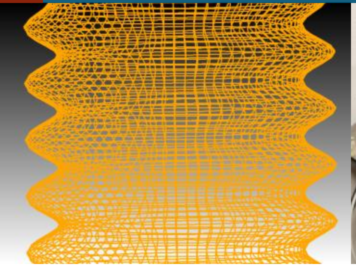
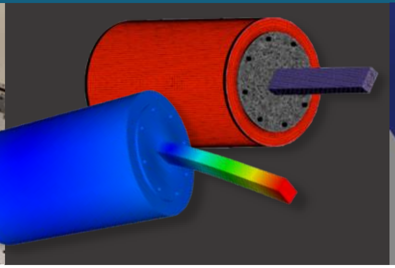
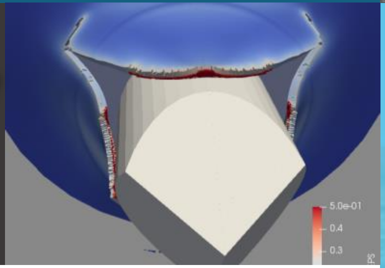
Fielding Advance Diagnostics to Understand Joint Dynamics







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SAND2023-07599PE

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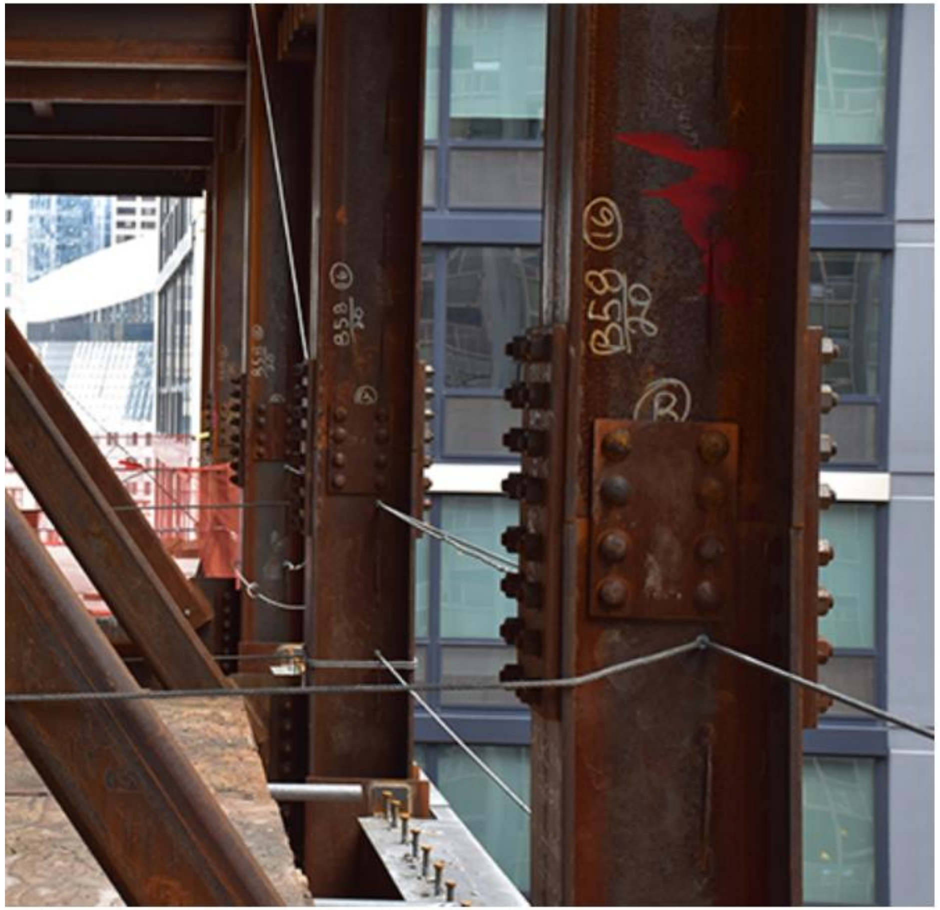
Background

○ Motivation:

- Bolted joints are known to be sources of nonlinearity in bolted structures which are well studied but not well understood
- Traditional sensing modalities (e.g., accelerometers) does not localize measurements to places like joints which are contributing to the nonlinearity
  - Oftentimes, hard to measure inside and around a joint (small deformations)



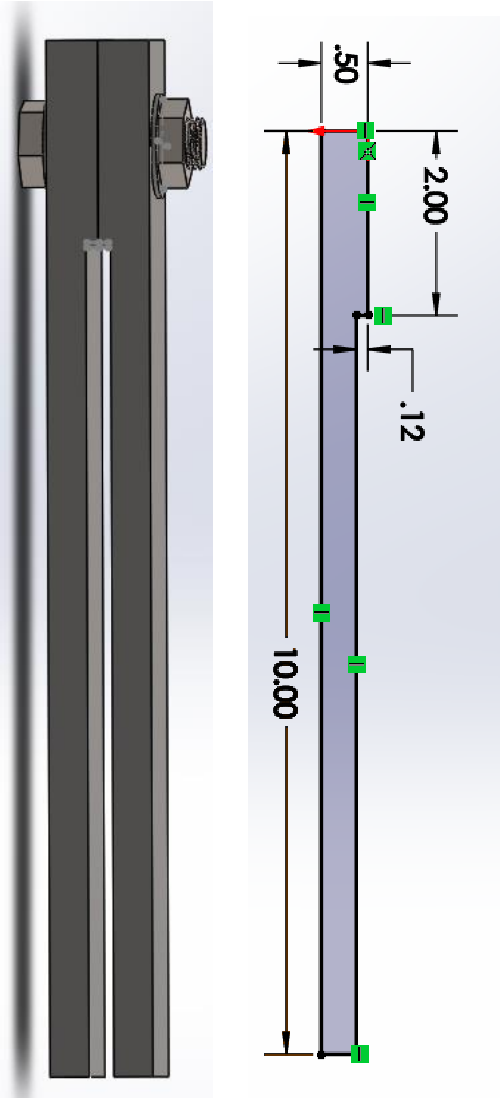
Source: AISC

Background

○Objectives:

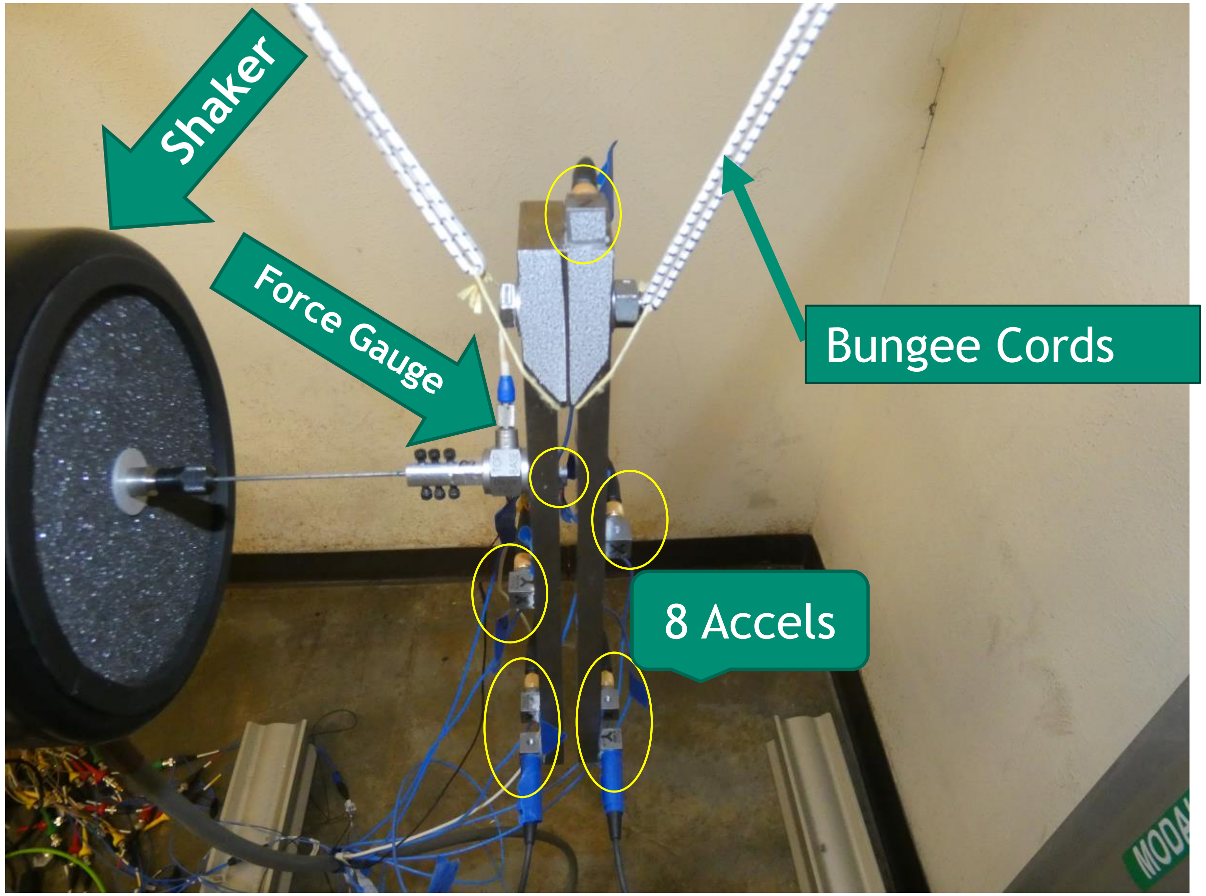
- Use high-speed cameras combined with digital image correlation (DIC) to acquire full-field spatio-temporal dynamic measurements of a single-bolted C-beam during linear and nonlinear modal tests.
- Use phase-based motion magnification (PMM) to observe deformations within the jointed region during vibration
- Assess a solid mechanics model of the beam to replicate the physics of the experiment

Main Objective: can we observe differences in the bolt joint gapping/deformation as the structure resonates at different amplitude levels?

