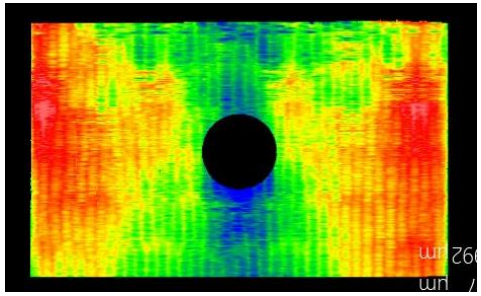
Nut, Hex, .3125-25 UNF-2B

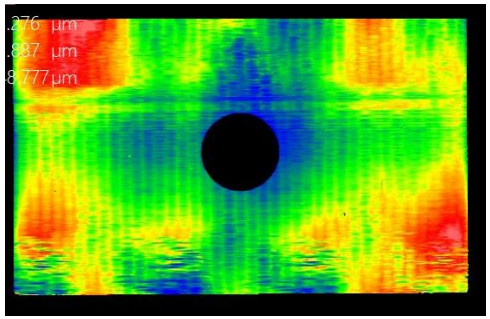
	Nut 1 (Right)	**Nut 2 (Left)**
Mass (slug)	2.87E-05	2.8E-05
Density (slug/in^3)	**9.1E-04**	**9.0E-04**

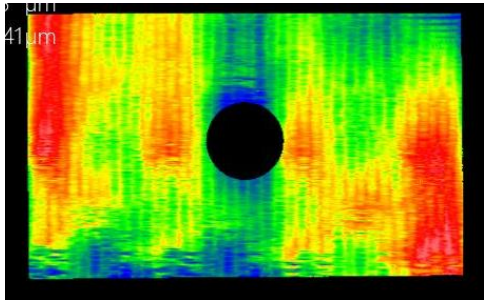
Single Beam Structure: Model Updating of Surface Geometry



- High sampling frequency data set!
  - ~8,000 by 5,000 samples or 40 million samples
  - Find closest data point for each node







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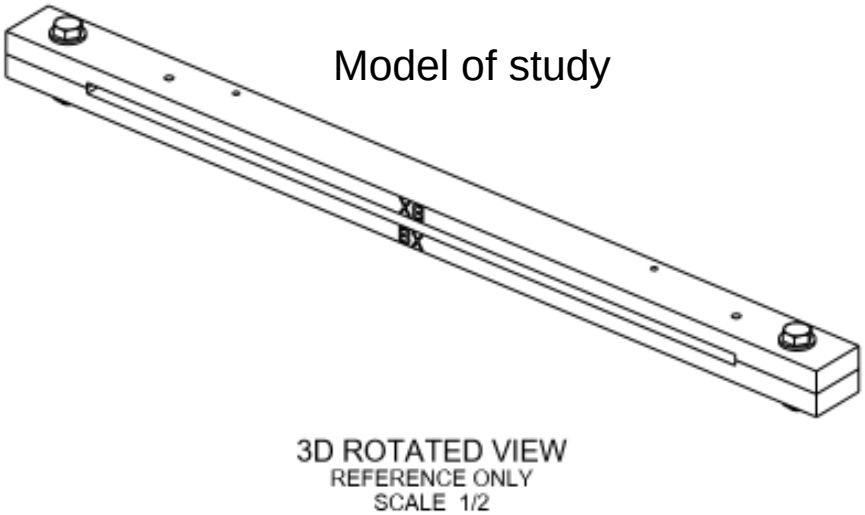
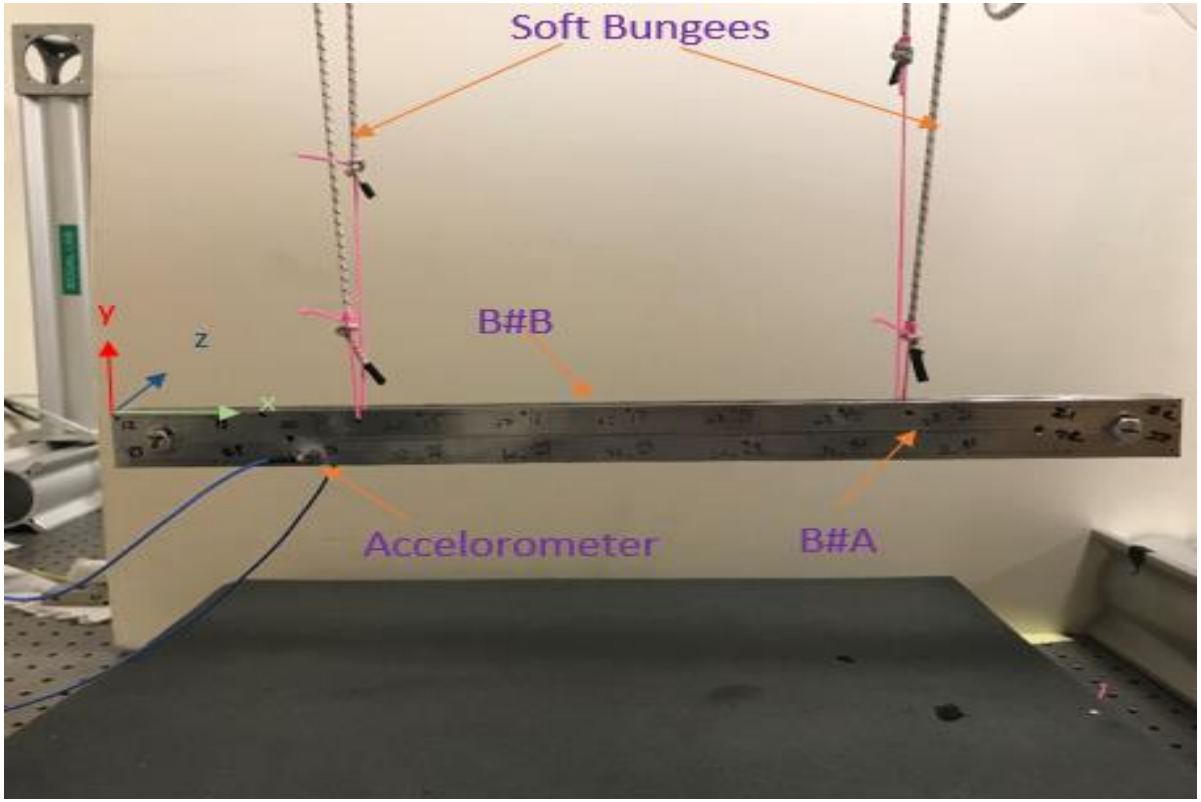
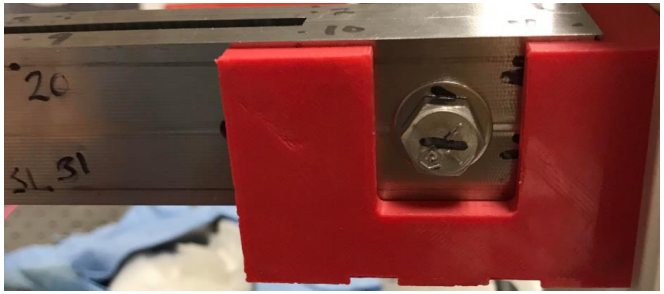


