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## Tensegritree: Integrating Tensile Integrity into Furniture to Reduce Earthquake Damage

Dessa Bulaong<sup>1</sup>, Andreus Rodge S. Cordova<sup>1</sup>, Alvin S. Eusebio<sup>1</sup>, Princess Elise R. Fernando<sup>1</sup>, Timothy James R. Marquez<sup>1</sup>, Clark Kent S. Santiago<sup>1</sup>, Asly Danaya M. Santos<sup>1</sup>, Maria Isabelle D.C. Santos<sup>1</sup>, Mary Grace Delos Santos<sup>1\*</sup>

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### ABSTRACT

Few furniture designs are built around the concept of withstanding earthquakes. This capstone project aims to integrate tensegrity into furniture to replicate the earthquake safety measures used on larger scales with seismic isolation and withstand earthquakes better than traditional furniture. The researchers tested the product at the Philippine Institute of Volcanology and Seismology (PHIVOLCS), located at Diliman, Quezon City. The researchers made use of the institute's earthquake simulator to have the earthquake intensities scaled accurately. They made use of true experimental research design, which gave them access to the scientific method in making the designs for the furniture. The researchers conducted the experiment in four phases, denoted as the research phase, the design phase, the experiment phase, and the evaluation phase. The results showed that the calculated t-value of 35.317 is greater than the critical t-value of 2.56. This meant that tensegrity-integrated furniture is significantly more earthquake-resistant than traditional household furniture. Measures such as adding weights to the structure's base increase further increase its stability. Tensegrity integrated into furniture is a modern take on earthquake safety measures, similar to existing ones like seismic isolation. And with the proper setup and more improvements, its earthquake resistance factor can save lives.

### INTRODUCTION

Natural disasters have given struggles to humanity since the beginning. Inventions and discoveries have helped humans predict when calamities like storms will occur, allowing them to prepare and mitigate the damage they caused. However, there are still unpredictable disasters that have devastating impacts on human lives, with earthquakes being the most well-known.

Earthquakes are sudden shaking of the earth due to seismic or volcanic activities. Their nature makes them unpredictable even to seismologists, or experts on geological occurrences. Due to the lack of understanding of the fundamental physics of earthquakes, experts are unable to tell when an earthquake will strike (Kelety, 2023). The most humans can do is mitigate the damage they deal with when it happens.

Humans have already taken measures on reducing the damage caused by earthquakes. Whether it would be using seismic isolators or using shock absorbers on larger scales, buildings can be made earthquake-proof (BigRentz, 2022). These have all achieved their purpose of preventing buildings from crumbling down. However, earthquakes also cause damage to the interiors of buildings.

While collapsing buildings cause the majority of the damage during earthquakes, falling heavy furniture and household objects can cause major injuries and even casualties (California Earthquake Authority, 2020). In the event of an earthquake, it has been advised to stay far from tall shelves as they can collapse on people.

Tips on earthquake-proofing the interior of houses involve either fastening or nailing large furniture to walls

(Butler, 2021). Applying anti-earthquake measures in traditional households can be effective. There are also products that exist which can be installed in household furniture to minimize their chances of collapsing. Yet, there are only a few accounts of furniture that are built around the concept of withstanding earthquakes.

A structural principle exists which is applied not only in architecture but also exists in human anatomy. This principle is known as tensile integrity or "tensegrity" for short. Structures with this principle have components under continuous tension that causes their other components to experience constant compression, thus holding up the structure (Ansys, 2020).

Applying this principle to furniture causes the furniture's base to move less due the top layers moving more freely and the chord networks isolating the weight, causing it to sway relative to any ground movement as opposed to it toppling over. It shares similarities with seismic isolation, in which rubber-bearing isolators and dissipators cause buildings to sway relative to earthquakes, protecting their structural integrity (Antoniu, 2022).

This type of furniture not only provides more safety but may also appeal to those that want more modern-looking aesthetics for their homes. The chord structures that hold up the furniture make it seem as if it is floating, giving an unnatural look to it that some may consider appealing.

