Mass Mitigation in Structural Designs Via Dynamic Properties

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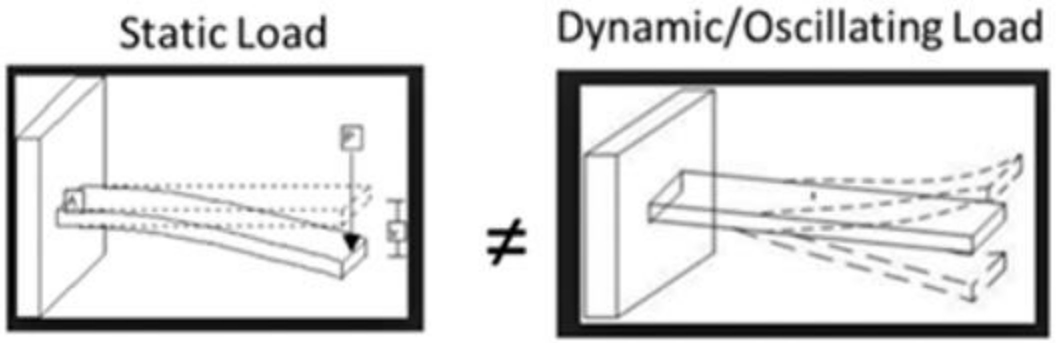
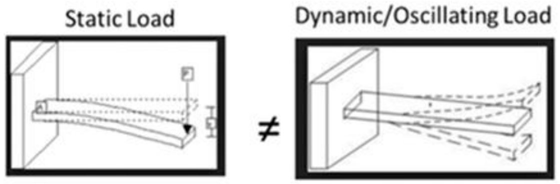
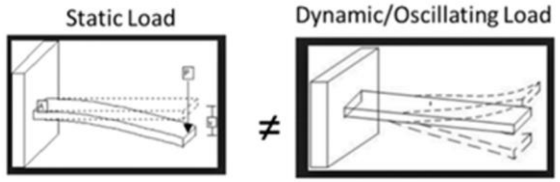
NASA/MSFC/ES61



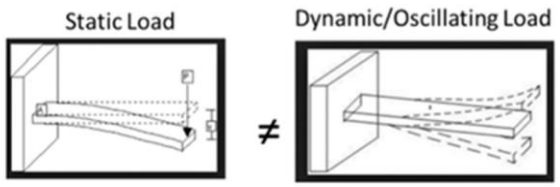


Introduction

- The subject presented here is, qualitatively, the order of magnitude of conservatism embedded in assuming a dynamic structural load or environment is applied as if it were static within the design/stress analysis process
  - Often, effective net CG load factors (accelerations) are derived from dynamic environments and then applied in an FEA as a static inertial load
  - This is a long standing engineering method
    - This is known to be conservative for typical ductile materials
    - The magnitude of conservatism is unknown

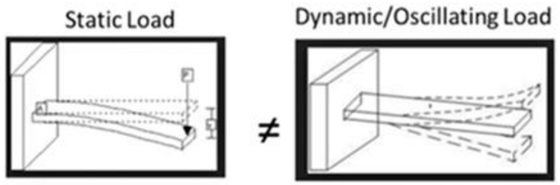


How much is this practice costing us?



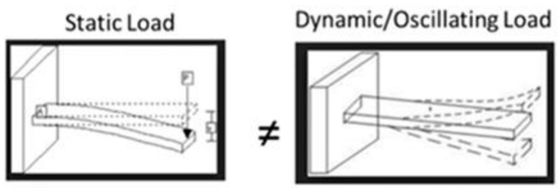
Introduction

- NASA/MSFC has invested resources via an internal "Technical Excellence" (TE) program in 2011, 2019 and 2020
- Now in 2021 efforts are exerted to roll it all up
- Tests have been performed in an effort to qualitatively demonstrate the order of magnitude of the subject conservatism
  - Is it substantial enough to justify developing a new or modified structural design paradigm?
  - The intended endgame of these efforts is a business case supporting that development



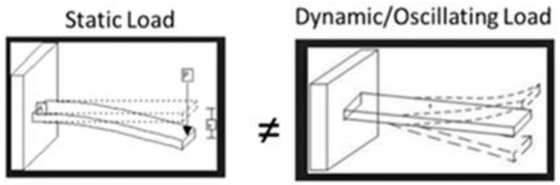
Motivation

- Hardware designed for space applications being as light as possible is paramount
- By and large, specifications for hardware include tight mass allocations
- A Launch Vehicle (LV) itself being as light as possible facilitates that LV being able to lift more payload mass to space
  - Decreases cost per lb. to space
- A payload being as light as possible facilitates options WRT which LV is contracted
  - Potentially decreases cost of LV



