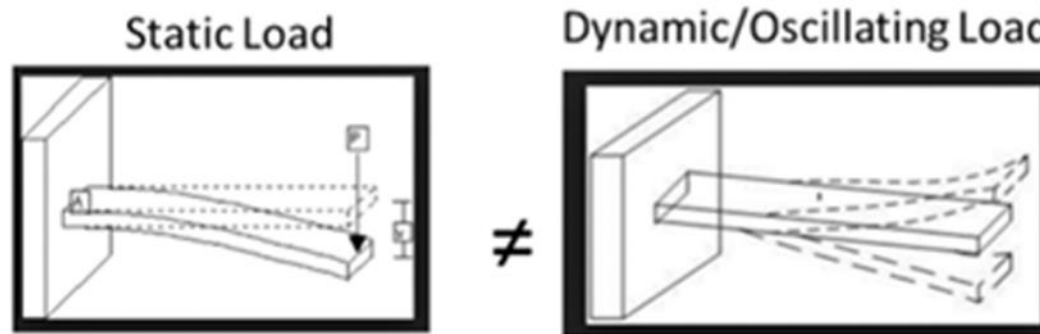


Conservatism in the Structural Design Process Associated With Assuming Dynamic Loads are Static 2024 EMI

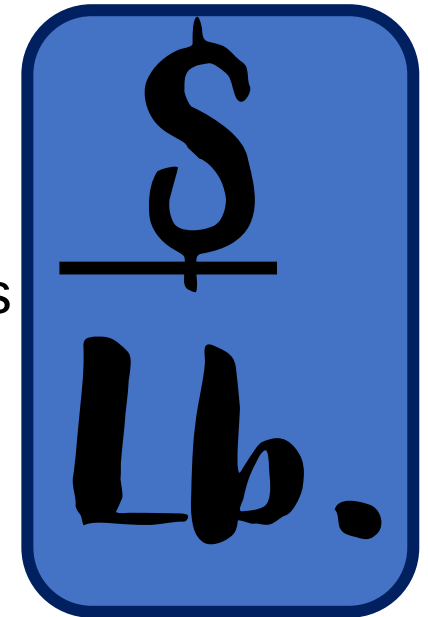
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Long Story Short

- The design of many space flight structures are driven by dynamic loads
 - Dynamic analyses provide peak responses to be used to size hardware
- Those loads are most often applied in stress analyses as static loads
 - Effectively assuming a dynamic load is static
 - This assumption is conservative resulting in unnecessarily heavy hardware
- Testing has qualitatively shown the magnitude of unnecessary mass
 - Solid Aluminum beam, bolted aluminum beam, welded aluminum beam
- Description of those tests and results are reported in this presentation
- *Ultimate end game: A new/modified design process resulting in lighter designs*





Background

- The design of space flight hardware is often driven by dynamic loads
 - Ignition, liftoff, stage separation, etc.
 - Envelopes of structural responses from all events or subsets of events are commonly used to size hardware
 - Peak dynamic responses often dominate the envelope
- However, it is very common to apply the dynamic load statically in the structural analyses that dictates the weight of the hardware
 - This, assuming that a dynamic load is static, is a longstanding engineering practice
 - This is applicable when the number of stress reversals does not create a fatigue condition



Background

- This conservatism results in unnecessarily heavy hardware
 - How much unnecessary mass is in structural designs due to this practice is not known
 - Tests have been done to qualitatively assess the magnitude of conservatism embedded in the subject assumption
 - Tests have been performed on Aluminum beams (one member, two members lapped/bolted, and 2 members welded)
- Results substantiate the notion that our assumption is notably/very conservative and there is mass to be saved via leveraging this in a modified design process
- **Motivation – the potential to save mass via a novel approach**



Objective

- The objectives of this presentation are:
 - Discuss theoretical basis
 - Describe tests performed and results
 - Discuss future work and the endgame