This capstone project aims to integrate tensegrity into household furniture such as tables and shelves to replicate the earthquake safety measures used on larger scales with seismic isolation for them to withstand earthquakes stronger than traditional furniture, thus mitigating earthquake damage.

<sup>1</sup> Dr. Yanga's Colleges, Inc., Philippines

\* Corresponding author's e-mail: [reductdl@gmail.com](mailto:reductdl@gmail.com)

### Hypothesis

The earthquake resistance of the furniture also serves as the baseline for the hypotheses of the project, with the two hypotheses stating the following:

$H_0$  – There is no significant difference in the earthquake resistance of tensegrity-integrated furniture and traditional household furniture.

$H_1$  – Tensegrity-integrated furniture is significantly more earthquake-resistant than traditional furniture.

The researchers will simulate earthquakes to know if they hold up during these disasters. These furniture items incorporated with tensile integrity will be called “tensegrity”.

### Research Questions

The researchers seek to create furniture integrated with the structural principle that is tensile integrity and to make the system optimal by answering the following research questions:

1) How much earthquake intensity can the furniture withstand?

2) How to further increase the earthquake resistance in the structure?

With this, there can be more options when it comes to earthquake preparedness in households, causing less damage and potentially saving lives.

## LITERATURE REVIEW

### Earthquake Damage

The Philippines, which has more than 7,000 islands, and is the second-largest archipelago in the world, is situated in the northwestern Pacific Ocean, in the direct path of the storm surges, landslides, and floods that are brought on by the world’s most powerful tropical cyclones. Periodic earthquakes and volcanic eruptions also take place within the Pacific Ring of Fire’s edge. People are more vulnerable and ill-prepared because earthquakes are unpredictable (Naval & Carig, 2017).

According to Causapin (2018), in the Philippines, earthquakes typically occur daily. There are likely to be weak earthquakes every month that the general population does not feel. Regarding earthquake occurrences, it suggests that a quake will typically happen at any moment in the area, albeit with a weak magnitude.

As of now, it is known that the tectonic faulting in the Earth’s crust’s brittle regions, which are concentrated along plate borders, is the only cause of the largest earthquakes, as determined by the seismic moment release energy (Dominguez *et al.*, 2017).

Added by Naval and Carig (2017), it is extremely likely that these terrible earthquakes will happen again in the future. Large urban earthquakes have the potential to devastate the built and natural surroundings, as well as to inflict significant economic loss and social unrest. The severity of the danger—such as ground motion and ground rupture—as well as the economic worth and susceptibility of the built environment and the occupants to the hazard all play a role in determining how much

will be lost and how much will be disrupted. During the earthquake, man-made structures’ collapse posed the biggest risk to people.

In the findings of Centeno *et al.* (2022), they found that many man-made factors frequently increase the risk associated with natural hazards in the Philippines. These include inadequate infrastructures that raise risks; environmental degradation brought on by unethical or corrupt activities like careless mining, quarrying, and illegal logging; inadequate community land-use planning; an increase in unauthorized settlers in urban and suburban areas; and a lack of disaster preparedness among many Filipinos.

The most effective method for avoiding earthquake-related fatalities is the creation and implementation of seismic safety codes. It is highly recommended to survive earthquake disasters to provide the public with the necessary information regarding earthquakes, such as the location of fault lines, earthquake preparedness, mitigation, and drills.

However, according to the findings of Baquiran *et al.* (2017), disaster preparedness strategies are either implemented intermittently or only when a crisis actually occurs. The frequency of a natural catastrophe and disaster readiness were found to be directly correlated. Disaster managers are less likely to plan for a natural disaster if it happens less frequently.

