Chapter 13
Mass Mitigation in Structural Designs via Dynamic Properties

J. Brent Knight

Abstract The efforts reported here are focused on mitigating unnecessary mass in aerospace hardware. The approach to remove this undesired mass from the design is to leverage both the dynamic strength of materials and the frequency dependency of strain. Analytically predicted dynamic responses of structures are often applied as static loads in stress analyses that ultimately dictate the weight of a structural design. Assuming a dynamic response is a static load and then comparing resulting stress predictions to a static strength property is a long-standing engineering practice. Doing so is known to be, or is assumed to be, conservative. However, little indication of the order of magnitude of embedded conservatism has been identified. NASA/MSFC efforts in 2011, 2019, 2020, and now in 2021 have begun to qualitatively show the order of magnitude of that conservatism. A quick turnaround engineering method is pursued to leverage the subject facets of physics for the purpose of decreasing the weight of flight hardware. Tests performed using simple beams and significant observations are described.

Key words Conservative design loads · Dynamic properties · Undue conservatism · Mass mitigation · Optimized structural design

13.1 Introduction

It is common, possibly almost exclusive, to use dynamic loads and environments to develop a structural design load that is applied as if it were static within the design/analysis process. Materials respond differently when subjected to dynamic loads as compared to static loads so this paradigm, assuming a dynamic load is static, has no physics basis. However, With Respect To (WRT) common ductile materials used in hardware designed for space applications, doing so is conservative. No work to quantify or qualify the amount of conservatism this introduces into the design has been identified. Therefore, one cannot determine how much this assumption costs a project or how much it limits Launch Vehicle (LV) or payload performance.

NASA MSFC has exerted efforts under its internal Technical Excellence (TE) program in 2011, 2019, and 2020 to quantify or qualitatively characterize the order of magnitude of conservatism imbedded in this engineering paradigm. In other words, how much unnecessary mass is in the design due to the subject assumption? If significant, perhaps it is worth investing resources to evolve a new engineering paradigm that leverages dynamic strength of materials and/or the frequency dependency of strain to facilitate lighter space flight hardware.

Highlights from 2011 efforts were presented at the Spacecraft and Launch Vehicle Dynamics working Group (SCLV) in 2012 [1]. The objective of this paper is to publish significant observations from all efforts to date.

J. B. Knight (✉)
NASA/MSFC, Huntsville, AL, USA
e-mail: brent.knight@nasa.gov

A. Amirkhizi et al. (eds.), *Challenges in Mechanics of Time Dependent Materials, Mechanics of Biological Systems and Materials & Micro-and Nanomechanics, Volume 2*, Conference Proceedings of the Society for Experimental Mechanics Series,
https://doi.org/10.1007/978-3-030-86737-9_13

13.2 Motivation

Ultimately, the motivation for this study is to develop a business case for funding to develop and evolve a new quick turnaround method to design hardware for dynamic environments that results in lighter hardware without necessitating development of new expensive “high performance” materials. Impacts or effects associated with assuming dynamic loads are static include:

1. Prevents optimizing structural designs WRT mass.
   (a) If there is significant undue conservatism in assuming a dynamic load is static then even with successful use of the state of the art optimization algorithms, hardware can still be made notably lighter.
2. Components and Secondary Structures (CSS), small items that attach to a LV, are sometimes notably heavier than need be due to design loads based on higher frequency accelerations.
3. Independent of the CSS mass, if the methodology used to assess the Primary Structure to CSS interface assumes dynamic loads are static and that includes unnecessary conservatism then that interface is more robust than need be. This can become an expensive engineering activity if the interface in question is a PS orthogrid or isogrid node. It should be extremely rare, if ever, that PS is sized to accommodate CSS.
4. PS itself is designed, in part, to dynamic loads. Therefore, there is undue conservatism/mass in PS designs that could be removed.
5. A given LV has limited uplift capability. If a payload is designed per the current method, that may limit the LVs that could transport that payload to space, since the payload would be heavier than need be.

Being able to leverage the subject facets of physics will enable a LV including all its subsystems being lighter which will allow the LV to lift heavier payloads. The same to be determined method will facilitate the payloads themselves being lighter. Both effects add, resulting in a much more efficient industry.