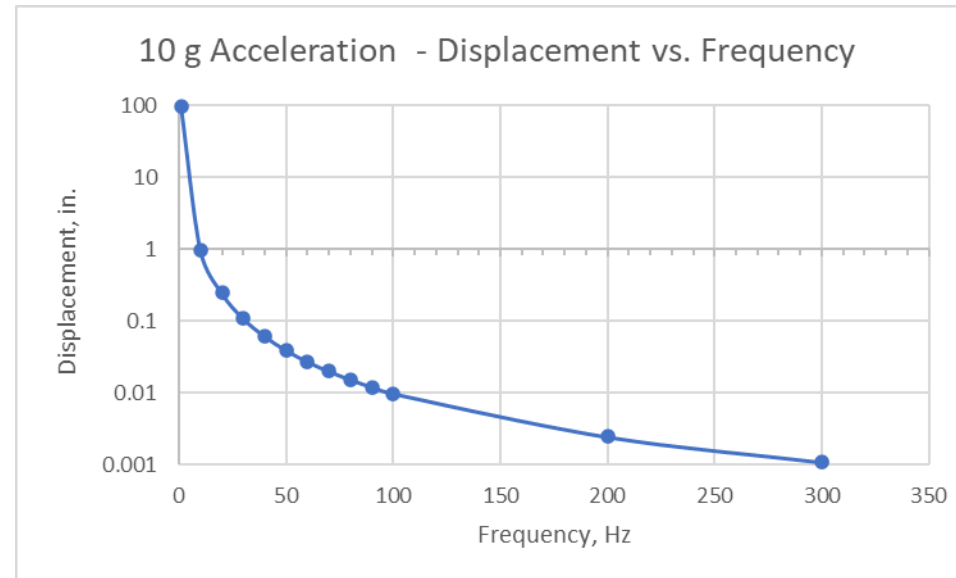


Frequency Dependency of Strain

- Loads don't break hardware, strain does
 - Fundamentally, $\epsilon = \Delta l / L$
- For harmonic motion:
 - $X = A \sin(\omega t)$
 - $\dot{X} = A\omega \cos(\omega t)$
 - $\ddot{X} = -A\omega^2 \sin(\omega t) = -X \omega^2$
- From Which,
 - $X = \ddot{X} / \omega^2$
- For a given acceleration, as we go up in frequency displacement goes down exponentially

Frequency Dependency of Strain

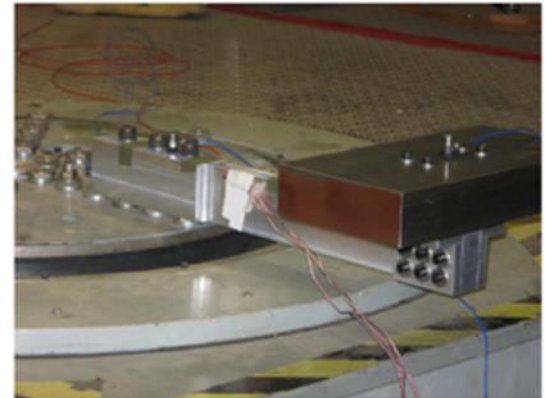
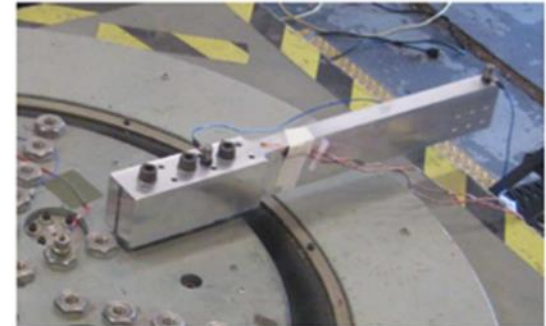
- Strain is a small fraction of displacement, so strain also decreases exponentially, for a given acceleration, as frequency goes up



Harmonic displacement associated with 10 g acceleration as a function of frequency

2011 Tests

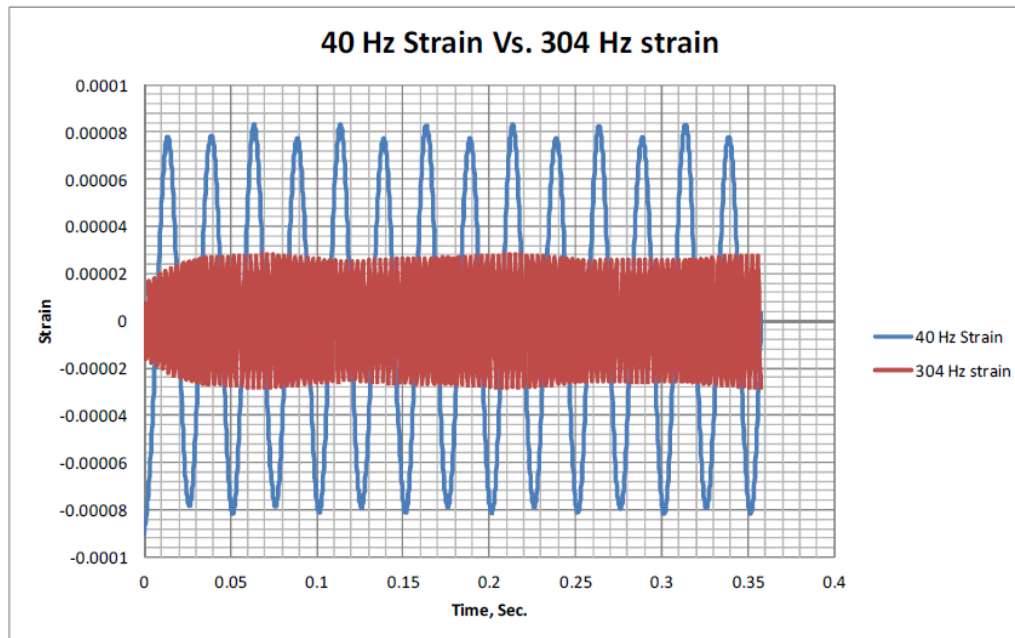
- In 2011, first tests performed to demonstrate the point
- A beam was designed to have its first mode at 300 Hz
- A Bracket and mass were sized/designed to shift that down to $\approx$ 40 Hz
- Both cases were the fundamental mode and had same cross section reacting the load
- The two configurations were subjected to a sine dwell test at their first mode
- The input acceleration for each case was calculated so that the two tests would have $\approx$ the same magnitude of oscillating force



