**Advanced Technologies for Hypersonic, Propulsive, Energetic and Reusable Platforms**
**REU-HYPER 2019**
**28 May – 2 August 2019, Orlando, United States**

**REU-HYPER 2019**

# Damping of Anisotropic Composite Structures Under Extreme Multi-Axial Mechanical and Thermal Loads

**Daniel Benitez**[1]

[1]North Carolina State University

**Dr. Jeffrey Kauffman**[2]

[2] University of Central Florida, Associate Professor, Department of Mechanical and Aerospace Engineering

## ABSTRACT

**Carbon composites are continuously used in aerospace structures to keep the weight of the aircraft/spacecraft down while providing equal or more strength than the opposing metal structure. One of the additional advantages of using carbon composites is for their high-temperature tolerance and low thermal expansion. In many cases, aerospace structures undergo extreme mechanical and thermal loading. For this reason, carbon composites are typically the best option for construction. However, due to their anisotropic properties predicting their vibrational and damping response under extreme conditions can be difficult. Previous research has been conducted on damping models with a vibrational response for isotropic structures experiencing membrane loads. This report will focus on the development of a damping model dependent on the mechanical and thermal loading of a carbon composite structure by employing a modified modal strain energy method. Composite plates will be tested in a dynamic test stand to determine their vibrational response while under extreme loading. The results of this study will help determine a damping model for the vibrational response of composite aerospace structures under extreme loads.**

## NOMENCLATURE

A = amplitude
f = frequency
n = peak number
t = time
$\delta$ = "slope" of the decay envelope
$\xi_r$ = damping ratio
$\omega_{d,r}$ = damped natural frequency

## 1. INTRODUCTION

The aerospace industry has a constant demand for aerospace structures consisting of lighter materials that are capable of withstanding aircraft/spacecraft inflight design loads. Originally metals, such as aluminum, were used for most aerospace structures and are still in use today. However, one of the major drawbacks of using metals is that even with their strength, they experience large thermal expansion and are relatively heavy compared to other competing materials. Composite materials have become popular as a substitute to metals in many industries, especially within the aerospace industry. Companies have resorted to using composites, more specifically carbon composites, to achieve both weight reduction and design load constraints. As opposed to metals, they offer the best strength to weight ratio with high-temperature tolerance and low thermal expansion. Unlike metals, composites tend to be anisotropic. The anisotropic properties of the composite make it difficult to determine the structure's vibratory and damping response. Aerospace structures undergo extreme mechanical and thermal loads; the addition of these two factors increase the difficulty to predict the damping response of the composite. Therefore, the objective is to develop a damping model dependent on the mechanical and thermal loads applied to a composite plate.

## 2. BACKGROUND

Previous research exist on several vibrational and damping models, in addition to, the development of damping models of structures under mechanical stress. To start with, Ref. [2] goes over a brief overview of the importance of considering damping in structural design and continues by defining different damping models such as modal, viscous, and structural damping. In a separate paper by the same author, a viscous damping model was developed for structural beams under various boundary conditions to provide a more accurate representation of frequency-based damping [4]. In Ref. [3], Lesieutre studies various damping models based for a simply supported beam experiencing membrane loads. Lesieutre finds that tensile loads on a beam increase the natural frequency and decrease modal damping while compression serves the opposite purpose. Most of these models used derivation methods in the form of analytical analysis and finite element analysis. Even though several models have been created to better represent realistic structural damping for beams under membrane loading, they do not consider the additional effects of thermal loading. In many cases, the models are derived analytically, whereas, this topic will focus on supporting a damping model with real test data from a structure undergoing mechanical and thermal loading.

## 3. MATERIALS AND METHODS

This report will focus on the development of a damping model which arcuately represents a composite plate under extreme mechanical and thermal loads. The approach differs in that the structure is anisotropic, thus, mechanical and thermal loading will have an increasing influence on the damping response of the structure.

Firstly, a dynamic test stand is designed to induce multi-axial loads onto a test article. The main function of the test stand is to apply either compression or tension on both planar axes of a plate. Mechanical loads are applied to an 8”x8” plate with a maximum thickness of 1/8th inch. The test stand consists of inexpensive materials and a simple mechanism to apply mechanical loads. Tensile loads will consist of 200% of the buckling load for each plate, whereas the compressive load will consist of 50% of the buckling load. Previously, a student created a stand that would induce compressive stress by using compressive springs attached to aluminum blocks and threaded rods to a simply supported plate. This design consists of a great concept; however, movement of the blocks are restricted by the threaded rods. With the student’s setup it is impossible to apply any tension onto the simply supported plate. As a result, grips are involved in the design of the test stand.