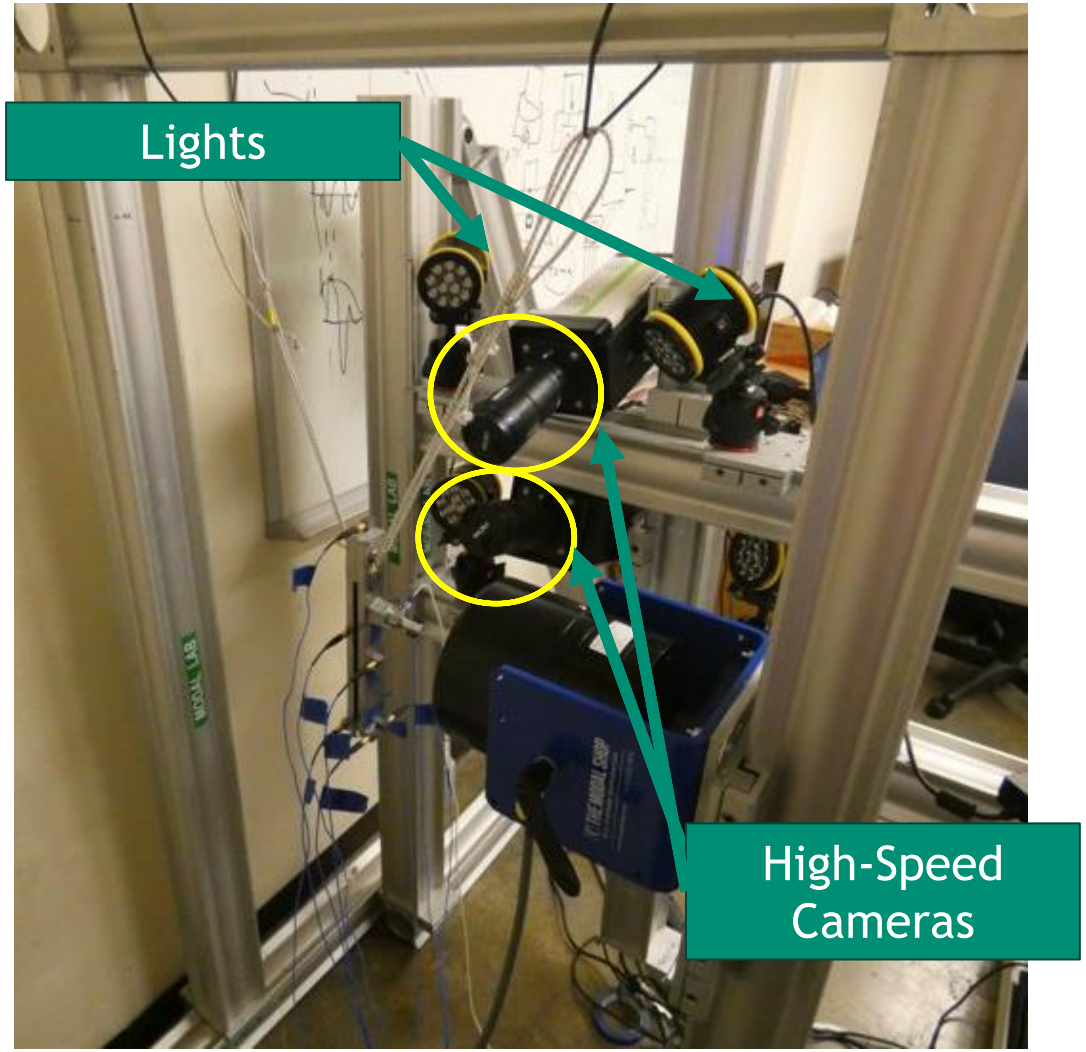


C-bolted Beam

Experimental Test Setup

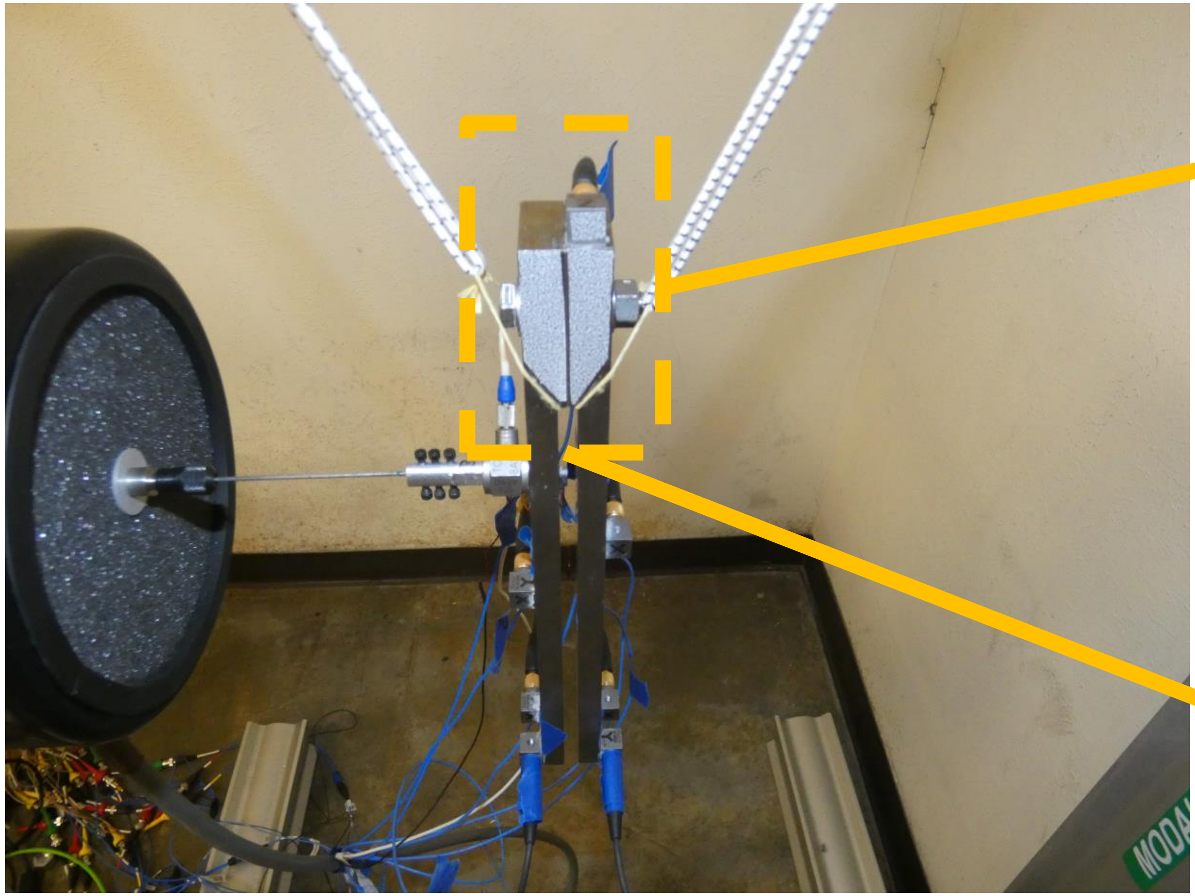


C-Beam Experimental Setup

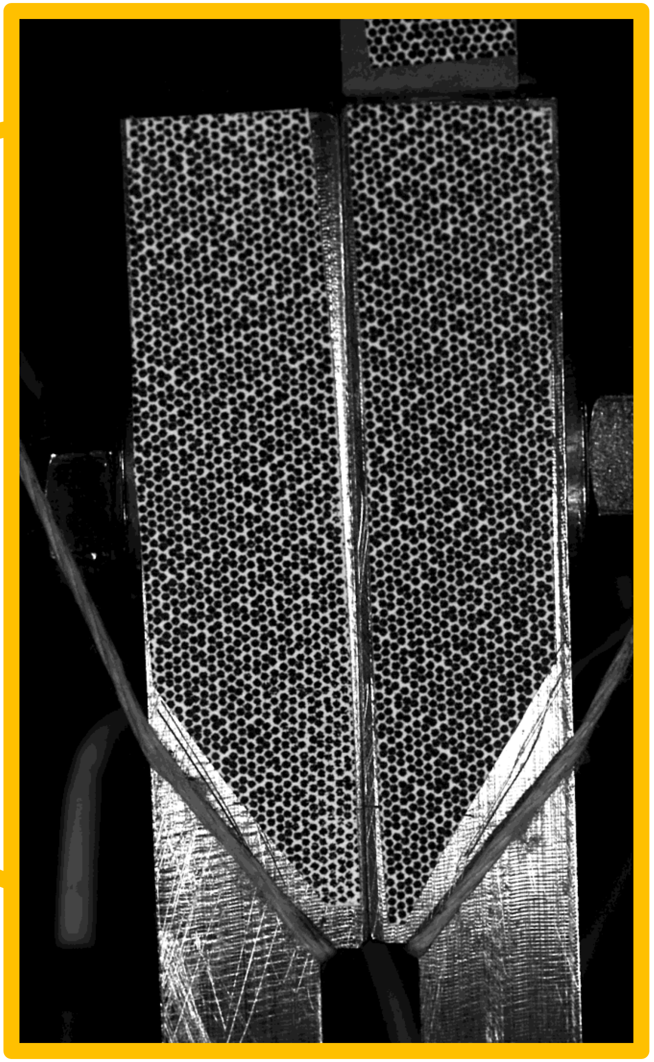


Cameras and DIC Setup

Experimental Test Setup



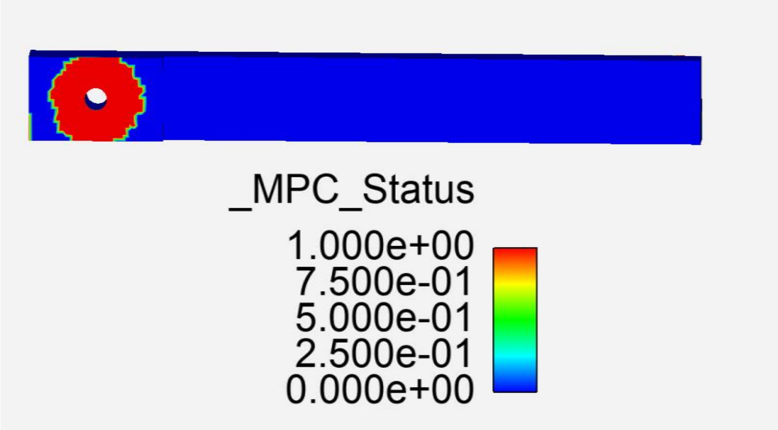
C-Beam Experimental Setup



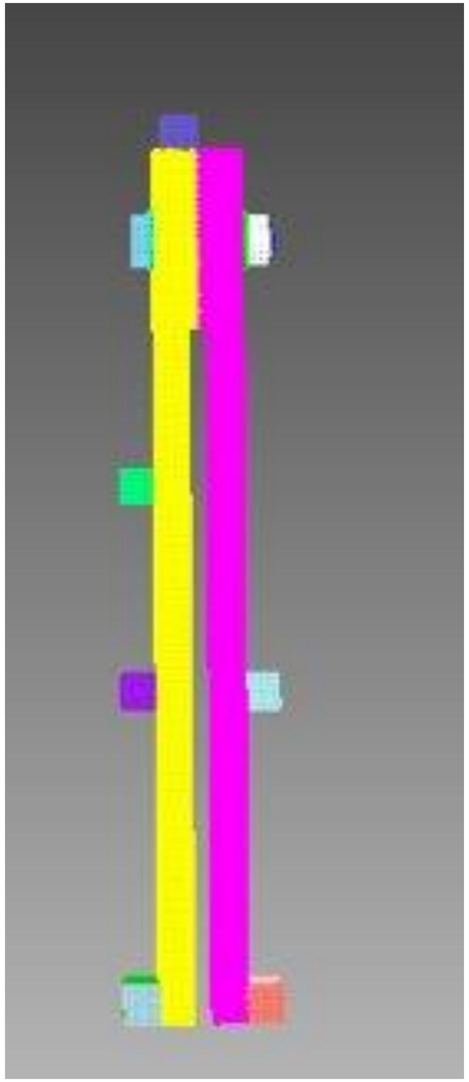
Speckle Pattern

Finite Element Modelling

- Developed Solid Mechanics (SM) and Structural Dynamics (SD) models using Sierra finite element codes and CUBIT
- Analysis procedure:
  - **Step 1**: Apply preload to bolt to predict the preloaded equilibrium state
  - **Step 2**: Linearize the model about the preloaded state and predict the vibration modes using eigen-analysis
  - **Step 3**: Apply a sine wave force at resonant frequency for different force amplitudes to observe joint behavior near resonance
- Applied torque was set to be 154.12 in-lb (14.14 Nm)



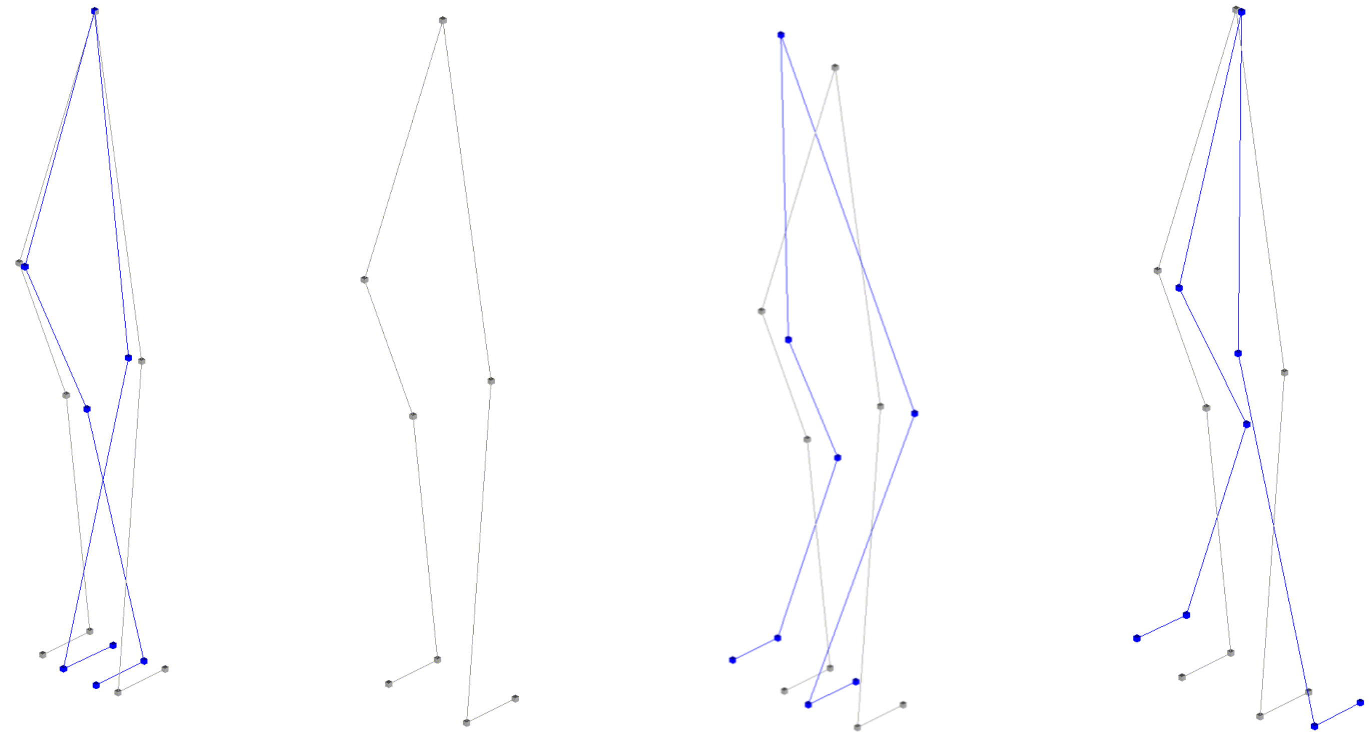
Example of the linearized preload area on the joint



Finite Element Model (FEM)

Experimental System Identification

- Conducted experimental modal test using random burst to determine the first 4 elastic modes of the test specimen:

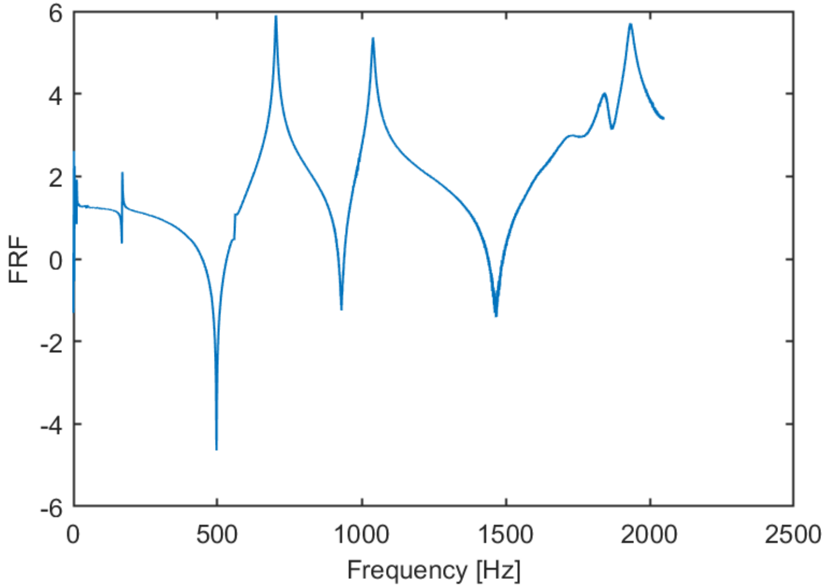


Mode 1
169.54 Hz

Mode 2
560.73 Hz

Mode 3
702.79 Hz

Mode 4
1039.48 Hz



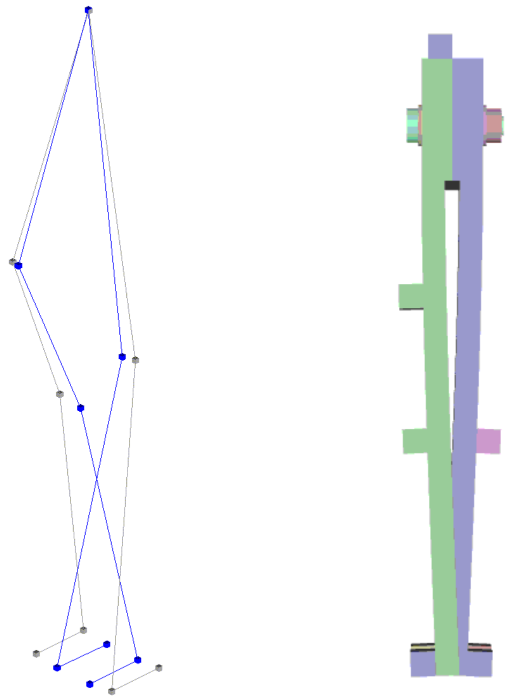
Driving Point FRF

FEA Validation

- Eigen-value analysis was conducted to validate the FEA model
- First elastic mode is the target mode for this investigation since it causes the joint to gap

Mode Shape and Frequency Comparison

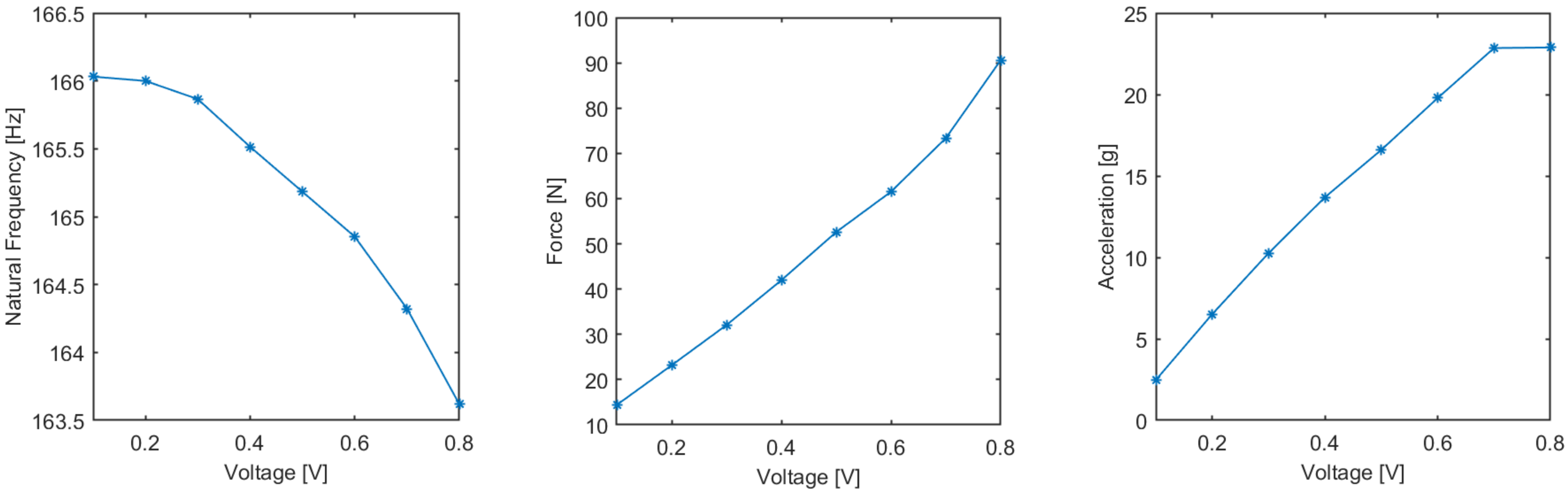
Torque = 154.12 in-lb				
Mode	FEA Results [Hz]	Experimental Results [Hz]	Percent Error [%]	MAC
1	165.33	169.54	2.48	0.9905
2	554.44	560.73	1.12	0.994
3	688.4	702.79	2.05	0.9915
4	1019.1	1039.48	1.96	0.9898



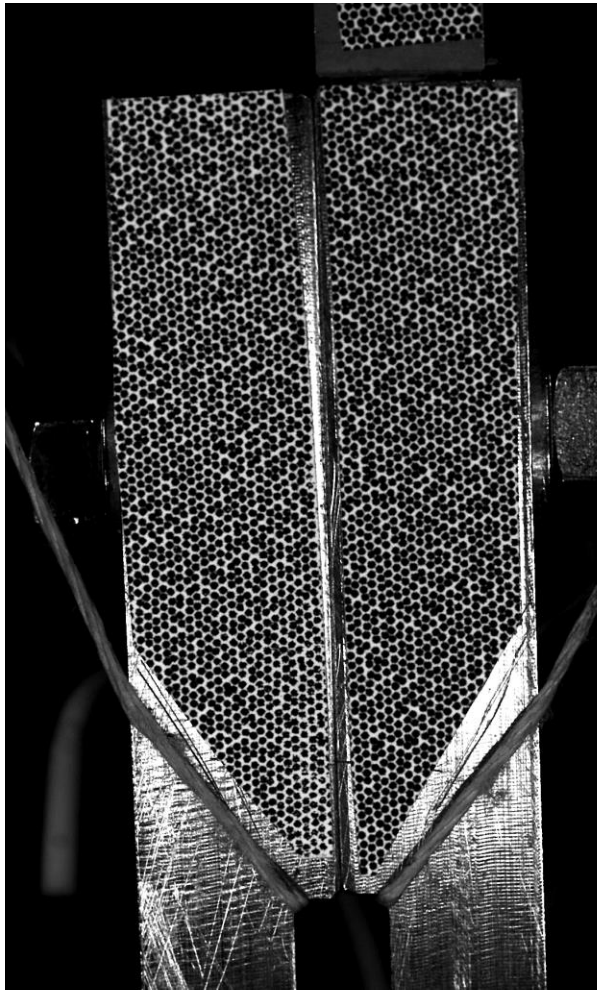
Comparison of First Mode Shape Exp (left) vs FEA (right)

Normal Mode Testing: Experimental Non-Linear System ID

- Normal mode tests were conducted to excite the beam's first mode at different voltage levels: 0.1 — 0.8V (Testlab Module)
- The joint deformation was recorded using the high-speed cameras
- Backbone curves were constructed as function of the fundamental frequency and corresponding force and response amplitudes

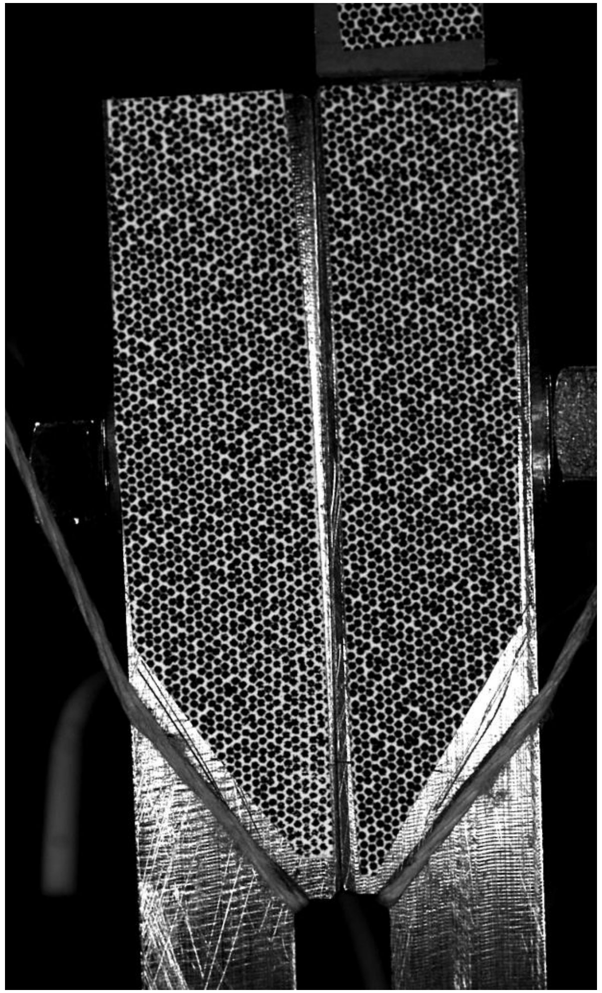


Normal Mode Testing: Workflow for Video Processing

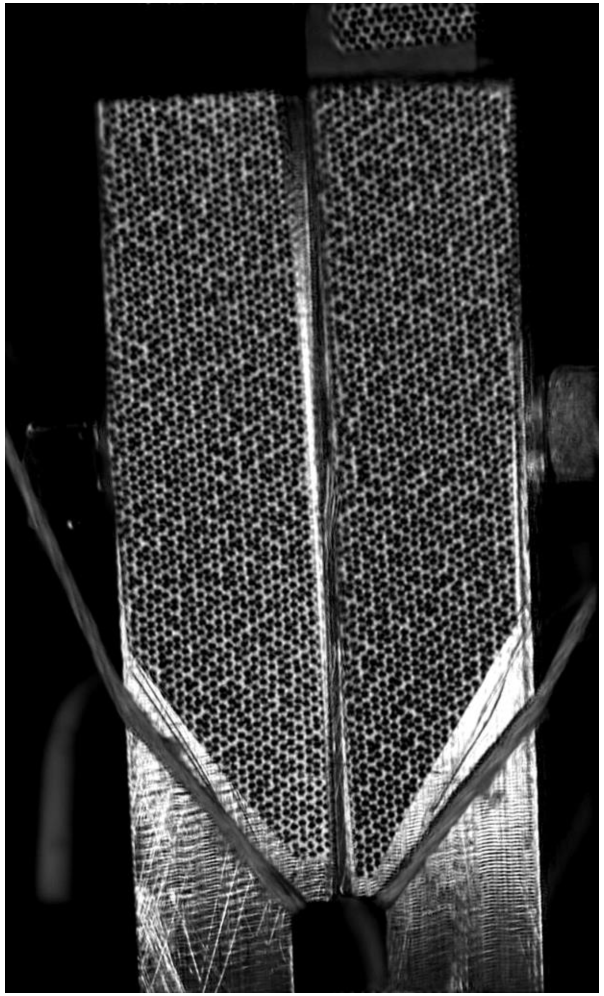


Raw Video

Normal Mode Testing: Workflow for Video Processing

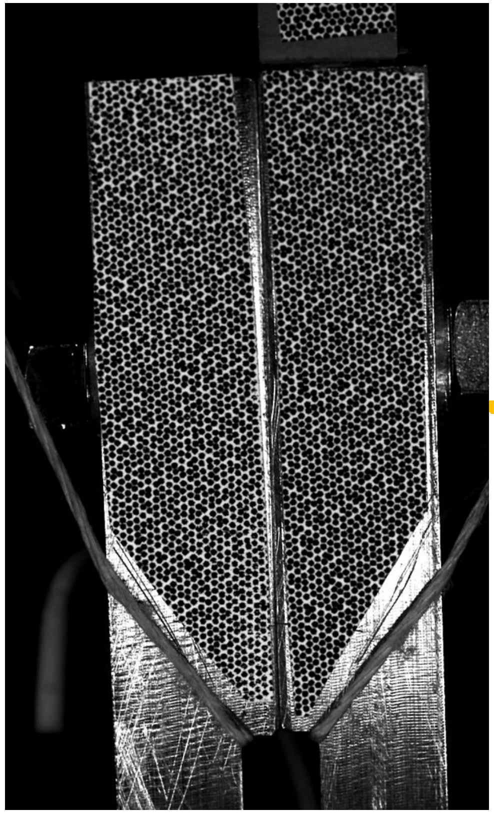


Raw Video

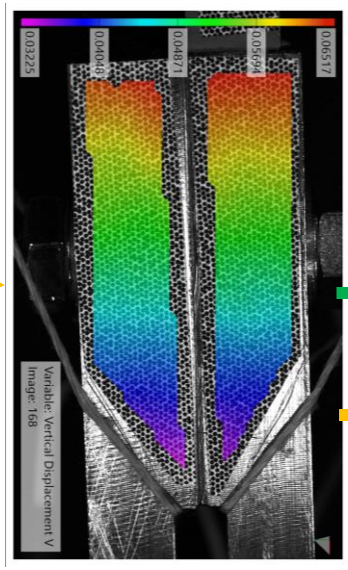


PMM (x10)

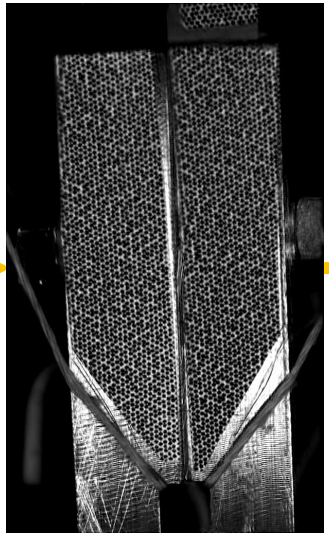
Normal Mode Testing: Workflow for Video Processing