### Impossibility of Earthquake Prediction

Earthquakes have been known for their damage and unpredictability. Due to its destructive potential, humanity has long sought a method for predicting earthquake trends. Predicting an earthquake entail stating the precise time, magnitude, and location of a forthcoming earthquake. Prediction models are classified as either short-term, long-term, or intermediate-term. Despite the scientific community’s efforts, no valid and reliable method has yet been discovered due to the phenomenon’s inherent unpredictability. (Vardaan, 2019) . Earthquake prediction was deemed impossible due to either the limitations of current and foreseeable knowledge or the chaotic nature of seismic phenomena. This was accompanied by a sense that efforts toward prediction were a waste of money and time. Predictions were viewed as exhibiting poor scientific rigor, which, when combined with false alarms, could harm the reputation of earthquake science by inciting mass hysteria and the resulting loss of life. Forecasting, as opposed to prediction, was deemed worthwhile because it could aid in earthquake preparation and mitigation efforts. As a result, the majority of participants explicitly avoided earthquake prediction in favor of forecasting. As a result, earthquake prediction became a stigmatized subject; associating with the concept of earthquake prediction could be detrimental to one’s career prospects. (Joffe, 2018) Furthermore, seismic activities are mostly located in the crust lithosphere or asthenosphere, it is not possible to simulate the accumulating process of matter and energy during the seismogenic process. Therefore, making

earthquake prediction a significant scientific problem. Even if remote sensing technology is used for earthquake prediction for almost 30 years, an in-depth study of remote sensing technology still is required to reduce the external disturbances that may accumulate noise to remotely sensed data. Major problems in earthquake prediction include; The unobservability of the seismic source since it's impossible to sense the interior of the earth. The uncertainty of precursor signals in meteorological and geographical environments has a huge impact on earthquake prediction. The uncertainty of remote sensing data and algorithms; the volume, type, and accuracy of the data. The complexity of predictive models such as deformation, gravity, electromagnetic signals, etc. Rareness of violent earthquakes, although earthquakes are common. Violent ones are quite rare. (Zhao, 2021)

Thus, earthquake occurrences in complex environments with uncertain elements are incorporated into point-process modeling, which results in stochastic predictions. A large uncertainty exists, in particular, in determining whether abnormal phenomena are precursors to large earthquakes, as well as in assigning urgency to a given earthquake prediction. (Ogata, 2017)

Is prediction utterly impossible or just extremely difficult? Observing subtle phenomena, forming hypotheses, and meticulously testing them against future earthquakes would require enormous effort over several decades, with no assurance that it will succeed. As a result, it appears unwise to invest heavily in monitoring potential precursors. (Geller, 2017)

As of now, seismology can help with earthquake hazard mitigation. Statistical estimates of the seismicity expected in a general region on a time scale of 30-100 years and statistical estimates of the strong ground motion are important data for designing earthquake-resistant structures. (Geller, 2017)

### Earthquake Safety Procedures

The Philippines has been identified as one of the most disaster-prone countries in the world, owing primarily to its geographical and geological location as well as its physical characteristics. As a developing country, the Philippines has been conducting safety planning and developing strategies to address the complex challenges posed by earthquakes. The government encourages authorities, private companies, groups, and schools to conduct concrete planning and earthquake drills on an annual basis to practice what to do before, during, and after an earthquake to increase the chances of survival while minimizing its dangers and damage.

According to a study conducted by Baylon *et al.* (2021), the Philippines, being part of the Pacific Ring of Fire, faces significant threats of massive infrastructure damage as a result of extensive earthquakes. The most vulnerable infrastructures are public school buildings, which are deemed significant structures due to them being places for education and shelters for times of need. Implementation of rapid visual assessments using the Safer Communities

through Safer Schools (SCOSSO) shows that a peak in ground movements cause causes school buildings to crumble.

In addition, the simulation study conducted by Naval, R. C., and Carig, E. T. (2017) called Rapid Earthquake Damage Assessment System (REDAS) was used to assess earthquake risk in Gundaway, a barangay in the municipality of Cabarroguis, province of Quirino. The simulation revealed that at an intensity of 7.8, Gundaway would have the highest total damaged floor area, covering 10,818 sq. m., and a damage cost of Php 69.8 million, with schools, commercial buildings, and some residential areas suffering major damage.

