

# **PROTECTING ART AND INCREASING AWARENESS OF TRANSPORTATION RISKS**

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Authors:

Daniela Cerkanowicz

Jacob Henry

Jacob Kaplan

Martin Walwik

Submitted to:

Professor Melissa Belz

Professor Lauren Mathews

Worcester Polytechnic Institute

Sponsor:

Dale Kronkright

Georgia O'Keeffe Museum

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## Abstract

Preserving historic art provides society with a greater connection to its cultural history. Unfortunately, insufficient protection from vibration for canvas paintings in transit threatens to rob us of this benefit. This project was sponsored by the Georgia O'Keeffe Museum (GOKM) who provided tools and suggestions for researching this ongoing problem. We designed and implemented an affordable method of using simple sensors to analyze the effectiveness of packaging materials at eliminating vibration. We used this analytic method to evaluate a variety of alternative materials to the conventional foams used in canvas shipping containers. Finally, we worked with the GOKM to create a draft exhibit design to raise public awareness of the museum's work to stop vibration damage.

# Executive Summary

## **Background**



*From the Faraway, Nearby (O'Keeffe, 1937)*

Georgia O'Keeffe was a remarkable artist of the 20th century. She was one of the first female artists to participate in the American Modernist movement (Randolph, 2017). E.C. Goossen, a leading art critic and curator of the 1960s, praised her as “a thoroughly representative American artist of the first rank,” (Scott, 2015).

Preserving the works of O'Keeffe for artistic value alone is justified, but art often holds significant meaning outside of its visual beauty or market-value. Art is important to preserve because it captures the thoughts and feelings of an entire era (Gerlach, 2014). Georgia O'Keeffe's work in particular is significant in that it relates to her struggle for independence during the Women's Rights movement of her time (Scott, 2015). It is important that such artwork continue to be shared for the historical connections they provide (Chute, 2011).

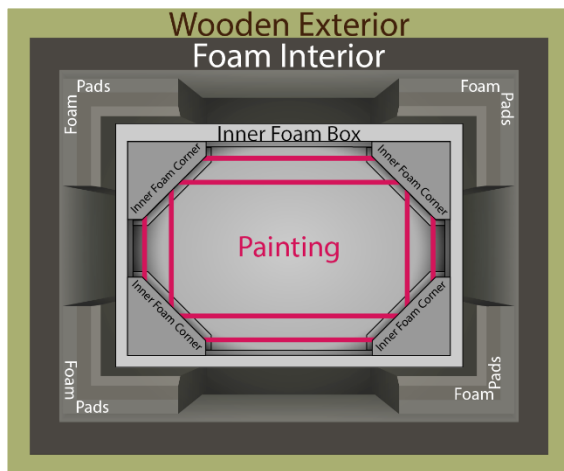
Historically, shipping techniques were concerned with keeping the work in place, not necessarily protecting it. The packing materials – often paper, rope, and straw – could scratch and disfigure the pieces being shipped (Keenpac, 2014). These methods led to many artworks being destroyed before reaching any museums.

During the 1950s the art world began to use more advanced protective materials such as foams and plastic shells (Shelley, 1987). Currently, when art is shipped it is placed in a foam lined box which is sealed and secured inside a foam lined wooden crate. This double crate design gives protection to the artwork from major drops and shocks that may occur during transportation.

## **What is Going Wrong?**

Despite the current protection of art packaged in crates and foams, works are still being damaged. The Georgia O'Keeffe Innovation (GOKI) group noticed that cracks in the oil paintings were appearing without any drops or shocks exerted on the artwork. They realized that the cracks were caused by vibrations created by the vehicles used to transport paintings. The vibrations cause the artwork to flex, which causes cracks to form as the dry oil paint bends. In an attempt to stop the damage, our team worked with the GOKI group to explore ways to dampen the vibrations.

## Project Goal



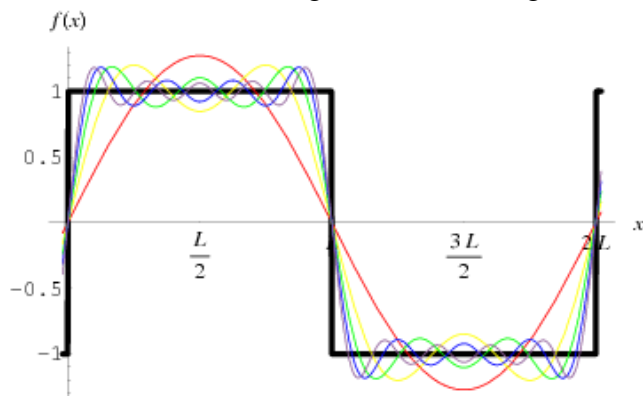
*Diagram of a typical canvas artwork shipment crate.*

The goal of this project was to help the Georgia O’Keeffe Museum better understand and prevent vibration’s effects on paintings in transit. To accomplish this goal, we first combined several existing vibration analysis techniques. We then used those techniques to evaluate the effectiveness of different conventional and nonconventional shipping materials. To conclude our project, we drafted a museum exhibit designed to help the public better understand the problems the museum faces in shipping artwork, and the steps taken to mitigate damages.

## Objective 1 Methods

For the GOKM to properly evaluate new container materials, they needed a method to measure vibrations. For their initial investigations into determining the cause of damage before our team’s arrival, the GOKI group relied upon extremely expensive tools such as a Multiple Scanning Vibrometer (MSV) and the Polytec Scanning Vibrometer (PSV). Ideally, the GOKM would be able to continue using these devices to test future designs and materials. However, renting these tools was prohibitively expensive and unsuitable for long term experimentation. In order for the museum to continue testing, a cheaper method of data collection had to be created. As a result, our team turned to accelerometers to collect data.

To provide a cost-effective solution, we designed our own data acquisition system. We decided to use an STM LIS3DH accelerometer, a lightweight, affordable sensor used to measure accelerations. To utilize the sensor, we used a microcontroller – a very small programmable computer specifically designed for interfacing with other small electronics – known as the Arduino Uno R3. The Arduino served as a “middleman” for the data, reading data over wire connections from the accelerometer and sending it via USB to a laptop. The small size, mass, and cost of the LIS3DH accelerometers allowed for us to easily place many of them within the small crevices of the crate while obtaining accurate readings.



*Example DFT approximating of a square curve using sine waves  
(Weisstein, n.d.)*

To obtain the vibration frequency spectra from the raw accelerometer data, we performed Discrete Fourier Transform (DFT) analysis. DFT analysis takes in a large number of data points over some interval of time, and tries to approximate a “line of best fit” through them by combining periodic wave functions (in this case, simple vibrations) of different frequencies. This provides an approximation of what frequencies of vibration are occurring at the accelerometer mount point (Brandt, 2011).

To perform this analysis, we used the programming language Python with the research module SciPy (Jones et al., 2001).

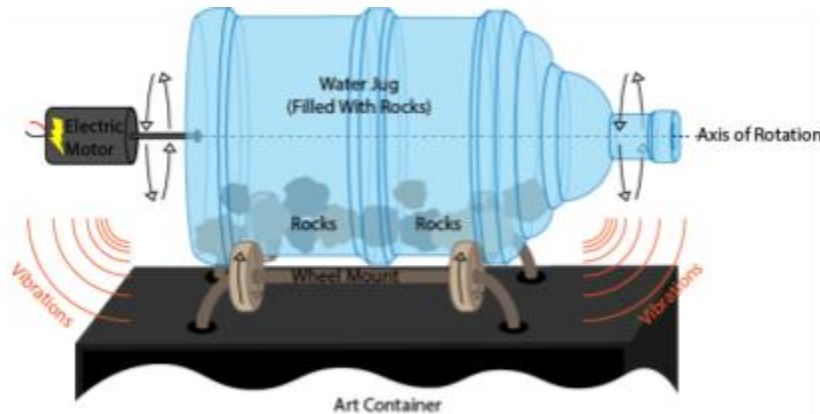
However, the standard DFT function requires all of its data to be from the same set of vibrations (Brandt, 2011), which would not work if there were irregular bumps or changes in vibration during transit. To account for this, we used a modified version of the DFT known as Welch's method. Welch's method breaks the accelerometer data into smaller windows of time, and performs DFT analysis on each window. The average of the spectrums is then computed (Welch, 1967).

## **Objective 1 Results**

In accomplishing objective 1, we were able to successfully wire the Arduino in a way that supported up to 32 accelerometers, and use these accelerometers to analyze vibrations at their respective mount point. Unfortunately, due to limitations in the Arduino's USB data output speed, we were limited in how many total sensor readings we could output per second. For this reason, we were limited to only 6 simultaneous sensors, which was sufficient for testing but not ideal. For future designs, we could use the same circuit design with a more advanced version of the Arduino, which would allow us to send the data over four times as fast (and thus support 24 sensors) with minor changes to our program.

## **Objective 2 Methods**

Before we tested different materials for damping, we first created a system that attempted to mimic the vibrations experienced in transit. We designed our vibration generating machine by filling a large water jug and with many rocks of different sizes. The jug was placed on 4



*Diagram of our water-jug shaker used to generate vibrations*

mounted wheels to rotate freely about its central axis. A hand drill was used as a motor to rotate the water jug. As the jug rotated, the rocks tumbled chaotically, creating vibrations. We measured these simulated vibrations with accelerometers, as explained in objective 1, to check whether these vibrations were actually similar to trucks' vibrations.

After establishing our vibration generating system, we tested different alternative materials to the traditional packing foam. We first tested the crates with their current PEU foam. After obtaining these baseline readings, we lined the existing foam with various alternative damping materials and tested each with the method from objective 1. The different materials configurations we tested were:

- PORON; a urethane synthetic crystalline compound
- Sorbothane; a visco-elastic polymer
- Excelsior; fine curled wood shavings of aspen logs
- PORON + Sorbothane; (to determine if their benefits were additive)



## **Objective 2 Results**

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After analyzing the water-jug shaker's vibrations, we found that while it did not exactly mirror those produced by a transport truck, they were at least consistent enough to be used for reproducible experiments. Of the materials analyzed, Excelsior showed the most promising improvements to counteracting vibrations over other materials in most frequency ranges, but was not a clear best choice overall. The size and weight of a painting can alter how it responds to different frequencies of vibration, influencing the "best choice" of material. Nevertheless, the Georgia O'Keeffe Museum can continue to use this method of testing materials to evaluate the damping properties of any potential foam replacement.

## **Objective 3 Methods**

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For our last objective, we created a museum exhibit draft that established the current problems with art shipment and how the GOKM is working to alleviate them. Initially, we created a list of the individual core concepts of the project and how we might go about representing them. We needed to convey how art is shipped/why it is dangerous, what the museum is doing to protect art, and why protecting art matters.

Before drafting an exhibit, we interviewed Georgia O'Keeffe Museum curators Carolyn Kastner and Cody Hartley to get a sense of how to properly draft an exhibit as well as how to display technical information in an accessible way. We then set out to make several 3D model draft options for each of the core ideas we wanted to convey.

## **Objective 3 Result**

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We designed several modular drafts for the museum staff's consideration. The majority of the basic information was presented in writing, with an effort made to minimize size and complexity as suggested by the curators. The modules consisted of physically engaging tactile elements and interactive visual representations to help convey more technical aspects of the museum's work.



*Exhibit Module Draft Design: Touch-table materials display with video showcasing how they were used*

## **Conclusion**

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The GOKI group benefited from our work and will continue to explore materials and damping methods after our departure. We delivered a method of analyzing vibration damping effectiveness, and created a way to quantitatively compare one crate design's effectiveness to another. The applications of our findings will hopefully allow for museums to more safely transport art. It is important to note that our findings here do not apply solely to the works of Georgia O'Keeffe. Any insight gained into protecting her paintings are applicable to canvas artworks worldwide.

## Acknowledgements

This project would not have been possible without help. We would like to give special thanks to Dale Kronkright, head conservator of the Georgia O'Keeffe Museum, who was our liaison and gave invaluable insight into how we could best help the museum in its research. Dale was actually one of the people who started this research project at the museum, and we are glad we were able to work with him to solve this important problem. Additionally, we would like to thank Barbara Kimbell, a docent at the Georgia O'Keeffe Museum who acted as our liaison when Dale was abroad. We cannot overstate how much she helped us finish this project on time by helping us get the tools and materials we needed as quickly as possible. She also provided extremely helpful information and resources about the background of Georgia O'Keeffe, and the value of her work. We would also like to thank Carolyn Kastner, Cody Hartley, Sarah Zurick, and Shannon Bay for taking the time to be interviewed, as the advice they provided was immensely helpful in producing the exhibit drafts.

We would further like to thank Professor Melissa Belz and Professor Lauren Mathews for their support and honest feedback during this project. Finally, we would also like to thank Professor Fabio Carrera for organizing the Santa Fe project center and making this project possible.

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## Authorship

<b>Section</b>	<b>Primary Author(s)</b>	<b>Primary Editor(s)</b>
Title Page Graphic/Layout	Jake	Jacob
Executive Summary	Daniela, Jake	Jacob, Jake
1.0 Introduction	Jacob, Martin, Daniela	Daniela, Jacob, Jake
1.1 Significance of Georgia O’Keeffe’s work	Jacob, Martin	Daniela, Jake, Martin
W1.2 Importance of Preserving Artist’s Legacies	Daniela, Martin, Jacob	Daniela, Jacob, Jake, Martin
1.3 Causes of Damage in Transit	Daniela, Jacob	Jacob, Jake, Martin
1.4 Existing Techniques for Vibration Reduction	Daniela, Jacob, Jake, Martin	Daniela, Jake, Martin
1.5 Disadvantages of Current Methods	Jacob	Daniela, Jake
1.6 Project Goal	Daniela, Martin	Daniela, Jacob, Jake
2.0 Methodology	Daniela, Jacob, Martin	Daniela, Jake
2.1 Objective 1 Methods	Daniela, Jacob	Daniela, Jake, Martin
2.2 Objective 2 Methods	Daniela, Jacob, Martin	Daniela, Jacob, Jake, Martin
2.3 Objective 3 Methods	Daniela, Jacob, Martin	Jacob, Martin, Daniela
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5.0 Conclusion	Daniela, Jacob, Jake, Martin	Jake, Martin
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Appendix B	Daniela, Martin	Jacob, Martin
Appendix C	Jacob	Jake

## 1.0 Introduction: The Social Reasoning and Technology Behind Protecting Art

Artwork is important for providing cultural and historical background to modern society. Beyond their aesthetic value, the context surrounding an artist's creations can tell a broader story about their life and culture. For instance, Georgia O'Keeffe's paintings are mostly abstract depictions of flowers, rivers, and other natural features, but the story they tell is far more important: that of a woman rejecting artistic and gender norms, and moving far away to the American Southwest in pursuit of independence. It is important that as a society we protect the physical artworks of artists like O'Keeffe so that we do not lose the valuable cultural insight and historical perspective they provide.

The Georgia O'Keeffe Museum currently possesses and is responsible for the preservation of the majority of O'Keeffe's canvas paintings. Like most museums, the GOKM frequently transports many of its artworks around the world to be displayed at other art institutions. Recently, conservators at the GOKM noticed unexpected deterioration in many of their paintings, and suspected transport to be the cause of the damage. The museum created a research team, the Georgia O'Keeffe Innovation (GOKI) group, to investigate this issue further. Using advanced sensor technologies, the GOKI group discovered that even when protected by state-of-the-art canvas packing materials, the paintings were experiencing unsafe levels of vibrations when exposed to shipping conditions. Due to the ubiquity of the shipping container they tested, it was clear that this damage was affecting any canvas painting in transit, not just the works of O'Keeffe.

Currently, the GOKI group is working towards designing innovative packing systems to help prevent further damage to paintings worldwide. Unfortunately, as a smaller museum, GOKM is limited in its resources and access to technical expertise; it cannot afford the cost of continuing its initial method of experimentation. The rest of this chapter provides further details of why protecting artwork is important, and why current protective practices are insufficient.