Assembled Beam Structure: Experimental Modal Analysis

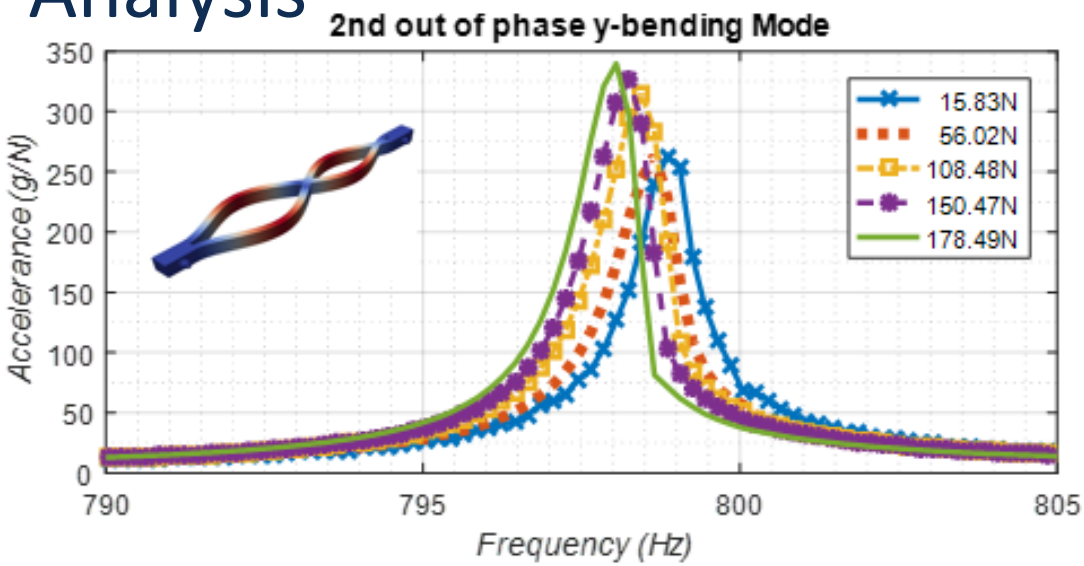
Torque Wrench

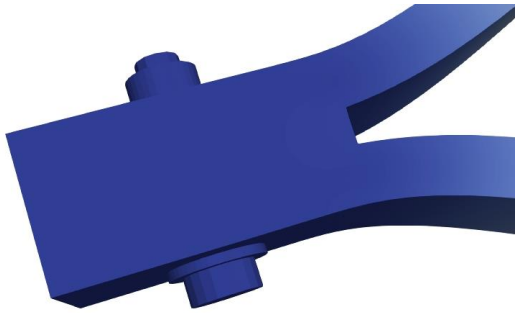




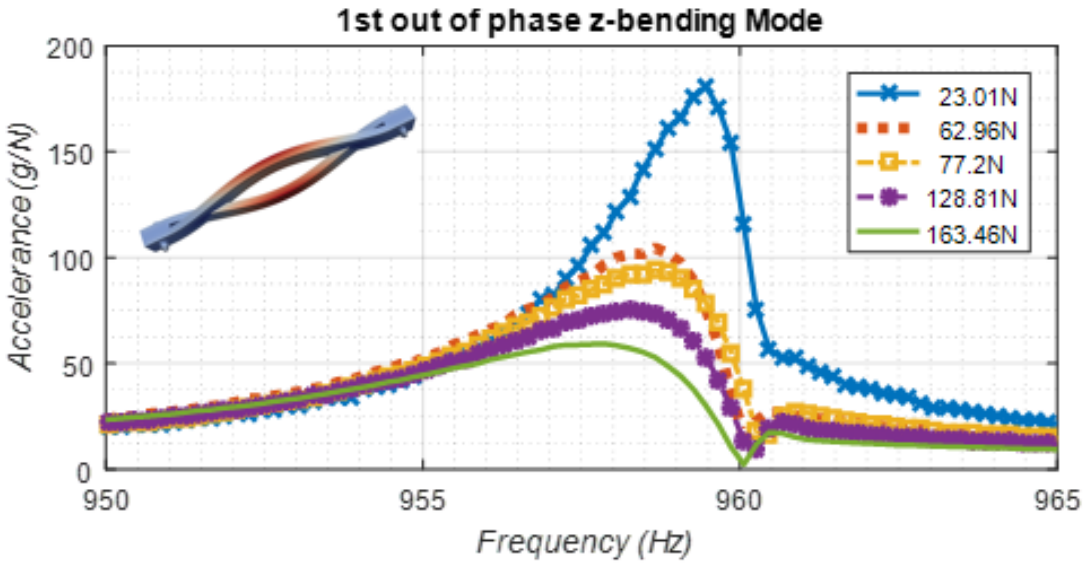
Alignment Tool

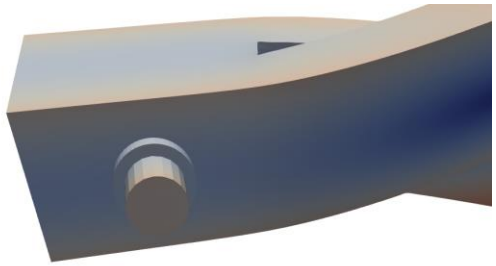
Assembled Beam Structure: Experimental Modal Analysis





Stiffness decreases





High shearing

Assembled Beam Structure: Experimental Modal Analysis

- Conversion between torque and preload

Accuracy of Bolt Preload Based on Application Method

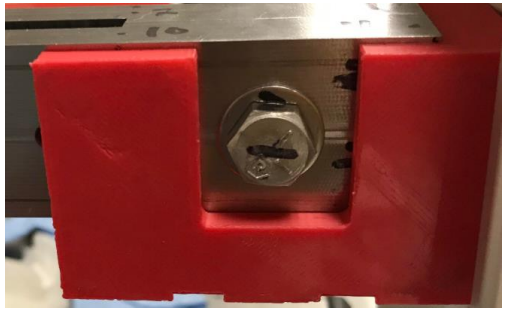
Method	Accuracy
Torque Wrench on Unlubricated Bolts [11]	± 35%
Torque Wrench on Cad-Plated Bolts [11]	± 30%
Torque Wrench on Lubricated Bolts [11]	± 25%
Preload Indicating Washer [11]	± 10%
Strain Gages[12]	± 1%
Computer Controlled Wrench (Below Yield) [12]	± 15%
Computer Controlled Wrench (Yield Sensing) [12]	± 8%
Bolt Elongation [11]	± 5%
Ultrasonic Sensing [11]	± 5%

- Motosh equation:

$$T = F\left(\frac{P}{2\pi} + \frac{\mu_t r_t}{cos(\beta)} + \mu_n r_n\right)$$

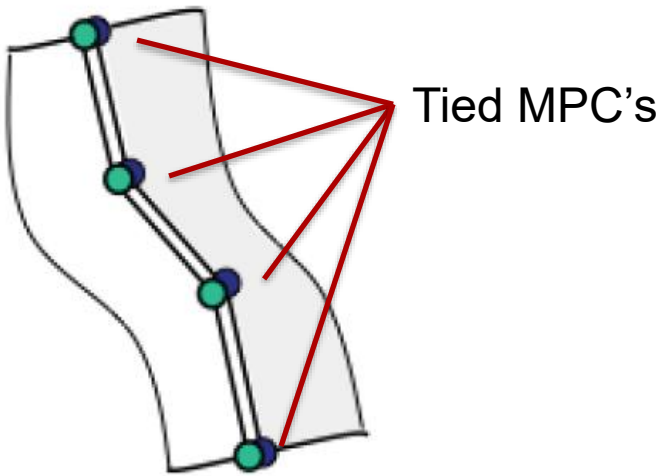
Computational Analysis: Preload Simulation Assumptions

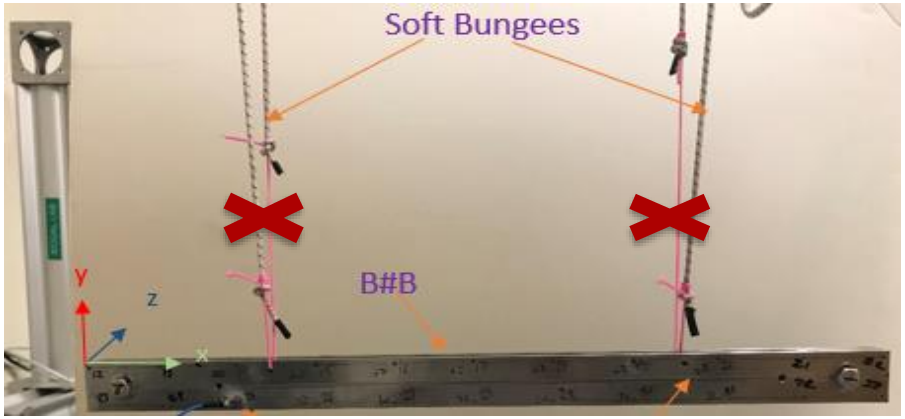
1. Preload is known
2. Washer is centered, beams aligned
3. Waviness in fastener surfaces is negligible
4. Coulomb friction
5. No rotation of beams about bolt axis
6. Elastic deformation



