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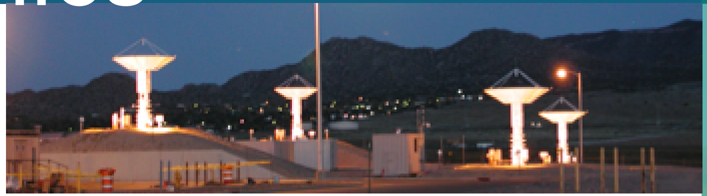
Sandia National Laboratories

Failing to Fail: Lessons Learned from Attempting to Fatigue a Bolt Using Structural Dynamics



PRESENTED BY

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IMAC XL

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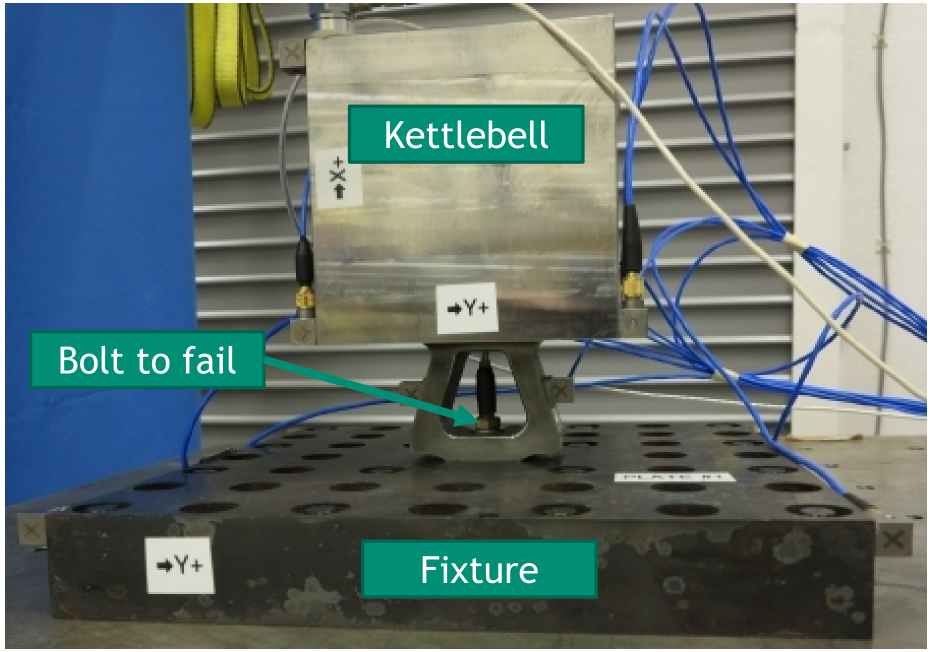
Motivation

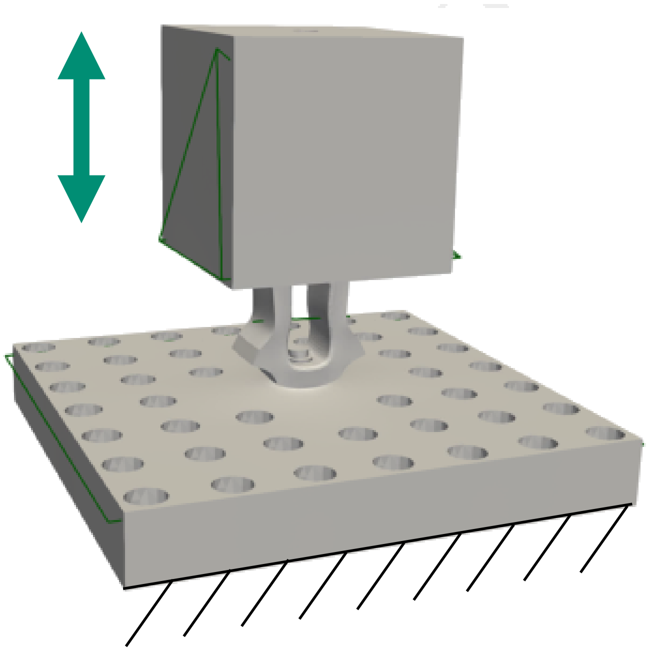
- Understanding fatigue failure of bolts in various dynamic environments is an important aspect in the design of jointed structures
  - While fatigue life data of isolated bolts exist, there are additional challenges in predicting fatigue failure in the context of a joint under extreme dynamic loading
- Ideally, a finite element model (FEM) would be utilized which could predict the fatigue life of the bolt given the external loading of the dynamic environment
- To evaluate this capability, an effort was undertaken to determine how well a linear FEM could predict fatigue failure of a bolt within a joint
- The results of the modeling portion of this effort were presented at IMAC 39 [1] and are continued during a presentation at IMAC 40 [2].
- **This presentation is focused on the development of the fatigue test and corresponding results**

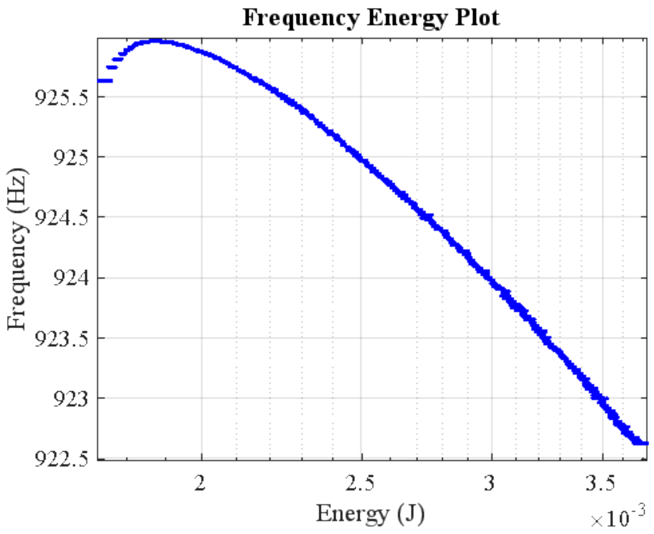


[1] Khan, M. et al "Evaluation of Joint Modeling Techniques Using Calibration and Fatigue Assessment of a Bolted Structure," *Proceedings of the 39th International Modal Analysis Conference*, virtual, 2020
[2] Submission 12411 "Nonlinear Characterization of Joint Exhibiting a Reduction in Damping at Higher Energy", Session 54 Jointed Structures II

Test Approach

- The motivation for this work is to design and conduct an in-situ fatigue test to study the fatigue failure of a bolt within a joint during a dynamic environment
- As a first attempt, the approach was to excite and dwell at the axial mode of the structure with a modal shaker until the bolt failed
  - The response of the Kettlebell would load the bolt axially
  - Literature review indicated this would be the easier failure mode
- In order to apply the appropriate stress to the bolt, the structure had to be excited to a high level
- The joint is a source of nonlinearity within the structure, so the resonant frequency shifted as the amplitude of excitation increased
- Therefore, a closed loop controller was used to maintain resonance as the structure was brought up to the proper testing amplitude. **This test method is called nonlinear**