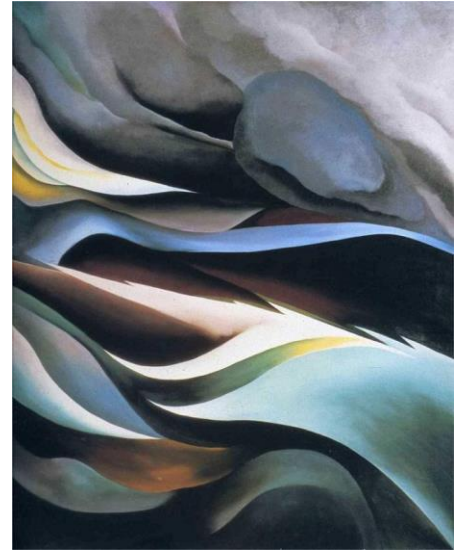
### 1.1 Significance of Georgia O'Keeffe's Work

Georgia O'Keeffe was a remarkable artist of the 20th century. She was one of the first female artists to participate in the American Modernist movement (Randolph, 2017). E.C. Goossen, a leading art critic and curator of the 1960s, praised her as “a thoroughly representative American artist of the first rank,” (Scott, 2015).

When viewed chronologically, Georgia O'Keeffe's paintings showcase her personal growth as an artist. As a young woman, she was considered a realist painter; most of her artwork captured the subject matter exactly as it appeared in reality. Her approach to painting changed in 1912 when she was introduced to the ideas of Arthur Wesley Dow, who believed that art could be created by the composition of lines, masses and colors to form harmony.



*Figure 2- From the Faraway, Nearby (O'Keeffe, 1937)*



*Figure 1- From the Lake (O'Keeffe, 1924)*

Dow's ideas greatly influenced O'Keeffe, who began experimenting with more abstract forms (Scott, 2015). An example of this can be seen in Figure 1, an abstract painting of Lake George. O'Keeffe described this method of abstraction as the best way to “get at the real meaning of things,” (Andrew, 2013).

Though her early abstract works focused on the city and countryside around New York, Georgia O'Keeffe is best known for depicting the American Southwest, which she believed represented the true natural beauty of America (Scott, 2015). An example of her iconic work of the Southwest can be seen in Figure 2, which includes both her famous landscapes and her signature skull motif.

## 1.2 Importance of Preserving Artist's Legacies

Preserving the works of O'Keeffe for aesthetic value alone is justified, but art often holds significant meaning outside of their visual beauty. Historically, art has captured the thoughts and feelings of entire eras (Gerlach, 2014). For example, Norman Rockwell's famous painting *The Problem We All Live With* (Figure 3) cut through the politicization and fear of racial issues to depict the core

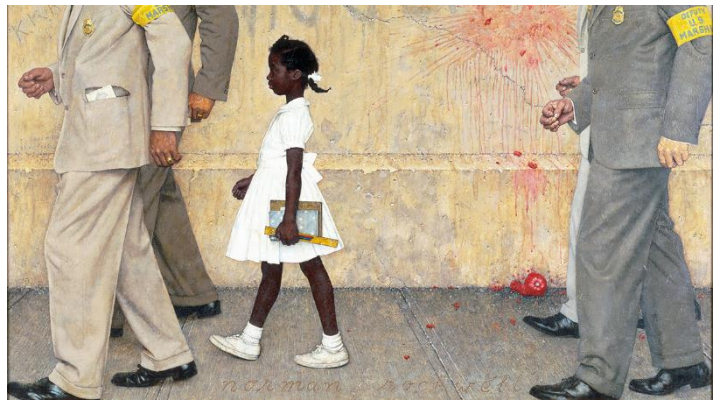


Figure 3- *The Problem We All Live With* (Rockwell, 1964). Oil on canvas

human struggles of African Americans of that era (Gallagher & Zagacki, 2005). His work tackled other big topics, such as fear during the Cold War, as well as the smaller pleasures of day-to-day life in the United States. Norman Rockwell's works are so well known for capturing America's symbols and values that he is known as "The People's Painter" (Gerlach, 2014). In general, paintings and art help people reflect upon their views, and sympathize with others (Francis, 2012).

In a similar way to how Rockwell's work has become synonymous with the cultural attitude of the mid 1900s, O'Keeffe's work and personality were important aspects of the Women's Rights activism of her time. O'Keeffe grew up in the 1920's and adopted the decade's new ideals of female independence (Scott, 2015). O'Keeffe's technical skills, original artwork, and outspoken personality gave her a strong voice in the art world. This in turn gave her a platform for sharing her feminist political ideals (Palmer, 2017). O'Keeffe's frequent presence in the public eye forced people to look past the novelty of her gender and read more deeply into the meaning of the work itself. Achim Borchart Hume, a museum director of exhibitions at Tate Modern Art Gallery in London, England, explained the significance of O'Keeffe's work being displayed. He stated, "Many of the white male artists across the 20th century have the privilege of being read on multiple levels, while others—be they women or artists from other parts of the world—tend to be reduced to one conservative reading. It's high time that galleries and museums challenge this" (Ellis-Petersen, 2016). Hume went on to explain that for women to gain a professional status in the artistic world, their works need to be prominently showcased for long periods of time (Palmer, 2017). O'Keeffe's path to success as a prominent artist of the 20th century reflects Hume's claim. O'Keeffe herself stated, "Men put me down as the best woman painter...I think I'm one of the best painters," (Tate, 2016). By successfully overcoming the barriers against women in the art world in such bold fashion, O'Keeffe became a cultural icon to female activists of that era.

Artists like Rockwell and O'Keeffe have played a huge role in changing society, and it is important that we preserve their legacies, and the legacies of so many other influential artists. Sharing and preserving their works and the works of other artists allows us to continue to learn from the lessons they taught both in their art and how they lived their lives. Whether that be a lesson of American unity, or the power of feminism, art is worth saving and preserving.



### 1.2.1 Benefits of viewing art

Art must be shared for society to view and benefit from it (Chute, 2011). In 1999 over eighty percent of Americans believed that the arts have a positive impact on their community and their children (DiMaggio & Pettit, 1999). The United Nations Educational, Scientific, and Cultural Organization declared paintings, along with other cultural artifacts and practices, a “mainspring of cultural diversity and a guarantee of sustainable development” (UNESCO, 2003). In other words, art and other forms of cultural expression are beneficial to society’s creativity and growth.

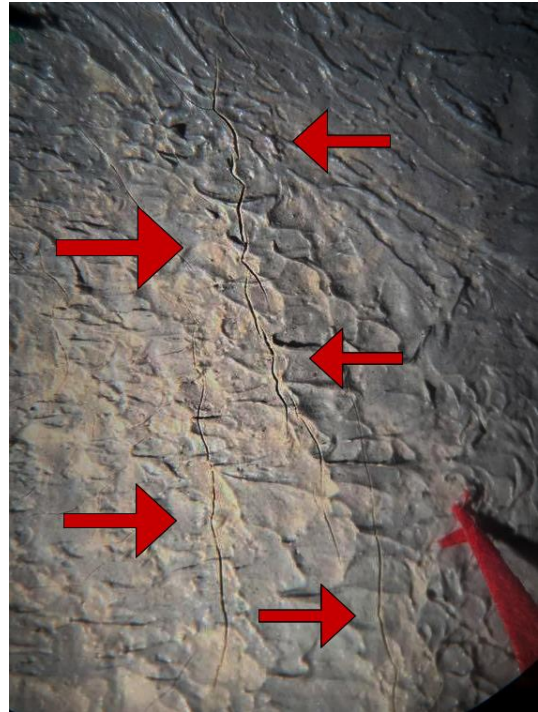
Studies have also found that visiting art museums can increase historical empathy and tolerance towards others (Greene et al, 2013). Children who create, view, and have been exposed to art experience a greater connection to their community than their peers (Brooks, 2005). Researchers have also found that viewing a painting in person can evoke a sympathetic neurological response, meaning the viewer feels very similar emotions to those experienced by the artist (Jeffers, 2009). Renowned curator Robert Rabinowitz has stated that viewing a painting in person allows one to experience a more authentic connection to the artist (R. Rabinowitz, personal communication, August 29, 2017). For these reasons, it is important that we continue to display paintings and other artworks for the public to experience. Therefore, we must find a way to make sure that original paintings are sufficiently protected when are moved between museums.

### 1.3 Causes of Damage in Transit

Museums dedicated to one artist, such as the GOKM, often possess nearly all of that artist’s work. This makes it difficult for people who are not close to the museum to view that artist’s creations, unless the artwork is shipped to other museums. However, such transportation is not without risk. In some cases, moving works between museums and collections causes catastrophic damage to the art. For instance, The Book of Kells, a priceless religious artifact written around 800 A.D., was damaged in flight by vibrations that dramatically changed the pigmentation of its pages (Parkin, 2000).

Any time a piece of artwork is outside of a museum’s protection, it is at risk of damage. More obvious threats associated with travel include such things as the works being dropped, scratched, or struck by an outside force (Canadian Conservation Institute, 2016). Although the effects of vibrations are not easily detected, they are significant. Vibrations are small repeating motions in a structure. They are problematic because of how easily they are transmitted through packing materials. The amplitude of a vibration refers to the size of these motions (Lohninger, 2009). In terms of a canvas surface, the amplitude of a vibration corresponds directly with how much the surface will bend; a higher amplitude means a higher chance of cracks forming (Lasyk, 2008).

Vibrations typically do not cause catastrophic damage to an object. But while the damages are individually minor, over time they can accumulate to be far more significant, and cause a slow but steady deterioration of the art (United States National Park Service, 1991). The solid surfaces of oil paintings slowly become cracked and split due to continuous vibrations brought on by shipment (Mecklenburg et al, 1991). Even with repairs, these disfigurements decrease the genuine “originality” by covering the strokes and styles the artist has applied, and in the worst cases, destroy it entirely (Grant, 2015). Figure 4 shows the damaging effects that can be caused by vibrations. The red arrows in Figure 4 point to the cracks that the vibrations have created at a microscopic level. Though these cracks are microscopic to begin with, over time they become increasingly large and detrimental.



*Figure 4 - O'Keeffe Oil painting cracks at 10x magnification*

Due to the very slow rate of vibration damage, it is easy to mistake the damage for the painting deteriorating with age. The Georgia O'Keeffe Museum was uniquely positioned to recognize the cause of their damage as vibrations because of the worldwide fame – and accompanying frequent shipment – of O'Keeffe's paintings. The GOKM paintings are frequently on tour, which was thought to have caused vibration damage to manifest more quickly compared to paintings in other collections that travel less. The smaller size of the collection allowed for closer scrutiny of the paintings after each trip by museum conservators, who were able to associate individual cracks with shipments (D. Kronkright, personal communications April 11, 2017). But even if Georgia O'Keeffe's paintings were particularly vulnerable due to their frequent travel, this is a problem faced by any canvas work that is transported long distances.

#### 1.4 Existing Techniques for Vibration Reduction

Historic shipping techniques were very basic, and often harmful to the artworks they were meant to protect. They were typically more concerned with keeping the work in place, not necessarily protecting it. The packing materials, usually paper, canvas, rope, and straw, would often scratch and disfigure the pieces being shipped (Keenpac, 2014). These primitive methods led to many artworks being destroyed before they ever reached a museum.

Common shipping practices have improved significantly since then. Cloth coverings were added to protect the surfaces of canvases. Around the 1950s, the art world began using more advanced protective materials, such as foams and plastic shells (Shelley, 1987). Foam inserts, as seen in Figure 5 within the crate, keep the painting in place as well as protect art when the crate

being shaken significantly. Foam inserts are usually effective enough that art is rarely damaged by small drops or impacts (Canadian Conservation Institute, 2016).

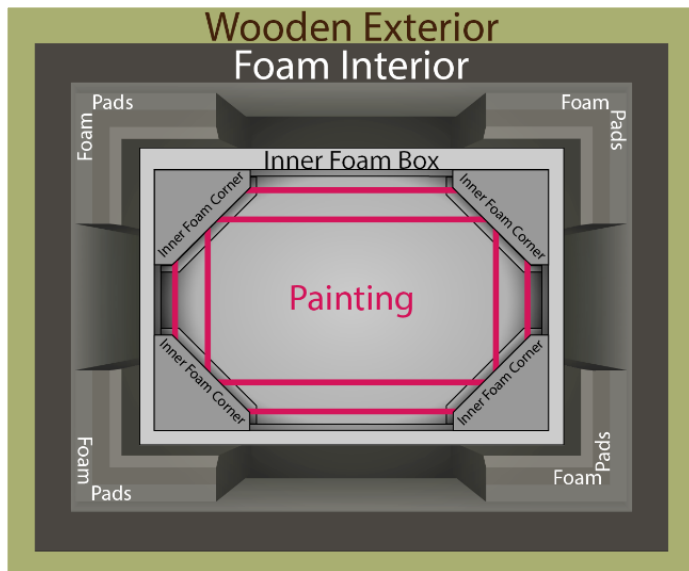


Figure 5 - Diagram of typical art shipment crate.

To protect from larger impacts the crate requires larger, softer foam cushions to distribute the force of the impact. However, if the foam cushions are not stiff enough, they give the painting too much freedom to move around inside the crate. This problem is solved by using multiple layers of foam. A common method of packing art used by many museums, including the GOKM, is to use multiple layers of protective material in a “nested” crate setup. A trained art packer will first set the painting inside a rigid frame to protect it from ripping or scraping against

its enclosure. The packer secures this frame in a tight-packed foam bed within a small padded box designed to keep the frame firmly in place and reduce higher frequency vibrations. This small inner box is then placed within a larger outer box (shown in Figure 5) with foam cushions designed to resist large impacts and reduce low frequency vibrations. The crate is then sealed and is ready for transport (Canadian Conservation Institute, 2016).

Although current methods are vast improvements over primitive rope and straw, art shipment innovation has recently stagnated. Comparing the guidelines of The Metropolitan Museum of Art’s published book on art shipping *The Care and Handling of Art Objects* (Shelley, 1987) with modern standards described by the CCI (Canadian Conservation Institute, 2016), both guidelines are almost identical, save minor changes in foam thickness and type. This would not be an issue if modern standards were satisfactory. However, these standards have shortcomings regarding certain types of vibrations, as described in section 1.5.

#### 1.4.1 Passive Vibration Control

Passive vibration control is the use of a static system to dampen vibrations (Chu et al, 2005). In practice, it means using fixed structures of materials (such as foam) chosen for their vibration-absorption properties to dampen vibrations. Current vibration control for canvases is largely limited to passive control with foam-like materials (Canadian Conservation Institute, 2016). In general, these materials are designed to protect against a particular range of vibration frequencies. Polyester-urethane (PEU) foams have this property, and can effectively dampen certain vibrations that pass through them. Museums construct art crates with PEU foam padding for this reason (Mecklenburg et al, 1991). However, when the GOKM staff performed experiments on these PEU foams, they determined that PEU does not sufficiently reduce the low-frequency

(20-50Hz) vibrations which cause resonance damage in canvas paintings (D. Kronkright, personal communication, April 4, 2017).

Unfortunately, the commonly used PEU foam also has significant disadvantages besides improperly reducing vibrations. Though PEU foam is cheap, its production method uses toxic cyanide, and the foam is non-recyclable (Canadian Conservation Institute, 2016). Additionally, all foams decay as the small bubbles within the foam collapse, compromising the foam's ability to dampen vibrations. Minor vibrations are unlikely to cause decay, but major shocks will permanently degrade the foam. When this occurs, the foam no longer protects artwork from vibrations, and has to be replaced entirely (D. Kronkright, personal communication, April 4, 2017).