Computational Analysis: Modal Analysis Assumptions

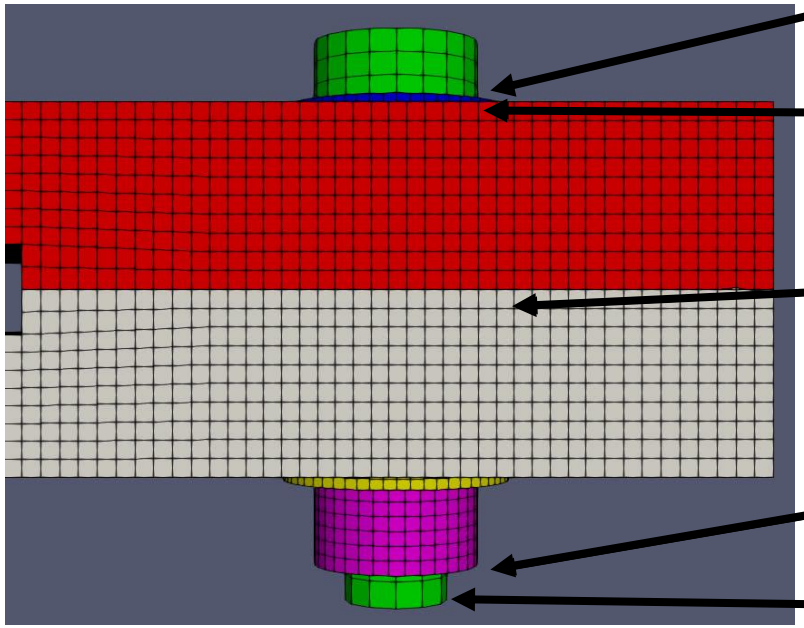
1. Faces with nodes in contact remain in contact
2. No damping
3. Free-free boundary conditions





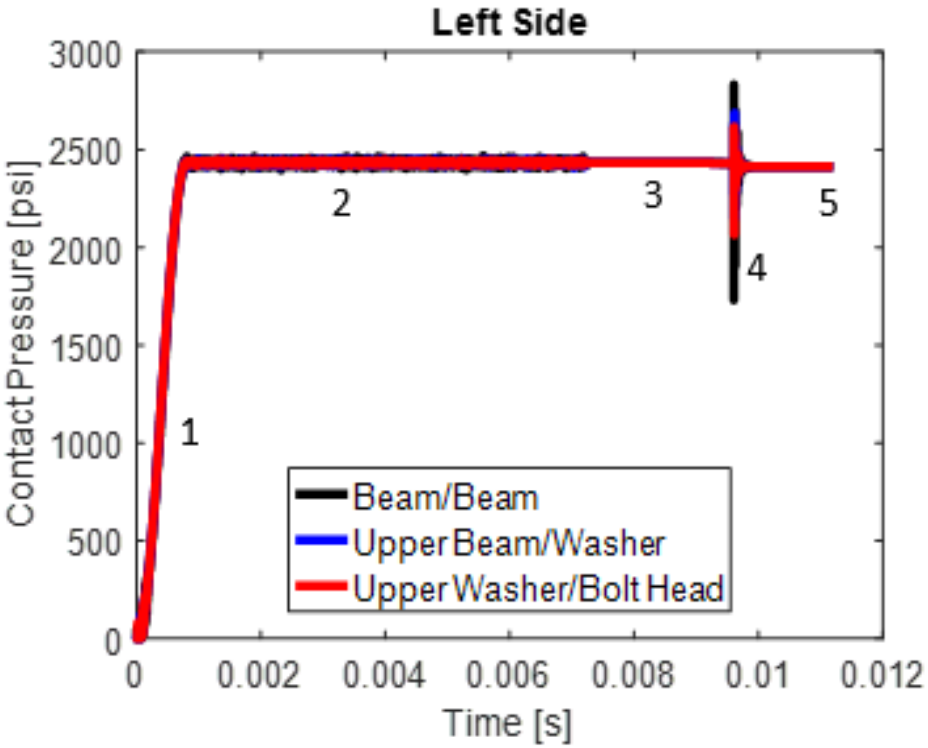
$$-\omega^2 Mx + i\omega \overset{0}{\cancel{C}}x + Kx = 0$$