School plays an important role in the education of a community's next generation, who are still in the developmental stages of their lives. Safer and more resilient schools can save children's lives, provide a haven for the local community, serve as a temporary shelter, and help restore normalcy to society in times of disaster. Nassirpour *et al.* (2018) conducted the study, introducing a set of tools for rapid yet dependable visual multi-hazard vulnerability prioritization of school infrastructure against potentially destructive natural hazards such as earthquakes, typhoons, and floods.

Altovar, A. T. (2017) found that using the Shortest Route Algorithm to find the shortest way out of the building during earthquakes, floor plans with indoor measurements can be used to construct a viable earthquake evacuation route plan. The findings of this study are aimed at helping schools, particularly students, by providing information that will increase their awareness and sensitivity to earthquake preparedness.

Limlengco *et al.* (2016) conducted a study that aimed to create software that can send a message to a police station, hospital, and other related agencies in an emergency situation such as a fire or earthquake. To assist the user in an emergency, the application will find the shortest route out of the building, block a path, and send a distress message to help the user during an emergency. In accordance with the findings of this study, Centeno *et al.* (2022) also conduct a study that concludes that respondents' communication behaviors, as well as their media and non-media information sources, are significantly related to their level of knowledge and attitude toward disasters, as well as their practices before, after, and during disasters.

### Seismic Isolation

A structure can be isolated from the ground to be protected against the devastating effects of earthquake vibrations, which is the basis for the design method known as seismic isolation. Additional flexibility tends to be included at the base of the structure to attain this result and satisfy all in-service functional requirements. To manage the deflections that occur across the isolation interface, additional damping is also offered. (Acero, 2018)

The Seismic Isolator is an anti-seismic device that ensures

zero damage to a building in the event of an earthquake. Its objective is to isolate the building from the detrimental ground movement. Because destructive earthquake movements are horizontal rather than vertical, a building with seismic isolators will simply sway rather than vibrate back and forth in varied directions due to inertial pressures, causing deformation and damage.

Seismic isolators are typically cylindrical or square in shape, frequently made of natural or high-damping rubber with a lead core, and can take on any shape according to the needs of the building. While the rubber functions as a spring, the lead core dampens and eliminates vibrations. Because it absorbs seismic energy, floor acceleration will be decreased, preventing damage to the building's structure and ultimately the building's contents from being damaged. (Luna, 2021)

The use of base isolation is a particularly efficient method for reducing the seismic response of civil engineering constructions. This method is based on the idea that decreasing a structure's seismic demand is more effective than increasing its capability for earthquake protection. The primary principle of base isolation is to reduce the stresses caused by earthquakes that are transferred to the superstructure. Decoupling the structure from ground motion reduces the need for ductility and lowers inter-storey drifts, preventing seismic energy from entering the building. This decoupling is done by introducing the structural elements with low horizontal stiffness between foundation and superstructure which minimize the fundamental frequency of structural vibration to a lower value than the leading energy containing frequencies of earthquake ground motions and it also offers a means of energy dissipation which decreases the propagated acceleration to the superstructure. The Base Isolation protects the structure and its non-structural elements against seismic damage in this way. (Solita donami and Dr. Ajay Sharma, 2016)

Only the horizontal components of ground shaking are isolated by traditional elastomeric and lead-rubber seismic isolation bearings. Lead-rubber bearings are similar to elastomeric bearings in that the vertical stiffness is generally thousands of times greater than the horizontal stiffness.

On the other hand, sliding bearings have far higher vertical rigidity than elastomeric bearings. Additionally, heating has an impact on the typical strength of friction pendulum bearings. In general, previous attempts to establish three-dimensional isolation have not resulted in a system that is workable and economical. Tensegrity structures are made up of axially loaded components, typically cables and bars, and have distinct geometrical forms that are self-stressed. They are thus mechanically and materially effective structures. Depending on the imposed prestress, the system's shape, and the size of the external load, the elastic response of the investigated structure may change from stiffening to softening.