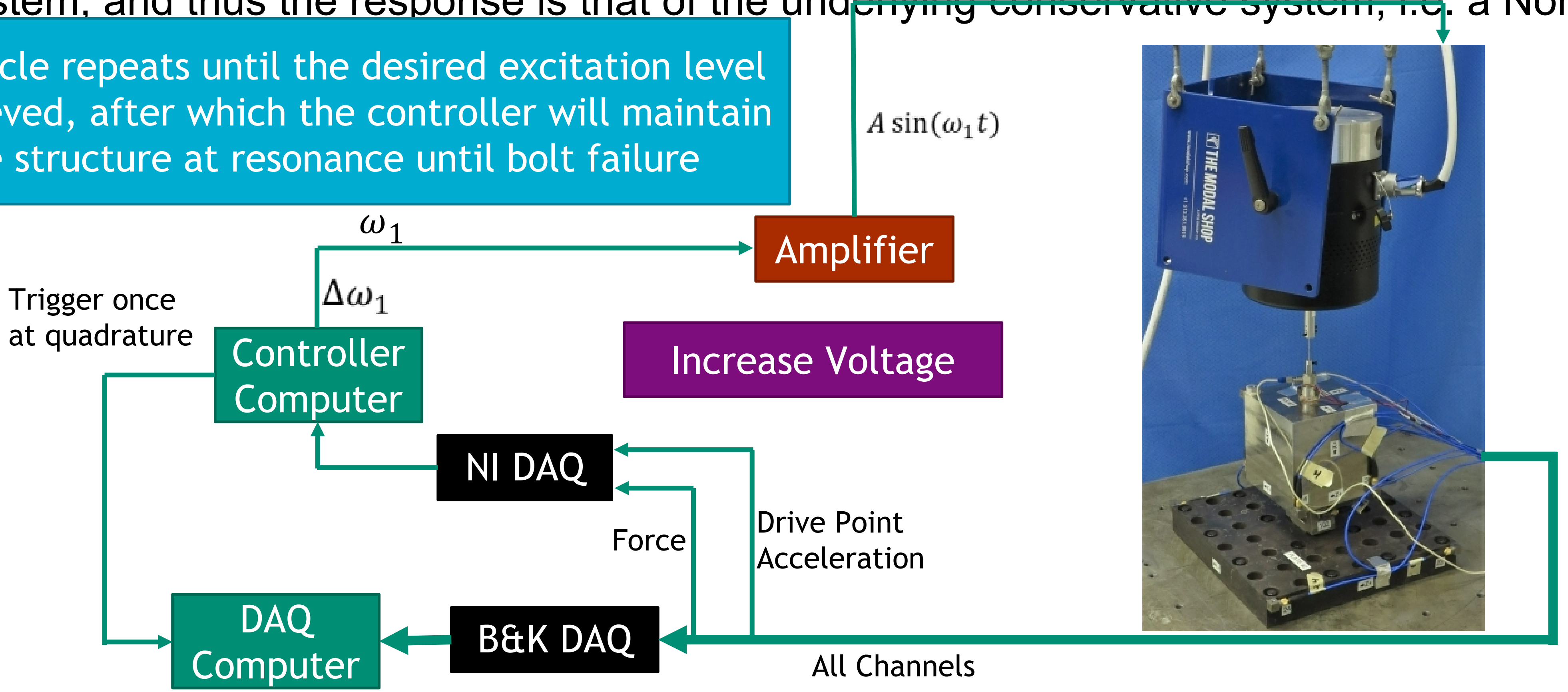




Test Method—Nonlinear Force Appropriation

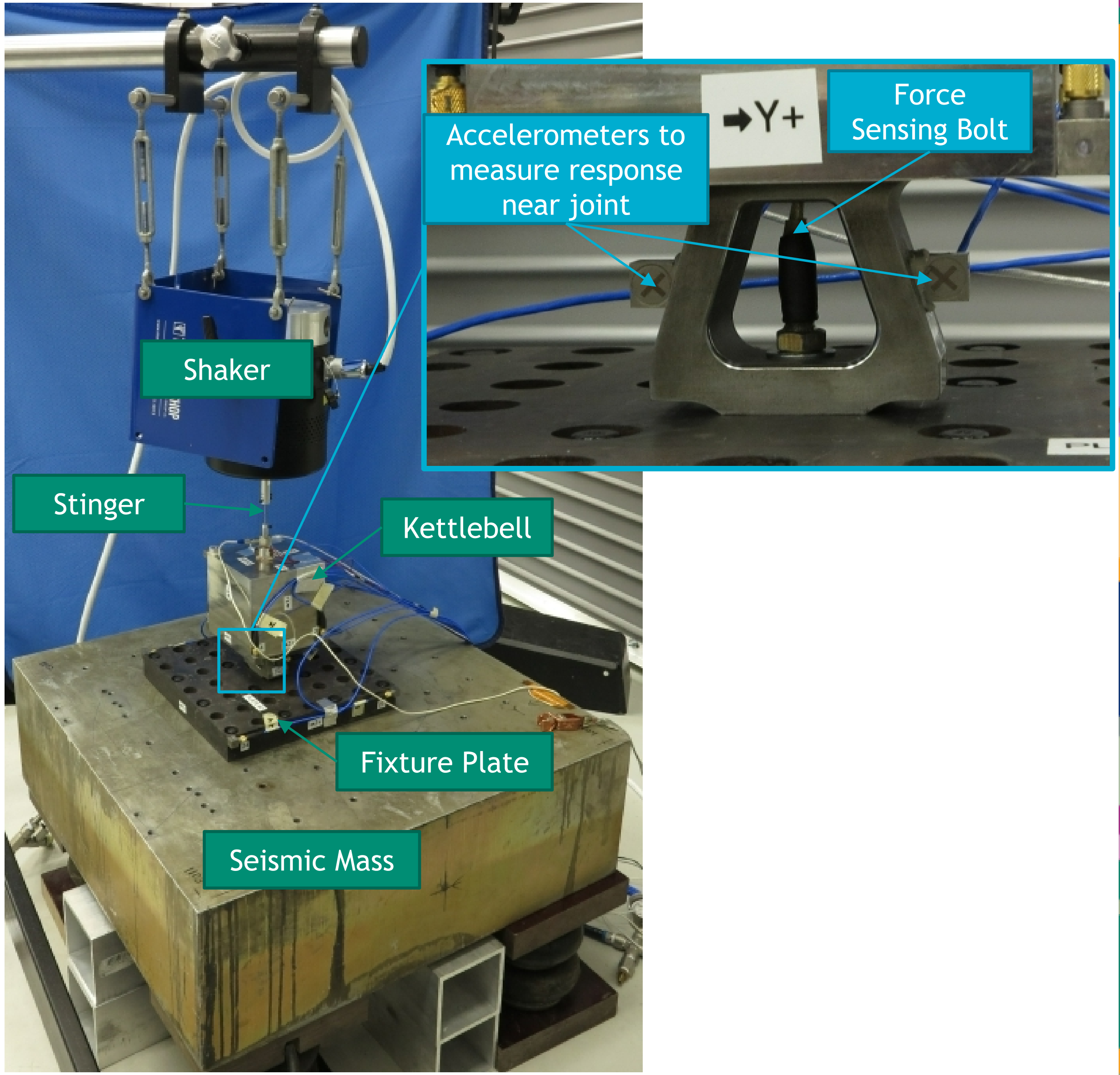
- Nonlinear force appropriation is a method used in nonlinear structural dynamics testing where the excitation is maintained at 90° out of phase (i.e. in phase quadrature) with the acceleration response
- Under this phase condition, the excitation is assumed to balance the energy dissipated by the system, and thus the response is that of the underlying conservative system, i.e. a Nonlinear

This cycle repeats until the desired excitation level is achieved, after which the controller will maintain the structure at resonance until bolt failure



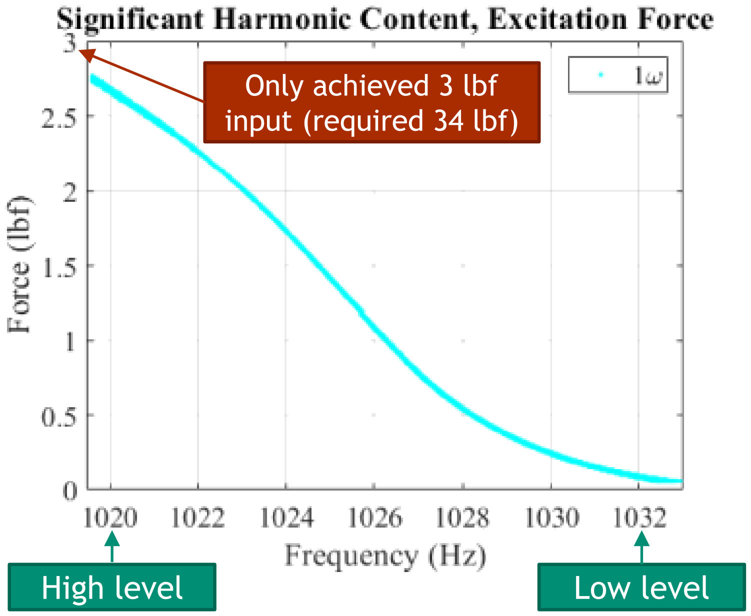
Test Set Up

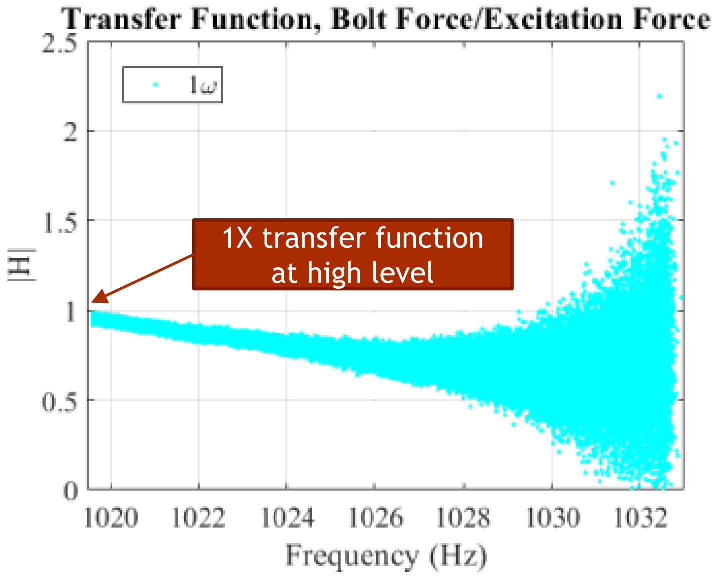
- The Kettlebell was attached to Fixture Plate using a force sensing bolt. This allowed for monitoring the force in the bolt during assembly and testing.
- This assembly was bolted to a seismic mass to approximate a fixed-base condition
- A modal shaker was used for excitation
- Excitation force and responses were measured with a load cell and accelerometers, respectively
- According to initial linear analysis results and basic fatigue calculations, **170 lbf are required in the bolt to fail it in fatigue**.
- To accomplish this, the test must satisfy the following
  - Excite only the axial mode
  - 5X amplification from excitation force to bolt force
  - 34 lbf excitation force to top of Kettlebell

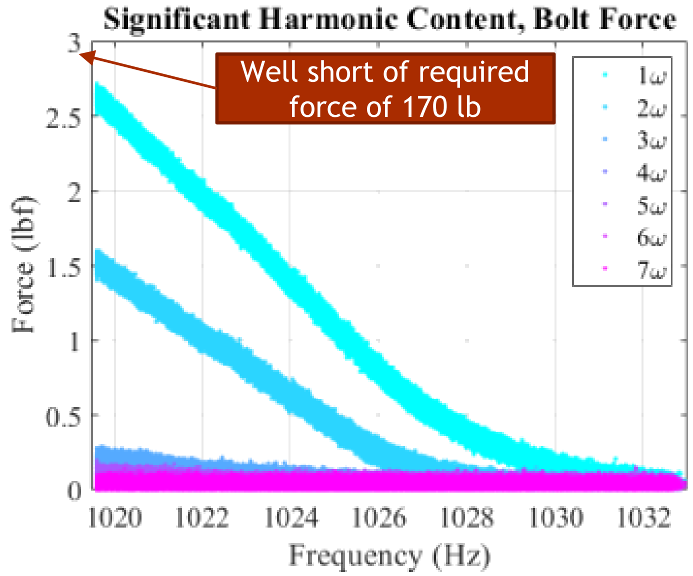


Attempt #1—Fully Torqued Bolt

- NFA was conducted on the structure where the bolt had a preload of 2,100 lbf.
- During testing, the electrical limit of the shaker amplifier was reached, but insufficient load was applied to the bolt in order to fail it in fatigue



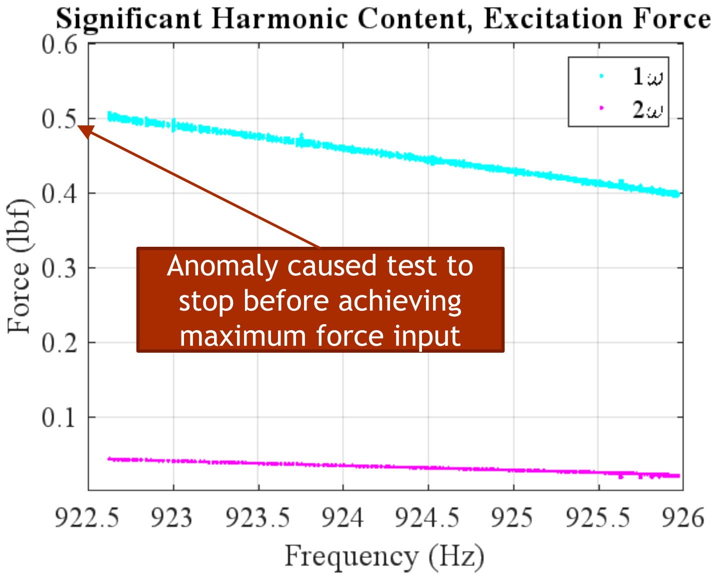


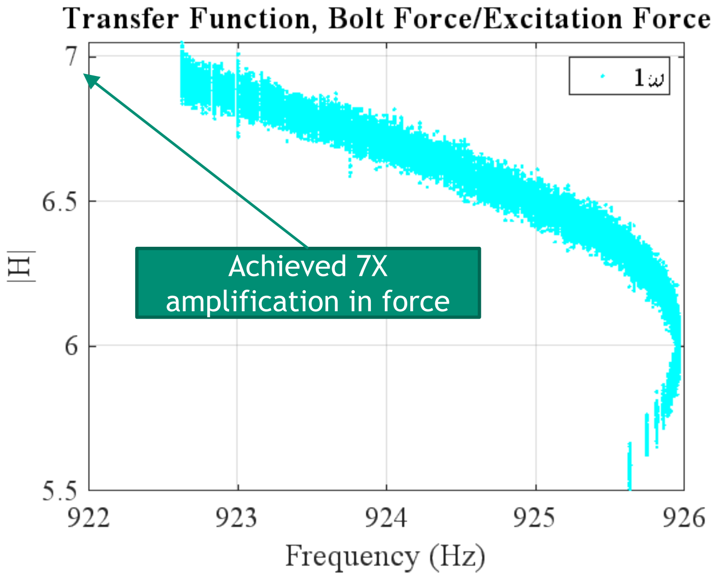


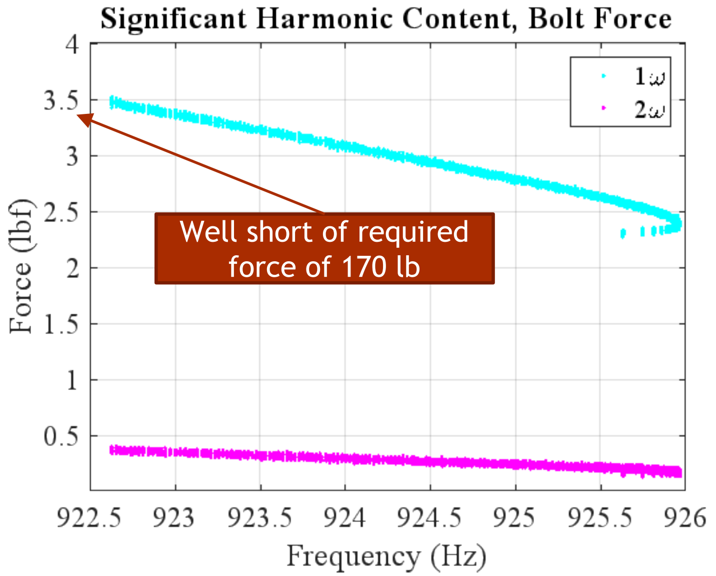
Too much of the joint force was carried by the Kettlebell and Fixture material at the interface. Therefore, **the torque was greatly reduced so that the bolt would take more of the load.**