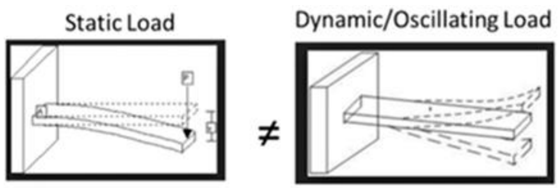
Motivation

- A component or secondary structure that attaches to a LV being oversized and the method used to analyze the primary structure (PS) side of that interface being overly conservative can result in unnecessarily robust PS
  - For example the node of an orthogrid or isogrid structure should not be sized to accommodate a small component (certainly not due to “higher” frequency loads)
    - The dog wags the tail, the tail does not wag the dog ☺
    - But in some cases, to show PS good on paper within the current paradigm becomes very challenging and unnecessarily expensive
- Significant effort has been exerted to develop optimization methods
  - WRT minimizing mass, even after successful use of the best optimization algorithms, if assuming a dynamic load is static is very conservative, hardware is still notably heavier than need be and far from optimal WRT mass



Motivation

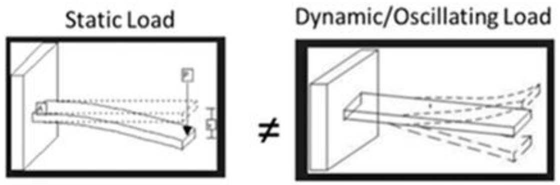
- Often hardware is thought to be overly robust
  - The magnitude of the specified design load is likely most often thought to be the cause
  - Numerous efforts have been exerted to better dynamic loads and environment prediction methods
  - While design loads clearly contribute much to the weight of the design, the manner in which they are incorporated in pertinent stress analyses dictates that final weight as well
- This effort is motivated to demonstrate that dynamic loads are static in stress analyses is very conservative
  - ***Developing a quick turnaround method to leverage dynamic strength of materials and "frequency dependency of strain" has significant value***



Background

- Mass = $
- However, while in a fast and furious LV development project or an aggressive payload development project, often items are known to be heavier than need be
    - If an item meets its mass allocation with positive Margins of Safety (MOS) it is likely more often than not signed off and the next task initiated due to schedule
    - Mass is important but ***"Schedule is King!"***

A quick turnaround method that leverages the dynamic strength of materials and/or the "frequency dependency of strain" is needed

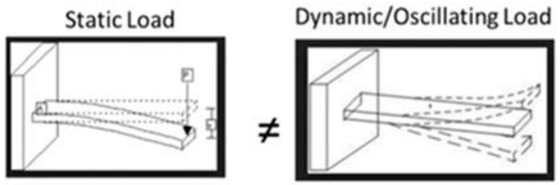


Tests

- Test were performed in 2011, 2019 and 2020 using aluminum beams as test articles
- First efforts in 2011 aimed to simply demonstrate that if all relevant variables except frequency were held equal to the extent possible measured strain associated with “higher frequency” motion would be less than that associated with “lower frequency” motion
  - For a given acceleration, as one goes up in frequency, displacement goes down for harmonic motion, and strain is a small fraction of that displacement

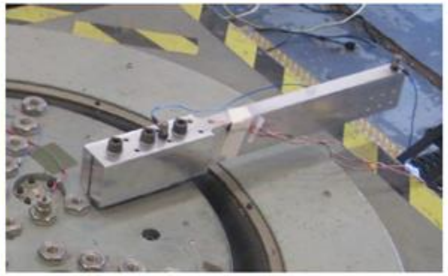
$X = A\,Sin(wt)$ $\qquad$ $\dot{X} = A\,Cos(wt)$ $\qquad$ $\ddot{X} = -Aw^2\,Sin(wt)$