Case	Weight (Lb.)	Frequency (Hz)	Effective Oscillating Force (Lb.)
1	4	300	98
2	46	40	92

2011 Tests

- Results – measured 40 Hz and 304 Hz strain



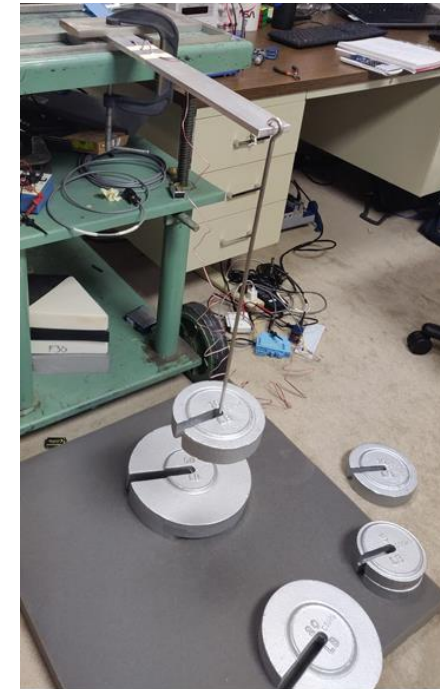
Case	Weight (Lb.)	Frequency (Hz)	Effective Oscillating Force (Lb.)	Measured Strain
1	4	300	98	3.00E-04
2	46	40	92	8.40E-04

The low frequency case, Case 2, has 6% lower effective load but 2.8X higher strain

- A factor of approximately 3 was observed between the two cases

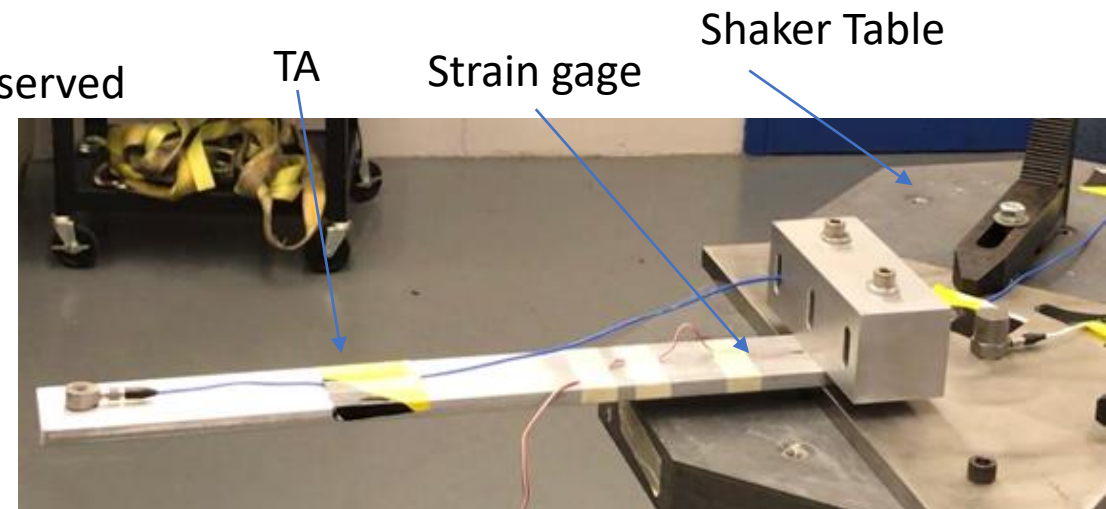
2019 Tests

- Tests were planned to compare static to dynamic loadings of an AL 6063 cantilevered beam (2"X0.375"X16")
- Static test:
 - The Test Article (TA) was subjected to the static load that was expected to result in Plastic Deformation (PD), ≈ 80 Lb.
 - ≈ 1 " tip deflection while loaded
 - Slight PD did occur