#### 1.4.2 Active Vibration Control

Active vibration control is a type of system that actively identifies vibrations and mechanically counteracts them (Chu, Soong, & Reinhorn, 2005). It differs from passive vibration control in that it is generally more expensive, but is usually much more effective at completely eliminating vibrations (instead of just reducing them). An example of this technology is used in noise cancelling headphones, where specialized speakers cancel incoming sound waves – because sound waves are *vibrations* in the air (Encyclopedia Britannica Editors, 2015). A similar technique could be used to counteract vibrations in the crate. Typically, this system uses a microphone to detect the incoming vibration wave, and then uses speakers to generate the *inverse* of the wave. The inverse wave will cancel out the original wave so that no motion occurs; a phenomenon known as *destructive interference* (Encyclopedia Britannica Editors, 1998) (Zangi, 2002). A more advanced use of such technology can be found in helicopters. Helicopters use acceleration-detecting devices known as accelerometers to detect vibrations within their fuselage, and generate inverse vibrations in order to protect delicate components from being damaged (Ford, 1999).

Unlike passive vibration control, active vibration control technologies require electricity and more advanced sensors and mechanical components. However, they do not typically degrade as easily as foam and other passive materials do. Long term, active vibration control could prove to be a more effective method than passive vibration control if the GOKM can successfully implement it.

#### 1.5 Disadvantages of Current Methods

To better explain the issue with current vibration control methods, some background is required. As previously mentioned in Section 1.3, vibrations are simple, repetitive motions in an object or material about a rest point. The frequency of a vibration is how many times per second it passes the rest point (Lohninger, 2009), and the amplitude is essentially the strength of the vibration. Simple harmonic motions, such as the repeating movement of a spring, pendulum, or musical instrument, are examples of vibration at a single frequency (Weisstein, 2017). These simple vibration systems will always prefer to vibrate at their own single frequency, which is known as the *natural frequency* of a system.

More complex vibrations, such as the movement of a truck bed on an uneven road, cannot be represented by a single frequency. They are instead composed of a multitude of overlapping simple vibration waves known as the frequency *spectrum* - essentially a graph of frequencies and their corresponding amplitudes (Brandt, 2011). A picture of a spectrum is a *spectrogram*. In the case of the art-carrying crate on a truck bed, the majority of the vibration spectrum is in the 0 to 100 Hz range (D. Kronkright, personal communication, April 4, 2017)

Though the artworks in transit are experiencing a broad spectrum of vibrations at different frequencies, the concept of that single natural frequency is still very important due to a concept known as *resonance*. If a neighboring object (such as the truck bed) is vibrating at the natural frequency of an attached object (such as the canvas), that attached object will experience greatly amplified vibrations at that natural frequency in a phenomenon known as *forced harmonic motion*. See Figure 6 for an illustration of how the resonant frequency affects amplitude.

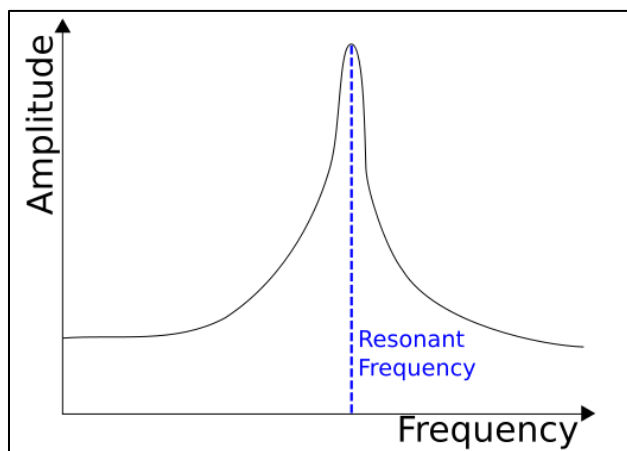


Figure 6 - Simple Resonant Frequency Amplitude Graph  
(Wikimedia Commons, 2009)

Essentially, even if measurements of vibration on the canvas frame show a seemingly low vibration amplitude at the natural frequency of the canvas, the canvas itself would be experiencing much stronger forces due to the amplifying effects of resonance (Parker, 1983).

Current shipping standards did not take resonance into account. Seemingly low amounts of vibration at the natural frequency of the canvas can cause severe fluctuations, damaging the painting (Michalski, 1991). Even when paintings were secured in containers designed to protect against vibrations, the GOKI group observed that they still experienced significant resonant motion (D. Kronkright, personal communication, April 4, 2017). To protect the artwork, special precautions must be taken to dampen the specific natural frequency of the canvas. Currently, the GOKI Group is investigating measures to prevent or at least reduce this resonance, in order to lessen the damages done by vibrations to their paintings.

### 1.6 Project Goal

The goal of this project was to enable the Georgia O'Keeffe Museum to better understand how vibrations affect paintings in transit, to provide insight into the best design techniques for preventing these vibrations, and to help share GOKM's work with the public. It is important to note that our findings here do not apply solely to the works of Georgia O'Keeffe. Any insight gained into protecting her paintings are applicable to canvas artworks worldwide.

## 2.0 Methodology

In order to help the Georgia O'Keeffe Innovation (GOKI) group, our goal was to increase public awareness of the dangers of shipping canvas artworks, and improve upon current shipment techniques in order to better protect artwork in transit. We developed a low-cost method of analyzing vibrations throughout a shipping container. By applying this analytic method to simulated transportation vibrations, we were able evaluate how effective different materials were at protecting paintings against harmful low-frequency vibrations. Finally, we designed a special museum draft exhibit to display a simplified version of the museum's research for public viewing at the GOKM.

Our objectives for achieving this goal were as follows:

1. Develop a low-cost alternative to current vibration measurement tools to allow the GOKM to continue experimentation.
2. Identify and evaluate both traditional and non-traditional materials for damping vibrations.
3. Design a draft exhibit for the GOKM to showcase how artworks become damaged in transit, and the steps the museum is taking to protect them.

### 2.1 Objective 1: *Determine cost efficient alternatives to current vibration measurement tools to find best choice for museum's continued experimentation.*

For the GOKM to properly evaluate new container materials, it needs accurate measurements of how well they mitigate vibrations. For their initial investigations into determining the cause of damage, the GOKI group relied upon extremely expensive tools such as a Multiple Scanning Vibrometer (MSV) and the Polytec Scanning Vibrometer (PSV). Both of these use beams of light to measure subtle movements of points across a surface. These tools are state-of-the-art, and the data they provided served as the foundation for the museum's understanding of how poorly current container designs perform. Ideally, the GOKM would continue using these devices to test future designs and materials. However, renting these tools was prohibitively expensive, and not suitable for long term use by the museum. For the sake of the museum's ongoing experimentation, we needed to determine the viability of alternative techniques that were less expensive than the MSR/PSV systems, while still providing informative vibration data.

#### 2.1.1 MSR Accelerometers – MSR145 and MSR165

Accelerometers are a type of sensor that calculate the acceleration of whatever they are attached to (Bao, 2000). Acceleration is defined as the rate of change of the velocity. In practical terms, accelerometers allow us to measure small changes in how a point on an object is moving. The highly sensitive nature of an accelerometers allows them to detect even the very small motions of vibration. More significant movement cause higher values from the accelerometer, which in turn indicate higher amplitude vibrations. In this way, an accelerometer can replicate the functionality of the MSR/PSV systems' vibration measurement at a single point of measurement.



A similar study (He & Jin, 2009) used this technique to measure vibrations in factory machinery to determine if parts were failing.

As a baseline for testing, we used accelerometers the museum already had on hand: MSR model 145 and 165 accelerometers. These accelerometers are relatively large sensors designed for long-term (up to several hours) data recording in environments requiring extreme heat and pressure resistance. The 145 can record at a rate of 50 samples/second in a range of  $\pm 15$  g's of acceleration in the x, y, and z axes (MSR Electronics, 2015). The 165 can record at a rate of 1600 samples/second in a range of  $\pm 200$  g's of acceleration in the x, y, and z axes (MSR Electronics, 2015).

We used the MSR 165 models because of its higher data acquisition rate, which allowed for more data points for analysis. Since we already had PSV vibration data on the GOKI prototype crate design (not pictured due to pending patents on its design), we performed our initial tests on that design with hopes that we could eventually compare our analysis to the PSV/MSV results. We placed one accelerometer on the exterior of the crate, one on the inner frame within the crate that holds the painting frame, and one on the canvas frame itself. We then enabled the accelerometers and ran the shaker device (described in section 2.2.1 Figure 9) for three trials of 60 seconds. In addition to using the shaker device, we also placed the crate on a small wheeled transport dolly, and pushed it around on uneven pavement for approximately 5 minutes. This initial test run of data gave us a framework to guide how we would implement our data analysis techniques

### 2.1.2 Data Analysis – DFT

To obtain the frequency spectra from the raw accelerometer data, we performed Discrete Fourier Transform (DFT) analysis. Essentially, DFT analysis takes in a large number of data points over some interval of time, and tries to approximate a “line of best fit” through them by combining periodic wave functions of different frequencies. This provides as an approximation of what frequencies of vibration are occurring at the data collection point (Brandt, 2011). Figure 7

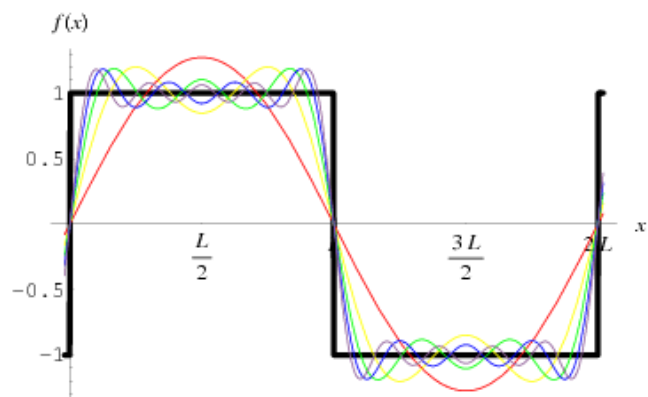


Figure 7- DFT approximating a square wave (Weisstein, n.d.)

shows an example of how DFT analysis attempts to approximate a square wave by successively adding wave functions, signified by the different colored lines growing closer to the “true” curve. These individual wave functions each represent a particular frequency of vibration, which was used to determine what vibrations were experienced at what amplitudes (Rabiner & Gold, 1975). To perform this analysis, we used the programming language Python with the research module SciPy, which is often used for this sort of research (Jones et al., 2001). SciPy includes many tools for data analysis, including functions which perform variations of the Discrete Fourier Transform.

However, the standard DFT function expects all of its data to be from the same set of vibrations (Brandt, 2011). For example, if one used it to analyze musical pitches in a song recording, it would fail to properly account for changes in instruments or notes, and would instead try to find a matching sound (vibration) for the *entire* song – which would be entirely incorrect!. In our methods of testing (2.2.1), we faced a similar issue of different parts of the data recording process having different vibrations because our vibration generating technique introduced was not perfectly consistent in the amount of vibration generated from moment to moment, and instead relied upon longer measurement periods to normalize. To account for this, we used a modified version of the DFT known as Welch’s method. Welch’s method breaks the accelerometer data into smaller windows of time, and performs DFT analysis on each window. The average of the spectrums is then computed (Welch, 1967). We used the default SciPy implementation of this method, with a time window of one second. Finally, we applied a flat-top windowing filter to reduce noisiness in the resulting spectrogram, and make peaks in the data more easily distinguished.

The resulting graphs of frequency/amplitude are known as spectrograms, and represent the amplitude of each component vibration frequency. To render the graphs of these spectrograms, we wrote a small Python utility which gathers all of the accelerometer readings for an experiment, and plots them into a single graph using the “Plotly” python library. The Python code was specifically designed to quickly generate these graphs for entire sets of experimental data, so that they could easily be compared with different graphing or DFT analysis configurations without the tedium of creating the graphs by hand.

### 2.1.3 Alternative Accelerometers – STM LIS3DH

Examining accelerometers further, we wished to more closely replicate the MSV/PSV behavior by measuring significantly more points on the container, including points on the canvas itself. Having more points would allow us to better visualize the vibrations, and better account for different parts of the same component (ex: outer frame) having different vibration spectra. Unfortunately, we had only 3 of the MSR165 accelerometers and did not have funds to secure any more, as they cost upwards of \$1000 each (MSR Electronics, 2015). Beyond cost, the MSR accelerometers weigh approximately 69 grams each - almost as much as the canvas itself. Mounting such a large mass to the canvas would likely have resulted in atypical movement, making the data useless in terms of measuring “real” canvas movement.

After some searching we selected the STM LIS3DH accelerometer. It is capable of up to 5300 readings per second in the x, y, and z axes in a range of up to 16 g’s of acceleration. More importantly, it is much lighter at 1.5 grams, meaning we had reasonable chances of placing them directly on the canvas without significant interference with its motion (STMicroelectronics, 2013). At a cost of \$4.53 per unit, we were able to afford 12 of them. Though they were less durable than the MSR sensors, this did not matter for our purposes.

The LIS3DH accelerometer on its own does not record data, and requires assembly and programming. To utilize the sensor, we used a microcontroller -- a *very* small computer specifically

designed for interfacing with other small electronics -- known as the Arduino Uno R3. The Arduino served as a “middleman” for the data, reading it over wire connections from the accelerometer and forwarding it via USB to a laptop. Arduinos can typically only connect with two LIS3DH accelerometers at a time, but using two 8-way connection splitting devices known as multiplexers, we were able to configure the Arduino to connect to up to 32 at a time.

To use these sensors, we needed to create a program which would tell the Arduino to read from each sensor, and send the resulting reading to the laptop. We also needed to create a program for the laptop to listen to the Arduino output and convert it into useable accelerometer data. It was important that both programs could handle readings at a rate of 200Hz. We wrote the Arduino program using the official Arduino Development Environment, using the standard libraries provided with the board. These standard libraries simplified the task of communicating with the multiplexers and accelerometers significantly. Using those libraries, the Arduino program was essentially only three steps:

1. Scan all multiplexer ports to detect active accelerometers, and remember them in an internal list
2. Wait for the laptop host program to signal it is ready to begin receiving data
3. For each accelerometer in the saved list, read and send the current acceleration. Once all have been read, wait until the next 200Hz interval, and repeat step 3.

The Arduino has a maximum data transfer rate of approximately 12 kilobytes per second, which is not very high. Since each additional accelerometer meant more data needed to be sent, then to maximize the number of sensors we could read at 200Hz, we needed to minimize how much many bytes were used per reading. We did this by eliminating unnecessary data from each packet. For instance, the ID bytes for each reading were unnecessary, since if we know how many sensors there are total, we could infer which one each reading was for by the order it was received in. The timestamps could also be minimized, by only sending a change in timestamp instead of the full time. Figure 8 shows the progression of byte usage from the first to the final version.

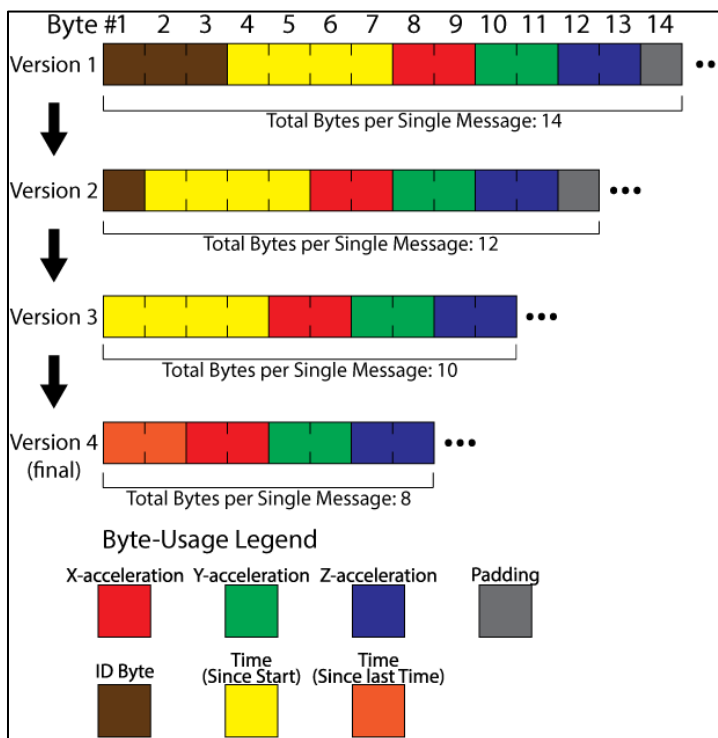


Figure 8 - Arduino Reading Size Minimization

The laptop software simply needed to receive and store all the Arduino readings. This was slightly more complicated than originally expected, as all of the above message size minimizing techniques had to be reversed to restore the original data. Because of this, our final version would need special code for determining which accelerometer had sent each message, and at what time. Once that was implemented, we had a full data recording setup which output files for each sensor in a folder denoting when the data was recorded.