$X = \ddot{X}/w^2$ $\qquad$ $\varepsilon \ll X$

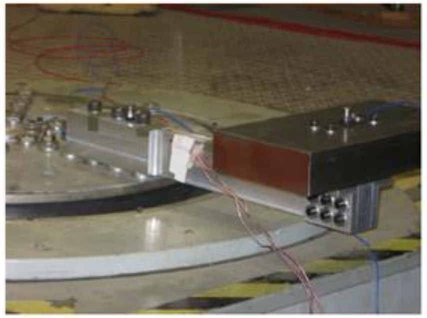


Tests

- 2011 Tests
  - Two cantilever beam configurations
    - Configuration 1: ≈300 Hz fundamental mode
    - Configuration 2: ≈40 Hz fundamental mode
      - Large mass added to shift f1 down

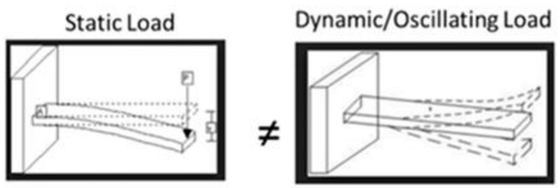


Configuration 1 – Beam without the mass
f≈300 Hz, M= 6.5 Lb., M_{CL}≈ 4 Lb.



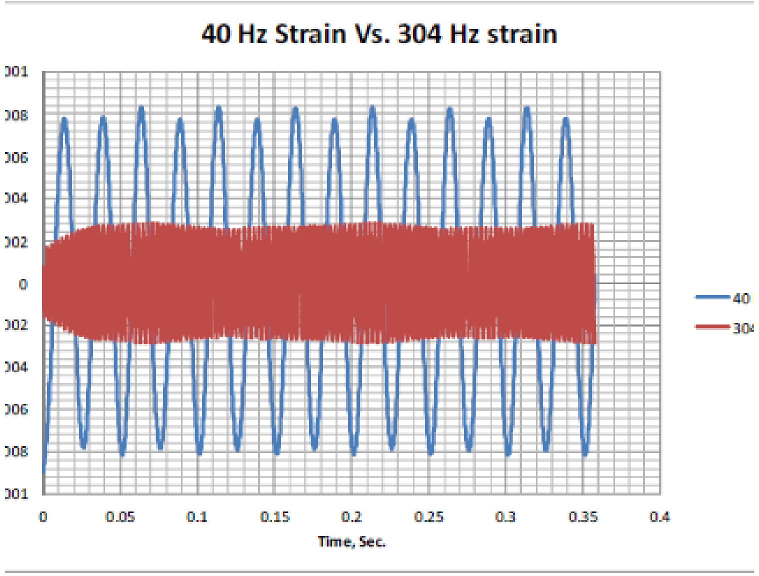
Configuration 2 - Beam with added mass
f≈40 Hz, M= 48.5 Lb., M_{CL}≈ 46 Lb.

MSFC 2011 TE Efforts

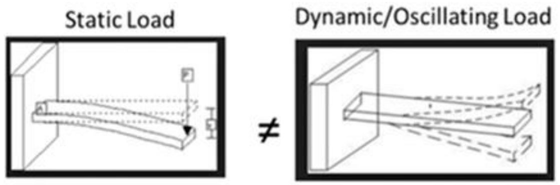


Tests

- 2011 Tests continued
- The input was specified such that the effective applied force would be close to equal
    - The input force was ≈ 95 Lb.
    - It was tuned to each configuration’s fundamental mode
- Measured strain differed by about a factor of 3

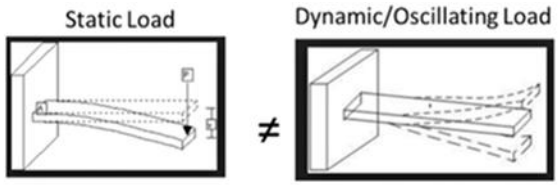


Frequency dependency of strain



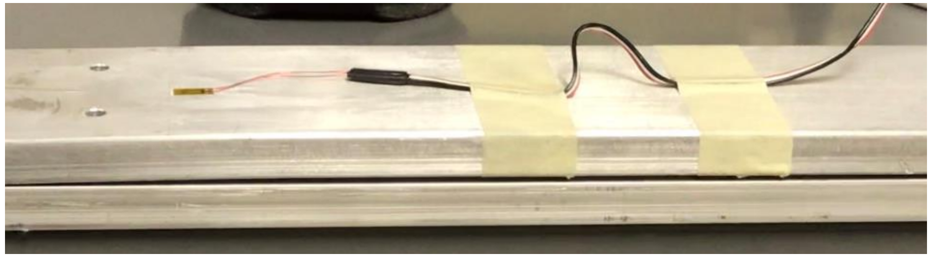
Tests

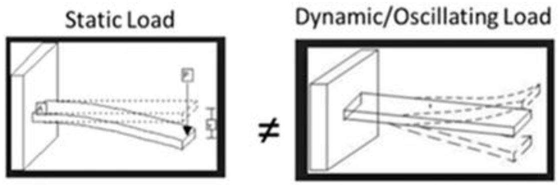
- 2011 Tests continued
- Take away points
  - Loads don’t break hardware, strain does and WRT strain, the frequency of the oscillating load matters
  - As was seen there is a significant difference in 40 Hz vs. 300 Hz