The test article is experimented on under a set of different loading conditions. Since the focus is on applying load on both the test article’s planar axes, there will only be 3 load sets:

- Tension-Tension (T-T)
- Tension-Compression (T-C)
- Compression-Compression (C-C)

The plate is symmetrical along both load-bearing axes; thus, only one set of T-C exist. Whichever axis is under tension or compression will have no effect on the plate’s stress distribution or on the experimentation. For each case, a tension or compression load is first applied only on one axis before the grips are engaged for loading in the other axis. This prevents any initial deformations from effecting the secondary loading.

It is predicted that plate geometry may impact the stress distribution across the plate under the T-T load set. During experimentation, it is ideal that most of the induced stress is experienced across the center area of the plate. Applying tension on the plate by using a set of grips should result in high stresses near the grips or at the corners of the plate. The stress distribution across the plate under the T-T load set will be analyzed using finite element analysis. In the analysis, different plate geometries are analyzed to determine their effects on the distribution. The plate will be modeled as close to real conditions as possible.

An 8”x8”, aluminum plate with a thickness of 0.025 inches is used for preliminary testing. The preliminary experiment only involves clamping down the plate on all four sides with the grips. Data is gathered by using an impact hammer, accelerometer, and Data Acquisition Unit (DAQ) alongside LabVIEW. The response of the dynamically loaded plate is gathered through FRF amplitude, FRF phase, and acceleration plots. There is an input (impact hammer) and output (accelerometer) point on the plate, as seen in Fig. 1. The natural frequency and damping ratio of the test article are calculated using the Half-Power Bandwidth Method and Logarithmic Decrement Method, as shown in the equations below. The damping analysis is carried out using MATLAB code for each method.

Half-Power Bandwidth Method

$$\delta = \frac{1}{n}\log\frac{A_o}{A_n} \tag{1}$$

$$\xi_r = \frac{1}{\sqrt{1+\left(\frac{2\pi}{\delta}\right)^2}} \tag{2}$$

$$\omega_{d,r} \approx \frac{2\pi n}{t_n - t_o} \tag{3}$$

Logarithmic Decrement Method

$$\xi_r = \frac{\Delta\omega}{2\omega_r} = \frac{\Delta f}{2f_r} \tag{4}$$

Figure 1: Input-Output Point

## 4. RESULTS AND DISCUSSION

For the final dynamic test stand design, it is determined that clamping onto the plate will provide better and consistent results for applying both compressive and tensile loads. To accomplish this four sets of grips are designed, as seen in Fig. 2. The grips clamp onto the plate by tightening down two mounted feet per grip. The feet apply distributed pressure along the plate's edge through a ¼ inch thick aluminum bar. These grips are completely effective in that the plate cannot be pulled out when a grip is engaged. Springs offer a simple and inexpensive method for calculating the loads applied to the plate. Using the springs' stiffness and a specified displacement, the approximate force exerted on the plate is calculated. For plates with varying thickness and buckling loads, the springs can be exchanged to account for the difference in mechanical load. The springs attach to the blocks using bolts and washers or hooks.

The clamps attached to springs glide along the path of the t-slotted frame to keep the load consistently applied on either of the plate's axes. However, when attempting to freely slide the grips along the frame, they become difficult to move in a single motion. This may cause problems when the springs are engaged, causing the load to be carried by the frame instead of the plate.