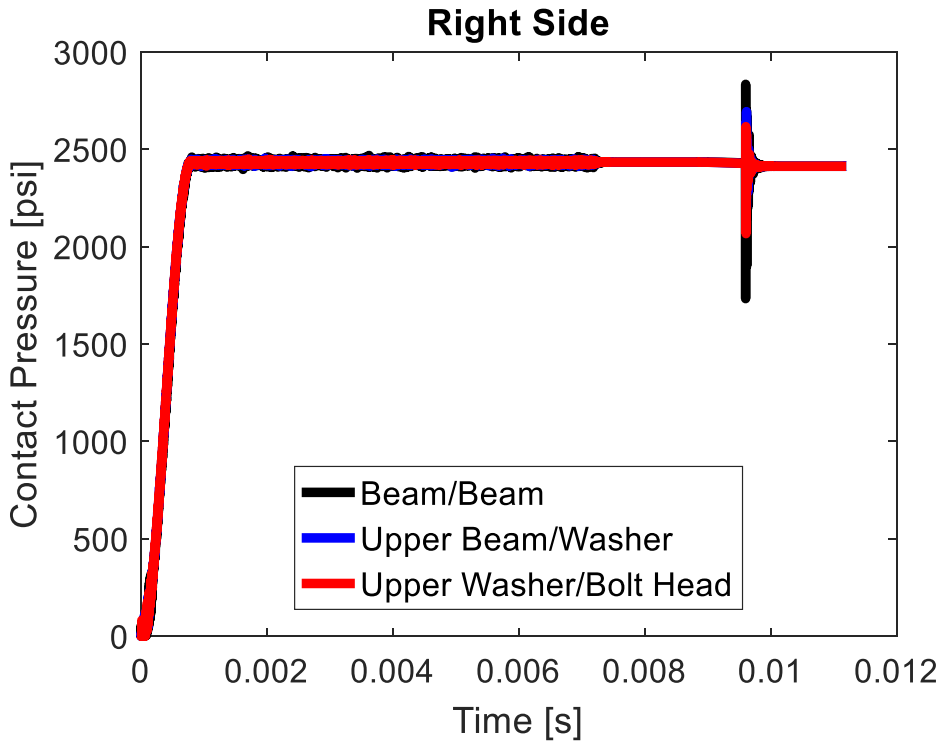
Computational Analysis: Contact surfaces and boundary conditions



Step	Applied Load	Bolt to Nut Contact	Nut Boundary Condition
1	Ramp up	No friction	Fixed
2	Hold	No friction	Fixed
3	Hold	Glued	Fixed
4	Ramp down	Glued	Fixed
5	Off	Glued	Free