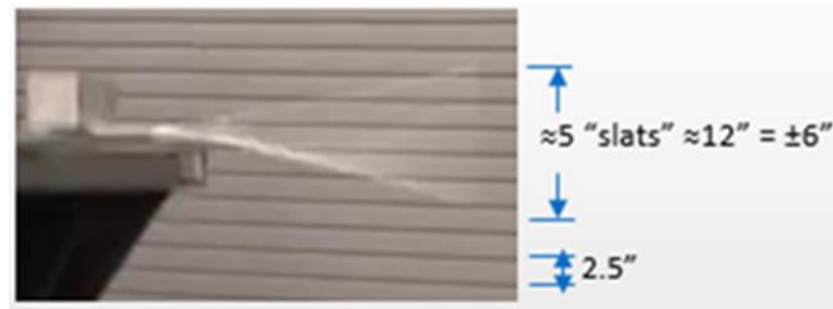
2019 Tests

- The TA was instrumented with a strain gage and mounted to a shaker table
 - Numerous sine dwell and random tests were performed
 - The objective was to identify trends in strain and frequency
 - Dwelling at the fundamental mode, ≈ 43 Hz, and 15g input
 - Two unexpected results
 - Much higher tip displacement was observed without PD
 - Much higher measured strain than expected



2019 Tests

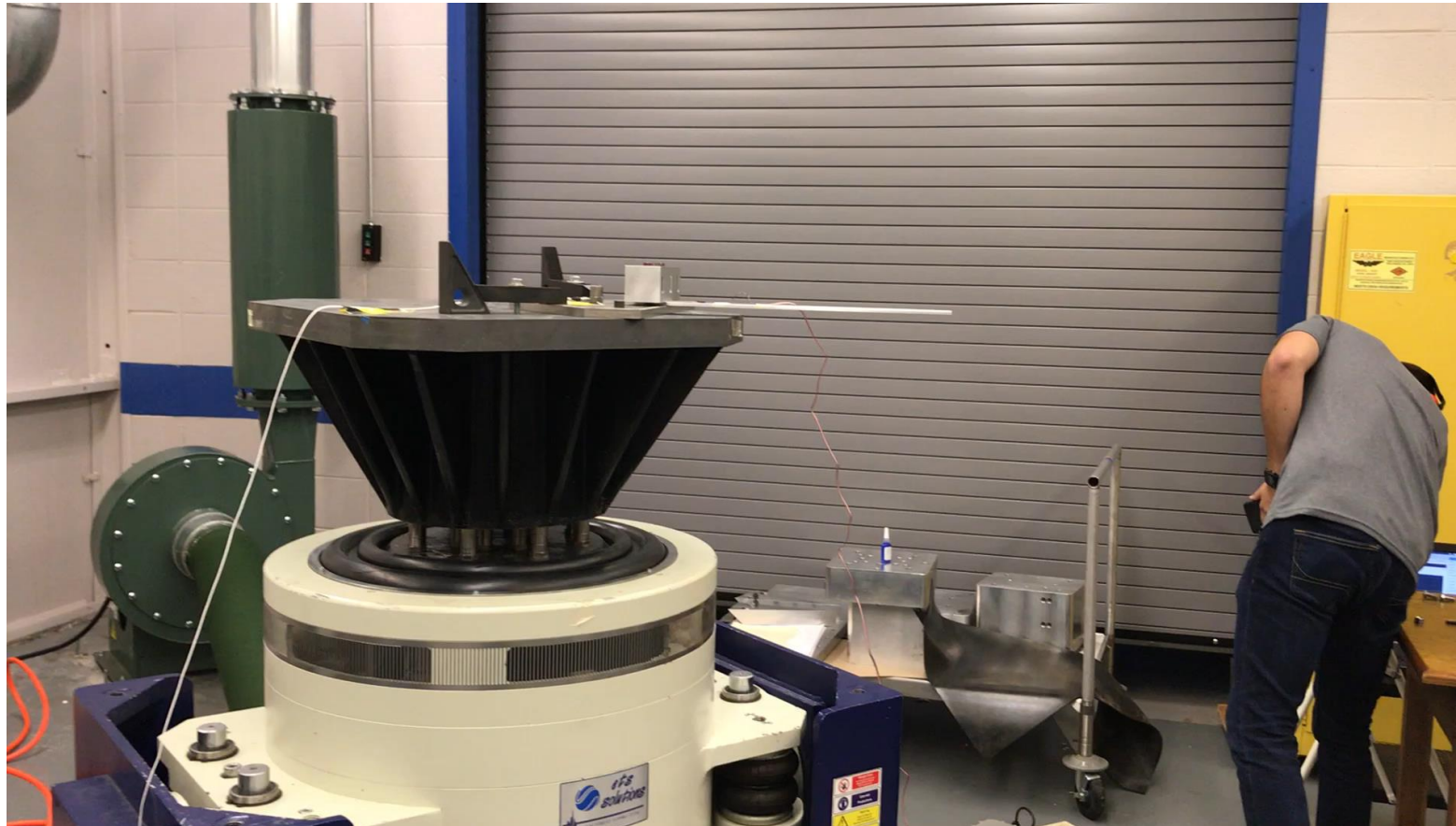
- Tip displacement
- The observed displacement was estimated to be $\pm 6''$
 - To be compared to the $\approx 1''$ static displacement that did result in plastic deformation