Attempt #2—Reduced Torque

- The Kettlebell bolt force at assembly was reduced from 2,100 lbf to about 250 lbf
  - This reduced force should quicken the onset of the preload loss of the joint, resulting in larger bolt forces



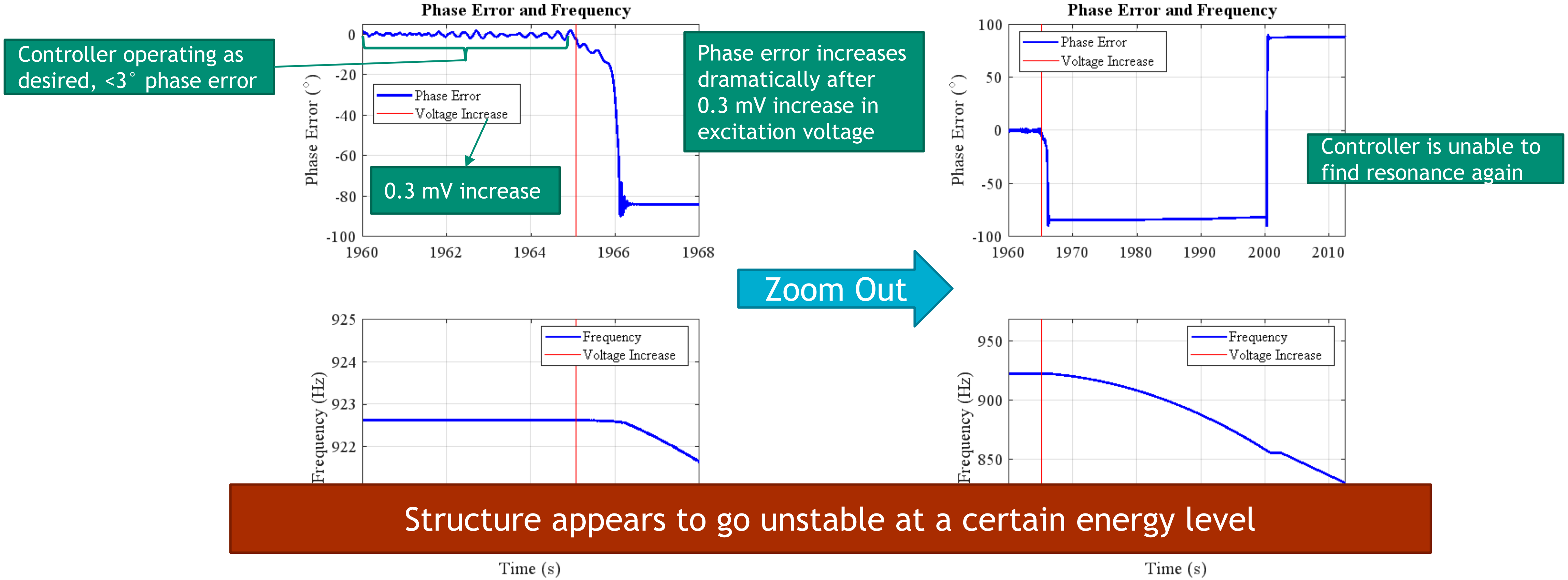




These results were promising, but an anomaly stopped the test before the desired fatigue conditions could be met.
WHAT HAPPENED?!

Attempt #2—Reduced Torque, NFA Results

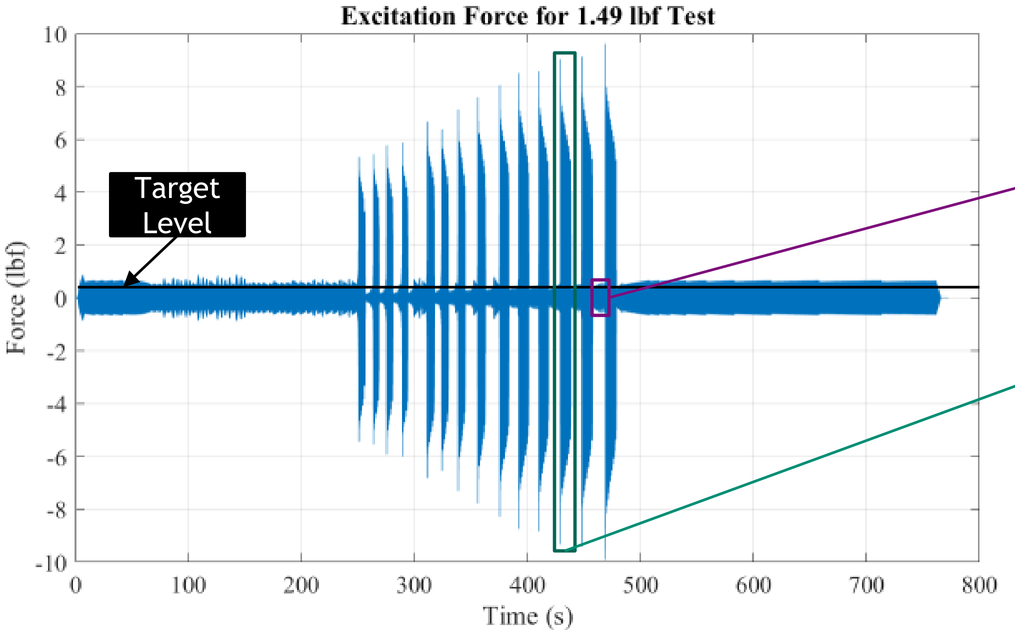
- During the NFA, a threshold was reached where
  - There was a noticeable change in the dynamics
  - The controller could no longer maintain the structure at resonance
- Many additional NFAs were conducted and a similar event happened every time

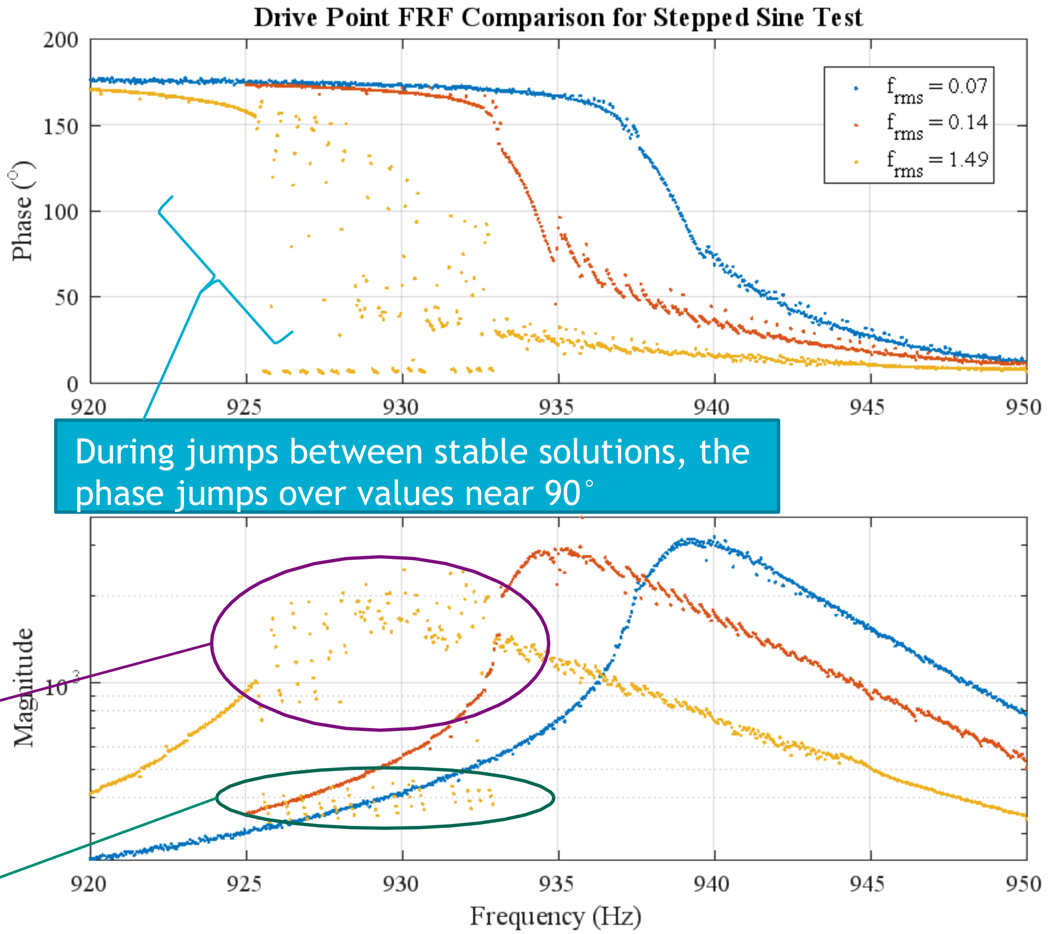


Structure appears to go unstable at a certain energy level

Attempt #2—Reduced Torque, Stepped Sine Results

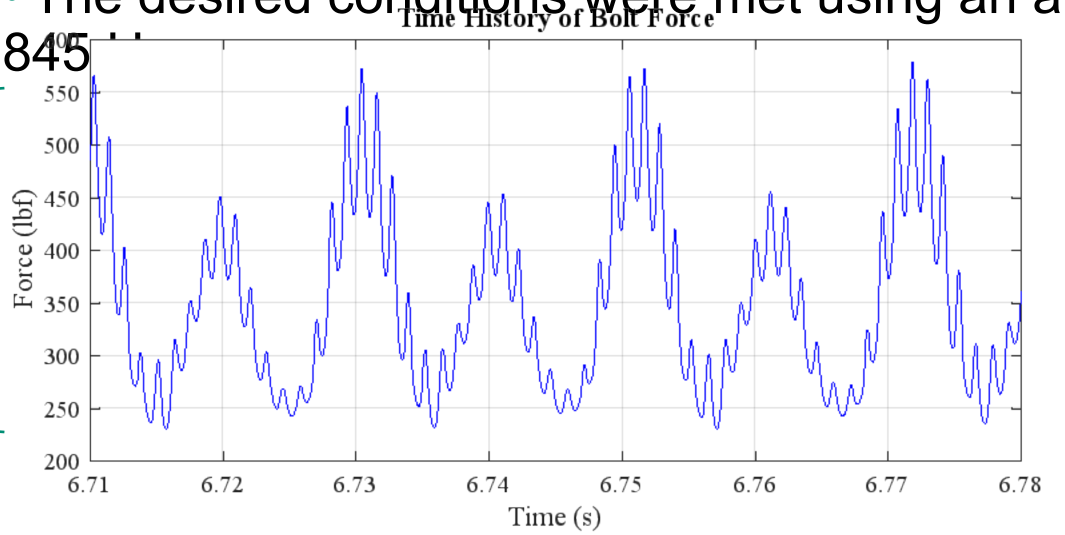
- To help diagnose the NFA test results, stepped sine tests were conducted at different force levels
  - Force control used to maintain a specified level throughout each test
  - Generally performed well except in the instances where the system was unstable
- At high forcing, there appeared to be stability issues as the system vacillated between two different states