The weight of hardware is dependent on the load that it was designed to sustain. Therefore, it is important that no unnecessary component of load be imbedded in the resultant design load. Focus on perceived overly conservative design loads and on developing methods to decrease high loads is longstanding. However, the manner in which loads are applied in the stress analysis process is equally important WRT the final design weight. Little, if any, work has been done to show how much the subject assumption is costing a project has been done. *With it demonstrated that there is significant gain to be realized, funding to develop a new or modified engineering method will be pursued. That method will include measurement/development of frequency dependent material strength properties and a to be determined criteria that will facilitate defining a frequency threshold, for a given hardware item and specified environment, above which oscillating loads can be omitted in the structural design load development process.*

13.3 Background

Within the design phase of a new Launch Vehicle such as NASA’s Space Launch system (SLS), efforts are exerted to design hardware within defined structural mass specifications. However, it is common for the mass of a given piece of hardware to be greater than need be due to schedule. If an item is designed and it has positive margins of safety it is likely more often than not signed off and engineering moves on to the next task. In many cases, mass could have been whittled away from that design but in that moment, meeting schedules is more important.

Methods exist to design for dynamic environments that are closer to physics based as compared to applying a derived net Center of Gravity (CG) acceleration as a static inertial load in a stress analysis, and they may provide mass relief. Those methods are likely more laborious/time consuming than the current approach. They also, in cases, necessitate additional testing which takes time.

Anecdotally speaking, minimal mass is very important in space flight hardware but in a fast and furious design project, “*schedule is king!*” For this reason, proposed new engineering methods have to be quick turnaround methods comparable, WRT required labor, to the current.

The current vision for a first cut modified method is to develop frequency dependent strength properties for materials commonly used in space hardware. That property would be used to assess predicted dynamic stresses. Also, criteria to be used to deem accelerations above a determined frequency threshold for a given hardware item negligible are to be developed. These envisioned methods are to directly plug and play into the current engineering flow so little to no schedule impact is perceived.

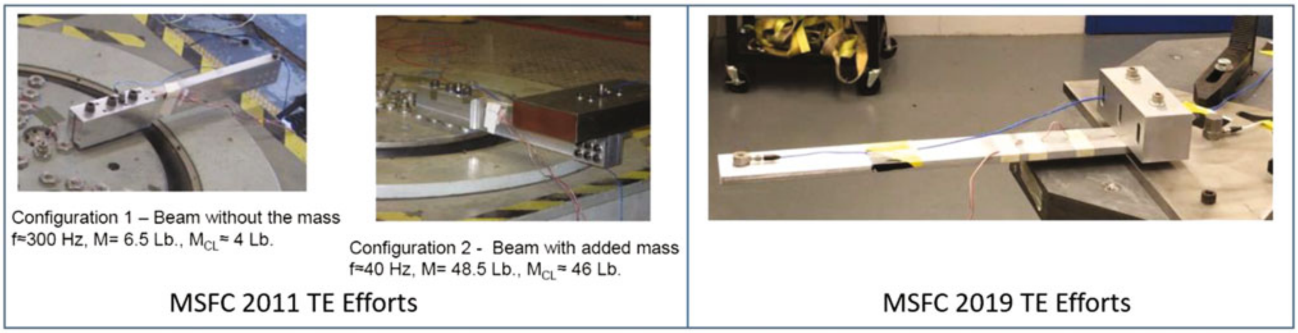

Fig. 13.1 Free vibration test articles and setup

Fig. 13.2 Forced vibration test article and setup

13.4 Tests

Two types of tests have been performed to qualitatively assess the order of magnitude of conservatism in a structural design that was based on applying a dynamic load statically. In both cases, simple aluminum beams were used as the Test Article (TA). In the first test type, "Free Vibration Test" (FrVT), the TA is a cantilever beam attached to a shaker table and in the second, "Forced Vibration Test" (FoVT), one end of the beam is fixed and a shaker is used to apply a specified sinusoidal force to the other end. Two FrVT graphics are shown in Fig. 13.1 and one FoVT graphic is shown in Fig. 13.2. There are two configurations associated with the 2011 activity. One is the simple aluminum beam alone and the other includes a large mass on the end of that beam to shift the first mode to a much lower frequency.

The FrVT configuration simulate a component mounted to (cantilevered) a LV wall. The FoVT configuration provides measured input forces to the TA.