- Recall that $\approx 1''$ tip displacement due to a static load resulted in PD
- The dynamic response did not result in PD

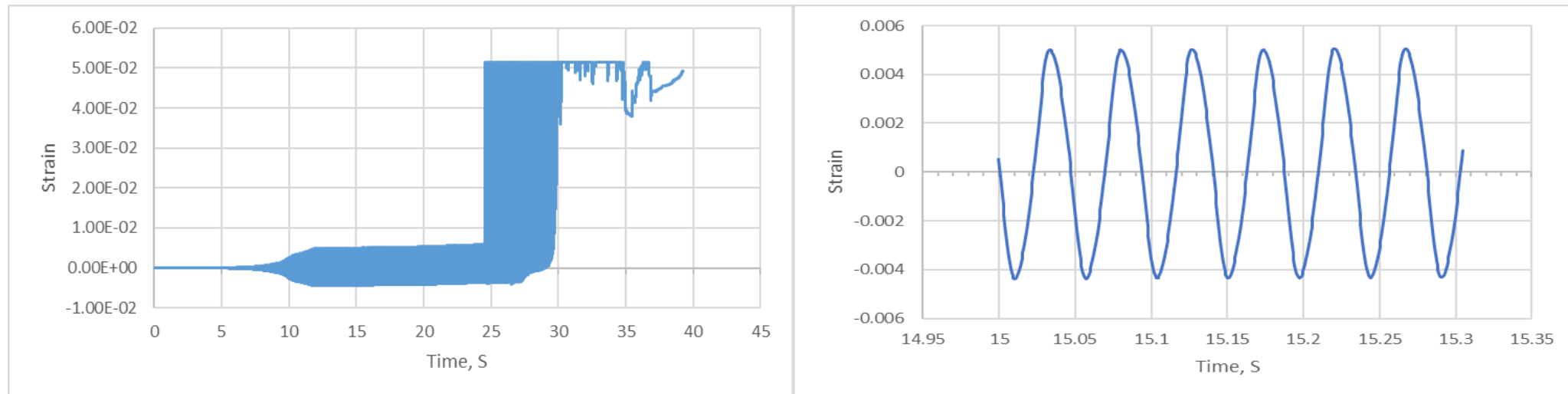
2019 Tests

15g @ 43 Hz first mode sine dwell



2019 Tests

- Measured strain
 - Measured strain was .0051 before the strain gage failed @ ≈ 26 S into the test
 - The ultimate listed in the cert for the AL 6063 TA is 27 kPsi and yield is 22 kPsi
 - The strain associated yield is 0.0022
 - The strain associated with ultimate is 0.0027

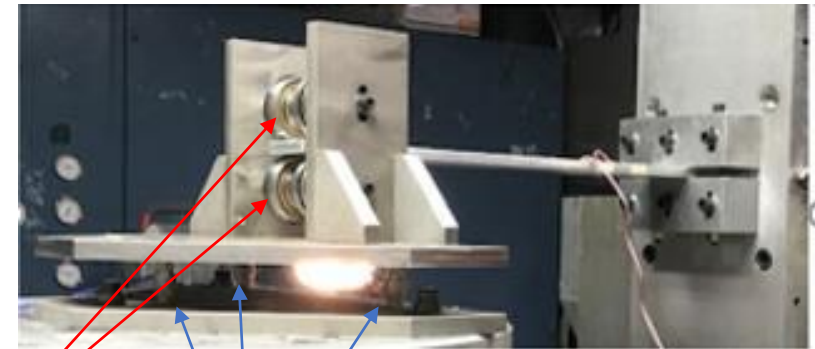


2020 Tests

- 2019 tests captured free responses to base input and compared static to dynamic displacement
- In contrast, 2020 tests applied oscillating external loads and compares static to dynamic forces
- 2020 tests utilized the same TA design as 2019 (AL 6063-T5, 2"X0.375"X16")
- One end of the TA was fixed, and a shaker table was used to dynamically load the other end
- Objective was to facilitate measuring the dynamic applied force