Tests

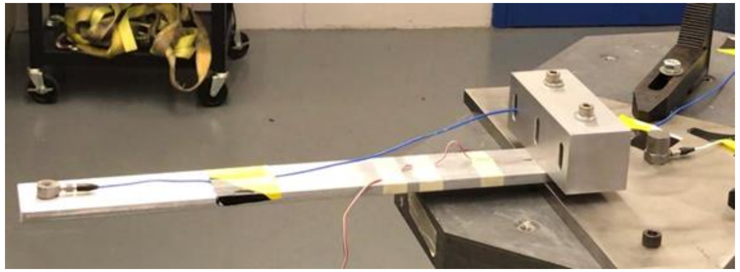
- 2019 Tests
- Prior to Dynamic tests, a static test was performed to demonstrate plastic deformation due to the predicted ultimate strength (≈80 Lb)
    - The corresponding predicted displacement < 1”
- Calibration weights were suspended from the TA



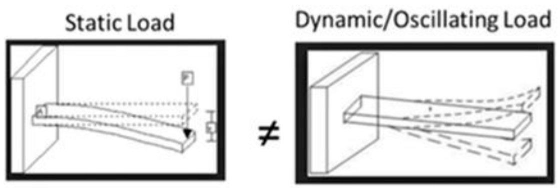


Tests

- 2019 Tests continued
- Like the 2011 tests, the 2019 test's Test Article (TA) was a beam cantilevered off of a shaker table but the purpose was a little different
  - Both sine dwell tests and random tests were performed
  - The intent was to look for trends in strain associated with different frequencies
  - Time has not permitted digging into all the test data but the most significant relevant observation will be described

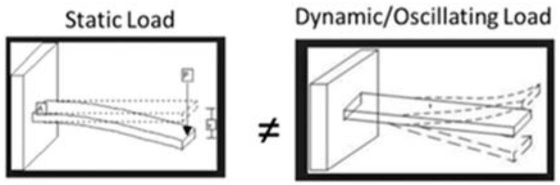


2019 TA, 2"X.375"X16" AL beam



Tests

- 2019 Tests continued
- At the end of the planned tests, the test engineer was asked to increase the input acceleration as much as he was comfortable with
  - The response accelerometer was removed for its safety
  - The sine dwell input was 15 g’s at the TA’s fundamental mode (43 Hz)
  - Strain was measured during the test but about half way thru the test the gage failed
    - Presumably due to very large displacements
    - Measured strain, prior to gage failure was over twice the ultimate
    - Plastic deformation did not occur



Tests

- 2019 Tests continued
- The observed displacement was estimated to be ± 6”
  - To be compared to the ≈1” static displacement that did result in plastic deformation
- Summary:
  - Measured dynamic strain > 2X static ultimate strength
  - Estimated dynamic displacement ±6” vs. 1” static
  - The material has much more capability to sustain dynamic loads than static loads