13.4.1 Significant Observations: 2011 TE Efforts

Figure 13.1 presents the TA and the test set setup's two FrVT configurations. The intent of these tests was to measure strain from two similar tests. One with a "low" frequency fundamental mode and the other with a "high" frequency fundamental mode and with close to an equivalent loading condition. The metric of interest was how much strain would vary due to the frequency of oscillation if all other pertinent parameters were held equal to the degree possible. In both cases, the beam/cross section reacting the load was identical. The acceleration input was determined by specifying that the effective response

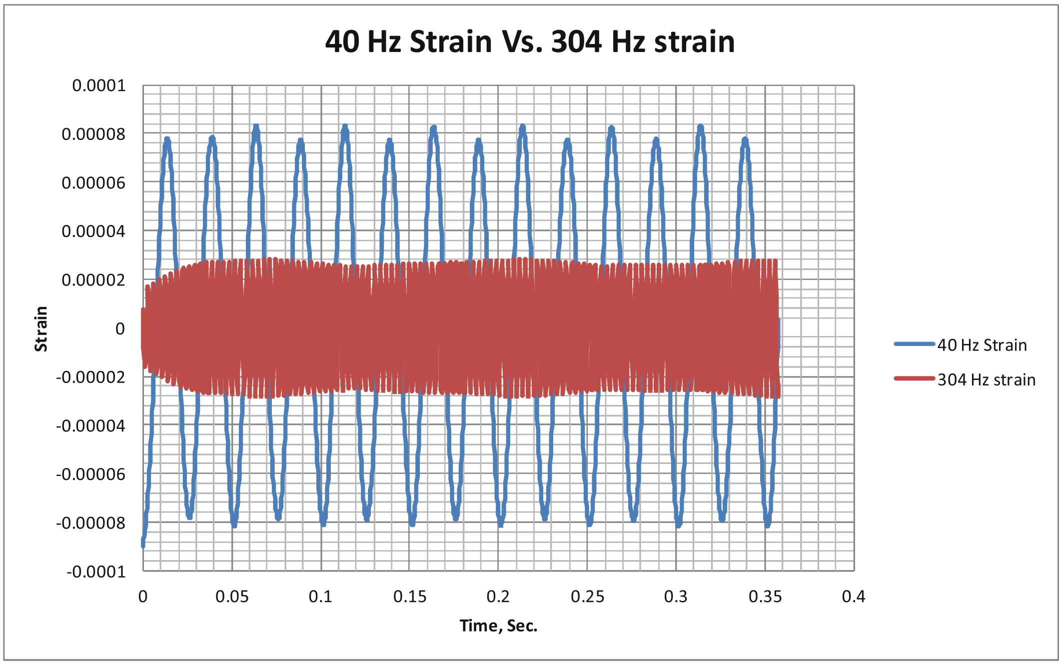

Fig. 13.3 2011 TE results

Table 13.1 Summary of 2011TE results

Configuration	Estimated force, Lb.	Acceleration, g	TA weight, Lb.	Peak strain	Fundamental mode, Hz[a]
1	98	24.5	4	0.00003	300
2	92	2	46	0.000084	40

[a](1) Approximate fundamental frequencies. (2) Input frequency

oscillating force for both cases be approximately equal and dividing by the mass in each case. The force was about 95 Lb. The tip response for configuration one was ≈24.5 g and that of configuration two was ≈2 g. Figure 13.3 shows the 40 and 304 Hz measured strain due to approximately the same load. *The low frequency strain was approximately a factor of three greater than the high frequency strain.*

This exhibits the "frequency dependency of strain" and that higher frequency motion, relatively speaking, can be expected to result in low strain. That being the case, strain associated with zero Hz is expected to be significantly higher than that associated with oscillating loads. Along these same lines, "low" frequency loads are more detrimental than "high frequency loads of the same amplitude. *All g's are not created equal!*

All of this equates to applying dynamic loads statically in stress analyses is conservative and as the frequency of the effective oscillating loads goes up the conservatism goes up as well. Configuration details and results are presented in Table 13.1.

13.4.2 Significant Observations: 2019 TE Efforts

Prior to dynamic testing, a static test was performed. Weights were suspended from the TA as shown in Fig. 13.4. The load necessary to reach the alloy's ultimate strength, about 80 Lb., was applied and a slight plastic deformation was observed. Figure 13.5 presents the post static test TA. The displacement of the TA tip while loaded was approximately 1″ which is consistent with predictions.

Like the 2011 efforts, 2019 efforts utilized the FrVT configuration but the objective was different. The TA and test configuration are shown in Fig. 13.1. Both sine dwell and random vibration tests were performed. The objective was to excite the first few modes of the TA and attempt to identify trends in measured strain WRT frequency of oscillation. The bulk of test results have not been post processed and summarized but one significant observation will be described.