Test Support
Structure (TSS) with
kinematic TA connection

Fixed
end



Bearings

3 load cells

The test was controlled
To the average of the 3
Load cell's output

2020 Tests

Test Set Up

Kinematic Test Support
Structure (TSS)



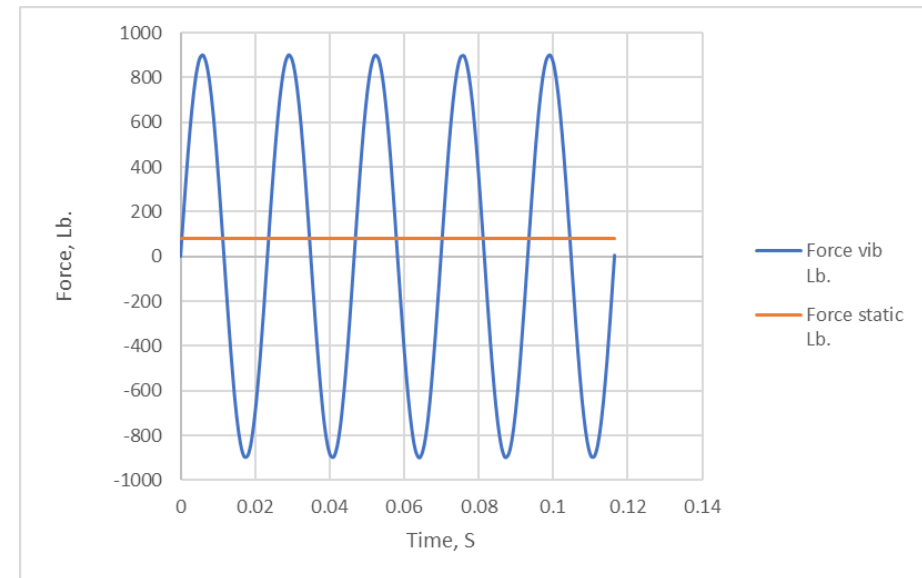
Fixed TSS

TA

Shaker

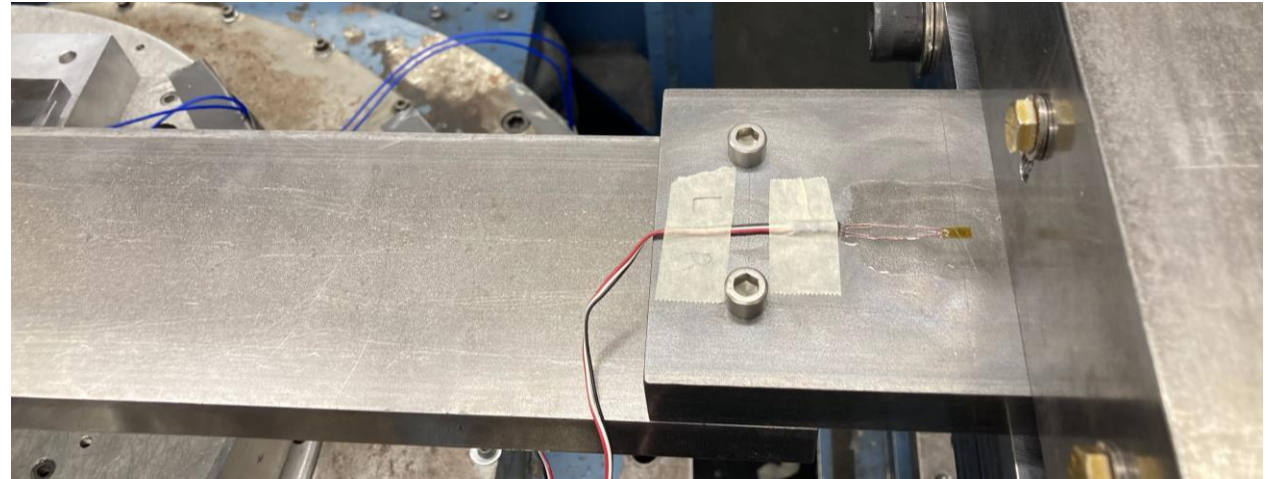
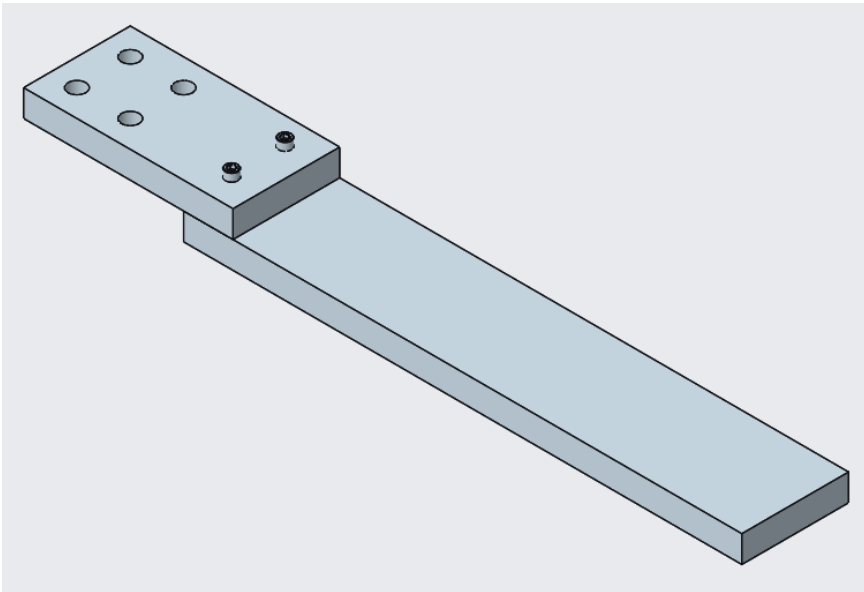
2020 Tests