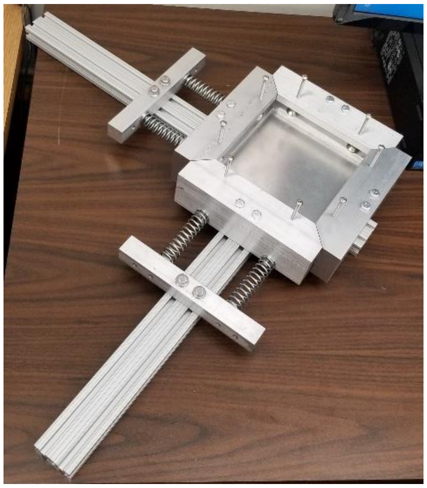

Figure 2: Dynamic Test Stand

Depending on the plate geometry and how that plate is loaded, the stress concentrations are highly affected. Two different plate geometries were analyzed in ANSYS. Both geometries involved an 8”x8”, 0.025-inch-thick, aluminum plate. One of the plates contained 1-inch square cut-outs at each corner. Figures 3 and 4 display the stress distribution in the x-axis from a displacement placed on adjacent sides. From the analysis, the symmetric conditions of the plate result similar data for both the x-axis and z-axis. Both plates experienced high-stress concentrations at the corners where the grips are engaged. However, the cutout geometry resulted in a much lower stress concentration. There is over a 50% drop in stress at the corner in the new geometry for a T-T test condition. For real experimentation, it is ideal to have a higher concentration towards the middle of the plate.

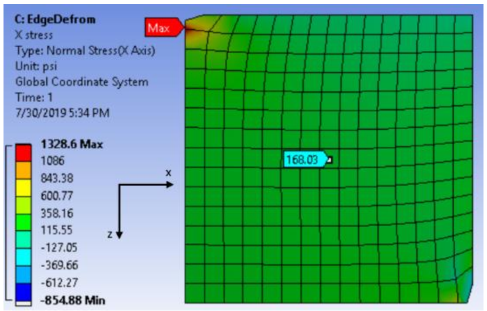


Figure 3: Plate Geometry Analysis

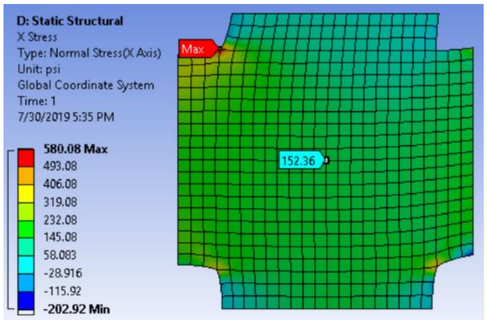


Figure 4: Cutout Geometry Analysis

## 5. CONCLUSION

The final dynamic test stand design proved to be useful in clamping onto the plate and providing tensile and compressive loads. Compressive springs are easily engaged; however, with the current design, the amount of tensile load may be restricted by the amount of force the user can exert. Also, while attempting to test the C-C load set, the grips will end up pushing against each other if there is enough deformation in the plate.

By using finite element analysis, the plate geometry in the T-T load condition is analyzed. Depending on the geometry used, the stress concentrations can vary. Using similar methods and with realistic boundary conditions, a proper geometry can be defined for the load case T-T. The stress is reduced by cutting out sections of the plate's corners. The ideal distribution for the load case will have low concentrations at the corners and more towards the center.

Furthermore, there is still much to do to complete this research topic. First, data analysis, using the Half-Power and Logarithmic Decrement method, on the preliminary experiment data must be completed. Experimentation with carbon fiber composites on the test stand is necessary to validate its effectiveness. If the test stand is not able to provide mechanical loading onto the plate, then it needs to be modified. Once the test stand is verified, a method to apply thermal loads on the test article needs development. At that point, depending on the method the test stand may need to be modified again. Also, it is beneficial to determine whether the order of application from mechanical and thermal loading will have any bearing on the results of the experiment. When both mechanical and thermal loading can be applied to the plate, damping analysis will provide results for the overall objective of this research topic.

## ACKNOWLEDGEMENTS

The authors would like to thank Chris Kelly, Andres Rodriguez, and Christian Vazquez for their continued support in the development of this project.

## REFERENCES

[1] Kauffman, J. L., Lesieutre, G.A., and Babuska, V., “Damping Models for Shear Beams with Applications to Spacecraft Wiring Harnesses,” Journal of Spacecraft and Rockets, Vol. 51, No. 1, 2014, pp. 16-22. doi: 10.2514/1.A32440

[2] Lesieutre, G., “Damping in Structural Dynamics,” Encyclopedia of Aerospace Engineering, edited by R. Blockley and W. Shyy, 2010, pp. 1–14.

[3] Lesieutre, G., “How Membrane Loads Influence the Modal Damping of Flexural Structures,” AIAA Journal, Vol. 47, No.7, July 2009, pp. 1642-1646 doi: 10.2514/1.37618

[4] Lesieutre, G., and Kauffman, J. L., “’Geometric’ Viscous Damping Model for Nearly Constant Beam Modal Damping,” AIAA Journal, Vol. 51, No. 7, July. 2013, pp. 1688–1694. doi: 10.2514/1.J052174