Raw Video



DIC Analysis



PMM

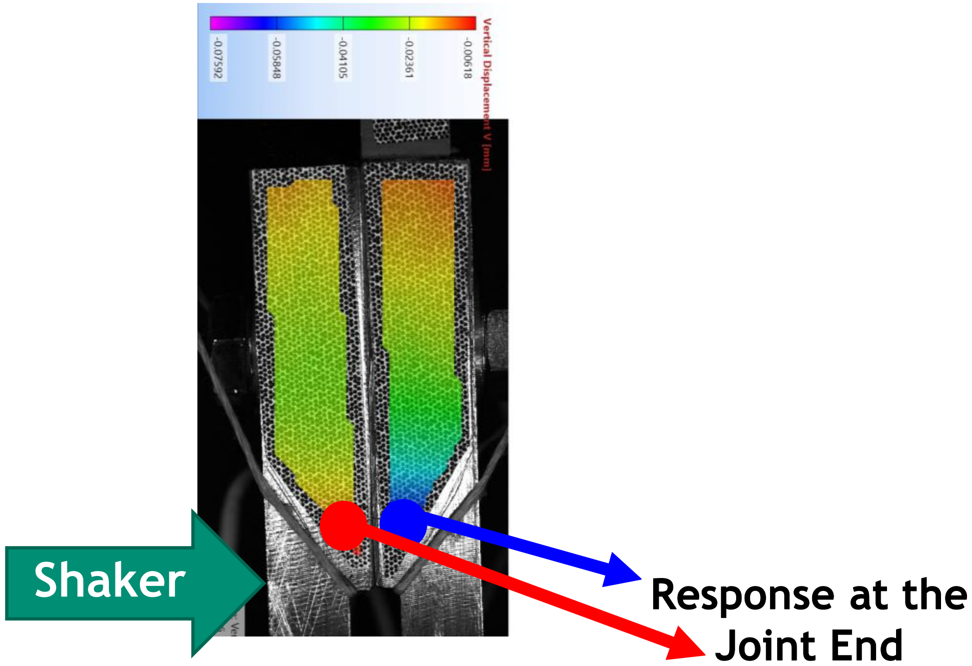
Joint Characterization

Joint Mechanics

Normal Mode Testing: Joint Mechanics

DIC | PMM | Joint Mechanics | Joint Characterization

- DIC analysis and PMM were used to understand the beam response during one cycle of oscillation:
  - The right beam flexes freely, while the left beam is restrained by the shaker

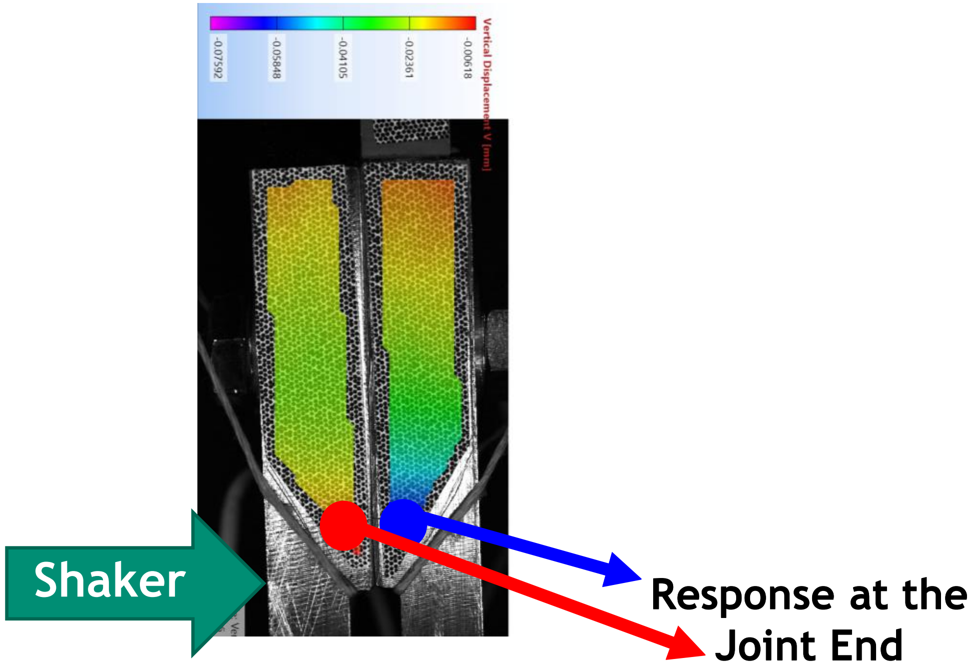


DIC Analysis

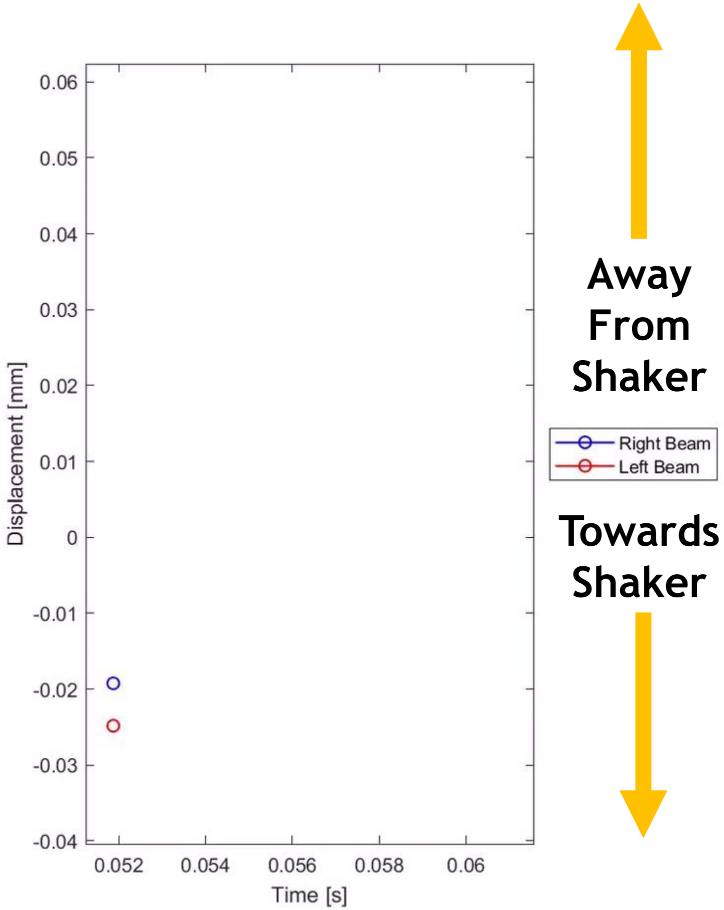
Normal Mode Testing: Joint Mechanics

DIC → PMM → **Joint Mechanics** → Joint Characterization

- DIC analysis and PMM were used to understand the beam response during one cycle of oscillation:
  - The right beam flexes freely, while the left beam is restrained by the shaker



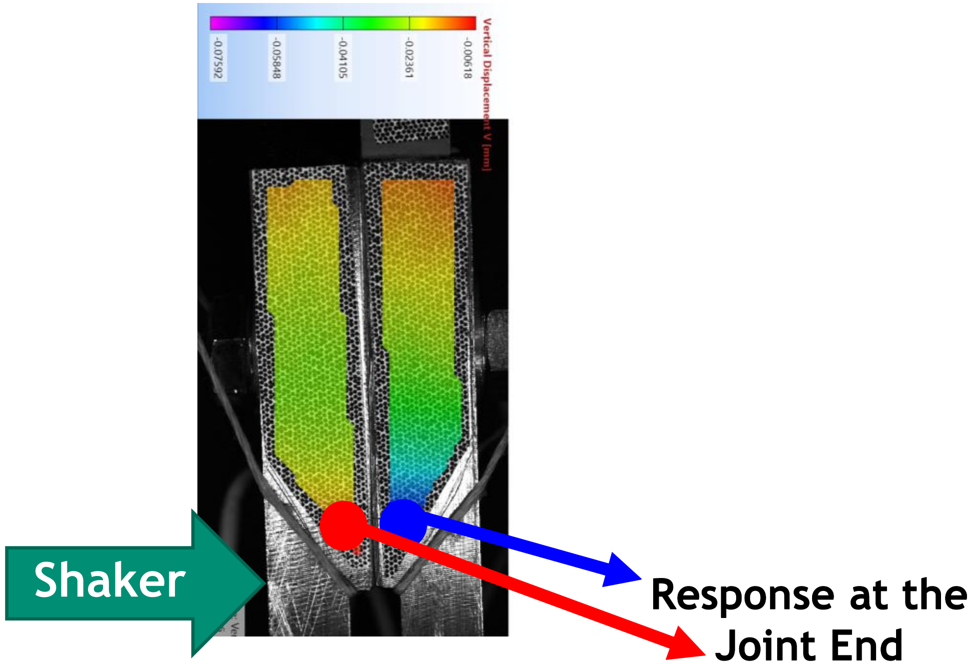
DIC Analysis



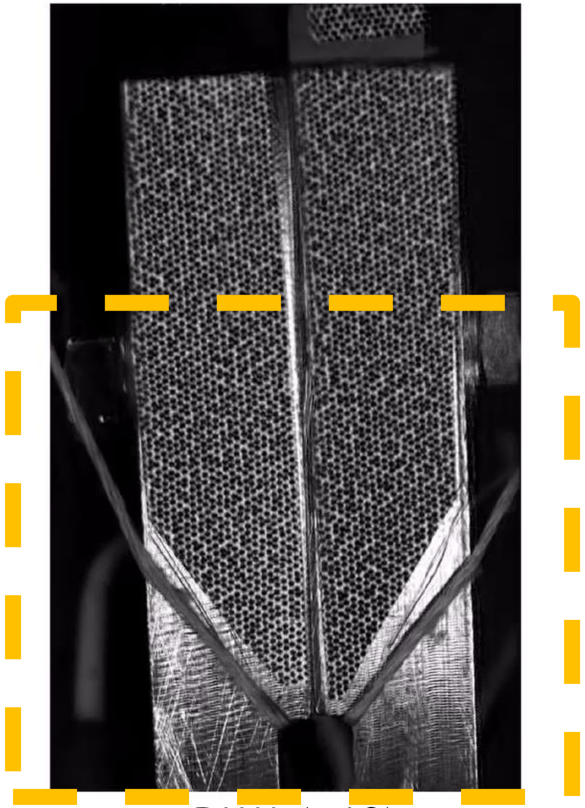
Normal Mode Testing: Joint Mechanics

DIC > PMM > Joint Mechanics > Joint Characterization

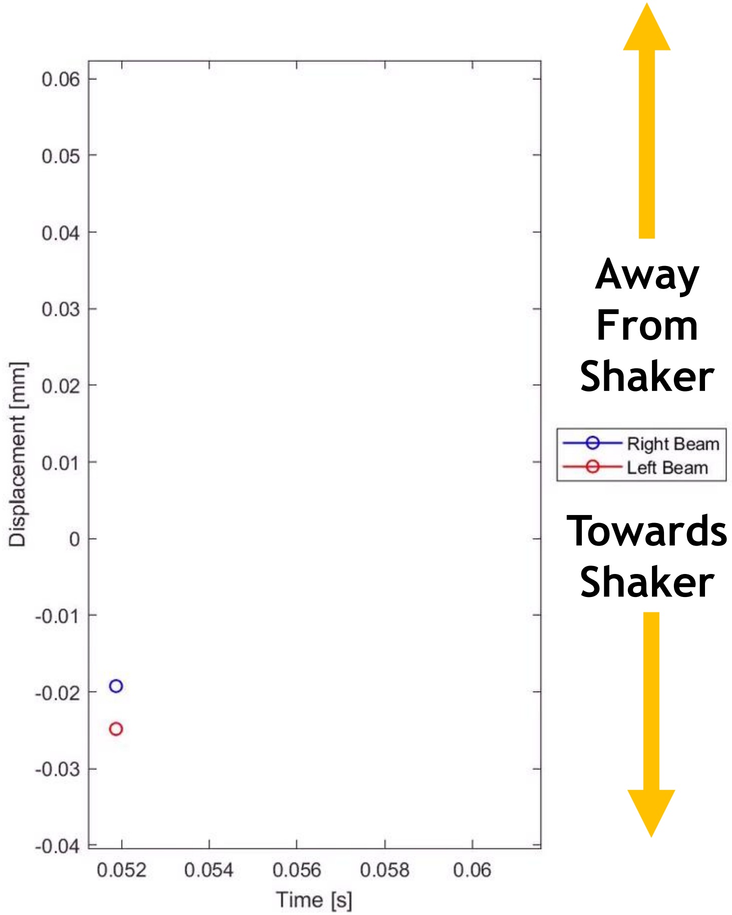
- DIC analysis and PMM were used to understand the beam response during one cycle of oscillation:
  - The right beam flexes freely, while the left beam is restrained by the shaker