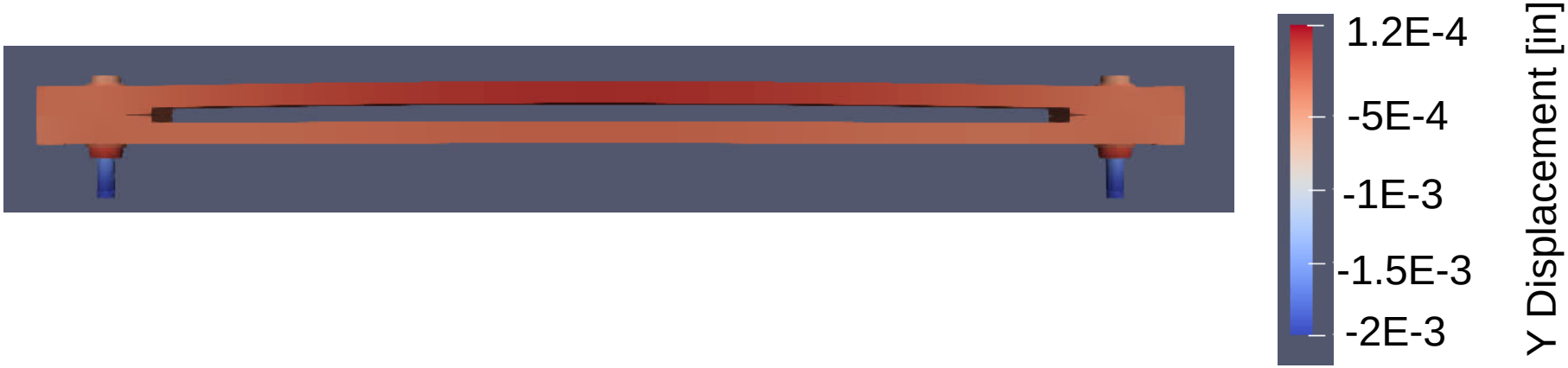
Computational Analysis: Preload Results

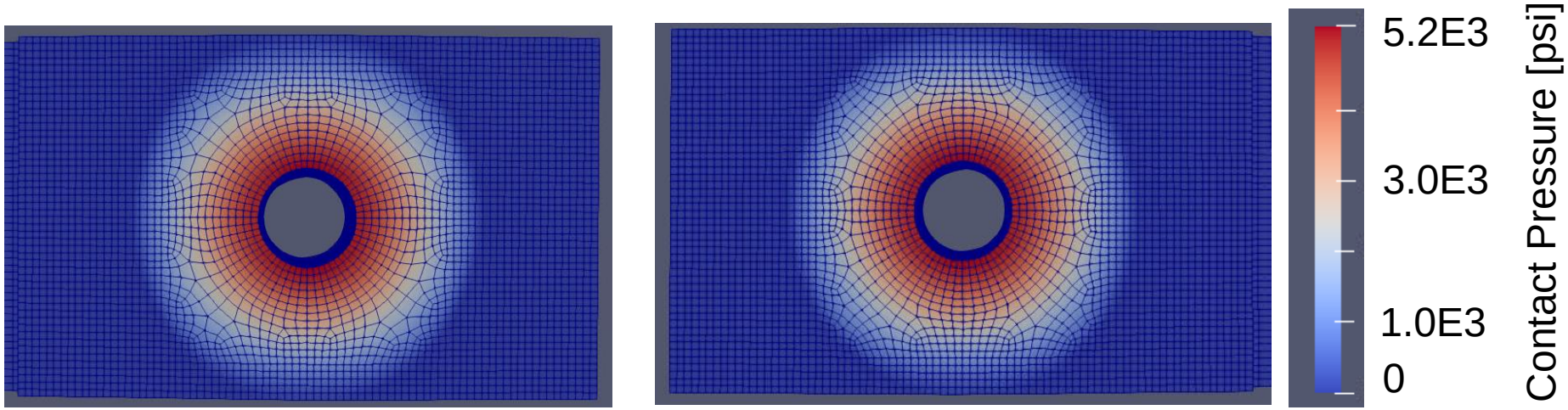




Step	Applied Load	Bolt to Nut Contact	Nut Boundary Condition
1	Ramp up	No friction	Fixed
2	Hold	No friction	Fixed
3	Hold	Glued	Fixed
4	Ramp down	Glued	Fixed
5	Off	Glued	Free