Fig. 13.4 Static test

Fig. 13.5 Plastic deformation

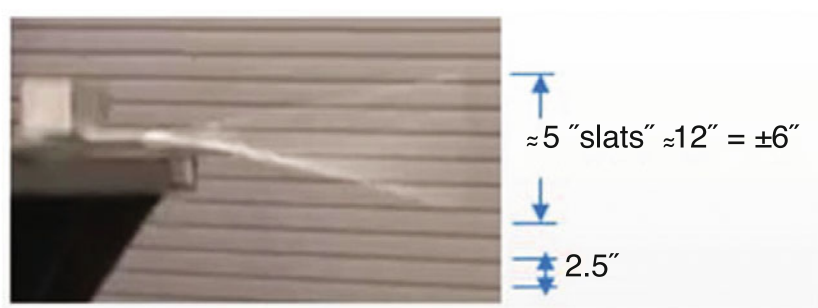

Fig. 13.6 Tip displacement

At the conclusion of the planned tests, the test engineer was asked to perform a final run and input the maximum amplitude acceleration that he was comfortable with and to do so at the fundamental mode of the TA. The response accelerometer was removed for its protection and 15 g was input at 43 Hz, the TA's first mode. Strain was measured in the test but about half way thru the test the strain gage failed, presumably due to the very large displacements of the TA. Figure 13.6 illustrates the magnitude of displacement that the TA experienced. An estimated $\pm 6''$ displacement was observed.

Comparing to the static test, approximately 1″ of flexure due to a static load resulted plastic deformation but ± 6″ of flexure dynamically did not. This alone illuminates the order of magnitude of conservatism embedded in assuming a dynamic load is static. Adding to that, the strain measured prior to strain gage failure was greater than twice the ultimate.

Fig. 13.7 TSS

Fig. 13.8 FoVT TA Constraints

13.4.3 Significant Observations: 2020 TE Efforts

Unlike 2011 and 2019 efforts, the 2020 efforts utilized the FoVT configuration shown in Fig. 13.2. These tests were performed to enable measurement of applied dynamic force directly. The primary target product from these tests was data that will support saying X pounds were applied dynamically to the TA without damage. Again, this rolls into qualitatively capturing the order of magnitude of conservatism in assuming a load is static in stress analyses.

The complete set of data from these tests has not been processed and summarized. The single most significant observation is described here. With one end of the TA fixed and the other engaged with the Test Support Structure (TSS) in a kinematic manner (situated between bearings in the TSS), the shaker table applied the dynamics load. The TSS included three load cells that separated the two steel plates and the test was controlled per the average of those measured forces. Figure 13.7 shows the TSS. Figure 13.8 shows the TA's constraints.

An applied force at specified amplitudes and frequencies was applied to the tip (approximately 0.5″ from the end) of the beam. *The most obvious significant finding was that at 40 Hz, categorically low frequency, the TA sustained 320 Lb. which is 4 times the static load that resulted in plastic deformation.*

Once again, findings make clear that there is significant gain to be realized via evolving a quick turn around stress analysis method that leverage the subject facets of physics.

13.5 Future Work

The work presented in this paper was relative to aluminum beams. Future efforts are planned to investigate different alloys and perhaps various composites. Additionally, efforts to assess joints are planned as well. Threaded fasteners, inserts, and welds are to be tested.

13.6 Conclusion

It has been concluded that there is significant undue conservatism in assuming dynamic loads are static in stress analyses that dictate the weight of hardware designed for space applications. When the envisioned dynamic strength properties and criteria are in hand, notable mass savings will be realized. Intuition suggest that similar results and conclusions will be arrived at for other alloys and possibly some composites.

Prior to implementation, similar tests are to be performed to assess bolted and welded joints.

Acknowledgments Efforts associated with the content of this paper were exerted as time permitted in between required project support. Over the course of years, numerous people and organizations have contributed to this effort. NASA/MSFC has provided resources on three occasions. NASA/MSFC/ET40 (Structural Dynamic Test Lab) and specifically Mr. Steve Rodgers, has provided support as time was available. MSFC management has proactively assisted in efforts to get support for this activity. Numerous interns have contributed much. The interns that supported are Rachel Pilgrim (spring 2019), Ashlee Bracewell (summer 2019), Miguel Alizo (Fall 2019), Marcio Simao (spring and summer 2020), and Ariel Ferrera (summer 2020).

Reference

1. Knight, J.B.: Undue Conservatism in Random Vibration Design Loads. SCLV, Aerospace Corporation (2012)