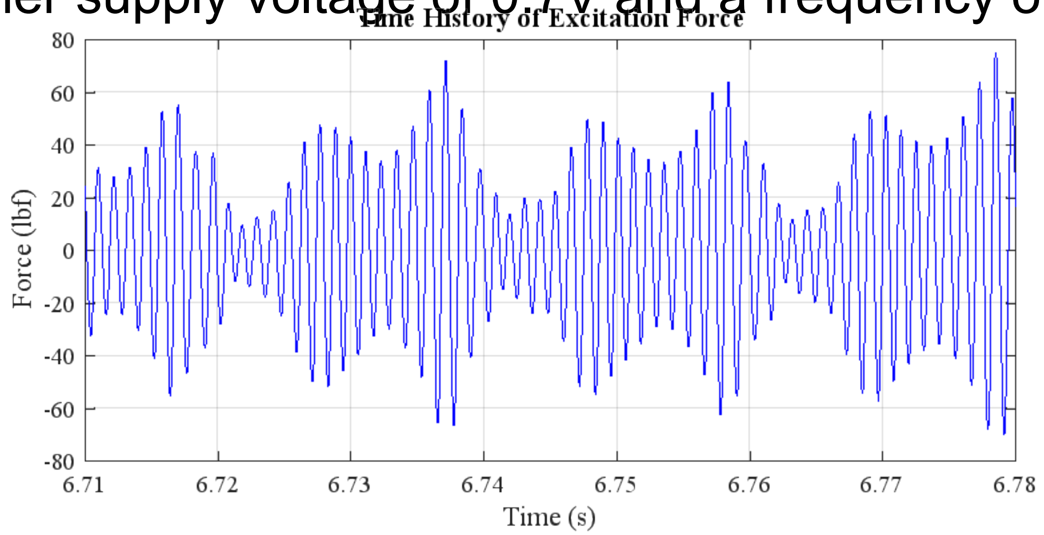


Ad Hoc Test Method Investigation

- The Attempt #2 results demonstrated that with the current controller that **NFA was not a viable option** to conduct the fatigue test and **was thus abandoned**
- There was a hope that the instability was only present for a limited voltage range
- A series of sinusoidal ad hoc testing was conducted at different voltage levels with frequencies near 900 Hz to determine if the desired bolt force could be achieved within the physical limitations of the shaker
- The desired conditions were met using an amplifier supply voltage of 0.7V and a frequency of 845



Bolt force is 300 lbf, nearly double the 170 lbf required according to initial predictions



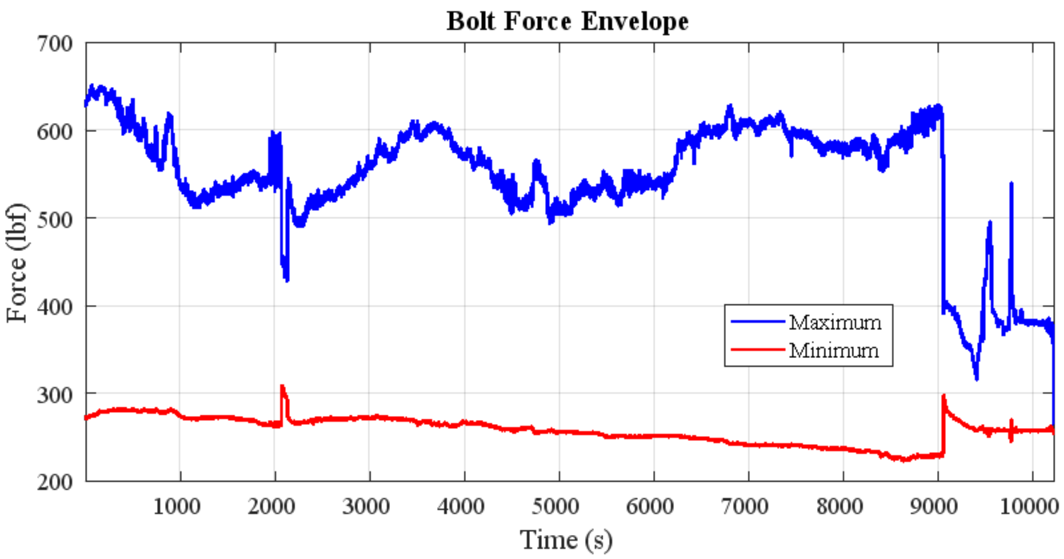
Shaker force remains below 100 lbf

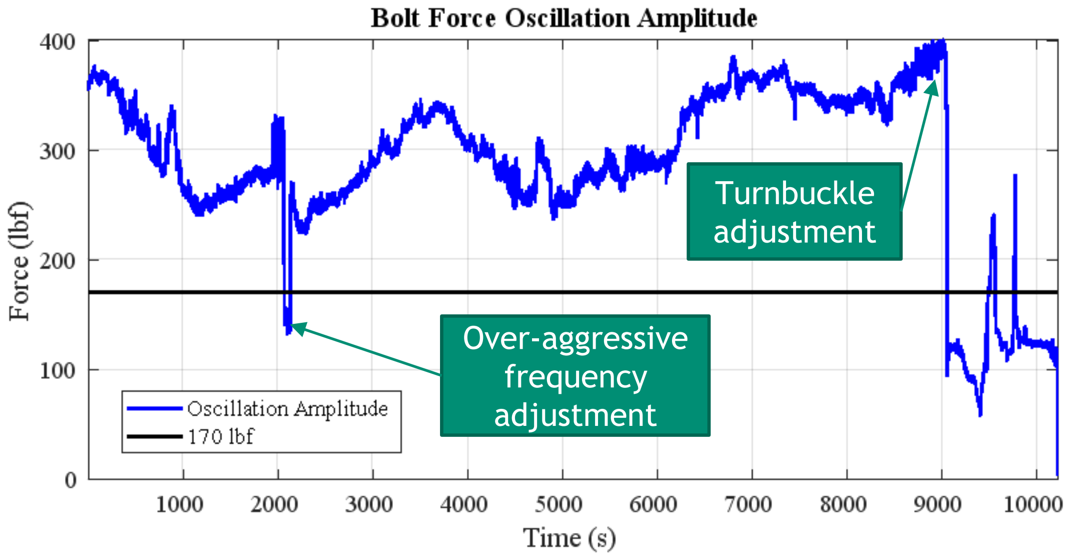
Attempt #3—Ad Hoc Method

- A fatigue test was conducted guided by the results of the ad-hoc investigation
- The frequency was slightly adjusted in order to maximize the peak-to-peak force on the bolt
- The original intent was to fail the bolt or achieve 10 million cycles of the excitation frequency (~850 Hz)
- The bolt force was monitored throughout the fatigue test. The excitation frequency was adjusted if the bolt force began decreasing

Attempt #3—Ad Hoc Method, Fatigue Test Results

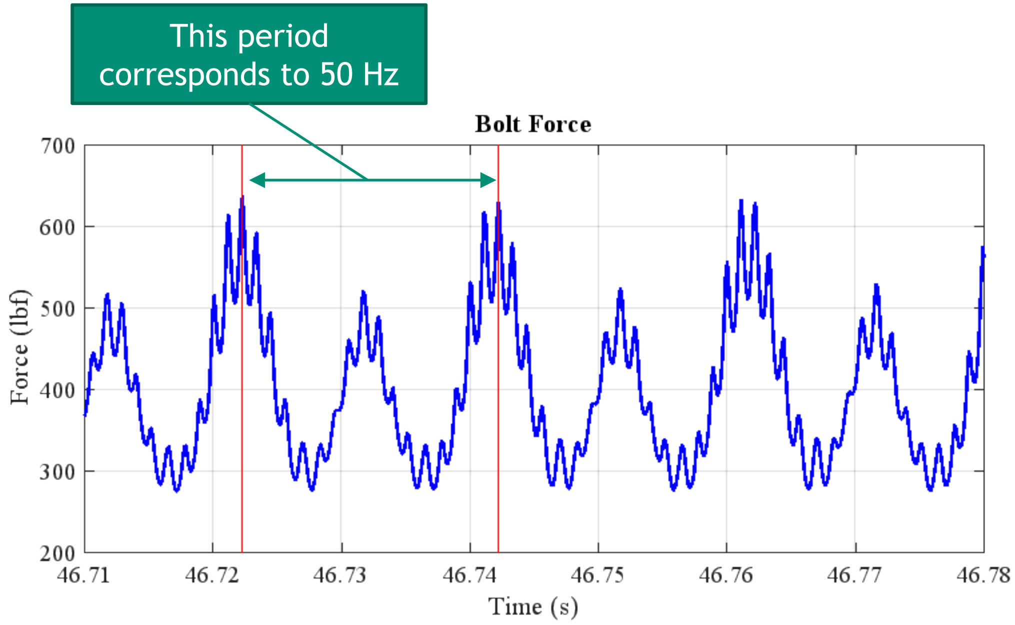
- The bolt force remained well above the 170 lbf threshold for the majority of the testing
  - The dip near 2000 s was the result of being too aggressive when adjusting the frequency to maximize bolt force
- Just after 9000 s, a slight adjustment of the shaker suspension resulted in an unrecoverable change in the dynamics
  - One of the turnbuckles supporting the shaker was vibrating/rattling so it was slightly adjusted with unfortunate consequences
- **The bolt did <u>not</u> fail during this test**

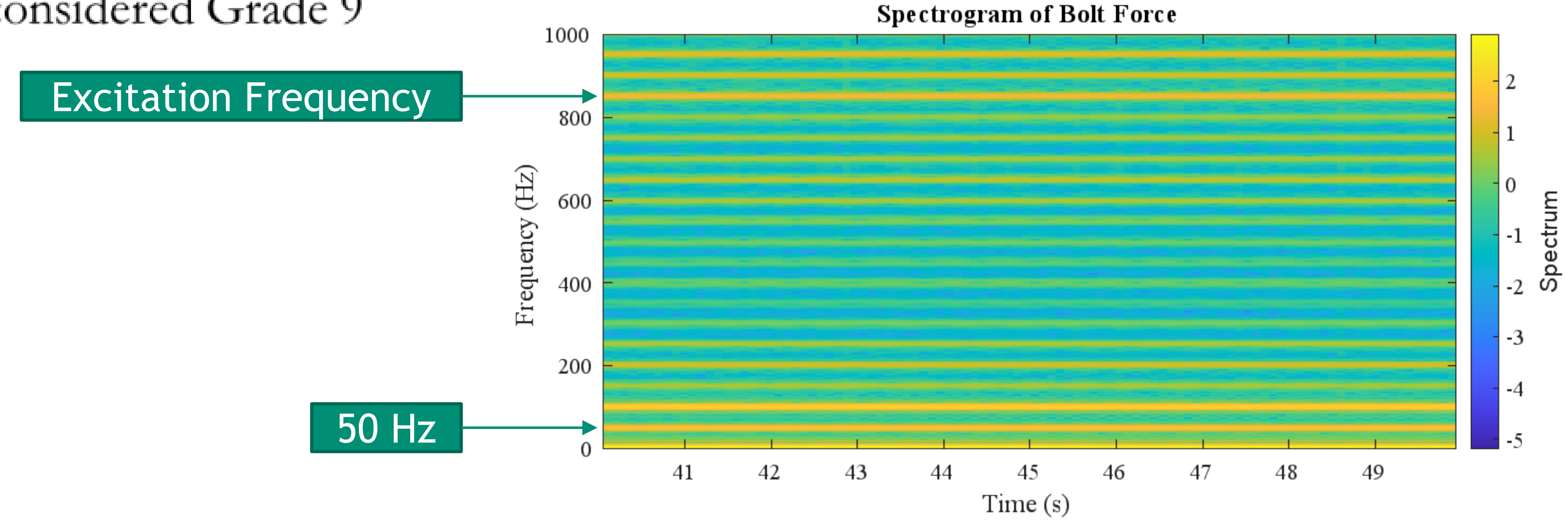




Attempt #3—Ad Hoc Method, Why Did the Bolt Not Fail?