As a first step towards evaluating the precision/accuracy of these sensors, we mounted them beside the existing MSR accelerometers. Then, we performed the same motor vibration-generation experiment as described in section 2.1.1. The resulting data from each MSR/LIS3DH accelerometer pairing was then analyzed and compared to see how closely they matched one another when analyzed with the above method. Since they were in the same location, our expectation was that the analysis would produce roughly identical spectrograms, both in terms of the overall shape as well as amplitude at each frequency.

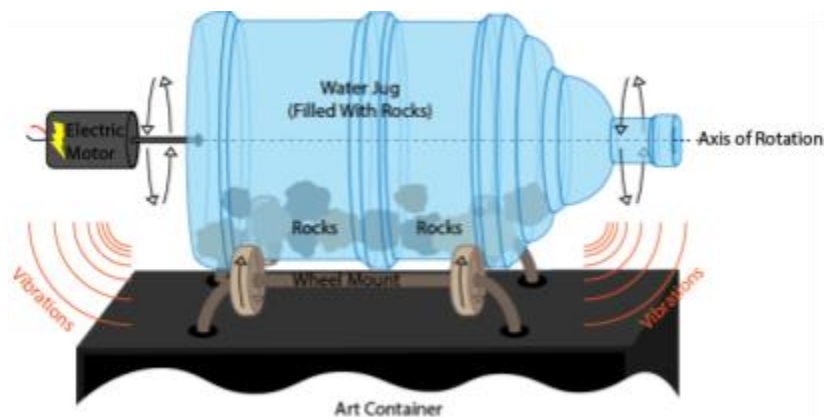
## 2.2 Objective 2: Identify and evaluate both traditional and non-traditional damping methods and materials:

Our second objective was to research possible alternatives to current PEU foams, and evaluate their effects on vibrations in a shipment crate. We evaluated each material's damping effects using the vibration analysis method established in Objective 1 to learn which potential material or combination most effectively dampened the vibrations.

### 2.2.1 Vibration Generation

Before we could test different materials for damping, we needed to first create a system to cause vibrations mimicking those caused during transit. Our solution was to design our own vibration generating machine. To accomplish this task, we took a large water jug and filled it with a mix of different sized rocks.

The jug was then placed on 4 mounted wheels so it could rotate freely about its central axis. The water jug was strapped to the wheel mounts to increase contact with crate system and thus allow vibrations to transfer consistently. The motor used to power the machine was a Dewalt 18-volt battery cordless drill. The drill's torque dial was set to #12, and with the power switch setting #1 was selected. The drill was then switched to the "drill-bit" setting on the left side. During the test the trigger was pulled



*Figure 9 - Diagram of our water-jug shaker*

halfway down to cause the shaker jug to rotate approximately once per second. See Figure 9 for a visual representation of the device.

To evaluate the vibrations generated by the device, it was placed on top of the crate and the motor was activated for sixty seconds. As the jug rotated, the rocks placed inside the jug tumbled chaotically, creating vibrations at the mount point. These simulated vibrations were measured using accelerometers, using analysis methods explained in objective 1.

In addition to our makeshift vibration system, we also evaluated a method of producing vibrations by placing the shipping crate on two dollies and wheeling it across the pavement outside. This method of obtaining vibrations created random noise due to the uneven and cracked pavement. We hoped that the similarity to actual truck transportation – wheels on pavement – would produce similar vibrations. Ultimately, we did not continue using this method outside these early tests.

To evaluate these methods, we compared them to the vibrations generated by a truck bed. Prior to our involvement in the project, the GOKM used MSR accelerometers to measure the movement of a truck bed in transit. We used the analysis methods established in section 2.1.2 to compare the vibration spectrograms of the truck bed to those produced by our vibration techniques. Ultimately, we decided to continue using the shaker device and not use the dollies for material testing.

### 2.2.2 Materials

After establishing our vibration generating system, we tested different vibration damping materials. We only investigated passive vibration control methods, as the GOKM staff was not comfortable with active control methods, due to the chance of catastrophic battery failure.

We started by testing the crate with its current foam application (see Figure 11 for reference) to generate baseline vibration readings for a standard museum crate. Next, we combined the existing foam within the inner frame with different damping materials (except excelsior, which entirely replaced the inner foam for its experiment) and tested them with shaker method described above. The different materials we tested were:

- PORON, a urethane synthetic crystalline compound (PORON® VXT™ 4701-70., 2017). Used in bicycle helmets and footwear to dampen impacts.

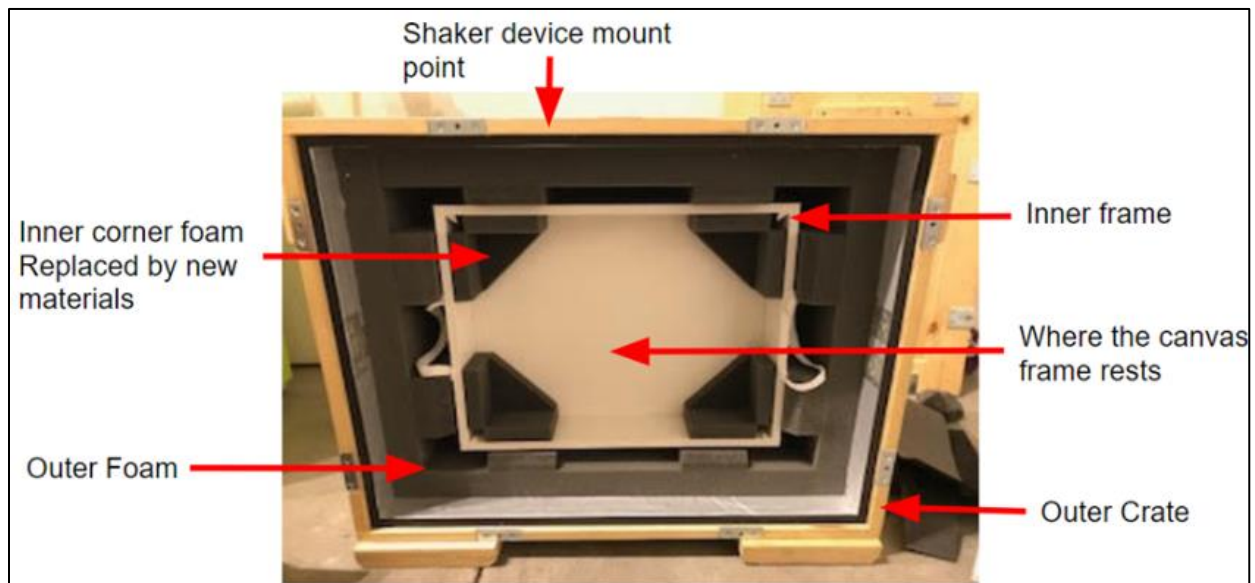


*Figure 10 - Excelsior (left), Sorbothane (disks in center), and PORON (right rectangular padding)*



- Sorbothane, a visco-elastic polymer that has the properties of both viscous materials (thick liquids which resist flowing) and elastic materials, such as rubber (Sorbothane Overview, 2017). Designed specifically for vibration damping.
- Excelsior, fine curled wood shavings of aspen logs similar to packing straw, but less prone to decay and bug infestation (Sediment Control, 2017).

See Figure 10 for visual reference of what the materials looked like. After testing PORON and Sorbothane with the existing foam, we decided to try combining them with the basic PEU foam to determine if their benefits were additive. Table 1 shows the combination and individual material configurations tested and their positioning. Figure 11 below shows a visual representation of the components of the experimental crate, and can be used as reference for how materials and accelerometers were placed.



*Figure 11 - Art shipment crate used in material experiments.  
Specific elements of crate labeled with arrows.*

To test the materials, we used the shaker jug vibration generator described in section 2.2.1 and the STM LIS3DH accelerometers described in section 2.1.3. The shaker was affixed to the top of the outer crate and spun for one full minute. To obtain a more accurate reading, the shaker was performed three times and averaged out for each material. Five accelerometers were used for this test and positioned to record the vibrations: one on the top of the crate, and one of each on the tops and bottoms of the inner frame and canvas frame. All accelerometers were glued on, oriented in the same way so their axes were parallel, and positioned so no contact was made with surrounding surfaces except the actual mounting point.



*Table 1. Experimental Material Configurations*

<b>Experimental Configurations:</b>	<b>Placements (See Figure 11 for visual reference):</b>
<b>Current foam (control)</b>	Default configuration. What the museum already uses.
<b>Current foam + PORON</b>	PORON was lined on the inner corner foams.
<b>Current foam + Sorbothane</b>	The conical Sorbothane mounts were placed at the center of each inner corner foam.
<b>Excelsior</b>	The inner corner foams were removed and the excelsior was placed within the inner frame and around the painting.
<b>Current foam + PORON + Sorbothane</b>	PORON was lined on the back-triangle pieces of the inner corner foam and Sorbothane was placed at the center of each side of the inner corner foam.

2.3 Objective 3: Design a draft exhibit for the GOKM to showcase how artworks become damaged in transit, and what the museum does to protect them.

For our third objective, we needed to create a museum exhibit that would showcase the current problems with art shipment and what work the GOKM has done to solve them. Initially, we created a list of the individual core concepts of the project and how we might go about representing them. Certain ideas, such as the general why and how of art transportation, were easily explained using text. Other ideas, like the mechanical causes of vibration in transit, would need more visual aids to explain. The more technical ideas, such as how vibrations spread and affect canvases, and the implications of different frequencies, were decided to be too difficult to explain without something to interact with for a greater understanding.

Before moving forward with drafting exhibits for the GOKM, we sought out professional insight to ensure our designs would be useful to the museum. We interviewed Georgia O’Keeffe Museum curators Carolyn Kastner and Cody Hartley to get a better idea of what criteria the museum looks for in its exhibit designs, as well as ideas of exhibiting technical information. We loosely structured the interview base on the questions in Appendix A, but the interview quickly diverged from that structure.

We learned that exhibit design is a long process, often going through many iterations and test runs before a museum would settle on a final design. Given our limited time frame, both Carolyn Kastner and Cody Hartley suggested we focus more on the creation of individual exhibit “modules” showcasing a key concept rather than attempt to create an entire exhibit. These modules would be able to be combined to form a more complete exhibit, and could serve as the basis for the GOKM’s future iterations of the exhibit. They also suggested having different variations of each module so the museum would have more flexibility in its design process.

Carolyn Kastner and Cody Hartley also suggested that for any written portion, the majority of the information presented should reside in the beginning of the paragraph, since many people

stop reading after the first few sentences. When asked how to best represent more technical concepts, they advised that we avoid complexity wherever possible. If nothing else, visitors regardless of technical knowledge should be able to grasp the core narrative an exhibit is trying to establish. People will remember material better if the exhibit first establishes *why* it is important. If we really needed to explain a topic such as vibration, they suggested we show it with a visual or interactive portion (C. Hartley, C. Kastner, personal communication Sept 27, 2017).

With these suggestions in mind, we concluded that we wanted to design a display that presented information in such a way that it established a simple narrative describing the steps the museum had taken to protect their works. We felt that the core concepts we needed to address were basics of art transport, the problems with the current methods, the techniques the Georgia O'Keeffe Museum is using to improve them, and why this was important to the visitor. We decided to create several draft exhibit elements for each of these core concepts. This approach allowed us to make the best use of our time and focus with the technical aspects of the project, which we had more experience with. Furthermore, our handling of the technical aspects would allow the GOKM staff to better utilize their curatorial experience without needing to worry as much about explaining technical details.

We were then faced with the problem of how to convert these ideas into modules that educated viewers without overwhelming them. As the curators suggested, we kept technical detail to a minimum. We made the first several sentences require little to no technical knowledge to understand, and used them to establish the broader narrative of the museums work. This ensured that any visitor would be able to understand the larger narrative that the GOKM is trying to establish. To convey more complicated ideas that could not easily be explained in text, we chose to use interactive elements so that visitors could learn about the concept without being overwhelmed by technical language. The inclusion of interactive exhibits has been shown to be beneficial to the understanding of technical materials (Gammon 2003). To draft these more complicated interactive portion, we used computer design software SketchUp to create multiple draft sketches of possible interactive and non-interactive exhibit modules (see Appendix B for early drafts of these exhibits).

To get more insight into how people interact with exhibits, we also tried to interview museum educators, who are closely involved with guiding visitors through the museum can give insight into how effective different display types are. After many delays, we were eventually able to interview GOKM educators Shannon Bay and Sarah Zurick. Unfortunately, it was too late to incorporate their suggestions into our exhibit designs. However, their responses to the interview question largely mirrored those of Cody Hartley and Carolyn Kastner. They emphasized the importance of interactive exhibits to explain technical concepts. They also asserted that the most important thing an exhibit needed to explain was *why* the content of the exhibit was important (Bay & Zurick, personal communication, Oct 5, 2017). They also provided several small suggestions that we incorporated into our recommendations.

An outline of the core concepts and how we planned to implement them can be seen in Table 2 below.

*Table 2. Exhibit Module Design Plan Outline*

<b>Central Concept</b>	<b>Detail of Module</b>	<b>What Will the Module look like?</b>
<b>What is happening?</b>	Shipping methods are a fairly simple concept, and can be easily expressed in writing. Vibrations likely need interactive portion due to complexity.	Text display explaining the basics of art transportation, with interactive element describing how vibrations come into play.
<b>What is the Museum Doing?</b>	Very Complicated and technical. Needed both text explanation and graphics to visually show experimental methods. Interactivity might help visitors connect what they read to real-world materials.	Text with visual representation of key elements of museum experiments. and an interactive display.
<b>What can you do to help?</b>	Easily expressed concept, more of an appeal to emotion than technical detail.	Display with small amounts of text, graphics of O’Keeffe, etc. optional.

## 3.0 Results and Discussion

This chapter enumerates our findings after carrying out the steps described in Chapter 2.0: Methodology. Note that the sections and subsections of this chapter, Results and Discussion, do not correspond exactly the subsections of Methodology.

### 3.1 Objective 1 Results

We designed a way to use inexpensive accelerometers to replicate the functionality of the expensive Polytech Scanning Vibrometer system. The details of our findings are below.

#### 3.1.1 MSR Data Results:

The MSR accelerometers recorded data from the vibration generating machine acting on the GOKM prototype crate’s internal frame and shaker mount point. The data was collected in three separate trials of one minute each, at identical motor settings. Using the data analysis methods described in section 2.1.2, we produced spectrograms (vibration graph) for the experiment. Since the MSR165 reads at 200Hz, this let us analyze vibrations with frequencies in the range of 0 to 100 Hz using the DFT methods. To account for variations between the three trials, the graph we produced shows the sensor data as a range, with a line denoting the average reading at each frequency through the middle. Note that the range is only really visible where the trials diverged significantly, such as at the 20Hz mark for the Frame’s acceleration. Anywhere it is not seen, the trials were simply similar enough to produce a visible range. See Figure 12 below for an example of the produced graph.