Computational Analysis: Flat beam results

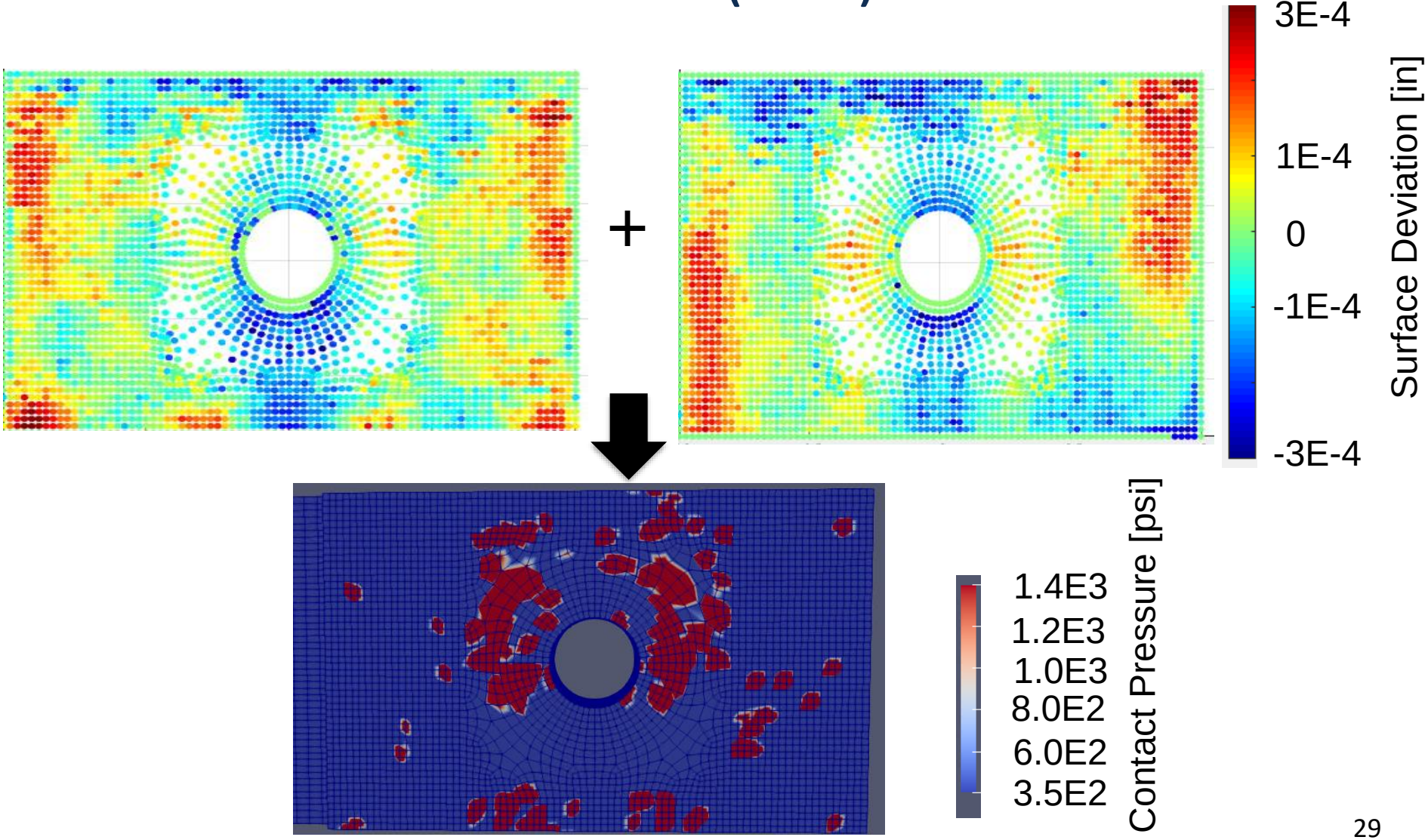




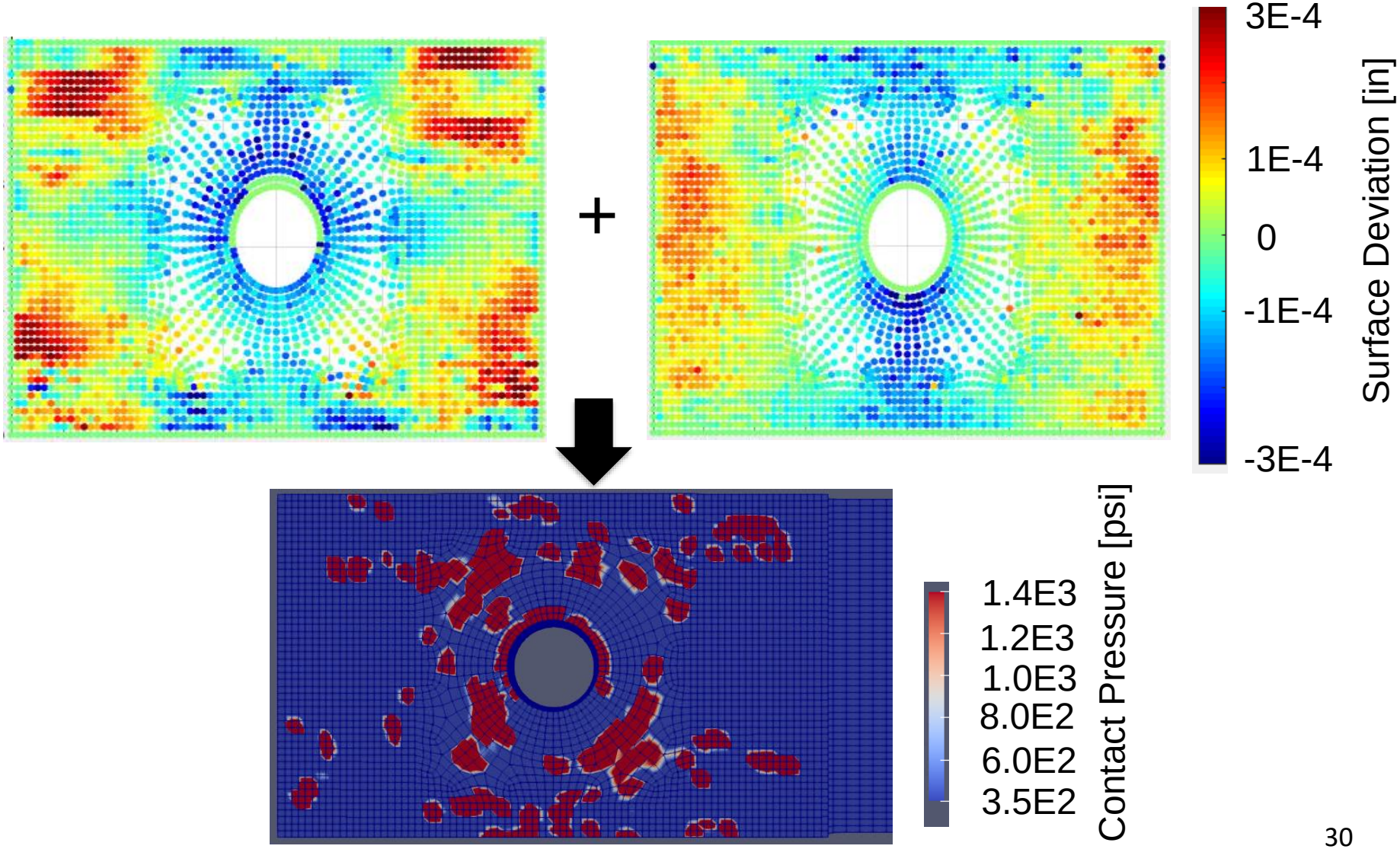
Left

Right