- The bolt force achieved its peak-to-peak amplitude at a frequency of 50 Hz, not at the excitation frequency of 850 Hz
  - Cycle count for 9000 s
    - 850 Hz × 9000s = 7.65 million cycles
    - 50 Hz × 9000s = 0.45 million cycles
  - Potentially did not achieve sufficient cycles for failure
- The fatigue failure conditions were derived for a Grade 2 bolt, but the force sensing bolt is considered Grade 9





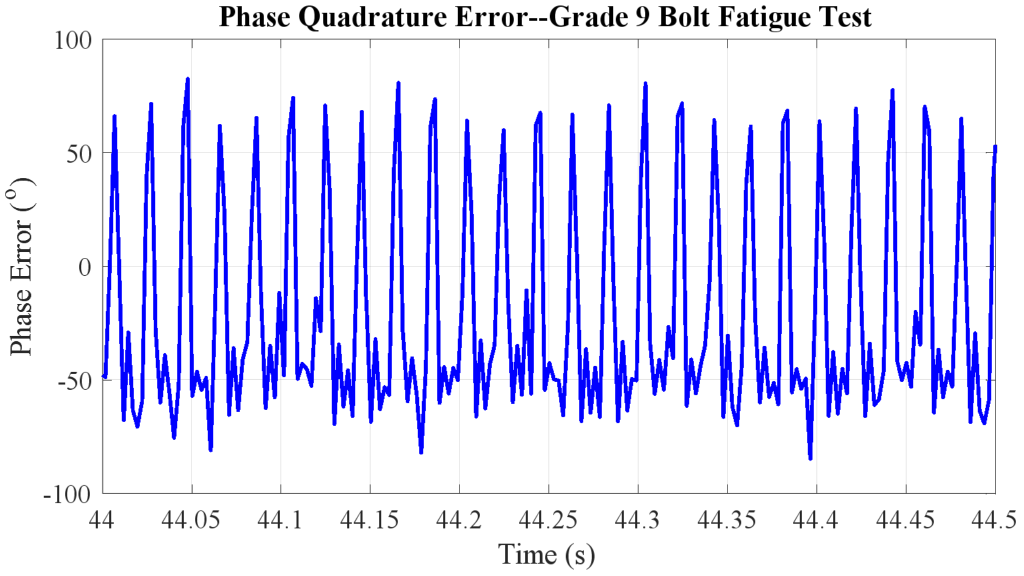
Attempt #4—Ad Hoc Method with Grade 2 Bolt

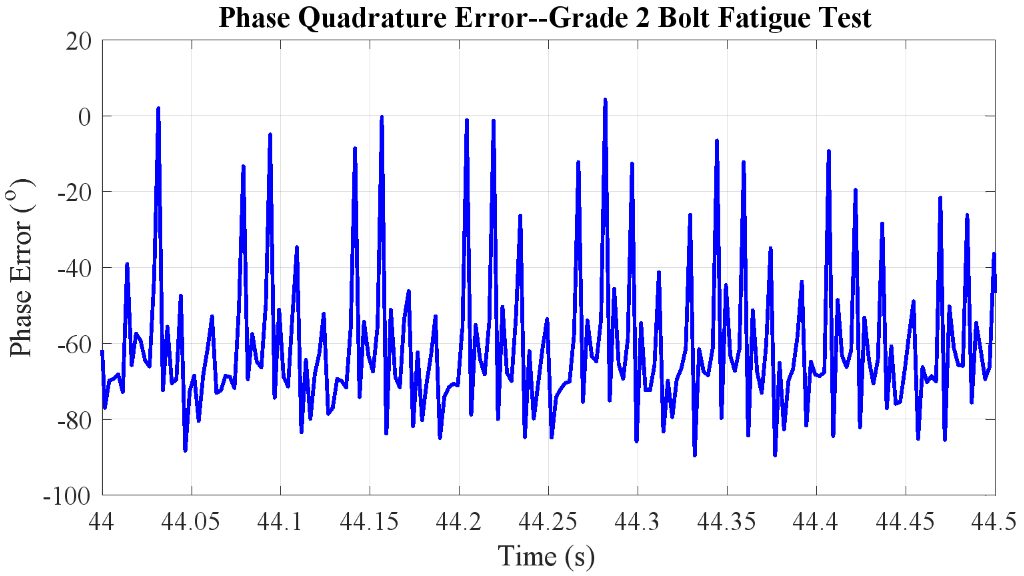
- The fatigue test was repeated with a Grade 2 bolt

- However, this bolt was not instrumented to measure force
  - Could not measure clamping force
  - Could not monitor bolt force during fatigue test

- Other measurements had to be used to **estimate** if the desired fatigue test conditions were met
  - Pattern of the relative phase between excitation force and drive point response
  - This appeared to be the most accurate indicator of the state of the system and was thus deemed the most appropriate to use at the time

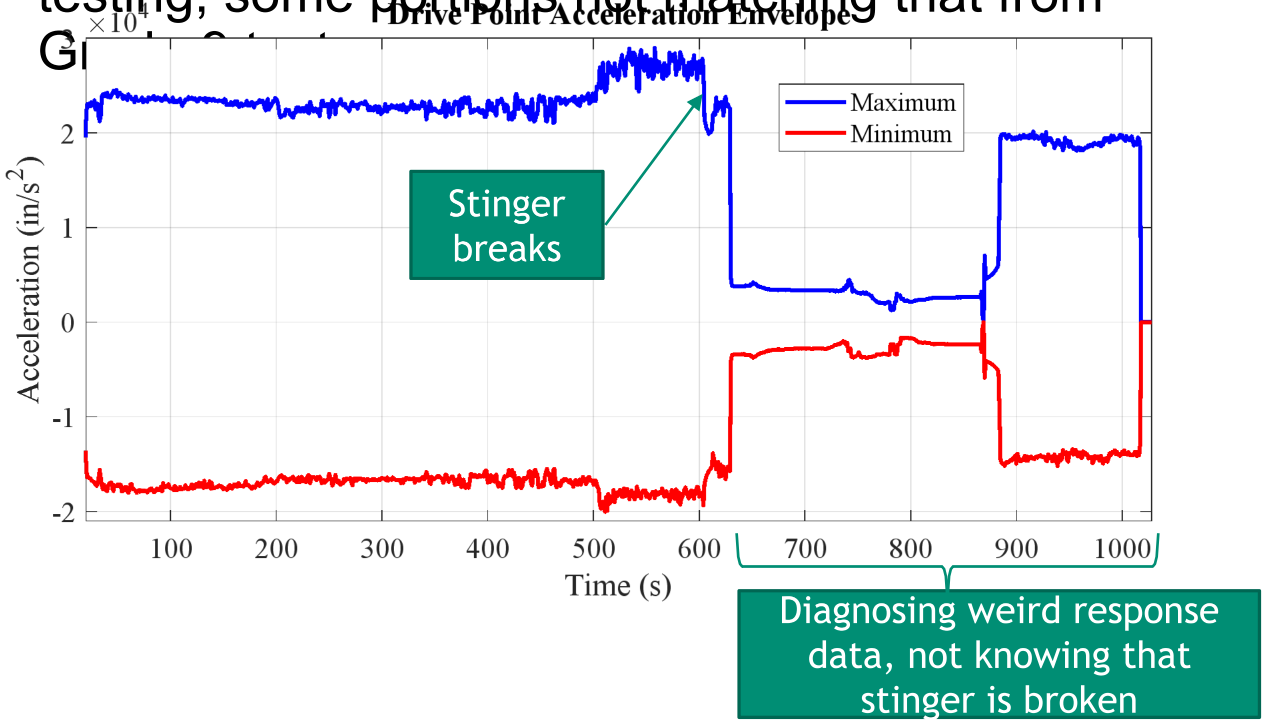
- There is no way to no for sure if the proper bolt force was applied; the test proceeded with a large uncertainty in this quantity