- The most significant observation was that at 40 Hz, the TA sustained > 900 Lb.
 - Prior, 40 Hz was thought to be “low frequency” and assuming it was static was erroneously thought to be a reasonably conservative assumption
 - 11 X the published static ultimate strength of the material
- Conclusion: Some material can sustain much higher dynamic loads than static



2022 Tests

- Bolted joint
 - The premise had been demonstrated for AL
 - Joints were then tested in the same manner as the previous manner
 - A steel beam was made via lap joining 2 members and connecting via bolts



2022 Tests

- Static test were performed
 - Predicted to reach ultimate at 377 Lb.
 - At 390 Lb. both bolts had plastically deformed
 - One was 0.021" deformation and the other was 0.0155

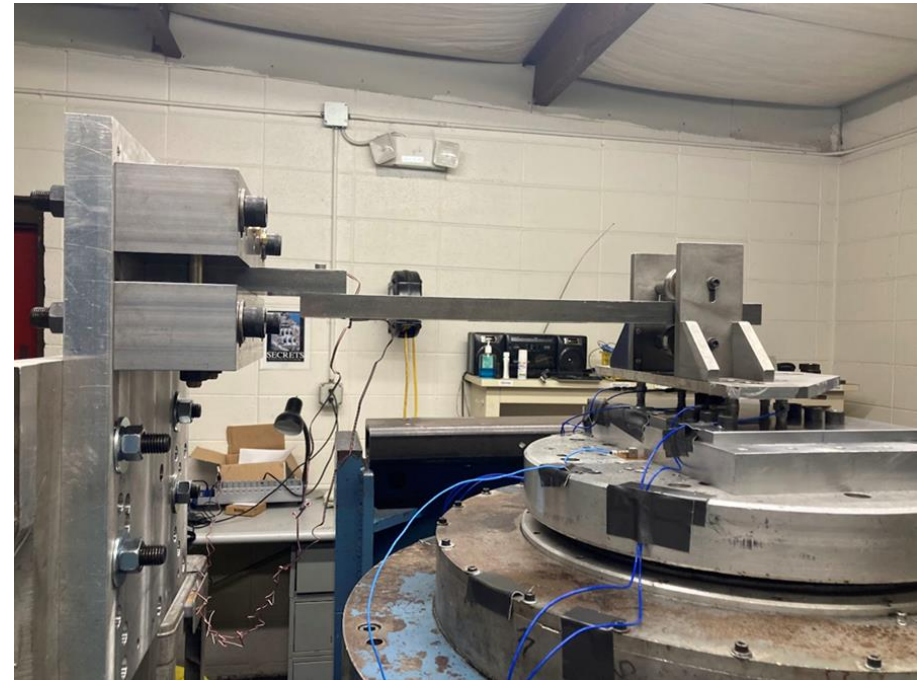


2022 Tests

- Multiple load levels applied at various frequencies

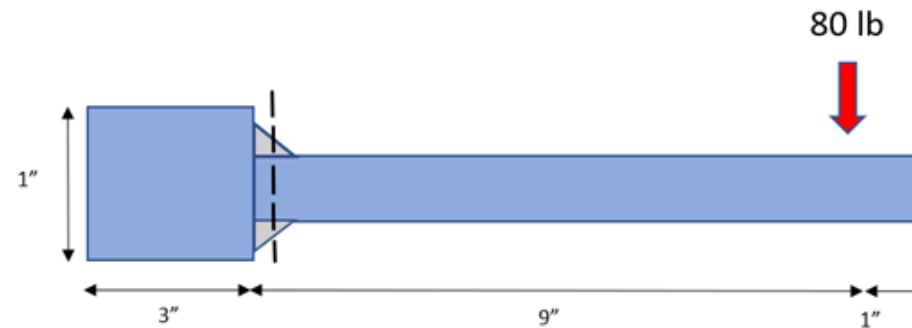
X Static Ult.	Load, Lb.	Frequency, Hz						
2	780	300	250	200	150	100	75	50
3	1170	300	250	200	150	100	75	50
>5	2000	300	250	200	150			

- Again, much higher dynamic loads were sustained than static with no PD



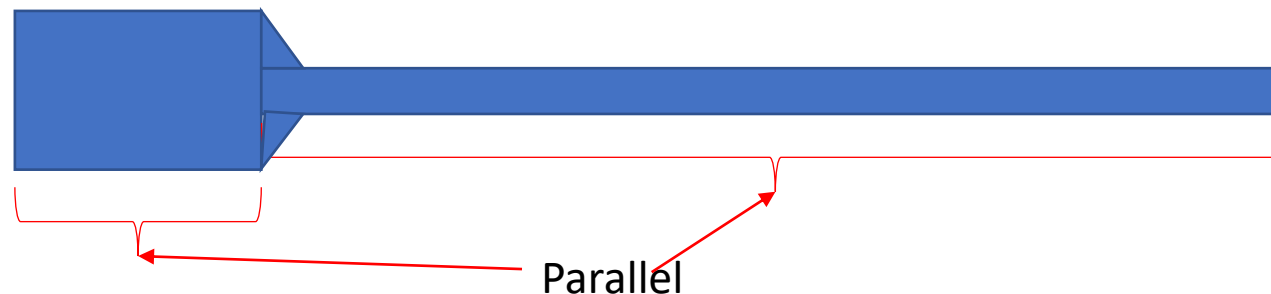
2023 Tests

- Welded joint
 - An aluminum beam was made via butt joining 2 members and connecting via 2 (top/bottom) 1" welds
 - ≈ 80 Lb. predicted to reach ultimate



2023 Tests

- Welded joint
 - Static tests were performed as before but required more steps and more care
 - Due to the nature of welds care was taken to ensure the two parts of the pretested specimens were parallel
 - A level was used to do so



2023 Tests

- The first static test was disregarded
 - Much higher load to fail
 - Used simple observation to determine PD
- Static test 2 and 3 utilized a bubble level and 4 and 5 used a digital level