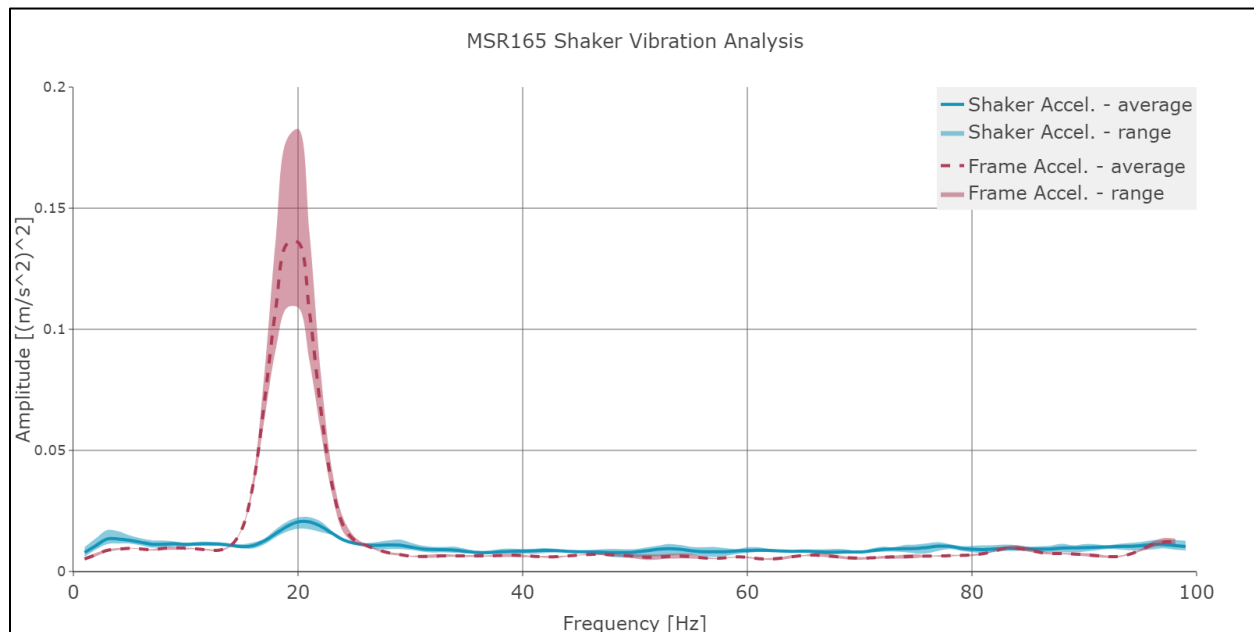


Figure 12 - MSR165 DFT Analysis of Shaker Vibrations (x-axis readings)

Figure 12 is in the same format as all vibration analysis graphs in this report. As such, the following analysis should serve as a basic guideline for interpreting any of these graphs. The graph represents our use of DFT analysis to reduce a complex vibration into its constituent simple harmonic vibrations as described in section 2.1.2. The graph's x axis is the frequency of each vibrations, and the y axis is proportional to the vibration's amplitude at that frequency (refer to section 1.5 for a more in-depth explanation of implications frequency and vibration). A high amplitude at a given frequency means that the sensor was experiencing strong vibrations at that frequency. Each colored curve represents the measurements of a single sensor, as specified in the legend. For example, in Figure 13, we can see the red curve represents measurements on the inner frame of the prototype crate, and the blue curve represents the frequencies under the shaker itself.

The appearance of distinct peaks in these graph is significant, as they are a clear indication of resonance (refer to section 1.5 for more detail of causes of resonance). As explained earlier, resonance occurs when a structure receives input vibrations at its natural frequency, and experiences greatly amplified vibrations at that natural frequency. In Figure 13, we can see a clear example of resonance causing high amplitudes at the 20Hz mark. Despite the shaker producing consistent vibrations throughout the entire 0-50Hz domain, the inner frame experiences drastically increased amplitudes at that frequency.

Since each experiment was conducted with three trials, we averaged the data from the trials to more easily compare between experimental configurations (e.g. different materials). For each sensor's line, the lightly shaded portion represents the min/max range at that frequency for all trials. The darker center line represents the average of all trials. In the case of Figure 13, one can see that among our three shaker trials, the blue shaker measurements were very consistent, whereas the red frame trial measurements diverged near the 20Hz mark.

### 3.1.2 LIS3DH Data Results:

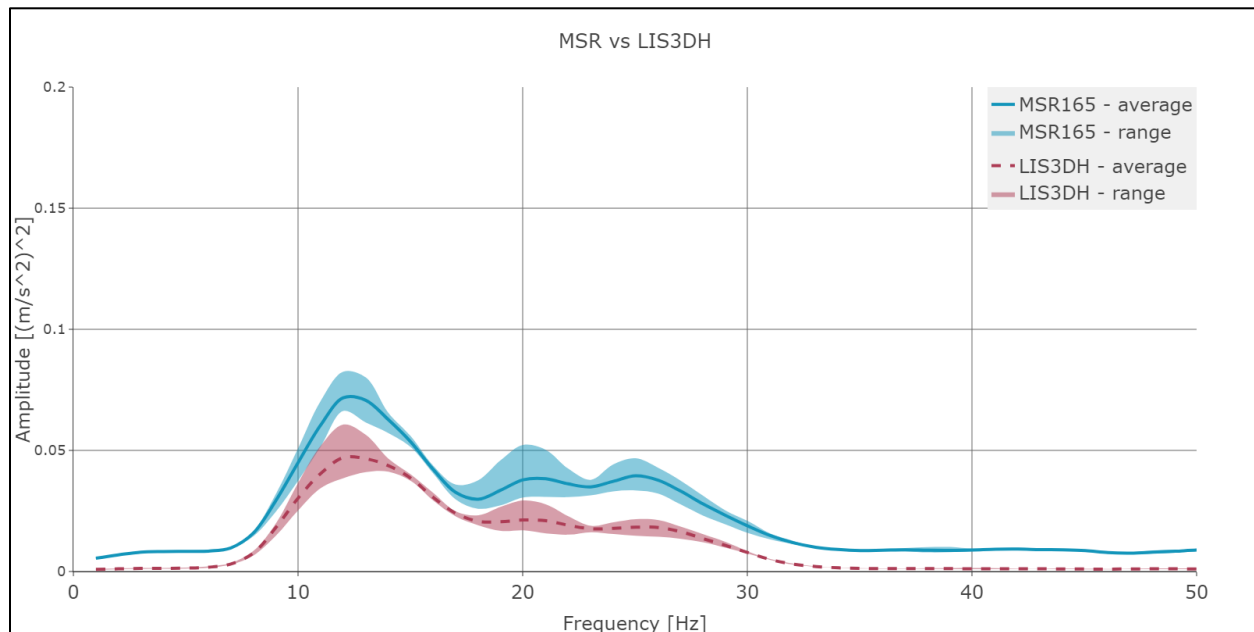


Figure 13 - MSR vs LIS3DH, Inner Frame X axis measurements, Side-by-side comparison

We assembled our electronics to support connecting up to 32 LIS3DH accelerometers. Unfortunately, due to unforeseen limitations in the Arduino's USB data output speed, we were limited by how many sensors we could add before the data transfer speed slowed too much. This initially limited us to no more than two LIS3DH accelerometers at the desired 200Hz read rate with our first version of the software. We overcame this by optimizing how we sent sensor readings over the connection (as described in 2.1.3), more than doubling our maximum readings per second. This allowed us to support 6 sensors at 200Hz by the end of our work on the software. For further improvements, the museum could use the software we created with a more advanced version of the Arduino (the Arduino Mega) that supports faster data output rates, which would allow them to support over 4x as many sensors.

The results of the comparison between the MSR165 and LIS3DH sensors can be seen in Figure 13. In this experiment, the MSR and LIS3DH sensors were placed directly next to each other, and recorded data for the same set of experiments. In theory, if the two techniques are similar in accuracy and precision, we should have seen almost identical spectrograms. As can be seen, the data follows similar trends in shape, but differs on the exact amplitudes, meaning the LIS3DH was somehow receiving lower vibrations than expected. This difference occurred in all axes, and across all locations where we placed the accelerometers (data not shown). We believe this may have been caused by the LIS3DH being ineffectively mounted using loose tape instead of glue. Unfortunately, we were unable to repeat the experiment as the GOKM only granted us access to the MSR165 accelerometers for a limited amount of time. For future analysis, we would recommend the GOKM repeat the side-by-side test with better mounting and the most up-to-date version of our software to shed light on this difference in amplitudes. If not, the data is at least useful in that its shape (if not exact amplitudes) lines up with the MSR data, so resonance and damping can still be seen.

### 3.2 Objective 2 Results

We designed a process of using our measurement system from objective 1 to measure the effects of different crate designs on vibrations. We then used this process to identify and evaluate both traditional and non-traditional materials for damping vibrations.

#### 3.2.1 Vibration Generation Analysis Results:

Before performing any real analysis on materials, we needed to be sure that our vibration generation methods were consistent and analogous to measurements from an actual truck bed. We tested the vibrations produced by the shaker-jug and pavement-dolly methods outlined in Section 2.2.1, comparing them to truck-bed accelerometer data that the GOKM had recorded prior to our team's arrival. Note that the dolly and truck bed are a single trial; however, both measurements exceeded 10 minutes in length (versus the shaker's 3 1-minute trials). Since the method of DFT we used is an average over time, it is unlikely that future trials would have significantly different results.

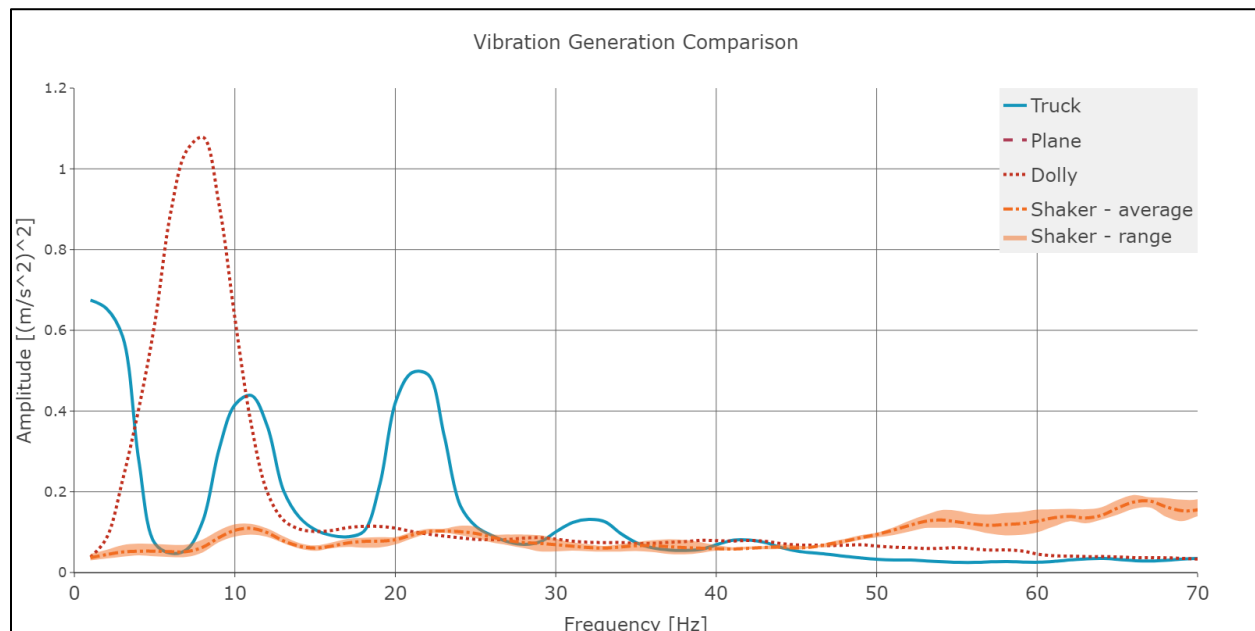


Figure 14 - MSR Vibration Generation Z-axis comparison

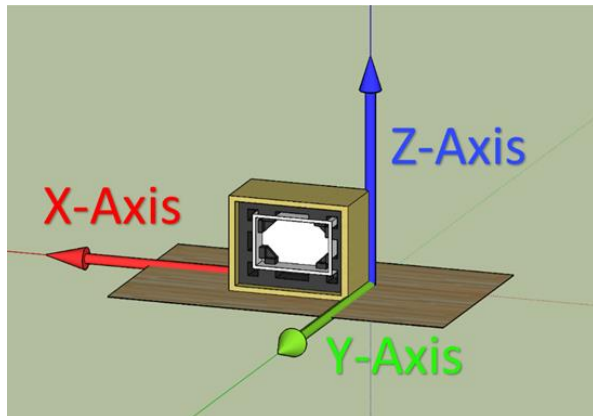
Figure 14 shows the result of comparing our vibration generation method (for an explanation of this type of graph, see section 3.1.1). In the 0-10 Hz range, all three methods produced wildly different results. In the 15-25 Hz range, the shaker and dolly produced roughly equivalent vibrations, but were still very different from the truck. In the 25-50 Hz range, both the shaker and the dolly were very similar to the truck, and could reasonably be used for simulating truck vibrations in this spectrum. Above 50 Hz, the dolly and truck remained similar, but the shaker had vibrations that were greater than those on the truck.

In terms of which vibration generation method is the best for creating transport-like vibrations, the answer may be neither. We had hoped that the wheels of the dolly on pavement would closely emulate the wheels of a truck, but that turned out to not be the case for the entire 0-



25 Hz range. The shaker was remarkably consistent in amplitude across the entire spectrum, but this consistency meant it did not exhibit the low-frequency peaks that the truck measurements recorded at all. However, the shaker's consistent amplitude made it useful for measuring resonance and damping, as the near-constant input amplitude made change in amplitude of inner sensors easily distinguishable. For this reason, we used the shaker jug for the rest of our material evaluation experiments, and suggest the GOKM do the same until it can find a more suitable alternative.

### 3.2.2 Material Evaluations:



*Figure 15 - Experimental Axis Diagram.  
The axes labels indicate the 3 directions of acceleration that  
the accelerometers recorded data for.*

We tested each of the material configurations described in section 2.2.2. Though we used 5 sensors across the crate in these experiments, the shaker measurements are omitted for visual clarity, and because we are mostly interested in the difference in vibration from the inner frame to the canvas frame. Of these, the canvas frame is more important because it is in direct contact with the canvas and thus is our best representation of what vibrations the canvas will experience (however, it does not include the effects of resonance). The inclusion of the inner frame is still useful because the material

was placed between the inner frame and canvas frame readings, so comparing them lets us see some of the damping effects of the material.

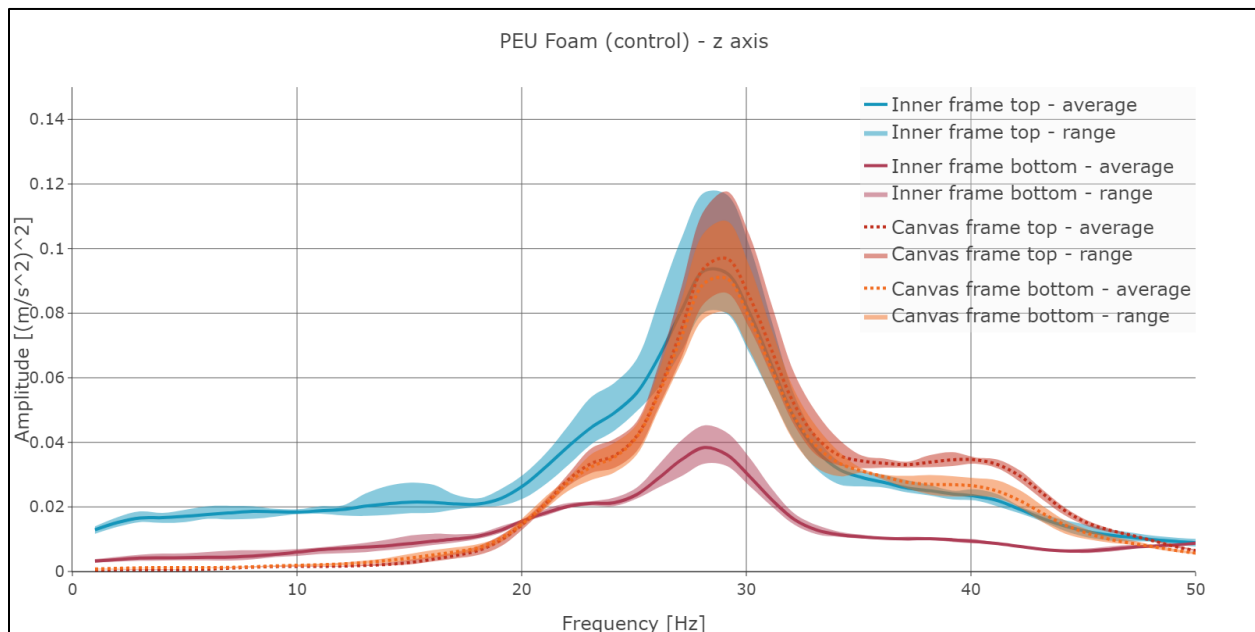
The accelerometers record data separately in the X, Y, and Z axes (see Figure 15). For example, a vibration measured by the accelerometer on the Z axis would be motion up and down. The graphs shown below (Figures 16-20) are all spectrograms of the accelerometers' Z axis readings. The X and Y axes spectrograms can also provide valuable insight, and are included in Appendix C, although we do not discuss them in depth in this report. Since different axes can exhibit drastically different vibration patterns, we cannot conclusively say anything about these materials without considering all 3 axes. However, the goal of this section is to demonstrate the method of analysis, not find an optimum material.