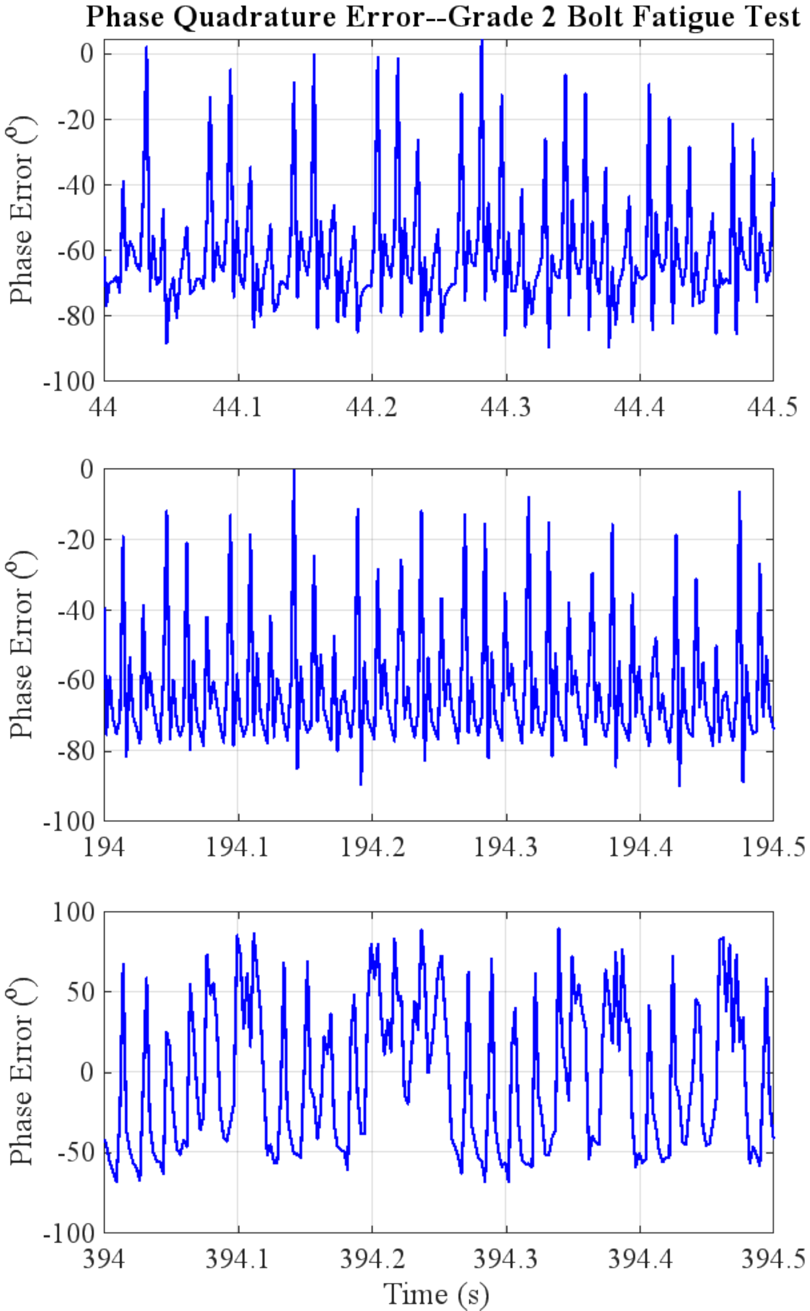




Attempt #4—Ad Hoc Method with Grade 2 Bolt, Fatigue Test Results

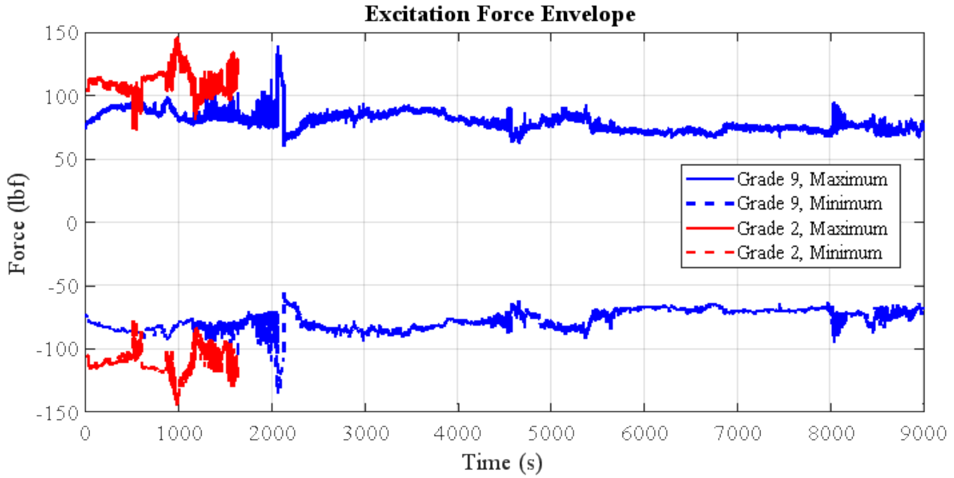
- **The bolt did not fail**
- The stinger failed in fatigue mid-way through the test
  - Stinger was replaced and testing restarted to complete 1 million cycles at 850 Hz
- Phase quadrature pattern changed throughout testing, some portions not matching that from Gr[illegible] test

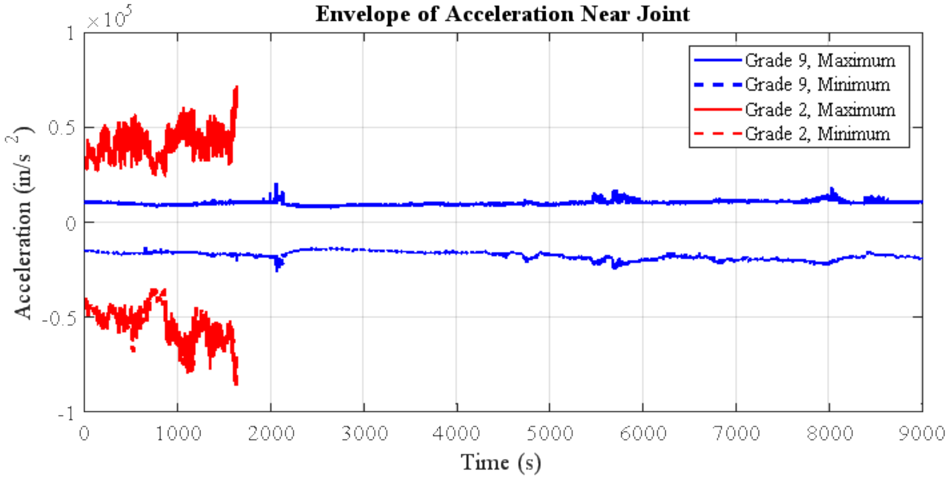


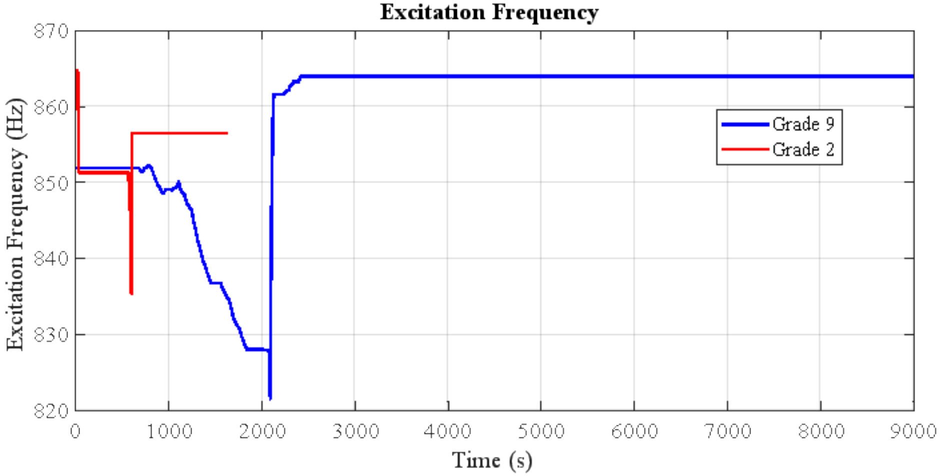


Grade 9 vs Grade 2 Fatigue Test Comparison

- It was unclear whether the desired bolt force was achieved during the Grade 2 fatigue test
- Select data from the two fatigue tests are compared as an additional method of evaluation of the Grade 2 test results





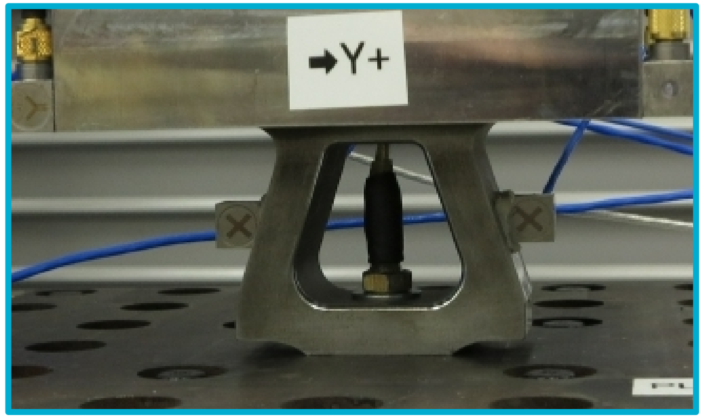


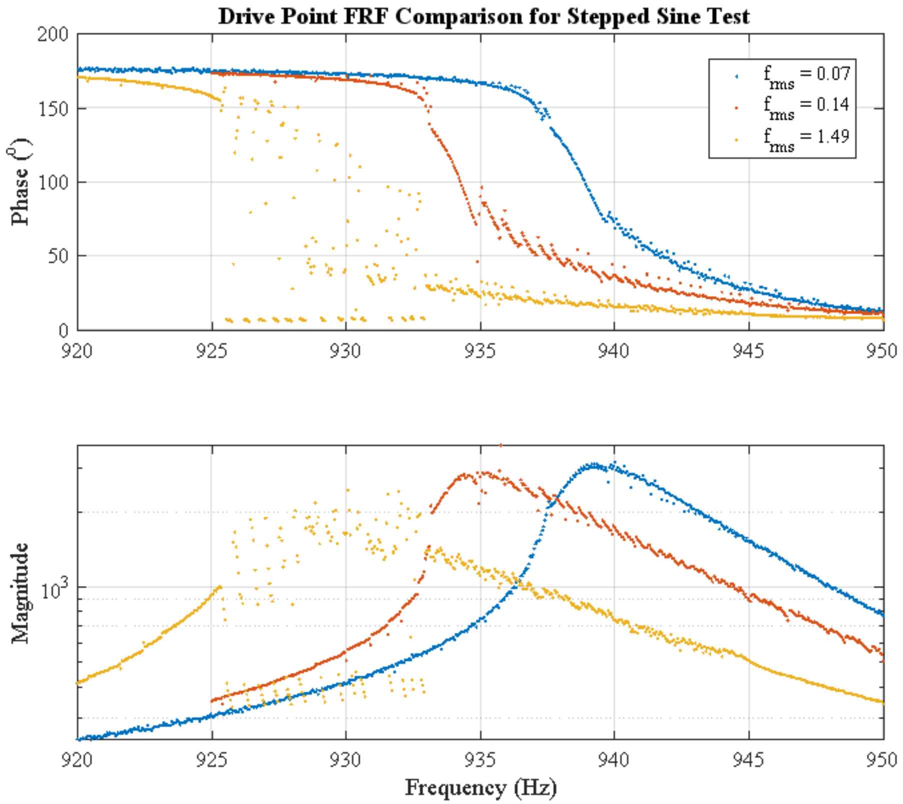
Interpretation 1
Larger acceleration near joint ⇒ **larger bolt forces in Grade 2**

Interpretation 2
Larger acceleration near joint for similar forces ⇒ lower damping ⇒ joint material taking more of the load ⇒ **smaller bolt forces in Grade 2**

Summary

- Several attempts were made to fail in fatigue a bolt within a joint using a dynamic environment with the end goal of comparing the results to those produced by a finite element model
- **Attempt #1**: NFA test with fully torqued bolt
  - **Outcome:** Did not fail bolt
  - **Reason:** Reached the amplifier output limitations before desired fatigue test conditions met
- **Attempt #2**: NFA test with bolt at reduced torque
  - **Outcome:** Did not fail bolt
  - **Reason:** Structural instability precluded excitation of mode before desired fatigue test conditions met
- **Attempt #3:** Ad hoc method with Grade 9 bolt
  - **Outcome:** Did not fail bolt
  - **Reason:** Among other reasons, fatigue test conditions were later determined to have been designed for Grade 2 bolt
- **Attempt #4:** Ad hoc method with Grade 2 bolt
  - **Outcome:** Did not fail bolt
  - **Reason:** The inability to determine the bolt force led to uncertainty in satisfying the necessary conditions for fatigue failure