Computational Analysis: Wavy Surface Results (Left)



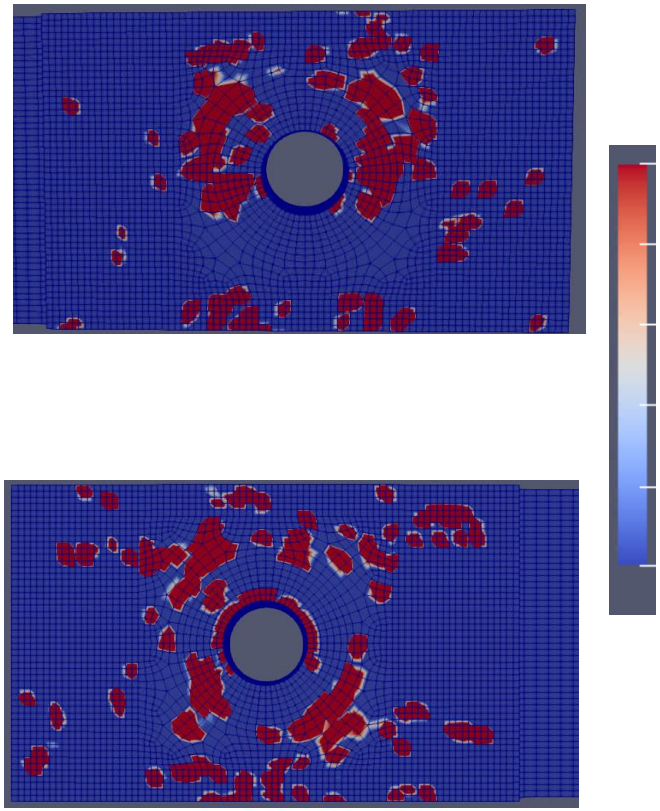
Computational Analysis: Wavy Surface Results (Right)