All the spectrograms in this section have been truncated to the 0Hz to 50Hz range, as the amplitudes over 50Hz are negligible. The most important frequencies to consider depend on the size of the canvas. Most canvases that the GOKI group tested have a natural resonant frequency between 10Hz and 40Hz, with larger canvases tending towards lower frequencies (D. Kronkright, personal communications Sept 18, 2017). All vibrations near the canvas's natural frequency will be amplified due to resonance. In order to minimize the impact of this resonance, the museum must select materials to specifically dampen around the canvas's natural frequency.

In each of these experiments, we are looking for reductions to the canvas frame vibration amplitudes compared to the current standard material (PEU foam).

In our analysis, we considered computing a percentage reduction for each material so that they could be empirically compared. However, the complex mechanics of vibration in a system like this do not allow for such oversimplification. For instance, in the Sorbothane spectrogram (Figure 17 below), such a simplistic measurement of damping would show Sorbothane to have negative damping, implying that it increased the amplitude of vibrations. But, as explained in the analysis of the Sorbothane experiment, the Sorbothane canvas frame measurements are still significantly lower than those of the PEU foam.

For an example explanation of how to interpret spectrograms like those below, see section 3.1.1.



*Figure 16 - PEU Foam (Control) – LIS3DH Shaker Experiment Spectrogram (z-axis)*

Figure 16 shows the vibrations of components of a shipping container using standard PEU foam with no modifications (except the attachment of sensors). In these graphs, we are looking at how changes in materials affect amplitudes for the inner frame's accelerometers (solid red/blue lines), and the canvas frame accelerometers (dotted orange/red-orange lines). If an experimental packing material was successful, we would expect to see a reduction in the canvas frame accelerometer amplitudes compared to this PEU foam spectrogram.

In the PEU foam graph, the 'canvas frame top' and 'canvas frame bottom' are almost perfectly aligned, indicating equal vibration throughout the canvas frame. This is a good indicator that the canvas frame was well secured by the PEU foam, as we would otherwise see the top and bottom readings diverge because one was held more/less rigidly than the other.

We can see that the canvas frame is experiencing almost no vibration compared to the inner frame in the 0-20Hz range, indicating good damping performance in that range. However, the canvas frame vibrations had equal or greater amplitudes than the protective inner frame in the 25-50Hz range, indicating the PEU foam's dampening effects were minimal in that range. Because of

this, PEU foam is likely fine for damping larger paintings with natural frequencies in the 10-20Hz range, but would likely provide little to no benefit for a painting in the 25-35Hz range.

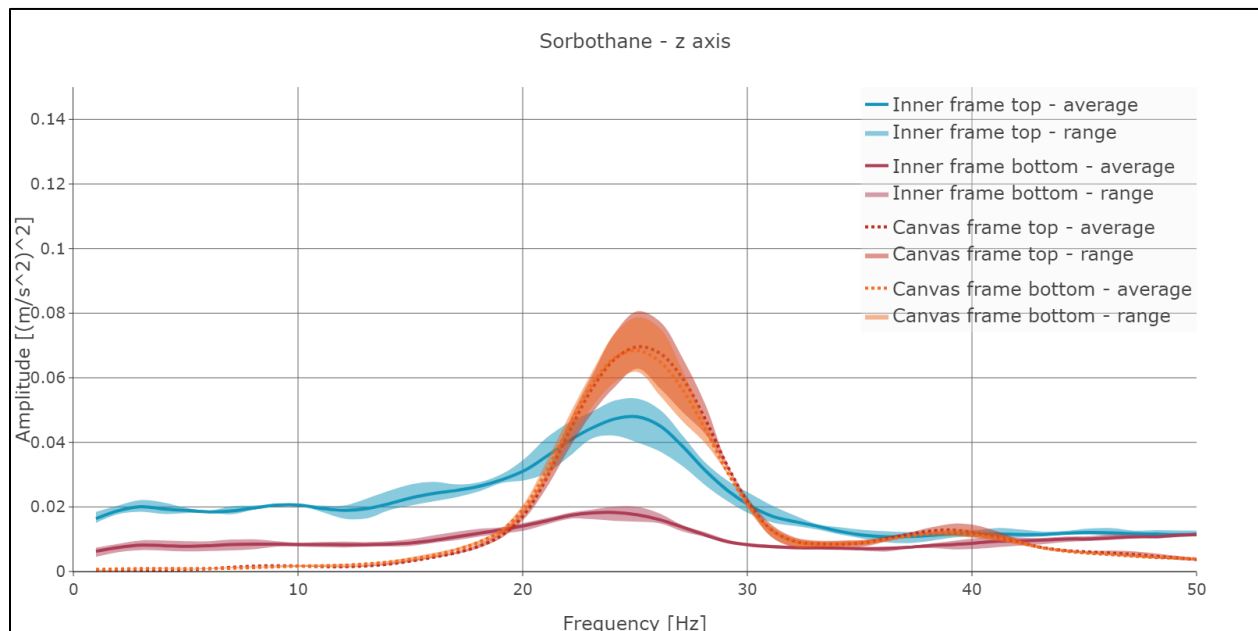


Figure 17- Sorbothane - LIS3DH Shaker Experiment Spectrogram (z-axis)

Figure 17 shows the vibrations of a shipping container with its inner-corner foam augmented with Sorbothane. Compared to the PEU foam, the Sorbothane has generally lower vibration amplitudes. Like the PEU foam, Sorbothane exhibited strong damping in the 0-20Hz range, as can be seen by the low amplitudes of the canvas frame vs the inner frame in that range. Even though the canvas frame vibrations exceed the inner frame in the 20-30Hz range, the canvas frame amplitudes still lower for Sorbothane than for PEU foam in this range. Additionally, in the 30-50Hz range the Sorbothane crate has almost no vibration compared to the PEU foam. As such, Sorbothane is likely an improvement over the PEU foam for any painting in the 10-40Hz natural frequency range.

Figure 17 also demonstrates some strange factors of this experimental setup. Despite roughly equivalent shaker input energy, the inner frame vibrations in Figure 17 (Sorbothane) are lower than those in figure 16 (PEU Foam). This difference is noteworthy as the inner frame is outside of the change in packing materials, so one would expect its measurements to be unchanged between different configurations. There are likely many factors at play here, and it is difficult to determine exactly why this occurred without further experimentation.

One possibility that we cannot dismiss out of hand is that experimental error occurred. Though the shaker generally created consistent amplitudes between these experiments, there was still some variation (potentially due to its battery declining. Between the PEU foam and Sorbothane, there was an approximate 15% difference in shaker amplitudes (not pictured) across the entire 0-50Hz range. However, the difference favored PEU foam; that is, the PEU foam experiment experience consistently lower input vibration amplitudes than the Sorbothane, which

would not at all explain why the Sorbothane still managed to have consistently lower amplitudes for its internal sensors.

A more likely possibility is that this is simply the result of more complex vibration mechanics. Vibrations do not only flow one way, but reverberate throughout entire mechanical systems such as this crate. Therefore, differences in material properties *inside* the inner frame could have affected how the inner frame itself vibrated. The Sorbothane within the inner frame could have acted as “sink” for the entire system, absorbing vibrations and causing an overall reduction in amplitude.

Regardless of the specific cause, this sort of vibration behavior further complicates the issue of objectively measuring damping within the crate. If nothing else, we recommend that the museum repeat these experiments just to be sure that nothing anomalous occurred.

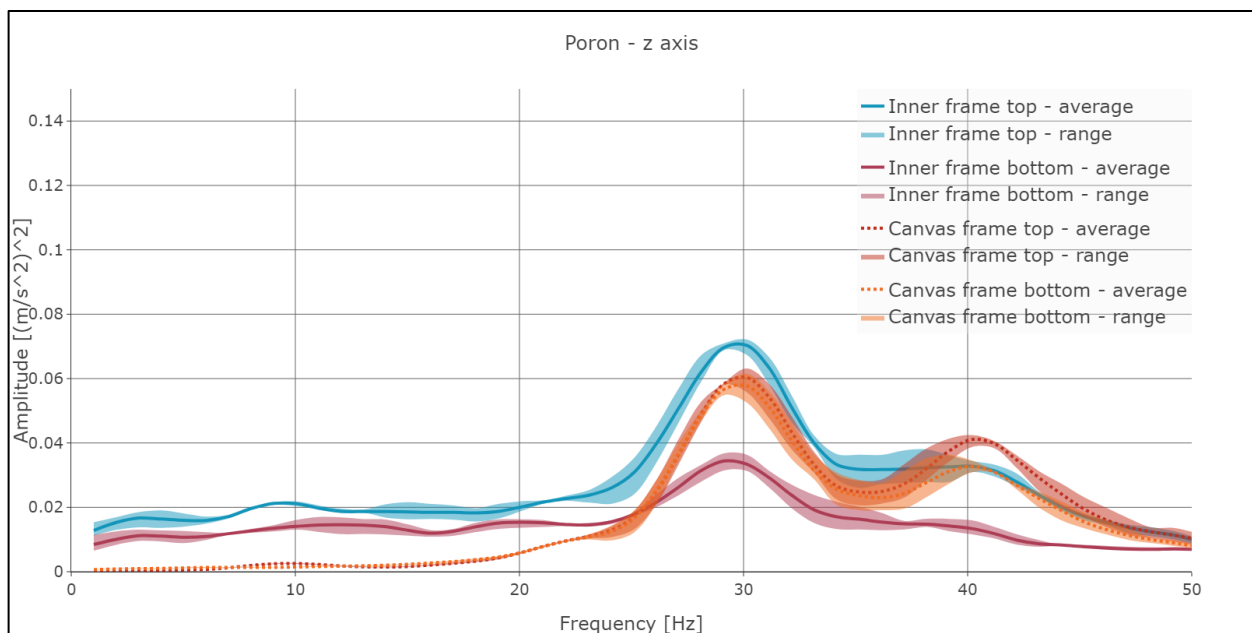


Figure 18 - PORON - LIS3DH Shaker Experiment Spectrogram (z-axis)

Figure 18 shows the vibrations of components of a shipping container with its inner corner foam augmented with PORON. Like Sorbothane (Figure 17), the PORON crate had generally lower vibration amplitudes than the PEU foam (Figure 16), even in the inner frame. This is despite the fact that PORON shaker input amplitudes (not pictured) exceeded those measured in the PEU foam experiments by as much as 50% in most frequencies.

PORON performed similarly well at damping in the 0-20Hz range as PEU foam and Sorbothane did. In the 20-30Hz range, PORON achieved lower amplitudes than Sorbothane and the PEU foam. However, PORON is not a clear improvement over Sorbothane, since PORON amplitudes in the 40-50Hz range are almost identical to those in the PEU foam, whereas Sorbothane showed significant damping in that range. In terms of canvas packing value, PORON is likely better than Sorbothane and PEU foam in the 10-30Hz range, but is likely no better than the PEU foam for the 30-50Hz range.

Regarding the significant difference in shaker input amplitudes mentioned above, differing by as much as 50%, we believe this was caused by a battery replacement for the motor about halfway through our experiments. We did not have time to repeat them, but would advise that the battery be fully recharged before each trial to ensure that the shaker motor is at the same level of power for each experimental trial.

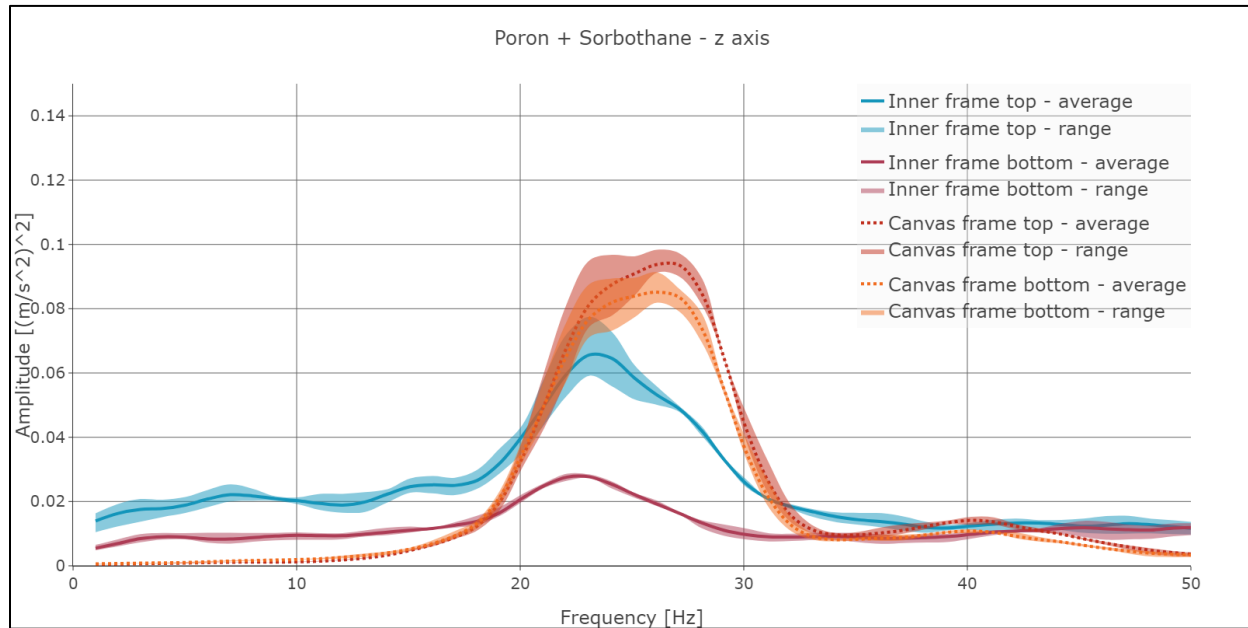


Figure 19 - PORON + Sorbothane - LIS3DH Shaker Experiment Spectrogram (z-axis)

Figure 19 shows the vibrations of a shipping container with its inner corner foam augmented with both PORON and Sorbothane. Like the Sorbothane on its own, this configuration was very effective at damping in the 30-40Hz range. However, the addition of PORON to the system did nothing to improve the 20-30 Hz range – in fact, it greatly increased amplitudes in that range!

This material combination is unlikely to be useful to the museum, because it is essentially the "worst of both worlds". However, it served as a great example of how unpredictably these materials can behave when combined, and emphasizes the importance of testing designs thoroughly.