DIC Analysis



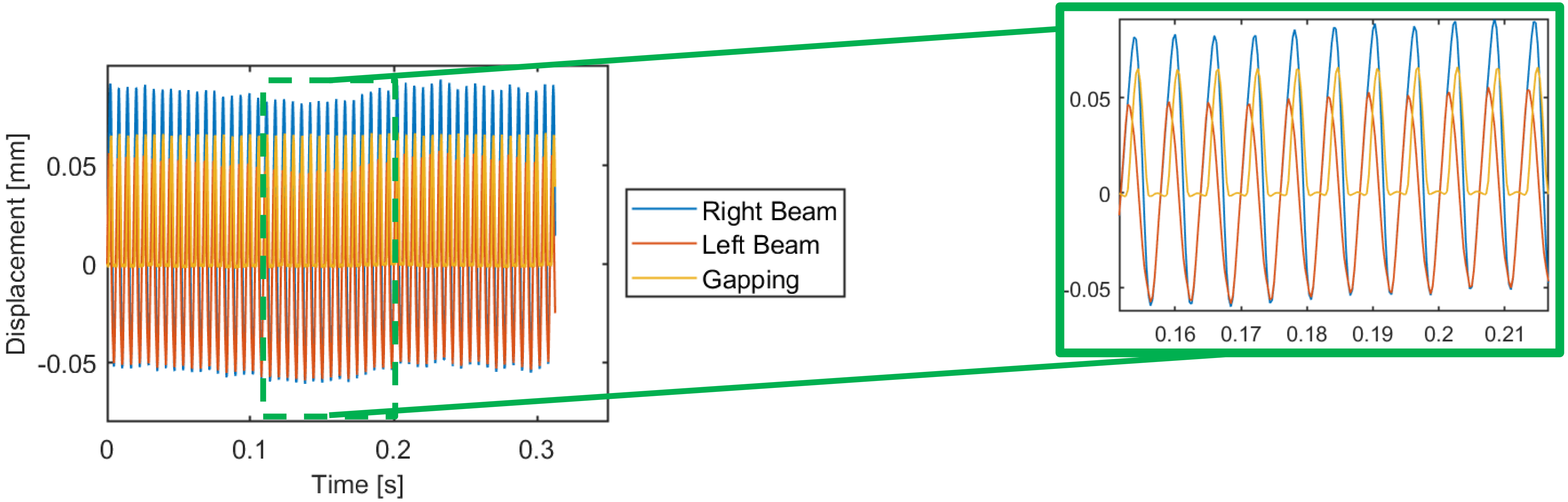
PMM (x10)



Normal Mode Testing: Joint Mechanics

DIC | PMM | Joint Mechanics | Joint Characterization

- DIC analysis were used to determine the gapping between beams



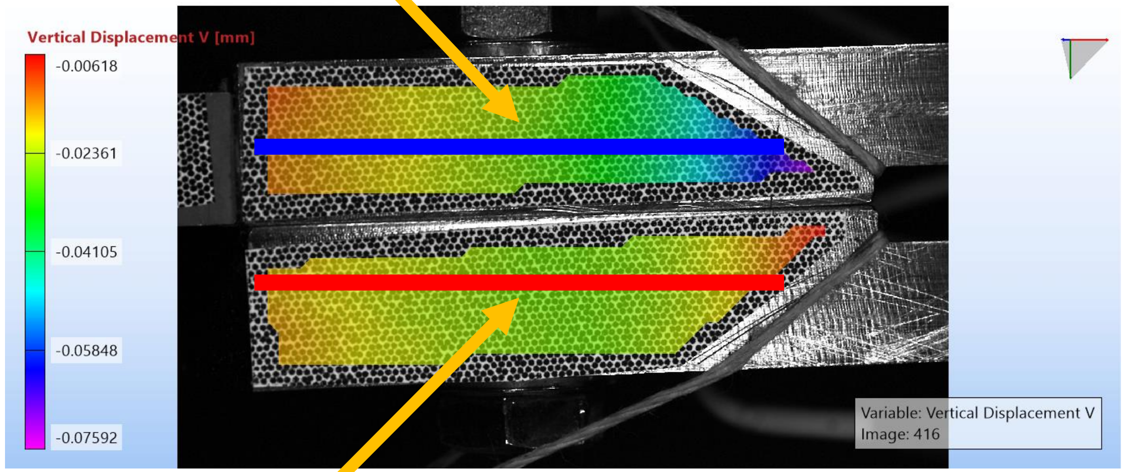
Joint Deformation at 0.4V

Normal Mode Testing: Joint Response Characterization

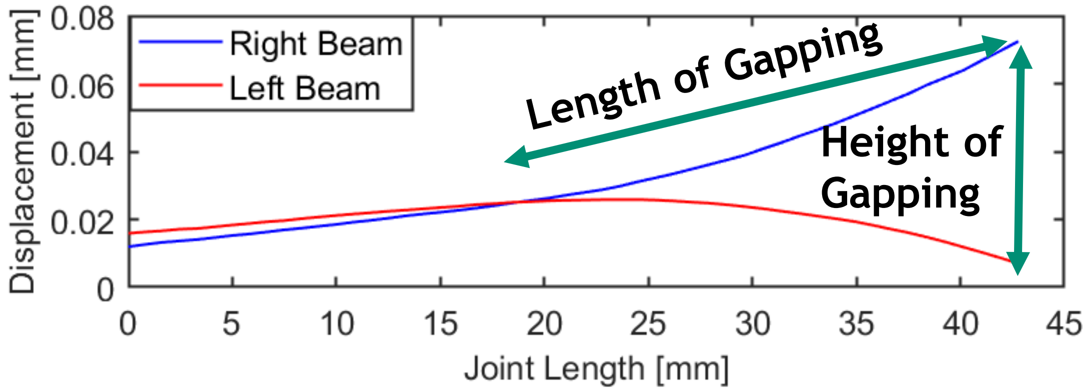
DIC > PMM > Joint Mechanics > **Joint Characterization**

- The length and height of the joint gapping were characterized using DIC analysis:

Response of the Right Beam



Response of the Left Beam



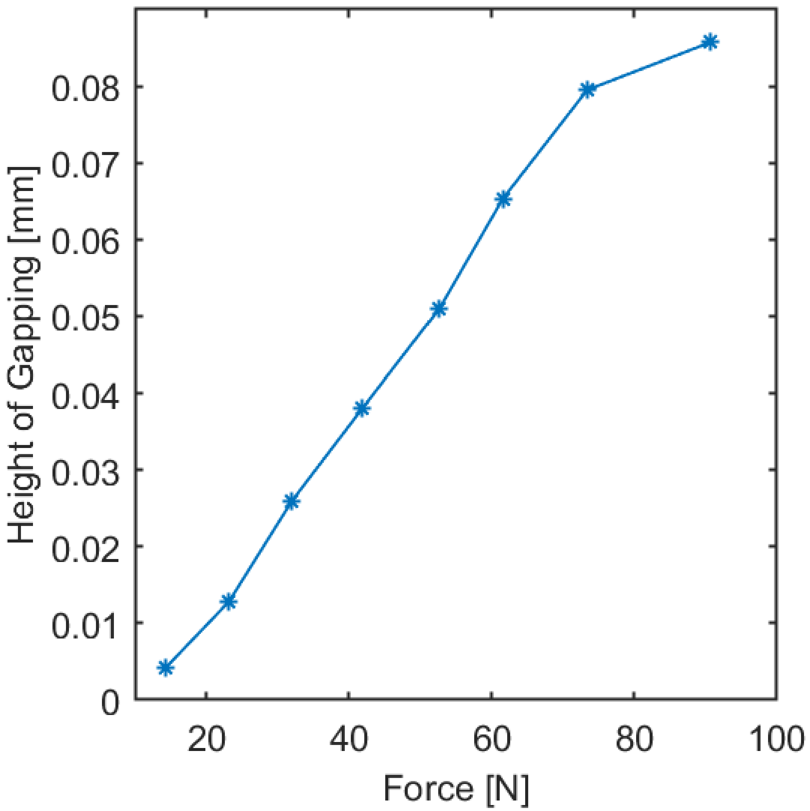
DIC Analysis at Maximum Joint Gapping (voltage level of 0.6V)

Joint Deformation at Maximum Gapping (voltage level of 0.6V)

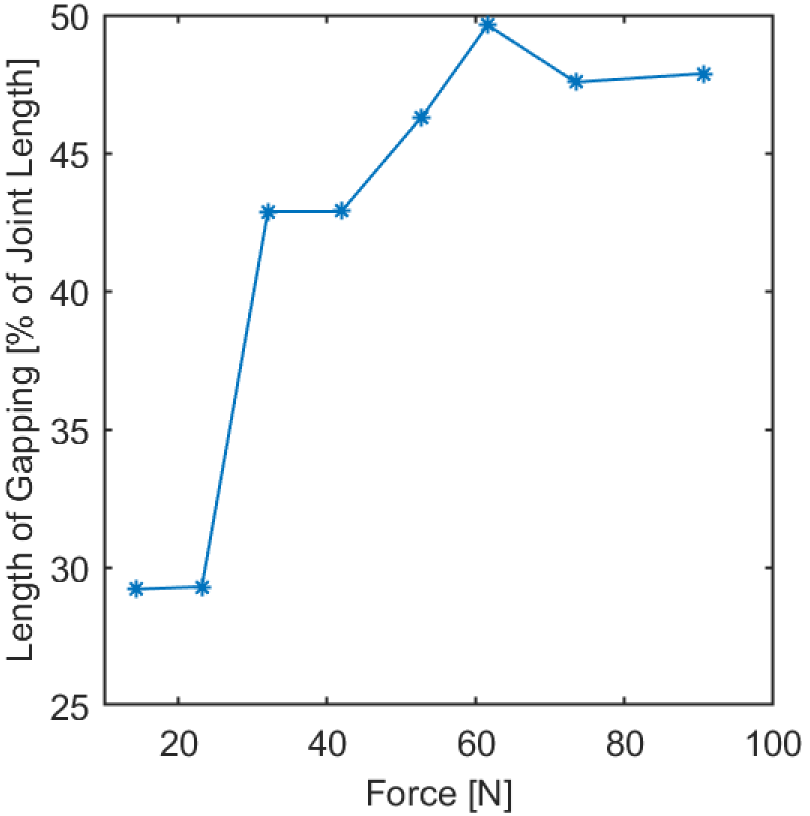
Normal Mode Testing: Joint Response Characterization

DIC | PMM | Joint Mechanics | Joint Characterization

- The height and length of gapping of the beam joint were characterized using the DIC results at each voltage (force) level



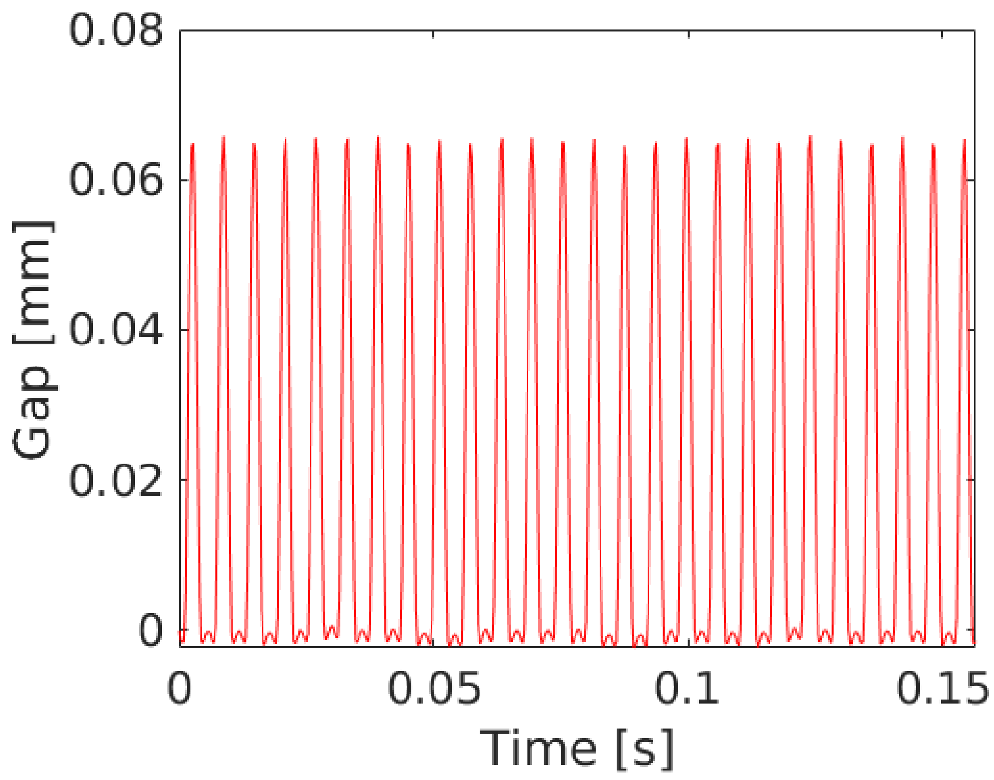
Height of Gapping Results



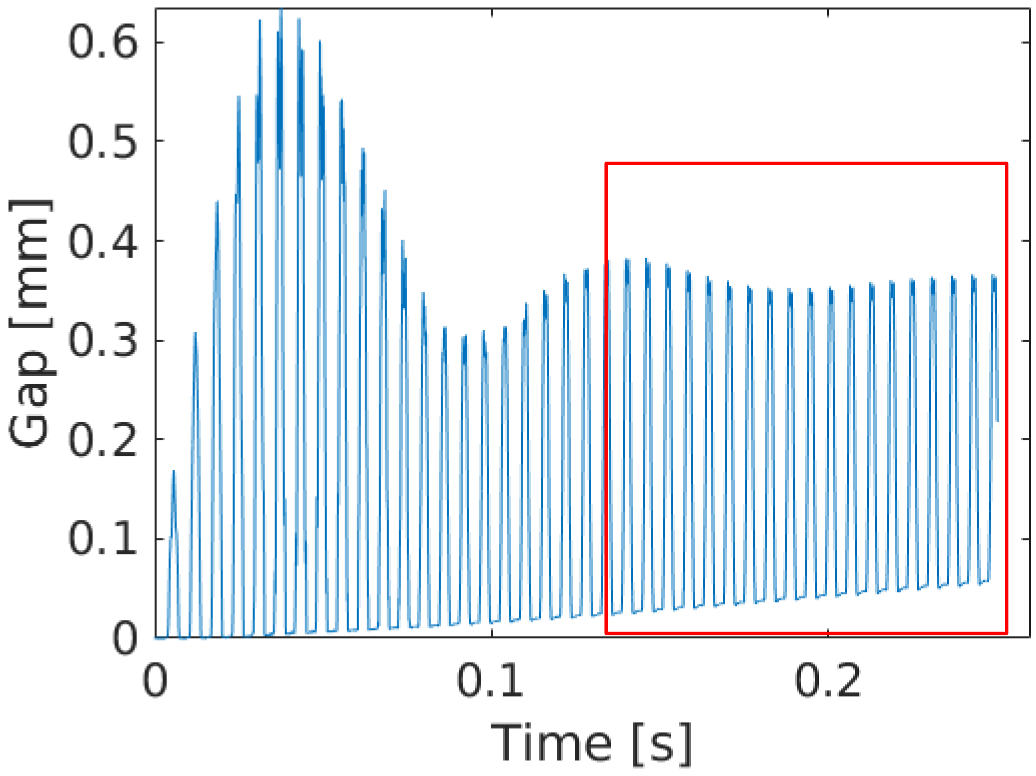
Length of Gapping Results

Normal Mode Testing: FEA Comparison (105N)