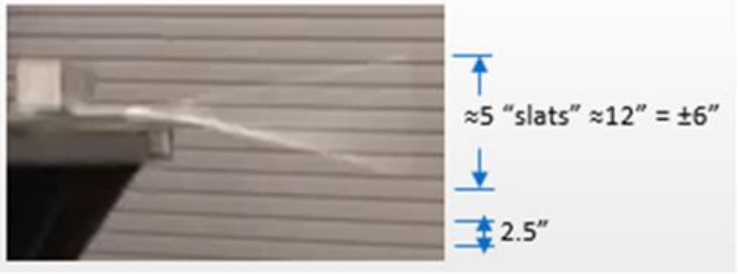
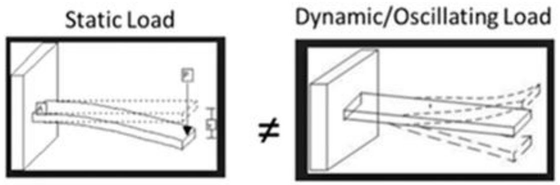
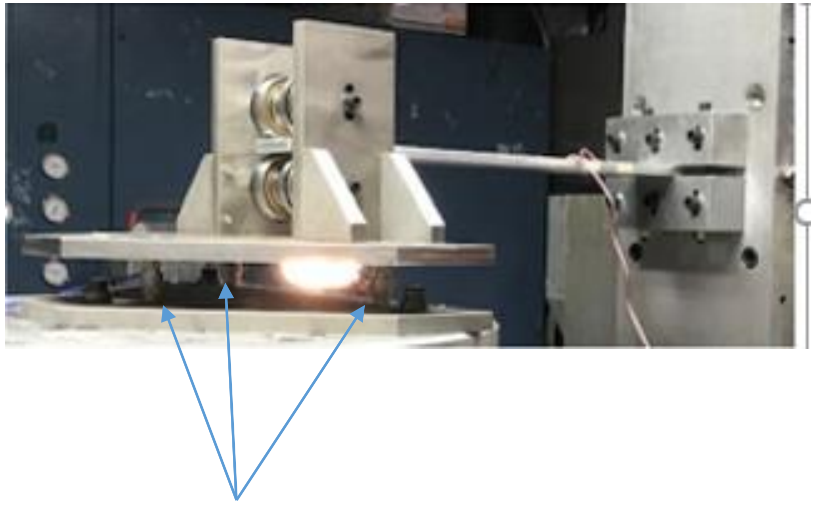


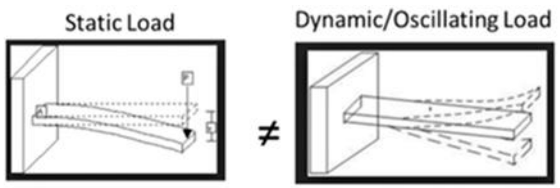
Figure 6: Tip Displacemnt



Tests

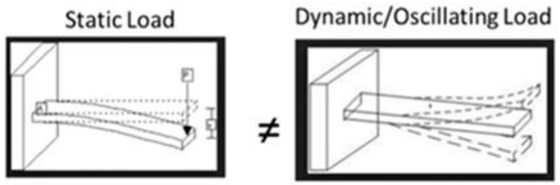
- 2020 Tests
- Tests utilized the same TA as 2019
- One end of the TA was fixed and a shaker table was used to excite the dynamically load the other end
- Objective was to facilitate measuring the dynamic force applied to the TA





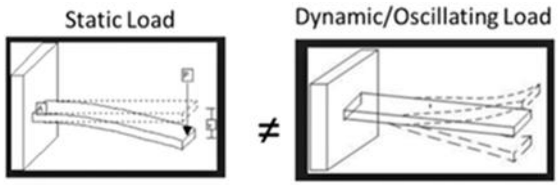
Tests

- Time has not permitted post processing of all the test data
- The most significant observation was that at 40 Hz, the TA sustained 320 Lb.
  - Four times the ultimate strength of the material
- *Again, the one liner significant take away is that some material can sustain much higher loads when the load is dynamic*



Future Work

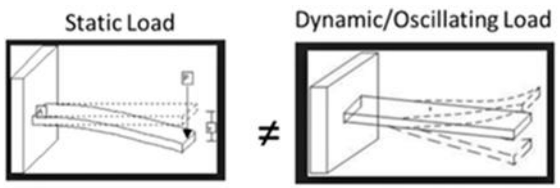
- Similar tests need to be performed, and are planned, to asses welded joints and bolted joints
- Intuition suggest that similar trends will be observed
- The envisioned end game is:
  - A mathematical method to determine a frequency threshold for a given design and specified environment above which the environment can be disregarded WRT development of structural design loads
  - Measured material strength as a function of frequency for common materials



Conclusion

- The objective of these efforts was to determine if there was enough bang for the buck, qualitatively, to pursue resources to develop the envisioned new or modified engineering method
  - The results thus far are favorable
  - The test performed show that loads applied dynamically have far less effect than static loads
    - *Therefore, to apply a dynamic load statically introduces notable unnecessary mass into a design*

Final Comment: Whittling away known and unnecessary conservatism in specified structural design loads is prudent. However, to optimize the design or show a design good on paper one should also look at how those loads are applied



The End

- Questions, comments, thoughts?

- Thanks!