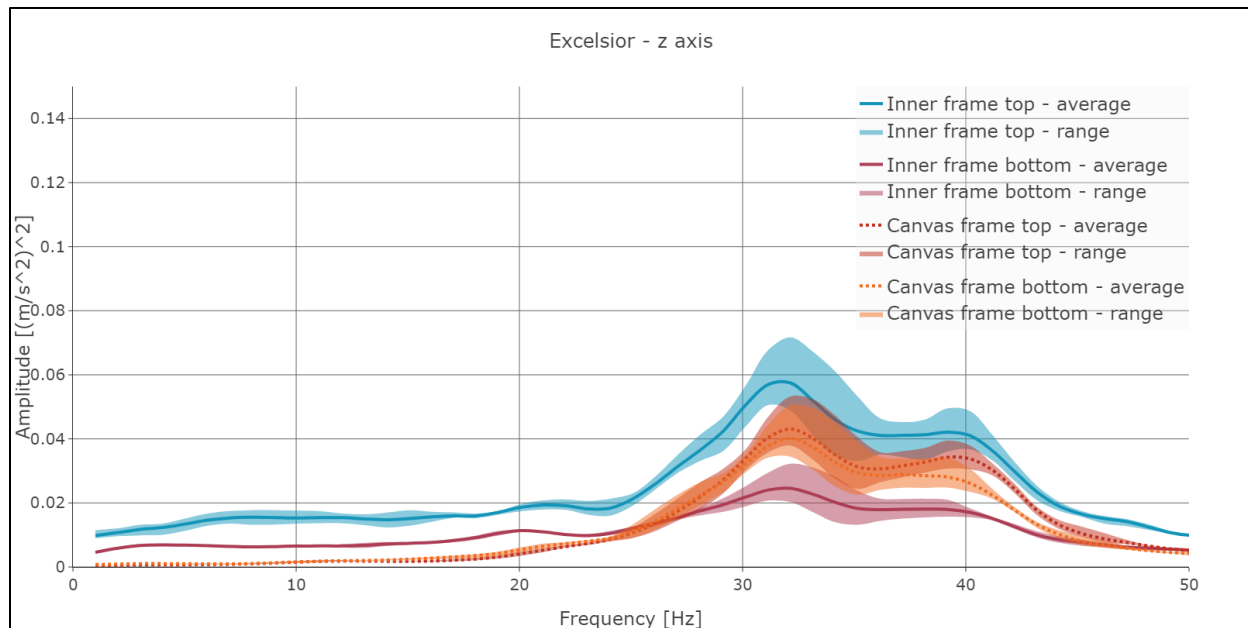


Figure 20 - Excelsior - LIS3DH Shaker Experiment Spectrogram (z-axis)

Figure 20 shows the vibrations of components of a shipping container with its inner frame stripped entirely of foam, and filled with Excelsior. The Excelsior crate, perhaps owing to the unconventional nature of the material, had a vastly different spectrogram than the other materials. The distinct peak at around 25-30Hz exhibited by the PEU foam (Figure 16), Sorbothane (Figure 17), and PORON (Figure 18) is entirely absent from this spectrogram. Instead, the 30-40Hz contains two lower amplitude peaks at around 33-40Hz. Despite these being peaks, their maximum amplitudes are approximately equivalent to PEU foam amplitudes at those frequencies. As such, one can view this spectrogram as if one took the PEU foam experimental results and almost entirely removed the 20-30Hz vibrations.

In terms of what this effect means for packing viability, it is very different compared to other materials. The maximum amplitudes seen are similar to those in the PORON experiments, but appear to have been shifted to a broad expanse of the 25-45Hz range. The minimization of the entire 0-30Hz range means this material would likely be excellent for paintings with natural frequencies in that range. However, its effects on the 30-40Hz range are, as stated before, very similar to those of the PEU foam and unlikely to be exceptionally valuable as a replacement.

### 3.2.3 Material Conclusions:

Ideally, we could select one "best" material from those tested, but such a clear choice does not exist. Without being able to test more specific types of vibrations than our shaker can produce, we cannot make generalizations about any one material's superiority. Furthermore, the analysis above is only on the Z-axis, which corresponds to vertical movement; looking at the graphs in Appendix C, one can see significant variation between the axes. Therefore, to make any meaningful conclusions about the materials, we would need to analyze all 3 axes. And even looking only at the Z-axis, no material objectively "better" than another. For example, Sorbothane



and Excelsior are both improvements over the standard PEU foam, but choosing between them involves deciding which range, the 30-50Hz or 10-30Hz range respectively, is more harmful to the specific painting and therefore a higher priority for protection. Ultimately, the best option depends on the painting the material is protecting, because the natural frequency of that painting is the frequency which must be reduced the most, as the natural frequency has proportionally the most significant effect on the movement of the canvas.

To conclude, there were no clear best material for general vibration damping. The vibration generation method (the shaker jug), though primitive, was consistent enough for us to be able to perform reproducible tests of the materials, and the GOKM can continue to use it until they decide to purchase something more advanced. The spectrograms gave valuable insight into the effects each material had on vibrations in the crate, and we are confident that the GOKI group can leverage their data analysis experience to interpret and use these graphs to further their research. Though there was no clear optimum solution, almost all materials have an advantage in some aspect when compared to the basic PEU foam. Hopefully these results and methods for analysis used can serve as a foundation for the GOKM's future experimentation, helping them to identify a superior design for protecting artwork.

### 3.3 Objective 3 Results

Our final deliverable for Objective 3 consisted of several module options that the GOKM curators will eventually base a full exhibit around. We did our best to incorporate the advice of museum curators Cody Hartley and Carolyn Kastner about how different people interpret, view, and react to museum exhibits. (See appendix A for transcript). From this interview, the most significant suggestions we utilized were how to make visual and interactive aids understandable and relatable. We tried to simplify the text in our modules to be as widely understandable as possible, and used interactive elements to help visitors understand and relate to the museum's work. We also interviewed GOKM educators Shannon Bay and Sarah Zurick, but due to time constraints were not able to incorporate their advice before the end of the project (See appendix A for transcript).

The modules were focused on addressing three core ideas: What goes on during art shipment, what the GOKM doing to make it safer, and how “you” (the visitor) can learn more about the problem. Each module consisted of a textual component talking about the core idea, as well as an interactive element to attract visitor interest and allow them to better relate to the discussed topic. The text was kept simple in order to avoid overwhelming the reader with unnecessary technical detail.

After brainstorming ideas of how to best represent each of the core concepts, we created several draft designs to become more familiar with the process – these can be found in Appendix B we ended up creating a total of 7 full featured modules. The modules were created using the computer design tool SketchUp, allowing us to create a visual representation of how our ideas might look in a real exhibit. The following is our different designed options for each module:

### 3.3.1 “What is Happening?” Module

Our first module was intended to show how art transportation works, and how vibrations affect crates in transit. We created three different module options for this core idea. The primary text (same for each module in this category) sought to establish the basic ideas of how art was shipped, and how art gets damaged. To allow the visitor to understand the more complicated concept of vibration, these options contain an interactive component to allow the visitor to see for themselves how vibration works.

#### **Core Idea: “What is Happening?” text component:**

*"Artworks from around the world are constantly being shipped from place to place for museum visitors like you to see. Unfortunately, when these pieces of artwork are shipped, they undergo damage from the vibrations created during transit. The movement of trucks, ships, trains, and planes, cause vibrations that go straight through the crate to the paintings they carry, which causes the painting to crack and split. To the right (insert similar picture to Figure 4), you can see how damaging cracks even formed in one of Georgia O'Keeffe's paintings!"*

**(This text is on the red placards to the left of each interactive option)**

#### **Option A: Transportation Vibration Simulation**

Our first design showcased a canvas painting behind a glass cover, with four buttons to the right of it. Each button was labeled a different transportation method and pressing a button caused the painting's crate to vibrate with the corresponding frequency. The different types of vibrations will show viewers the severity of each transportation method. Optionally, the frame could be surrounded by a standard crate to demonstrate how easily the vibrations transfer through the PEU foam. See figure 21 for visual.

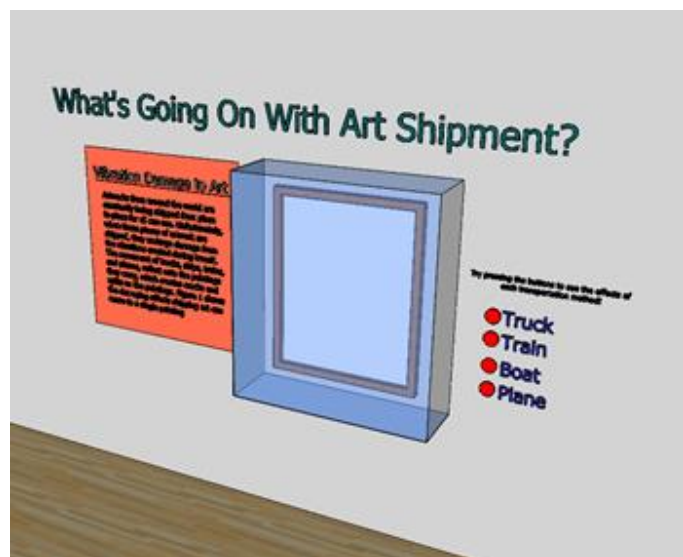


Figure 21 - Module 1 Option A: Transportation Vibration Simulation  
**Right text:** "Try pressing the buttons of each transportation method to see the different effects they have on the painting!"

### Option B: Manual Vibration

Our second design involved a hand crank attached to a canvas painting. The hand crank would drive a small vibration shaker similar to the one used in our experiments. This would allow viewers to manually inflict vibrations on the canvas frame to see how easily they affect paintings. Unlike Option A, the crank does not directly correspond to any mode of shipment, so its technical accuracy is not as good. However, the hand-driven nature allows the visitor to more easily relate the amount of force that they are applying to how much the crate is reacting. The shaker device itself (not pictured) could be visually modified to look like a truck's wheel to relate the vibrations the visitor generates to those generated in transit. See Figure 22 for visual.



Figure 22 - Module 1 Option B: Manual Vibration

**Right Text:** "Try turning the crank to see the effects vibrations have on the painting!"

### Option C: Interactive Game - Shipping Simulation

Our last design showed a touch screen monitor with an interactive game that takes viewers on a journey alongside art in transit. The game presents viewers with a series of packing options, routes, and transportation methods with which they can transport their painting across the world; while trying to minimize damage to their painting (similar to the computer game "Oregon Trail"). The game would teach viewers the challenges of transporting art. Though it does not directly show vibration, it can give the visitor a more comprehensive understanding of how difficult it is to protect against it. See Figure 23 for visual.



Figure 23 - Module 1 Option C: Video Game Simulation

**Above text:** "How far can you transport art without damaging it?"

**Below text:** "Transporting art is more difficult than you might imagine. Play this game to see what makes safely transporting artwork from one museum to another so difficult!"

### 3.3.2 “What is the Museum Doing?” Module

Our second module was intended to show the viewer what the museum was doing to stop the vibrations shown in the first module. For this module, we drafted three variations of a display table aimed at informing visitors what research the GOKM is doing about art shipment. A brief description of our and museum's work was placed on a placard next to the display table in each draft

#### **Core Idea: “What is the GOKM doing about this problem?” text component:**

*"The Georgia O'Keeffe Museum is working hard to protect its paintings from transportation vibrations. Researchers at the museum teamed up with college students from Worcester Polytechnic Institute (WPI), to find new ways to measure and combat these vibrations. They used the tools and materials on this table to measure and attempt to reduce this damage. The accelerometer (see item 1 below in display case) is being used to measure vibrations in the crate. The accelerometers are placed throughout the crate, and were used to analyze how different materials (see items x-y in display case) protect against vibration. The Georgia O'Keeffe Museum is still experimenting to find the safest and most reliable method of protecting its priceless paintings."*

**(This text is on the red placards next to each interactive option)**

#### Option A: Glass Enclosed Display Table

This design showcased the materials and tools we used (e.g. PORON, MSR165, etc.) on a table behind glass. The idea behind this glass-enclosed design was to showcase our tools to viewers without the risk of damage to the exhibit itself, as some of the materials (such as the MSR accelerometer) are very expensive. Next to each material is a small placard saying what the material is called, what it is good at, and real world uses of that material (ex. PORON used in bicycle helmets). The components on the table are not necessarily restricted to what was used in this project, and should include whatever future materials the museum tests and uses for its research. See Figure 24 for visual.



Figure 24 - Module 2 Option A: Glass Enclosed Display  
Contains experimental materials and tools used by GOKI

### Option B: Open Table Display

Our second option is essentially the same as Option A, but without the protective glass. This would let viewers touch and compare the feel of the different materials. Since the materials we used are not often encountered outside of industrial applications, being able to touch things like “Sorbothane” can give the visitor a better understanding of what exactly a vibration damping material is/feels like. There is a risk of theft and deterioration of the materials, so it is important that they are secured in some way and not too difficult to replace. It is up to the museum to decide whether this added expense is worth the benefit of interactivity. See Figure 25 for visual.



Figure 25 - Module 2 Option B: Open Table Display  
Contains touchable experimental materials and tools

### Option C: Open Table Display with Video

Our third option for this module incorporated the same table as Option A/B along with a large display screen displaying pictures and videos the museums research/experimentation. This lets the visitor see for themselves how the materials on the table were used to research painting protection. Ideally, each component of the table would have a button next to it that, when pressed, causes the screen to display a short demonstration of the capabilities of the corresponding table element. For instance, PORON could trigger a short video clip of a weight being dropped onto normal foam and PORON, to demonstrate the difference in how much energy is deflected/bounced by the PORON. These buttons could be used regardless of whether the table was glass-enclosed, as the individual videos could effectively replace the tactile interaction without fear of the exhibit being damaged by visitors' touches. See Figure 26 for visual.



Figure 26 - Module 2 Option C: Open Table Display with Video  
Video displays how the materials and tools were used in real experiments



### 3.3.3 “What can you do to help?” Module

The final module was designed to inform visitors about how they can learn more and help the museum. As the last module in the core narrative, it should give the visitor a strong takeaway about the importance of this research to protecting not only Georgia O’Keeffe’s paintings, but those of other artists around the world. The text component of this module is significantly more important than the interactive component, as we found it more difficult to appeal to visitor emotions without text. As such, we created only one module option for this core concept, and do not consider it fully necessary for this module to be effective.

#### **Core Idea: "How you can learn more about the problem" text component.**

*"Vibrations are currently one of the main threats to the preservation of Georgia O’Keeffe’s paintings. However, vibrations are also a threat to any other artists’ work that is shipped between museums. The Georgia O’Keeffe Innovation Group is committed to researching this problem until they are confident that artwork can be transported without fear of damage. For more information visit our website at [www.okeeffemuseum.org](http://www.okeeffemuseum.org)" (this URL may optionally be replaced with a QR code).*

(This text is on the red placard above the module)

#### Option A: Donation Box

In this module we created one draft of a donation box. Text in front of the box reads. *“To help the Georgia O’Keeffe Innovation Group preserve the legacy of Ms. O’Keeffe and other artists, we greatly appreciate any donations to fund further research into protecting art from vibration damage.”*

See Figure 27 for visual reference. The donation box itself is not of critical importance to this module. The core idea text above is far more important as it establishes the real importance of the experiments displayed in the exhibit. If the museum decides they do not like the idea of a donation box, we would recommend they keep the text component.



Figure 27 - Module 3 Option A: Donation Box



### 3.3.4 Combined Exhibit

The final exhibit draft design we created was not another module, but instead an example of how the previously listed module options can be combined into a single exhibit. This was mostly done as a proof-of-concept of how easily one can pick options from each module group to create a full exhibit. Breaking the problem up into multiple designs allowed us to more easily approach what we wanted to show in the exhibit as a series of easily manageable steps. More importantly, creating these interchangeable puzzle pieces gives the GOKM more freedom to modify our suggestions without having to rework them entirely. Since exhibit designs can undergo many revisions before their completion (C. Hartley, C. Kastner, personal communication Sept 27, 2017), we are satisfied that these modules will be very useful as an easily-modified baseline for this exhibit.



Figure 28 - Example Combined Exhibit  
Created by combining Module 1 option A, Module 2 option C, and Module 3 option A

## 4.0 Recommendations

If there was ever an opportunity for us to repeat or continue our project with the Georgia O'Keeffe Museum we would do a number of things differently. While we feel that our method was scientifically valid and well thought out, changing certain aspects could make the process more easily repeatable for the museum in the future.