Gapping prediction for experimental: 0.07mm
Gapping prediction for FEM: 0.300 mm



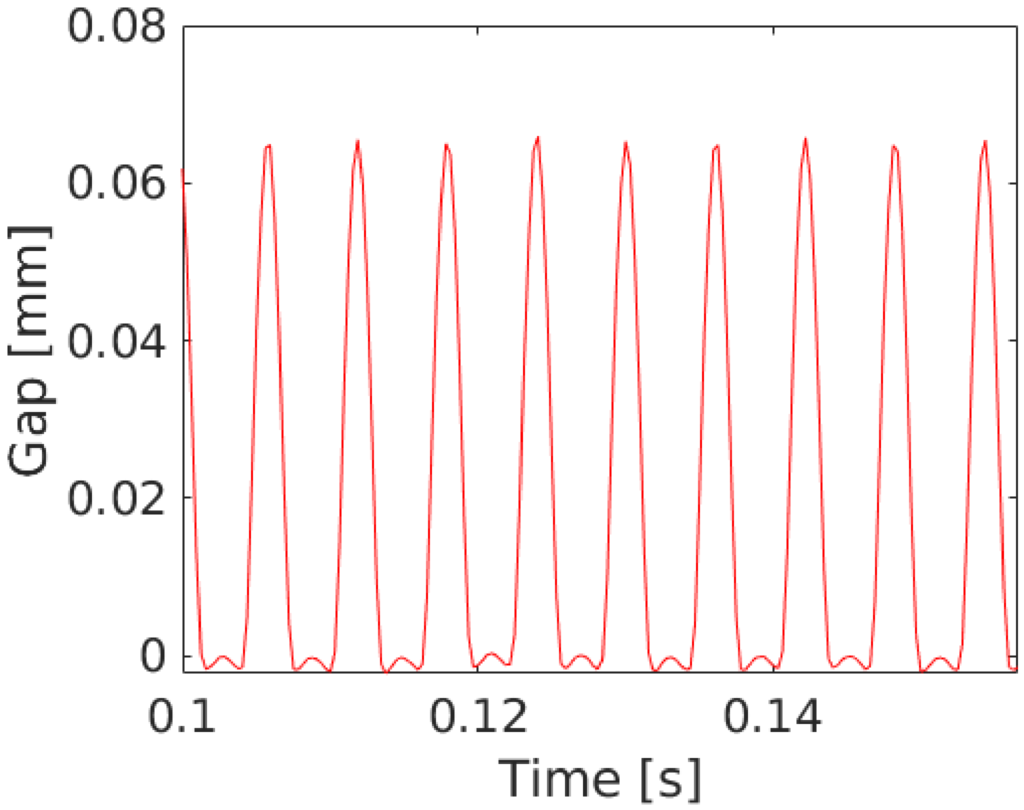
Experimental Results at 105 N



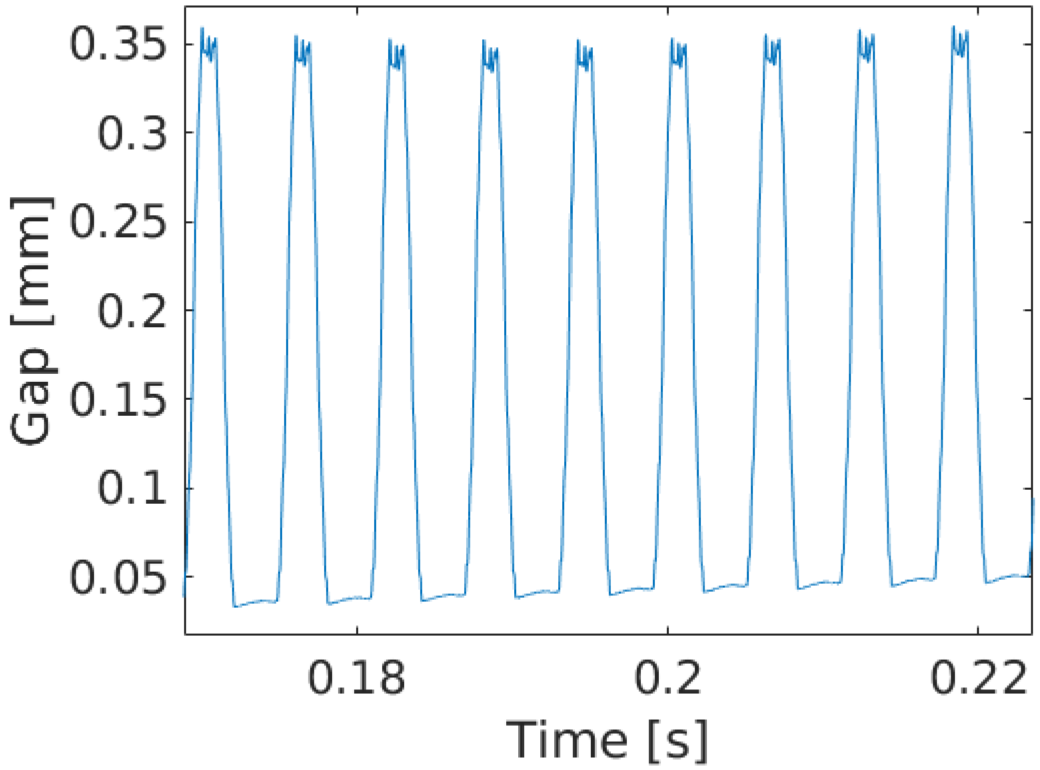
FEA Simulation Results at 105 N

Normal Mode Testing: FEA Comparison (105N)

Gapping prediction for experimental: **0.07** mm
Gapping prediction for FEM: **0.300** mm

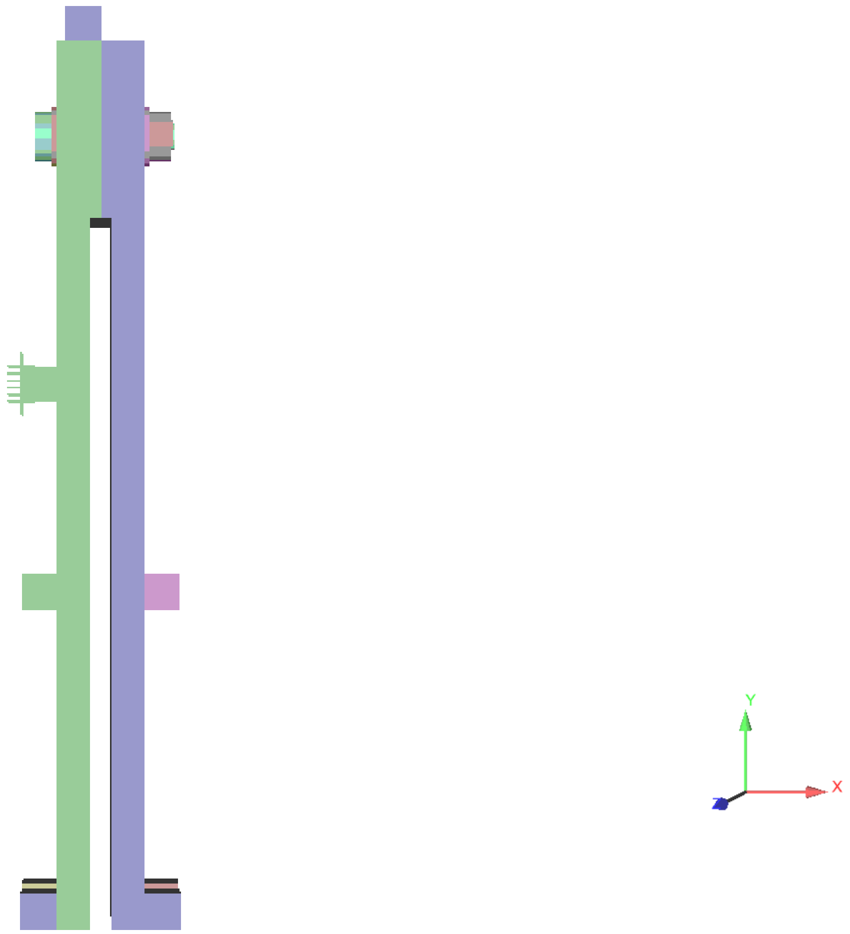


Experimental Results at 105 N Zoomed in

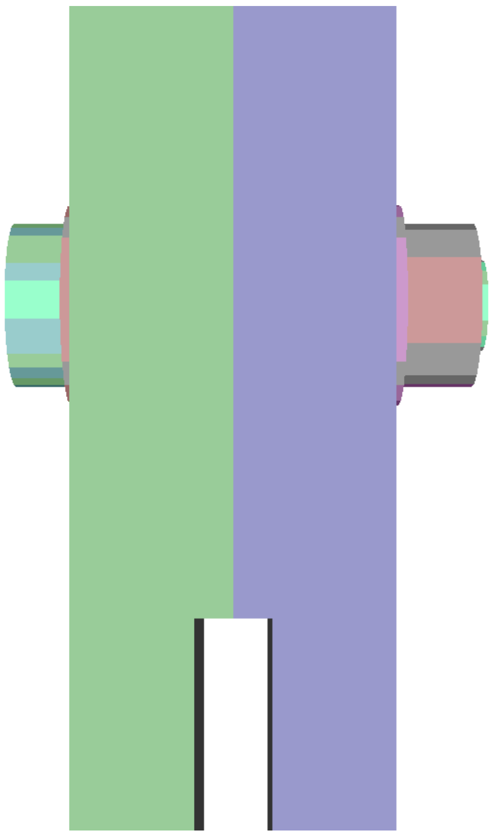


FEA Simulation Results at 105 N Zoomed in

FEA Displacement (105N)



Displacement at 105 N x10



Displacement at 105 N Zoomed in to the joint area x15

Conclusions/Future Work

- Nonlinearity of bolted joints are not well-understood
- High-speed imaging, DIC and PMM were used to characterize the nonlinear response of the bolted joint
- FEA results indicate a good qualitative agreement with experimental results
- Changes to the gapping behavior (length and height of gapping) were observed as function of the vibration amplitude

Future Work

- Study the impact of bolt torque on the nonlinear response of the beam
- Modify some of the input deck parameters for the FEA such as mass damping and coefficient of friction
- Add surface data to the FEA and analyze the results
- Optimize the contact definition to follow the experimental nonlinear behavior

Acknowledgments

- We would like to thank William (Bill) Flynn from Siemens for his assistance with the DIC setup and donating the cameras for the project
- We would like to extend our thanks to our mentors, Deborah Fowler, and Benjamin Moldenhauer for their guidance and support throughout the project