- Results:

Run	Load to PD Lb.
2	86
3	91
4	86
5	76
Mean	85



2023 Tests

- Welded joint – dynamic tests
 - Unlike previous tests, fractures did occur in these tests
 - Cracks in a weld were observed after the 400 Lb @50 Hz run

Load (lb)	Frequency (Hz)	Failure?
160	[300, 250, 200, 150, 100, 75, 50, 20]	No
240	[300, 250, 200, 150, 100, 75, 50, 20]	No
400	[300, 250, 200, 150, 100, 75, 50, ~~20~~]	No from 300-75Hz After 50hz welds had longitudinal cracks, likely due to a loose KTSS during run. Note: (20 Hz run was not executed)



Summary of Observations

- Static tip displacement of $\approx 1''$ yields PD
- Dynamic tip displacement of $\approx \pm 6''$ does not
- ≈ 80 Lb. statically yields PD
- 900 Lb. at 40 Hz does not
- Bolted Joint:
 - 390 Lb. statically yields PD
 - As much as 2000 Lb. (@150 Hz) does not
- Welded Joint:
 - Mean of 85 Lb. statically yields PD
 - 400 Lb. at 50 Hz does not

- *Work done thus far demonstrates the advantages of pursuing a new or modified design methodology*
- *A couple more tests are planned but otherwise this is considered accomplished*



Future Plans

- Summer 2024
 - Perform similar test on a piece of primary structure
 - Potentially, perform a centrifuge test and vib tests on a simulated avionics box
- Initiate efforts to devise a new/modified approach to designing structures to dynamic loads
 - Possibly develop a way to calculate a frequency for a given design and environment above which dynamic loads can be omitted
 - Hypothetically, for a given case, only consider 20 – 100 Hz of the 20-2000 Hz required spectrum



Background

Thanks!

If you have questions, thoughts, comments, or
concerns regarding this please let me know

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