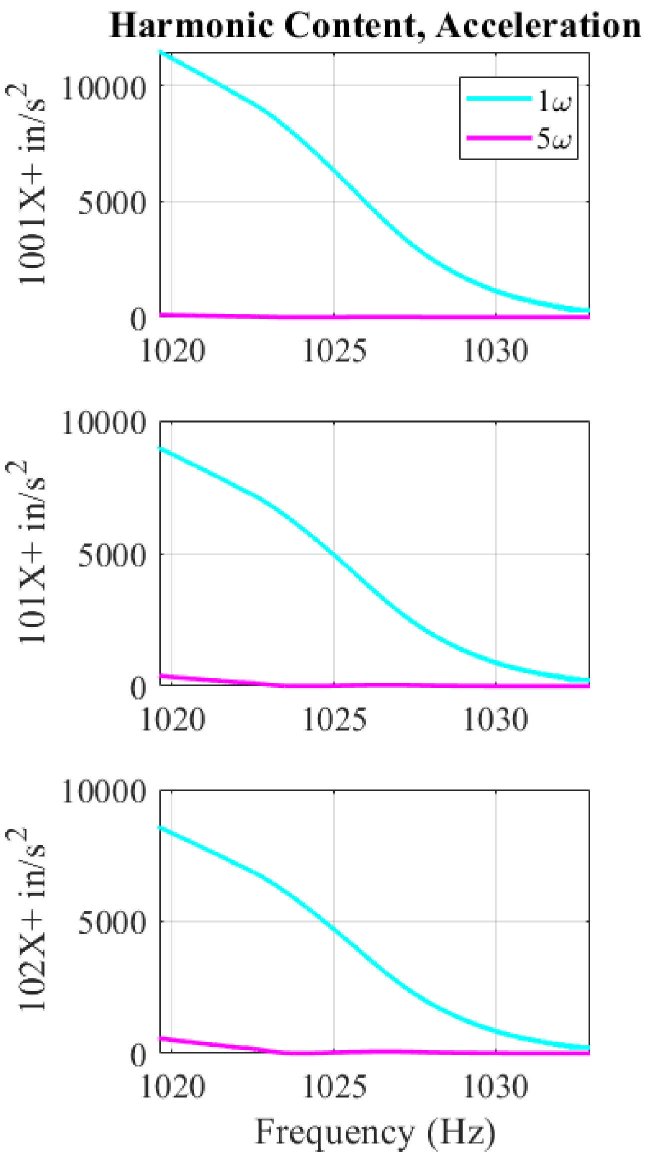


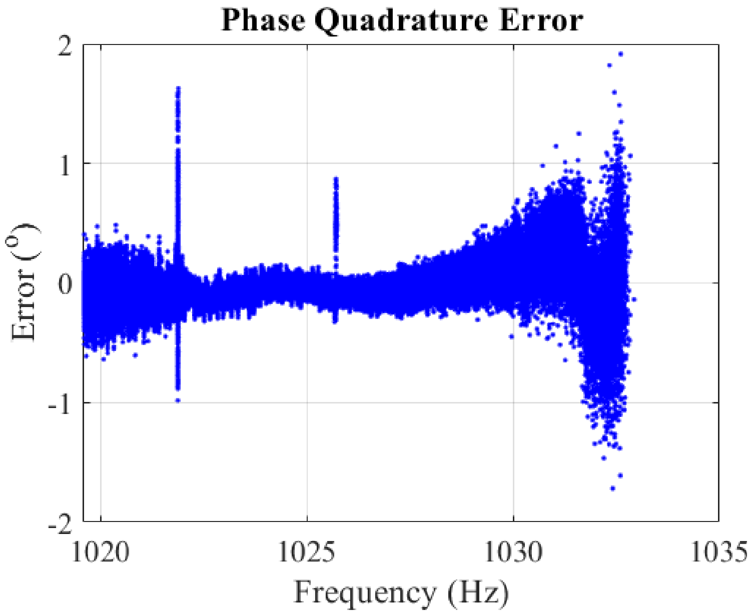
Lessons Learned

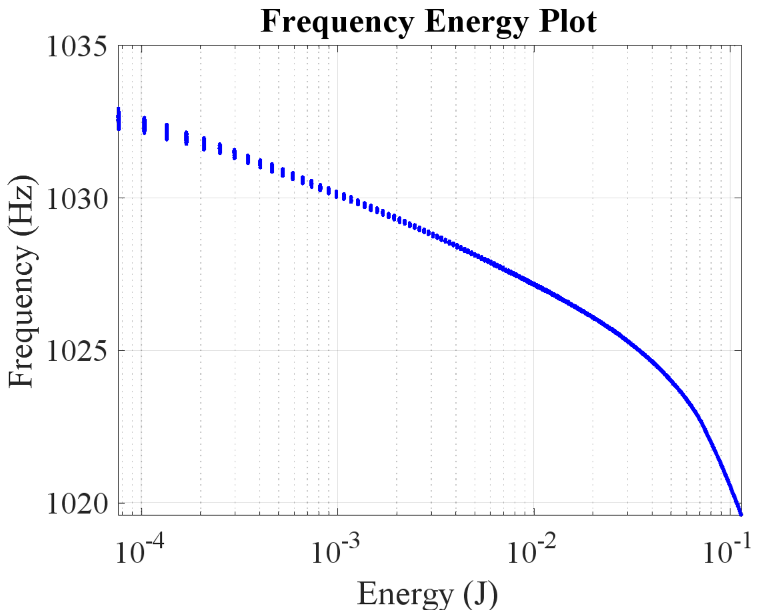
- **Lesson learned:** *Lower assembly torque quickened the onset of higher bolt forces*
  - Attempt #1 (fully torqued) did not get to sufficiently high bolt forces within the limitations of the test equipment, but the desired fatigue test conditions were met with Attempt #2 (reduced torque)
- **Lesson learned:** *An NFA control scheme which is able to stabilize structure is the recommended test method*
  - Conceptually, NFA maintains the structure at resonance, so if stability is maintained, the desired fatigue conditions should be met in a more controlled manner than the ad hoc method
  - **Potential Paths Forward**
    - Add capability to incorporate incommensurate frequencies to the NFA controller
    - Utilize a different NFA control scheme, e.g. Phase-Locked-Loop, Control Based Continuation
- **Lesson learned:** *A force-measuring bolt is essential for this type of testing*
  - Without having a direct (or reliable indirect) method of determining the force through the bolt, it is difficult to determine if the desired conditions are met for causing fatigue failure
- **Lesson learned:** *A nonlinear model of the joint (even if un-tuned) would have aided in diagnosing various testing issues (e.g. cause of instability during NFA, interpretation of dynamics during fatigue testing)*
- **Lesson learned:** *Utilize a high-output amplifier-shaker set-up*
  - Additionally, find a drive point (either through structure re-design or clever excitation DOF) that balances the test equipment limitations (shaker force output, amplifier electrical outputs, etc.)