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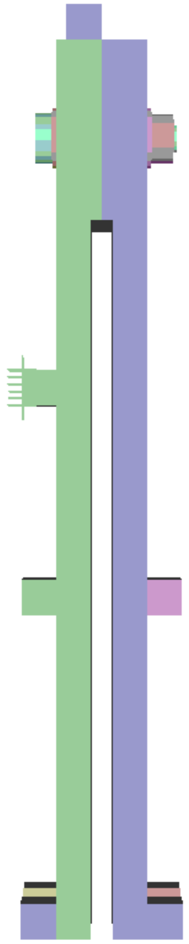
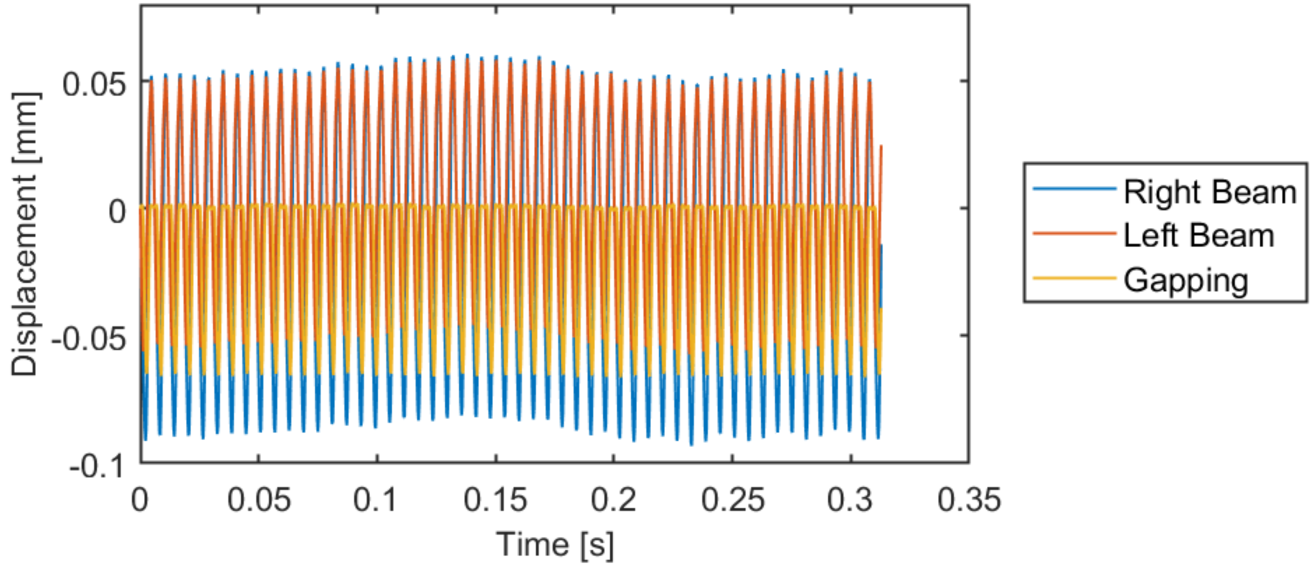
Appendix

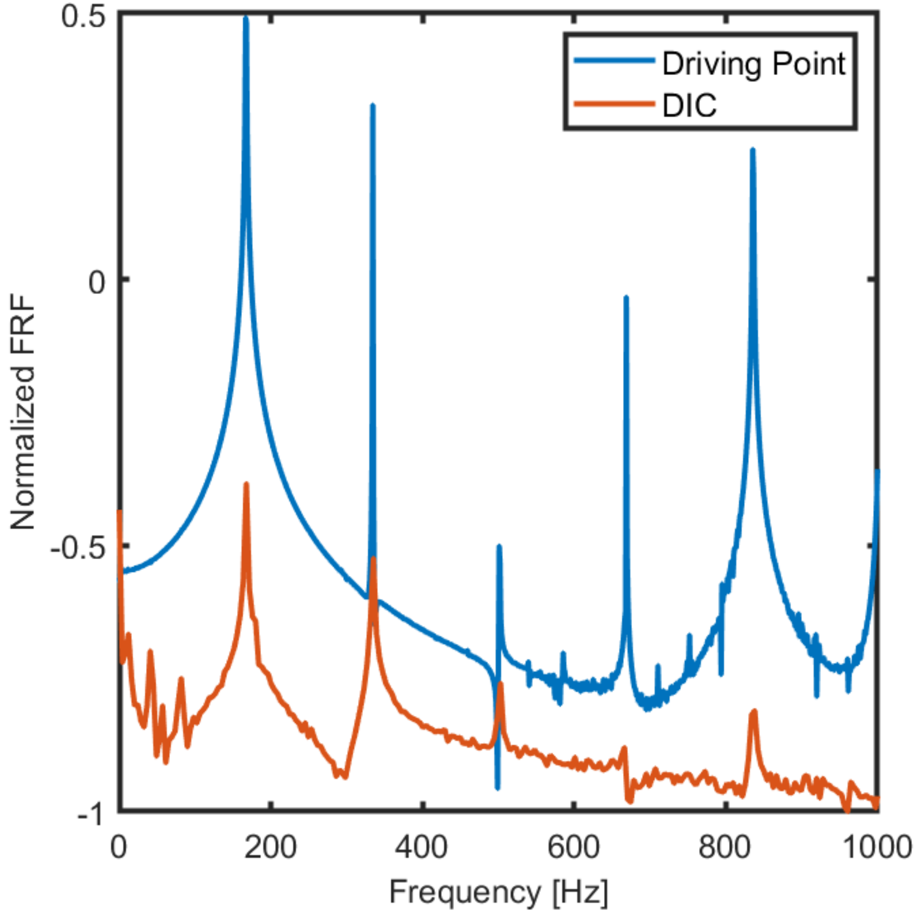


Displacement at 15 N

Appendix - Normal Mode Testing: Joint Mechanics

- DIC results were validated using the driving point accelerometer



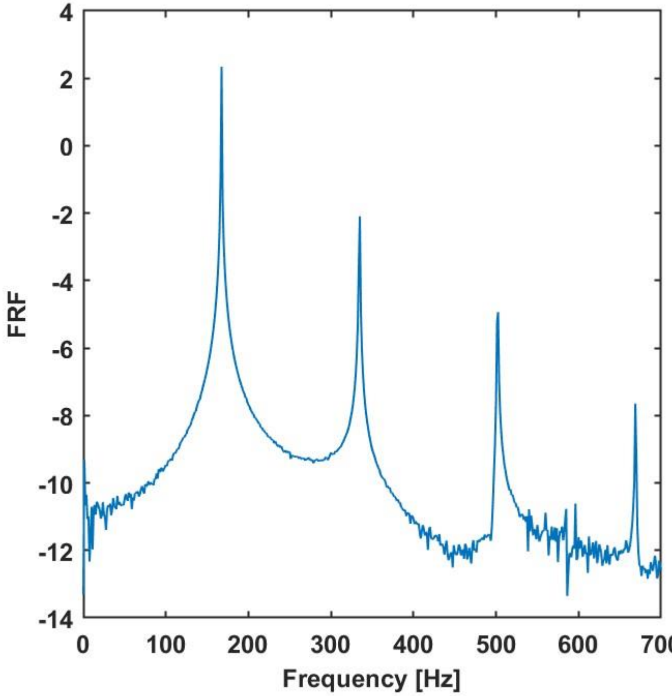


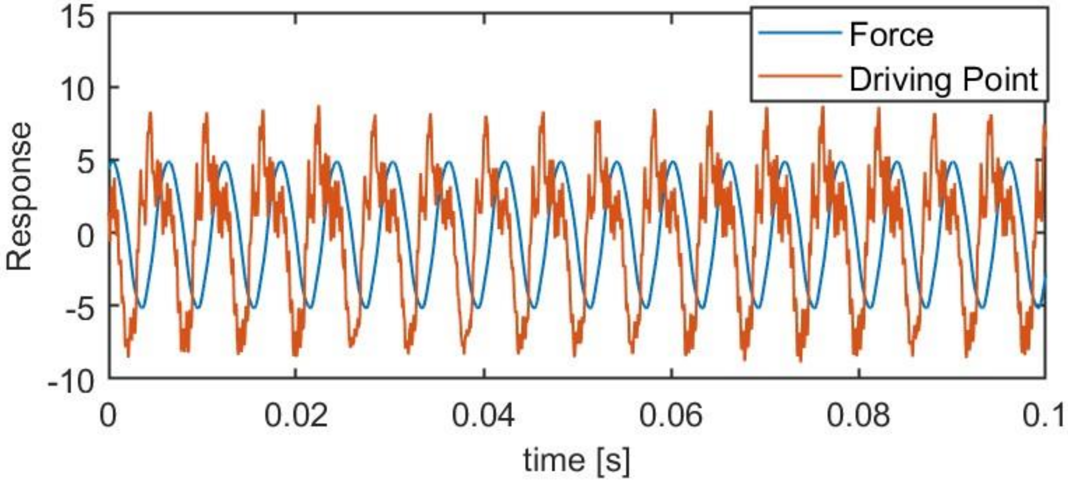
Appendix - Normal Mode Testing: Test Setup

- Sine dwell tests were conducted to excite the beam's first mode at different levels of excitation: 0.1 — 0.8V

- Active close loop was used to maintain a ~90° phase difference between the driving force and driving-point response (i.e., phase locking)

- The steady-state response of the beam was recorded using the high-speed cameras

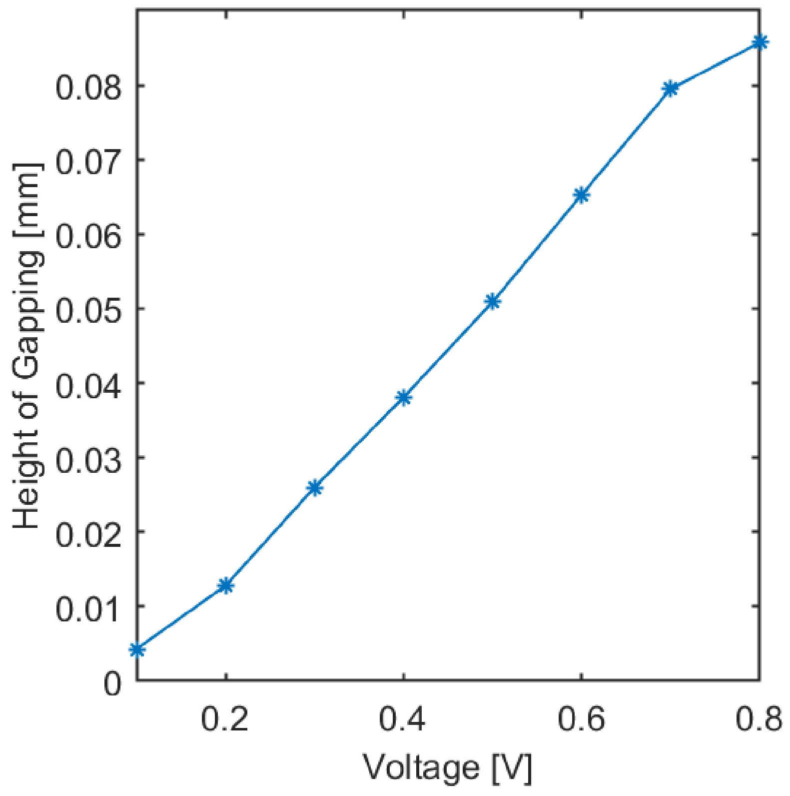




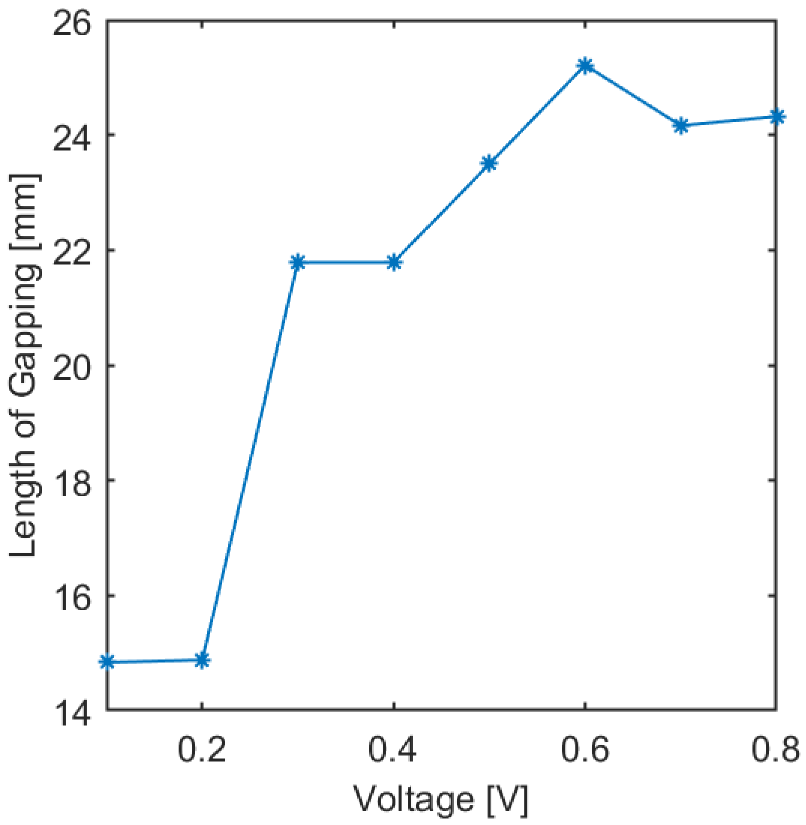
Appendix - Normal Mode Testing: Joint Response Characterization

DIC | PMM | Joint Mechanics | Joint Characterization

- The gapping and length of gapping of the beam joint were characterized using the DIC results at each voltage (force) level