A tensegrity system is a strong link between two axially loaded elements. A Class K tensegrity structure has at

most  $k$  compressive components attached to each node. (Skelton, n.d) The state of a continuous network of members in tension has been preserved implicitly.

It is currently evident that there are cable-bar cells with a discontinuous network of cables among the tensegrity systems. A self-stress state of balance can be created inside the tensegrity elementary cell by inserting a different set of connections. The author of the current solution proposed assuming a new Class (Theta) of tensegrity systems in this regard.

The current answer deals with an isolator that has a Class  $\theta = 1$  triangular tensegrity prism form. Only one compressive member is connected to each node if  $\theta = 1$ . The static indeterminacy of Class = 1 tensegrity prisms is one, and the kinematic indeterminacy is ten. In general, they can be efficiently stabilized by applying pre-tensioning forces. Following the initial load efforts of the mechanical models, it is evident that a good theoretical form of the single isolator will be a super-stable and soft configuration, i.e. without self-stress. The prismatic isolator's triangular bases allow for large relative mobility in both plane and rotary directions. (Rzeszów, 2019)

To meet the requirements of the current seismic design criteria, infrastructure and buildings must be sufficiently protected against earthquake excitations at the design level while minimizing serious damage. This study investigates the computational modeling of an energy-dissipating brace that prevents inter-story drifts and is based on tensegrity. The suggested brace combines Shape-Memory Alloy (SMA) cables or tendons with a rhombus-shaped D-bar tensegrity structure. Even after repeated mechanical cycles requiring stresses of up to 6%–8%, these tendons develop austenitic-martensitic austenitic (solid to solid) transitions, making them more vulnerable to mechanical stress when accepting strain and magnifying the stress into broad superelastic hysteresis. Additionally, this page discusses the 2D and 3D braces, two unique types of tensegrities. Due to their increased ability for energy dissipation and increased safety from buckling, 3D braces have been shown to be more effective. The intended bracing effectiveness opens the door for the creation of ground-breaking seismic energy dissipation devices that use tensegrity principles and superelasticity. (N.Singh, *et al.*,2020)

### Anti-Earthquake Furniture

The Great Hanshin-Awaji Earthquake of 1995 resulted in many injuries to persons inside buildings, even though the buildings themselves did not receive significant damage. This tumbling of furniture was the cause of over 50% of the injuries sustained indoors. Direct human injury is likely to occur during an earthquake with long-period ground motion, especially in high-rise structures. To decrease the number of victims inside, it is crucial to understand how furniture moves during seismic excitations. E-Defense of the National Research Institute for Earth Science and Disaster Resilience (NIED) has been confirming the movement and destruction of non-structural elements

such as furniture, exterior walls, ceilings, and glass under these circumstances. (Isobe, 2018)

Furniture that is not correctly fastened, particularly on the higher floors of tall structures that are subject to prolonged ground motion, can be fatal to people. Furniture that has fallen, like chairs and desks, could constitute lethal obstructions that obstruct effective evacuation. An efficient numerical code was created in this study to analyze how furniture moved while it was subjected to seismic excitations. The numerical code is based on the Gauss technique of adaptively shifted integration, a finite element scheme that offers more computational efficiency than the standard code. By using a sophisticated penalty technique, the frictional contact between the items was fully taken into account. On a shake table, several furniture excitation tests were run. In the trials, seismic waves were used to stimulate steel cabinets, and a device was used to record displacement data. (Isobe, 2018)

As stated in the study conducted by Felin (2022). The Lifeshell premise can provide a safe refuge during an earthquake in an efficient, cost-effective, and quickly deployable natural-based manner. Despite the fact that its features have been successfully demonstrated with a shock absorption test, the researchers do not suggest this technology as a substitute for proper anti-seismic building technology. Whenever the socioeconomic context prevents the effective application of anti-seismic building engineering standards, this technology should be used temporarily. (Fellin, 2022)