Back Ups

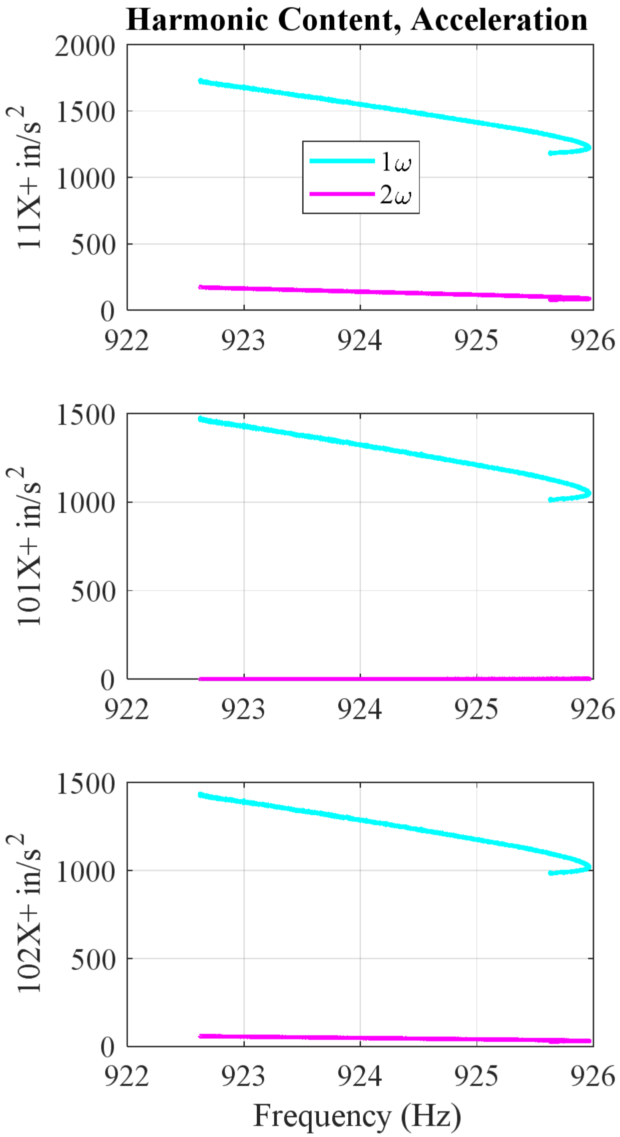
Attempt #1—More NFA Results

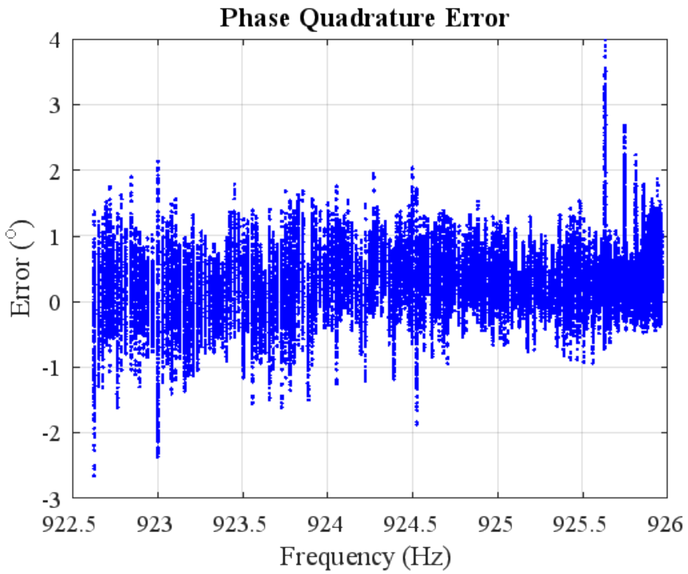


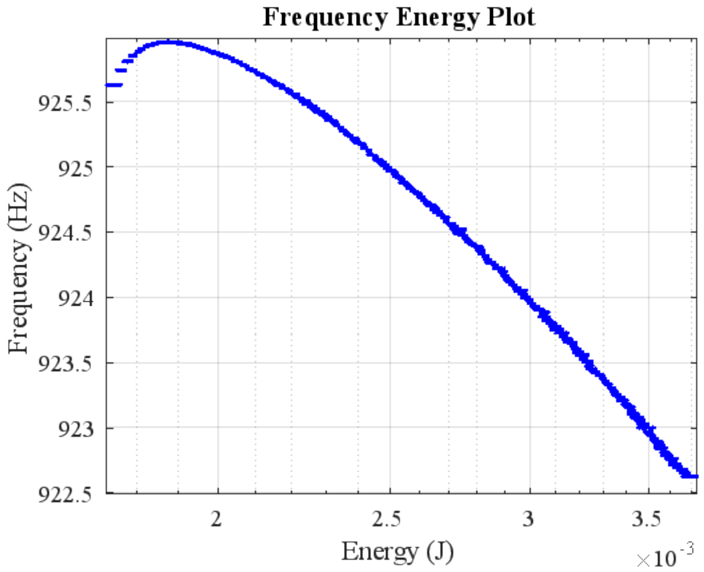




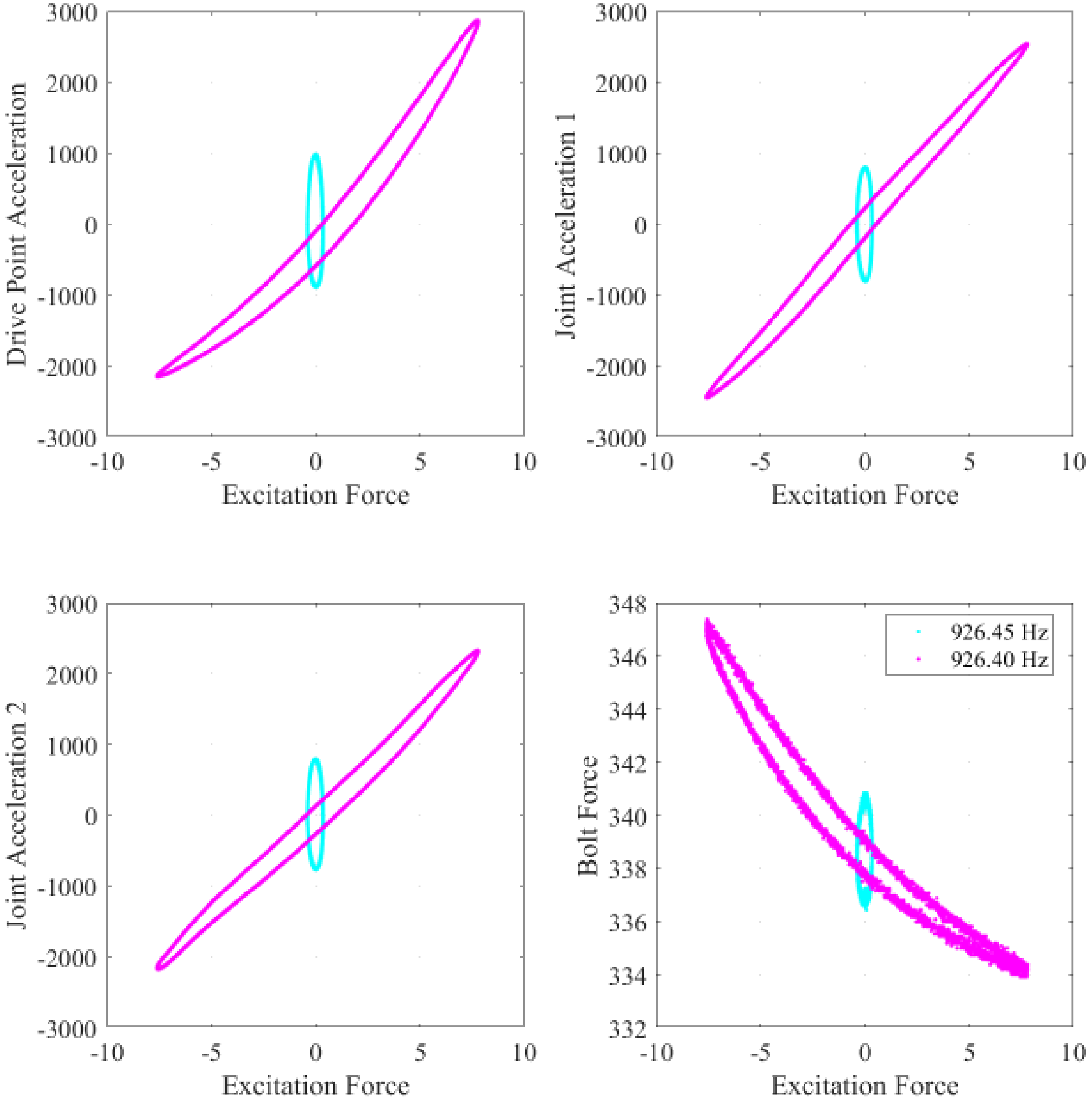
Attempt #2—More NFA Results



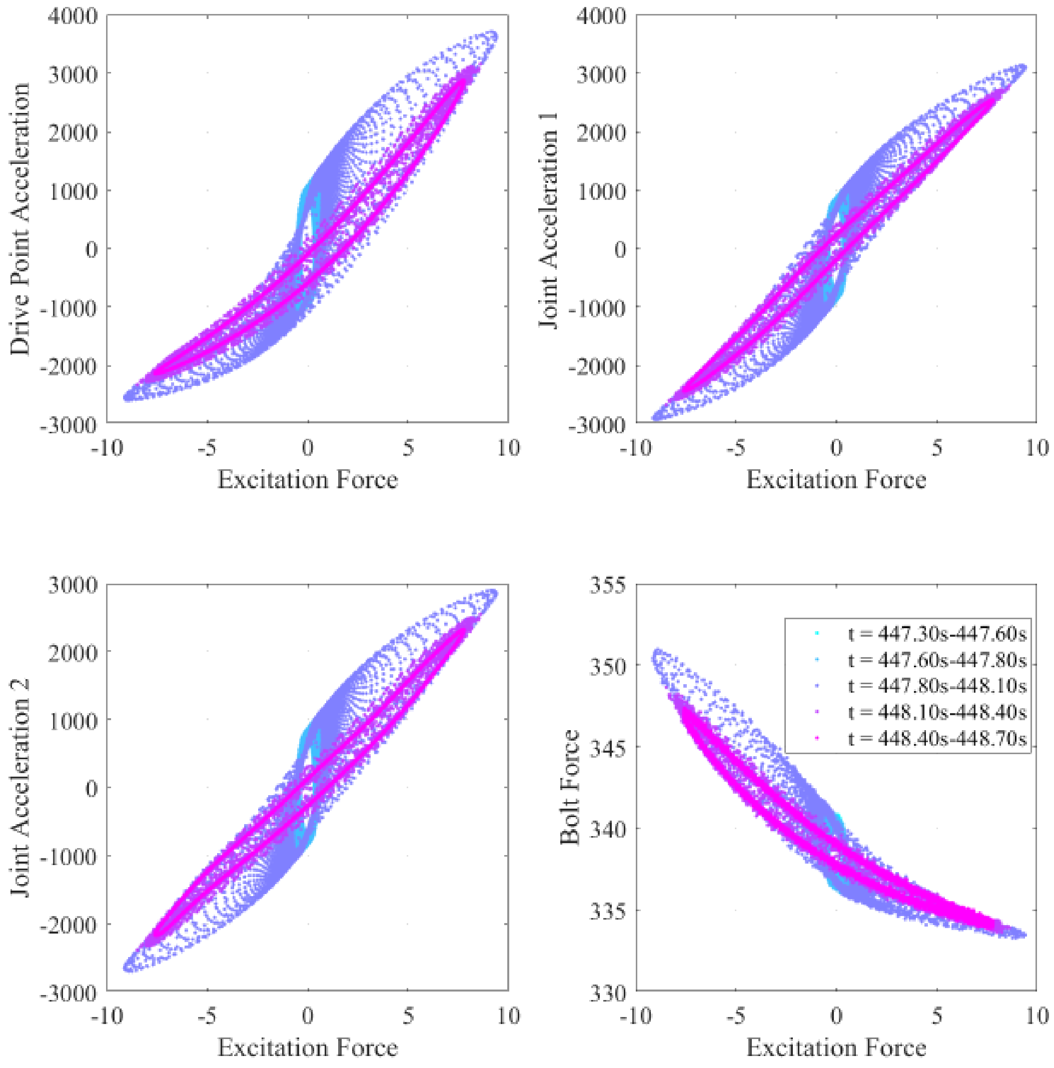


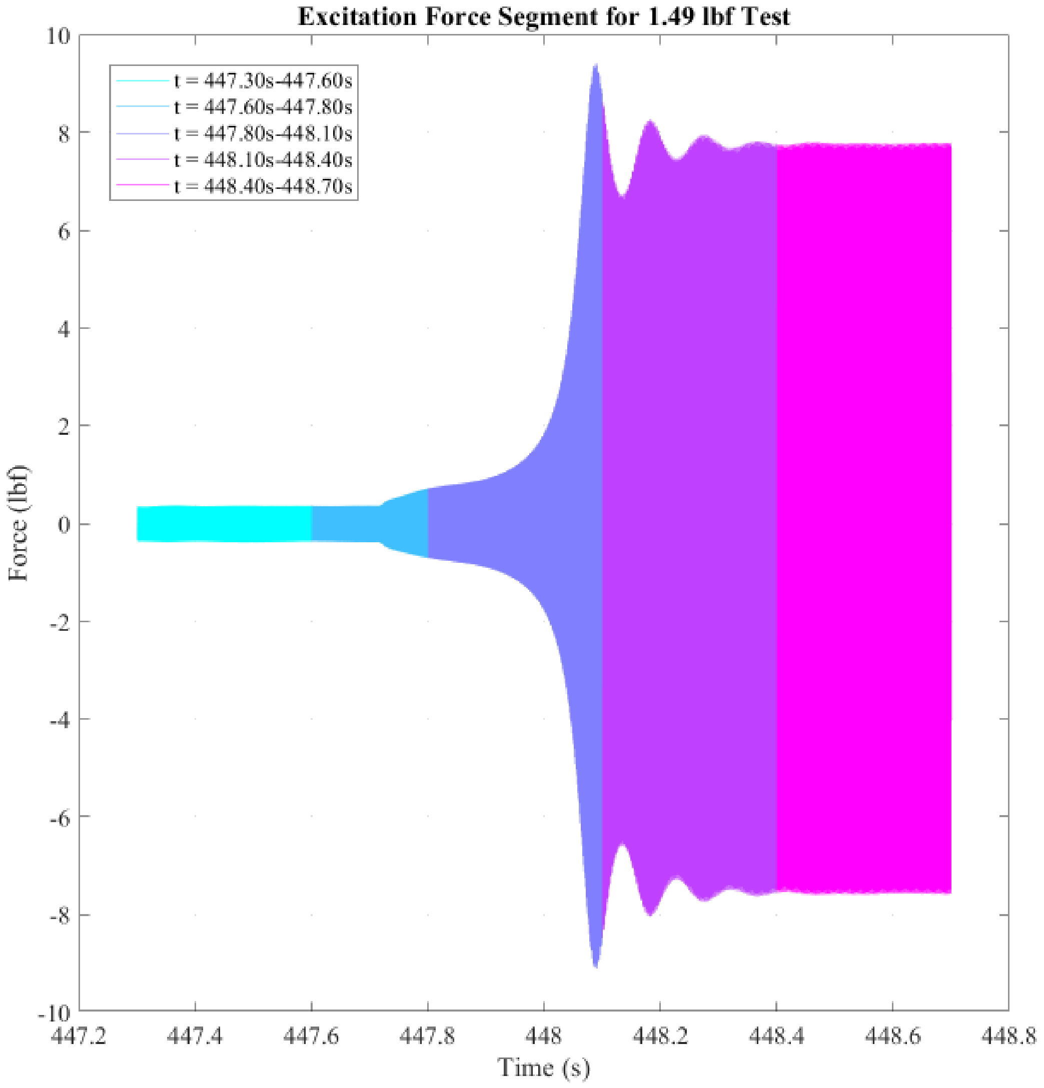


Attempt #2—Reduced Torque, Stepped Sine Results, State Changes



Exploring System Transitions During Attempt #2 Testing





Grade 9 vs Grade 2 Linear Modal Test Results

Mode	Frequency (Hz)		Damping (%)	
	Grade 9	Grade 2	Grade 9	Grade 2
1st Bending	101	101	0.79	0.23
1st Bending	127	137	0.42	0.30
Torsion	339	---	0.28	---
Axial	**944**	**959**	**0.21**	**0.13**
2nd Bending	1124	1139	0.05	0.05
2nd Bending	1452	1491	0.13	0.08