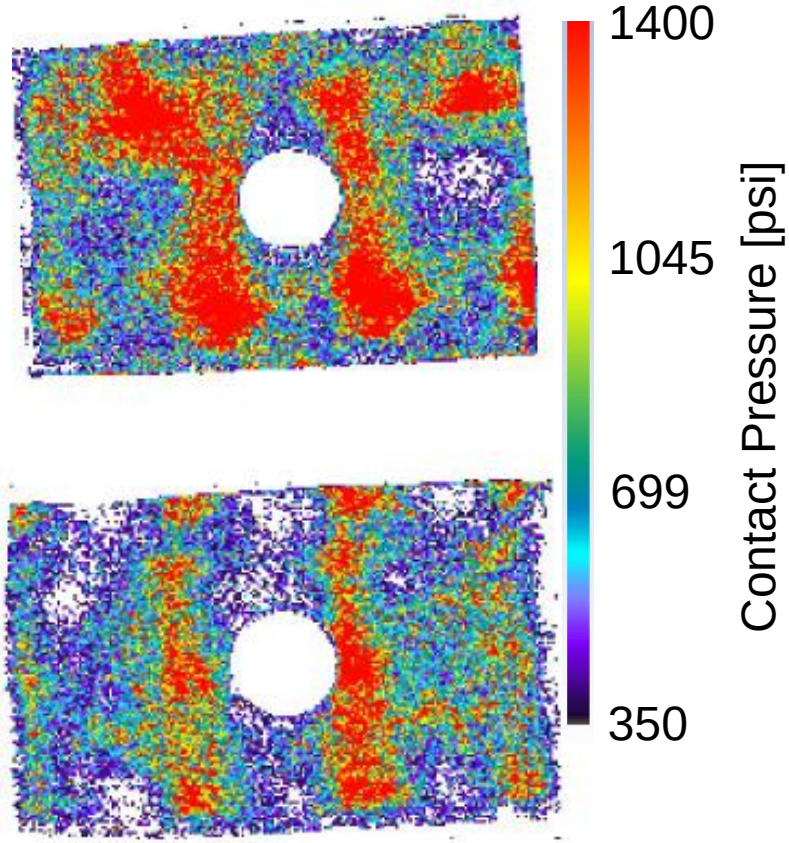
Computational Analysis: Comparison with pressure films

Left

Right

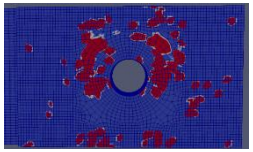
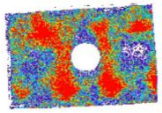
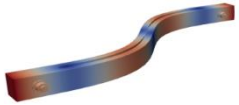
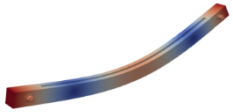


FEA Results

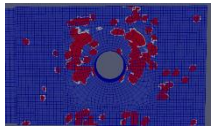
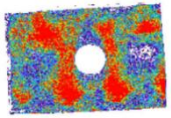
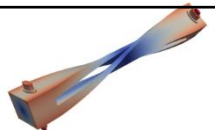
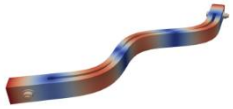


Pressure Film Data

Validation

FEA Natural Frequency (Hz) for different Mesh after Preload (Percent Error)				**Experimental Natural Frequency (Hz)**
From FEA	**Contact between Flat interfaces**			
	Full contact	***Partial Contact***	***Mesh Perturbation***	***Beam set 9 Torque 110 in-lb***
Mode Shape				
	303.3 (4.4%)	291.4 (0.4%)	289.7 (0.24%)	290.4
	364.4 (3.00%)	363.4 (2.7%)	356.0 (0.62%)	353.8
	529.5 (4.1%)	534.1 (5.1%)	514.8 (1.3%)	508.4
	593.6 (0.8%)	599.7 (0.2%)	597.3 (0.2%)	598.6

Validation

FEA Natural Frequency (Hz) for different Mesh after Preload				Experimental Natural Frequency (Hz)
From FEA	**Contact between Flat interfaces**			
	Full contact	***Partial Contact***	***Mesh Perturbation***	***Beam set 9 Torque 110 in-lb.***
Mode Shape				
	835.4 (4.7%)	800.0 (0.3%)	795.0 (0.3%)	797.6
	978.0 (2.3%)	932.0 (2.5%)	952.0 (0.4%)	955.6
	1178.5 (0.6%)	1182.8 (0.2%)	1183.4 (0.2%)	1185.6
	1386.0 (3.1%)	1394.0 (3.7%)	1357.7 (1.0%)	1344.4

Conclusions

- High-fidelity modelling of a benchmark jointed structure was conducted
- Applying tied MPC's to nodes in contact from a preload analysis accurately determines the stiffness of an interface
- Good agreement with experimental test data is found from nominally flat geometries yet still better agreement is obtained from perturbing mesh coordinates with surface profile data

Acknowledgments

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Questions?