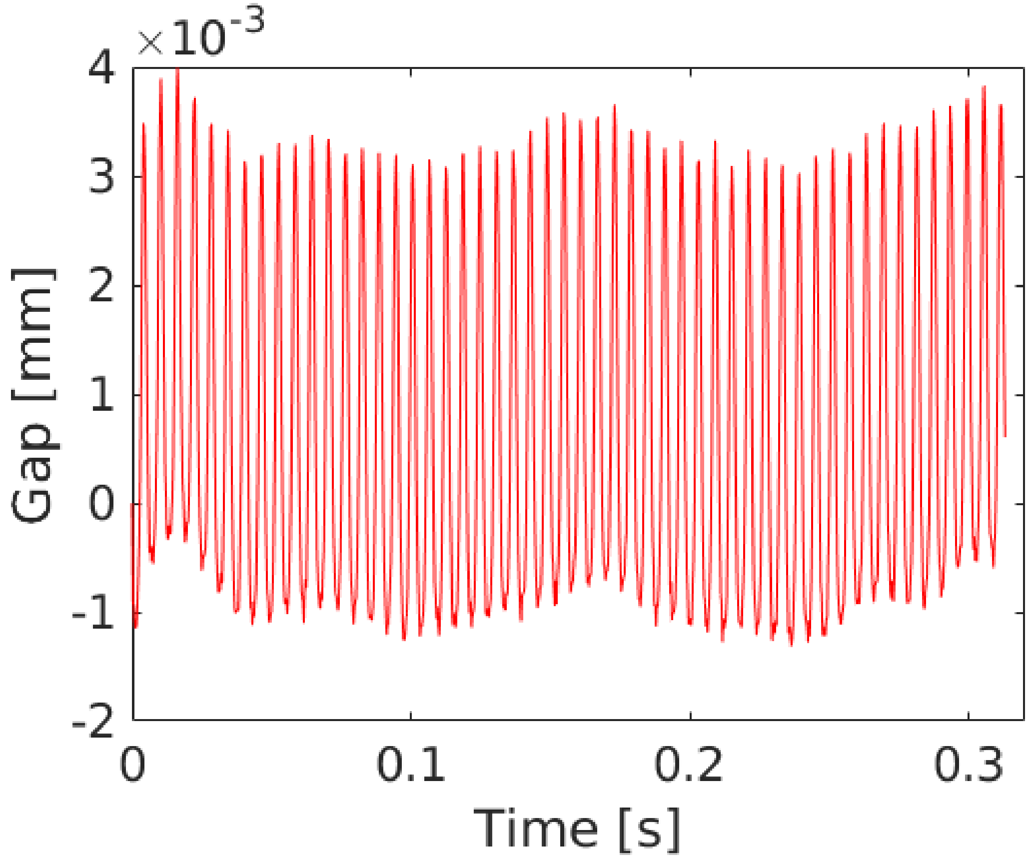
Height of Gapping Results



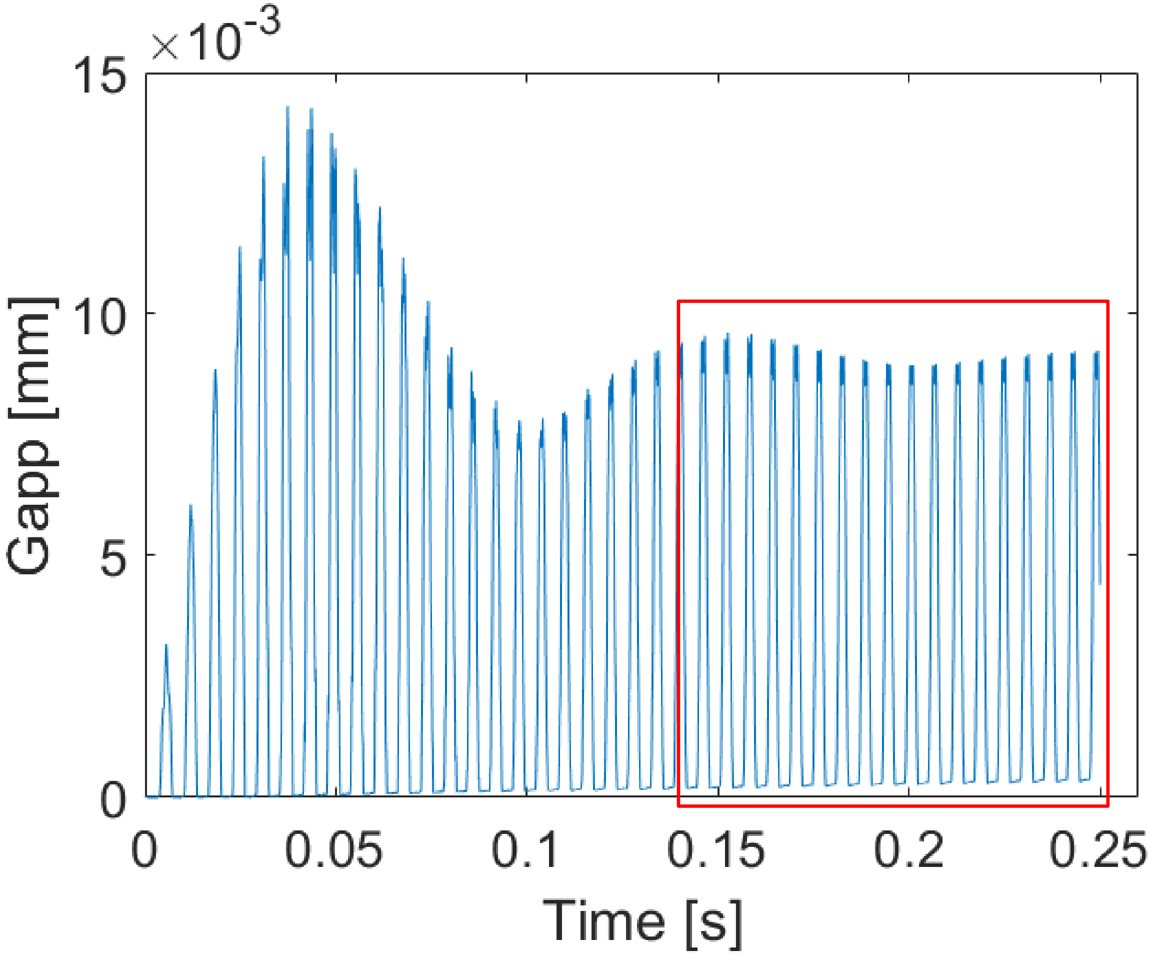
Length of Gapping Results

Normal Mode Testing: FEA Comparison (15 N)

Gapping prediction for experimental: $4.555E^{-03}$ mm
Gapping prediction for FEM: $9.20E^{-03}$ mm



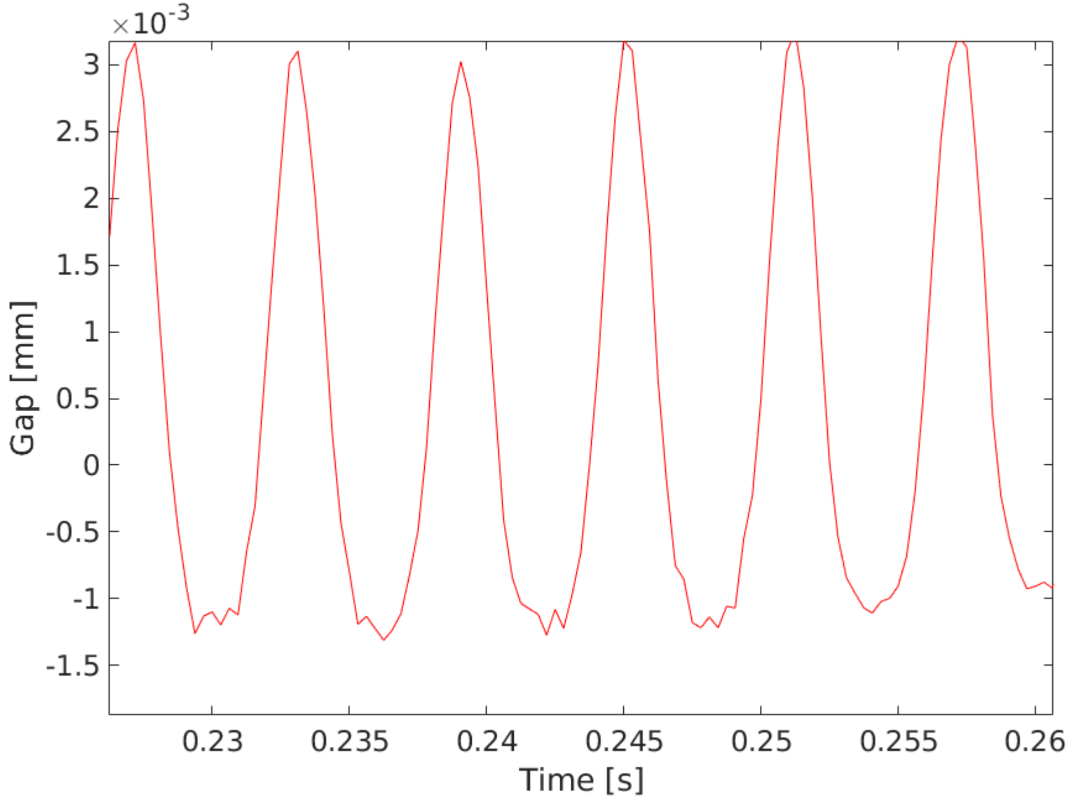
Experimental Results at 15 N



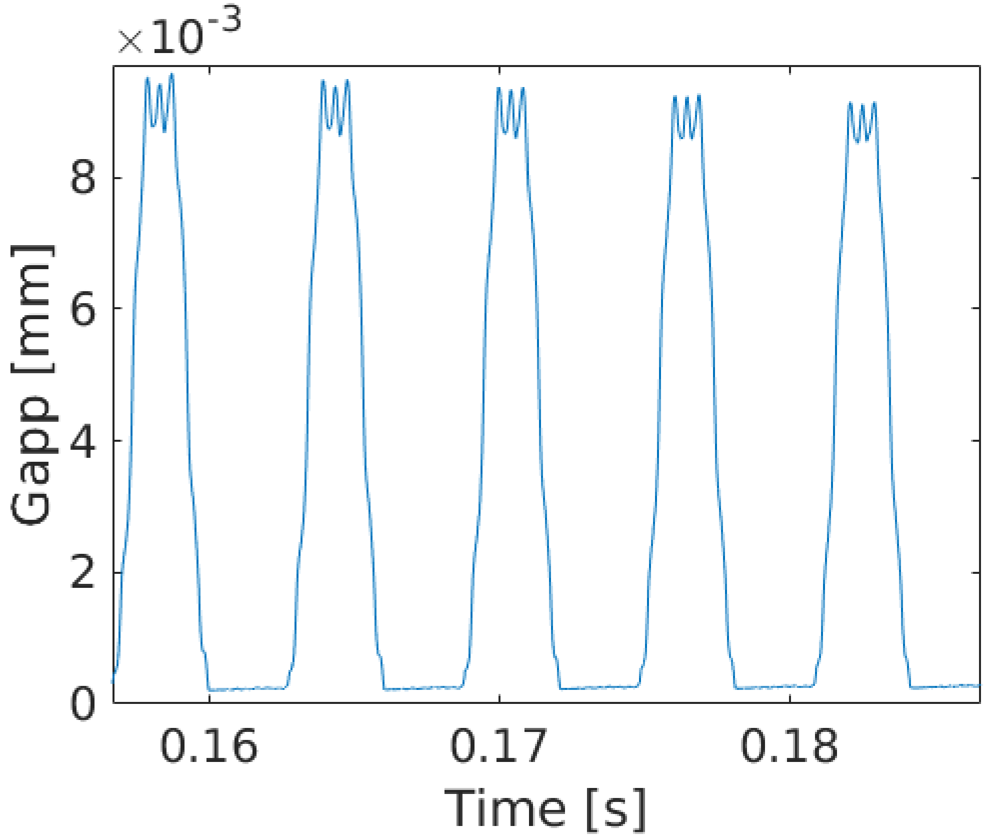
FEA Simulation Results at 15 N

Normal Mode Testing: FEA Comparison (15 N)

Gapping prediction for experimental: $4.555E^{-03}$ mm
Gapping prediction for FEM: $9.20E^{-03}$ mm

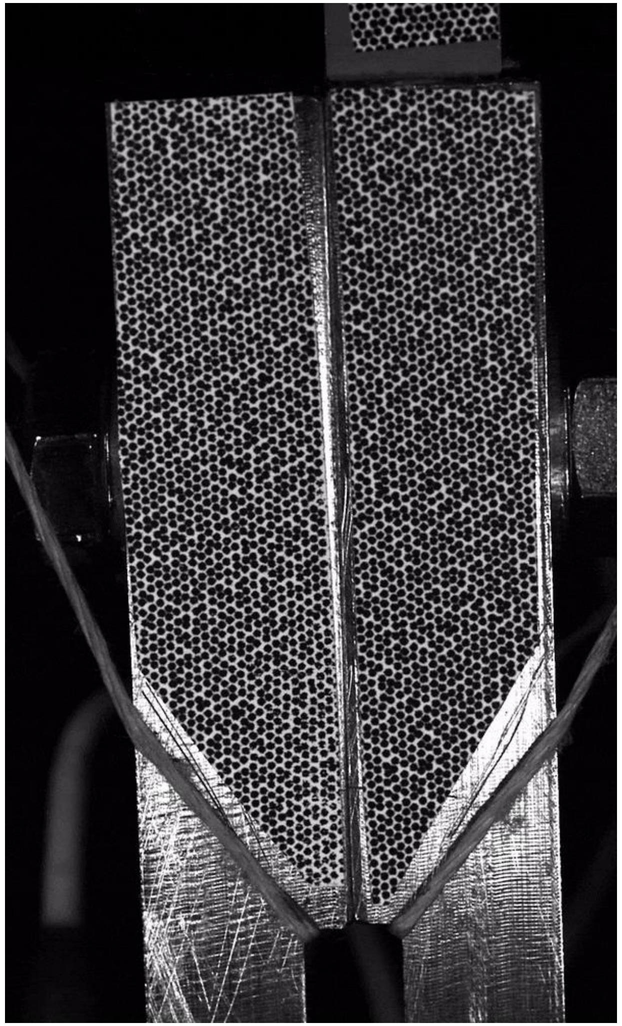


Experimental Results at 15 N



FEA Simulation Results at 15 N Zoomed in

Normal Mode Testing: Phase-based Motion Magnification



Raw Video

X7 Magnified