### **Objective 1 Recommendations:**

Though initial results of using our new accelerometer system from section 2.1.1 were promising, there are still many improvements that can be made in terms of its usefulness as a measurement system. Before the GOKI group fully commits to the new LIS3DH vibration measurement system over the MSR165 accelerometers, we recommend that they repeat the side-by-side LIS3DH vs MSR165 experiment described in section 2.1.3. We believe that improper mounting may have negatively affected our results when we conducted the experiment, but were unfortunately unable to repeat it ourselves due to limited access to the MSR165 sensors. Even

though the LIS3DH results are internally consistent, it is troubling that comparing the new system with the industry-standard MSR165 accelerometers shows such a significant difference in amplitudes. The results of Objective 2 using this method are still probably valid, since the LIS3DH accelerometers were attached in the same way each time, so comparing between them is valid.

To further validate our method of DFT analysis described in section 2.1.2, we recommend that the GOKI group find a way to repeat the vibrations used in its initial PSV/MSV experiments using accelerometers. Recall that the PSV/MSV systems are state of the art laser-based vibration measuring tools that the GOKM cannot afford to continue using for long term experimentation. By comparing the resulting spectrograms of our analytic method to those generated by the PSV/MSV software, we can ensure that the using accelerometers in this use case is valid. The museum does not necessarily need the PSV/MSV devices again, but it does need to use the same type of shaker device it rented for that experiment so that it can accurately recreate the vibrations that were measured by the PSV/MSV systems. Doing this experiment will allow the museum to evaluate how closely our analysis results replicate the PSV/MSV results.

If the GOKI group can repeat the experiments above, we would recommend that they also test the viability of using the lightweight LIS3DH accelerometers directly on a canvas surface. Measuring the canvas surface directly would allow the museum to ignore any guesswork about how the canvas will resonate, and observe painting movement directly by measuring the canvas surface itself. Unfortunately, though we took some initial steps towards testing this capability, we had no way of verifying that the behavior of the canvas we measured would have been the same had the canvas not been burdened by the additional mass of the LIS3DH accelerometer. If the GOKI group could repeat the vibrations used in the PSV/MSV experiments, they could compare the LIS3DH data with the existing data from the PSV/MSV experiments to see if this highly valuable addition to the system is possible.

Finally, if the museum decides to continue using the LIS3DH system, we would recommend they upgrade from the Arduino Uno to an Arduino Mega. This model has 4x as many serial connections, which would significantly increase the number of accelerometers the system can measure at once (up to an estimated 24 at least). This could be used to emulate the sophisticated MPV's (Multi-point vibrometers) ability to measure vibration across many points of the crate, and better account for potential differences between different points on the same component. Additionally, if canvas surface measurement is possible, then this could be used to visualize motion of the entire canvas, to better detect resonance.

## **Objective 2 Recommendations:**

Though our shaker tool produced consistent vibrations, it did not accurately represent typical artwork transport, and thus analysis of the effects on different frequencies vibration is of somewhat limited use for practical applications. If the museum wishes to exactly recreate the vibrations of a truck, they would need to seek out other methods. One type of tool that they could use to generate vibrations in a controlled experimental setting is known as a "Modal Shaker," which the museum has used in the past for MSV/PSV experiments. A Modal Shaker is a precisely

controllable device that can produce complex vibrations within a large range of frequencies. These devices are typically expensive (costing over \$1000), but would be able to accurately simulate any vibration (truck, plane, tarmac, etc.). Alternatively, the museum could opt to not *simulate* vibrations using a shaker device, and instead perform experiments on an actual truck/plane ride.

Additionally, we intended to reduce the graphs we produced down to more easily comparable metrics, but were unable due to lack of time. Our recommended analysis method to accomplish this would be to use the RMS method (root mean square) which reduces spectrograms like those in 3.2.2 into a single value representing the “total vibration” (Brüel & Kjær, 1982). Moreover, by scaling the RMS total for each sensor by the total mass of the object the sensor was attached to, the resulting number the total vibration energy in Joules, representing the energy in the object, not just how much it is vibrating (Encyclopedia Britannica Editors, 1998). This scaling based on mass would better account for differences in weights of materials, because current estimates favor heavier materials simply because they have higher inertia. This would also allow the museum to be able to empirically compare material tests without having to observe minor details about each spectrogram.

### **Objective 3 Recommendations:**

Though we are confident the proposed modules for the exhibit are a well-researched basis for an exhibit on this subject, there are several steps that we recommend the GOKM take to make sure the exhibit is as understandable and educational as possible. To ensure that the contents of the draft exhibit modules are understandable, we would recommend doing a test run on a control group that was made up of different aged museum patrons to measure how well they grasped the content of the modules. This information could later be used to correct the modules to ensure that the information is as easily digestible as possible.

We also suggest that it would be beneficial for the second module to give information about where in peoples everyday lives the materials are used, so the visitor can more easily relate to what their function is. For instance, PORON is used in bicycle helmets to protect from impacts, and Sorbothane is used in football cleats. We believe these facts will help the reader connect more to the written material, that it will be easier for the viewer to understand the technical aspects of the materials if they know where they come from/are used for.

Finally, the current drafts for "What is the Museum Doing?" module (section 3.3.2 lacked a physical representation of the actual shipping crate the GOKM uses. We recommend that the museum create a cross section of a common shipping crate, or, at the very least, provide a disused crate that visitors could look inside. By incorporating this visual and possibly interactive aid, viewers will gain a better understanding of how art is shipped, and where the materials we tested were placed.

## 5.0 Conclusion

Our team sought to help the GOKM in its mission to preserve the legacy of O'Keeffe and artists worldwide. Using low-cost sensors, we developed a system that let the GOKM better understand how vibrations affect paintings within transportation containers. We used this system in conjunction with several methods of generating vibrations to provide insight into the best design techniques for eliminating vibrations. Finally, we used the insight of museum experts to create a draft museum exhibit designed to help share GOKM's mission and findings with the public.

Our work proved beneficial to the GOKI group who continued to explore materials and their positioning after our departure. We delivered a method of analyzing vibrations at many points across the surface of a crate. Then, we used this method to evaluate a variety of potential replacements to the current PEU foam, and though many showed advantages over the PEU foam we were not able to meaningfully conclude that any one material was superior – more testing is required. Finally, we created draft components for an exhibit showcasing the work the GOKM has done to protect artwork in transit. The applications of our findings will hopefully allow for museums to continue its work on transporting art for viewing in a safer manner.

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## Appendix A: Exhibit Designer Semi-Structured Interview

### **Preamble:**

We are a group of students from Worcester Polytechnic Institute in Massachusetts. We have been working with the Georgia O’Keeffe Museum to better understand how vibrations damage paintings in transit. We are working on creating an exhibit that explains this to museum visitors. Our goal is to offer The Georgia O’Keeffe Museum suggestions towards how to best represent the problems with art shipment to the public, and your insights will be extremely useful in how effectively we convey this information.

Your participation in this interview is completely voluntary and you may withdraw at any time. If you would like, we would be happy to include your comments as anonymous. If interested, a copy of our results can be provided at the conclusion of the study.

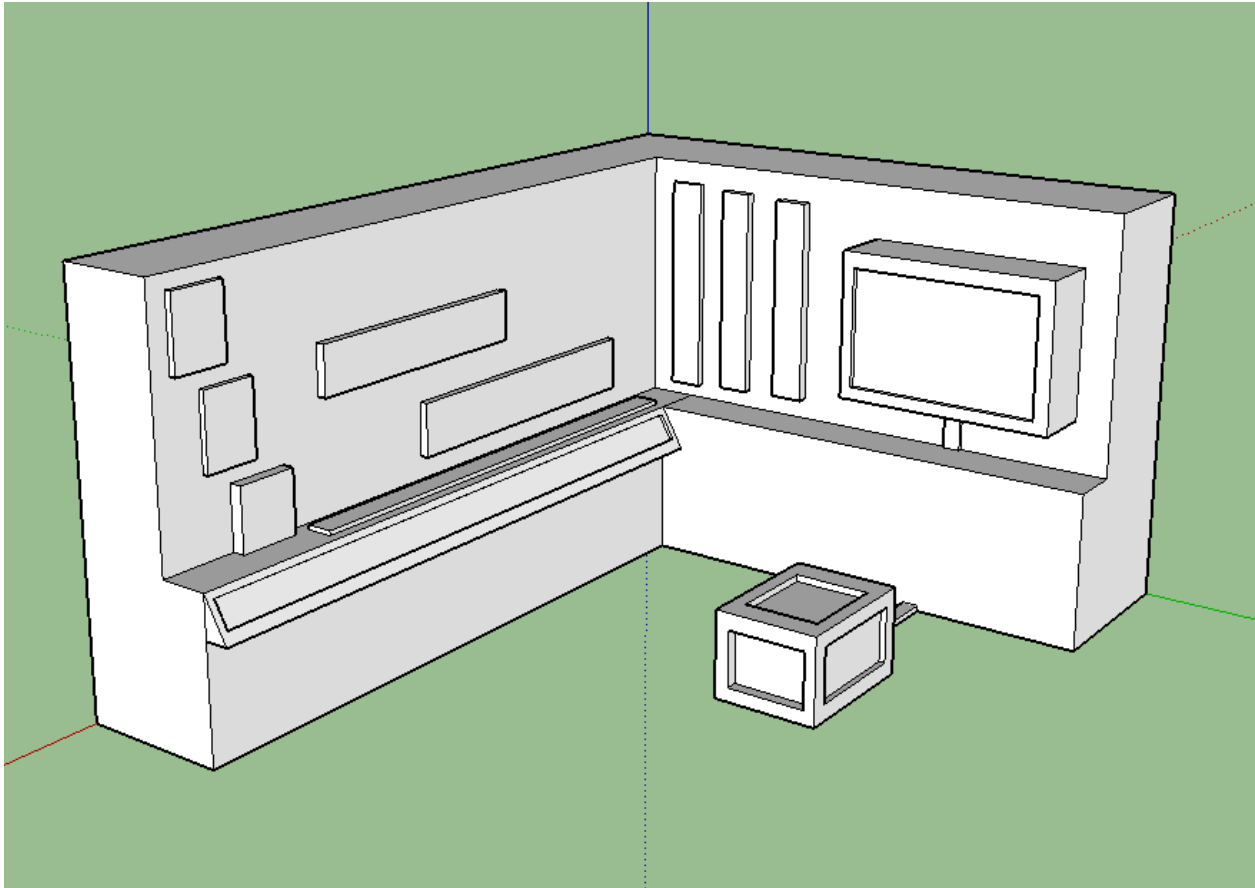
### Exhibit Design Questionnaire

1. What experience do you have in exhibit design?
2. Have you ever made an exhibit about the museum’s curation and/or operation? If so, how did it differ from a regular exhibit?
3. To you, what is the most important aspect of a museum exhibit?
4. What makes an effective educational exhibit?
5. Is graphical or textual information more important when designing an exhibit?
6. How does the inclusion of tangible/interactive elements impact an exhibit?
7. How do you successfully integrate more technical, hard-to-understand material into an exhibit?

*\*Note that this is only a rough guideline that we tried to follow going into each interview. In practice, our interviewees all quickly diverged from these questions.*

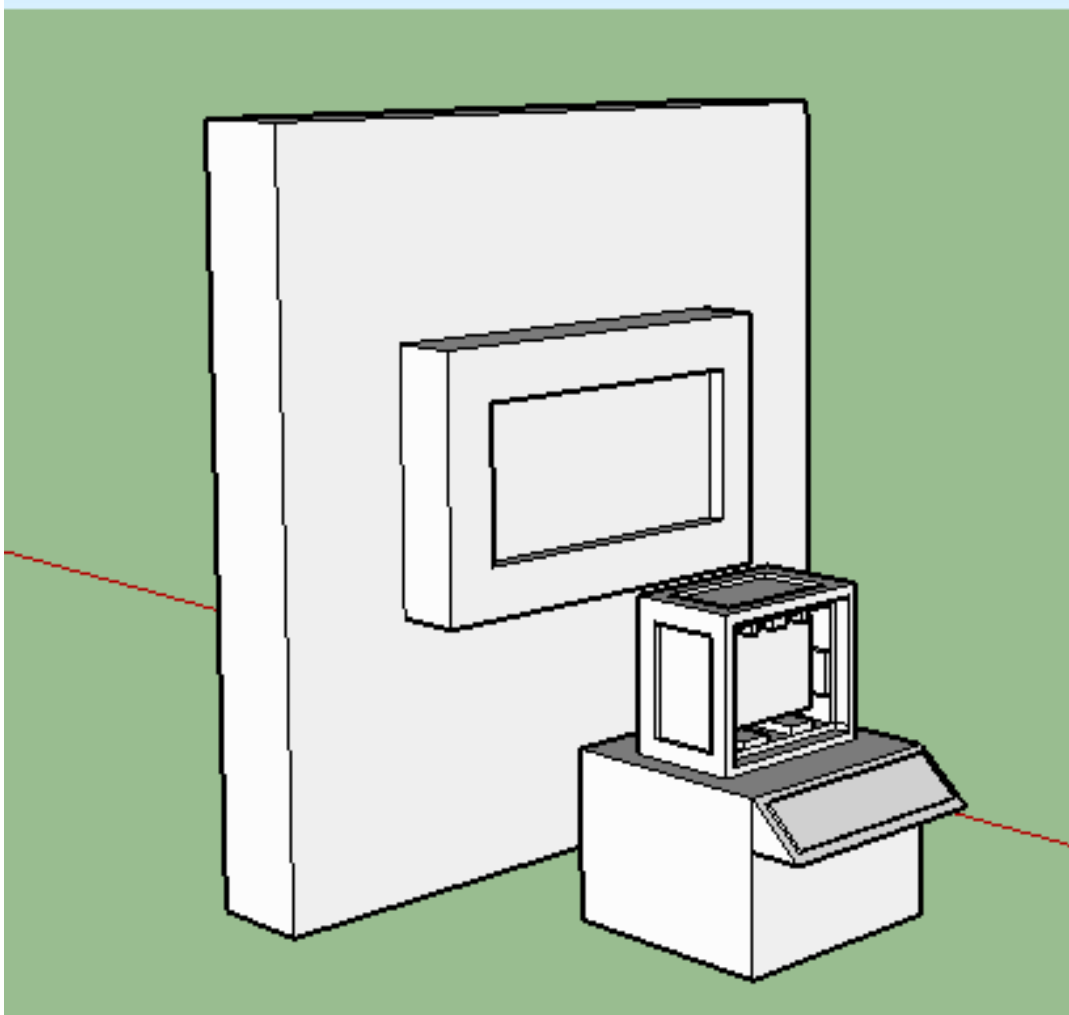
## Appendix B: Exhibit Early Draft Prototypes

### **Section 1- First Full Exhibit Draft Layout**



Section 1 showcases our earliest draft for how the exhibit design might be laid out, before we had decided on a modular setup. After meeting with Cody Hartley and Carolyn Kastner we began to focus more on drafting specific modules.

## Section 2 – Crate Display Detail



Proposed text: *“This type of crate is used by the Georgia O’Keeffe Museum to protect its paintings in transit. The wooden frame protects the painting from drops and impacts, while the soft foam cushions the painting, converting sudden jerking motions into gentle movements”.*

Section 2 shows the first modular exhibit proposal. This module showcases the interior of a shipping crate with a small panel describing what the different components do it works. A screen behind will show a short repeating video visually showcasing how the different materials stop impacts to the painting. This design was effectively replaced by the designs in section 3.3.2, as we felt focusing too much on the old design might mislead visitors as to what the new designs the GOKM was working on were.

## Appendix C: Additional Analysis Graphs

Below are all the graphs of the other axes that were omitted from 3.2.2, as comparing so many different graphs would become pointlessly confusing. No analysis is provided here, but the graphs are structured in the same way as in those analyzed 3.2.2, and can be similarly compared. For reference in how to interpret spectrogram graphs in general, see section 2.1.2