Furthermore, non-structural elements can be hazardous to people during seismic events. Building elements such as glazing or suspended ceilings shattering or collapsing, or building contents being flung around, cause injuries. Filing cabinets and equipment collapse, hazardous material containers burst open, and gas from ruptured pipes ignites. Damage scenarios differ from one building to the next and from one room to the next. (Hussain, 2017)

The purpose of the research was to critically analyze the state of the art of life-saving furnishing projects in the event of an earthquake, for already developed public and private contexts, whether they are commercialized products, patents, prototypes, or concepts, in order to bring out the design aspects deemed most relevant to implementing the life-saving performance in the event of an earthquake, as well as to highlight any latent needs not defined previously. Therefore, strengthening our claim that furniture can indeed survive an earthquake and in some cases save lives. (Galoppo, 2019)

Cabinet doors frequently swing open during earthquakes, spilling everything inside, making a huge mess in the best case and causing major harm or injury in the worst. Well, I suppose a new innovative creation (or, if the earthquake coincides with an electrical storm, perhaps a new life form) could result from it, but it's generally a good situation to avoid. Take into account not only the breakable dishes and glasses in those cabinets, but also the numerous oils, vinegars, liqueurs, condiments, and

jars-of-that that could fall out and smash onto the floor. It's a good idea to install earthquake-resistant cabinet latches, especially in a kitchen's high cabinets.

Numerous products advertise themselves as being earthquake-resistant latches. Push latches (also known as touch locks) are something I've long advocated for and have implemented in numerous flats and condos over the past 25 years or so. These are the latches that keep the cabinet doors from opening until the door is first pushed in to disengage them; the door is then pushed in again to close; and then the latches re-engage. In 2012, I posted a lengthy piece that was briefly the most popular post on this blog on installing these latches. The issue of whether an earthquake could shake the door just enough to cause it to bounce inward and open has been brought up on occasion. (Springer, 2018)

### Tensile Integrity

Tensile integrity also known as tensegrity is a system of a stable network that is a compression of bass and struts and has tension on strings or cables. The system's most foundational property is that it has one-dimensional elements of the structure that are axially loaded. Since bars are recognized as the strongest at withstanding tension, structures can be constructed together with load paths to make the most of each structural path. There is a study as well where Wang *et al.* provided a framework studies and minimal mass active tensegrity structures. A structure member's uncertainty is only across its length due to the absence of material bending in the member that gives a more accurate model. By the tuning of the lengths of the strings, the shape of the structure can be easily changed, and as the strings are prestressed, the inclemency of the structure can be properly tuned. This study of Shuo Ma *et al.* (2022) has confined dynamics developed from a system-level that is required for the field of structural control so as to get insight into the nonlinear tensegrity dynamics. It organized how the bar and string coordinated and connected with notations in the physical properties of the tensegrity system with the compact of vector forms. How the shape will function with the element was also formulated. And, with the use of the Lagrangian method, the tensegrity dynamics were derived with or without constraints. (Shuo Ma *et al.* 2020) Goyal *et al.* (2019) say in their study that tensegrity structures can also be prestressed to have unidirectional loading for all individual members, allowing tension and compression members to be designed independently. Tensegrity structures can also benefit from this freedom because they have a high strength-to-mass ratio. There is also a particular tensegrity structure topology that can provide a variety of self-equilibrium solutions corresponding to different prestresses values in the structure. The different stable prestress values provide a domain set for minimizing the structure's mass. It has been proven that tensegrity is to be an optimal mass solution for various loading conditions as a result of this minimization. To categorize the whole analysis of

a tensegrity structure, Modeling of Tensegrity Structures (MOTES) was used and has two categories for this. The first one is the static analysis that determines the tensegrity's minimal mass optimizing the tensile and compressive forces in the structure's bars and strings when certain external forces are present and when no external forces are present. Second, using a second-order matrix differential equation, the dynamic analysis simulates the dynamics of any tensegrity structure complexity (Goyal & Skelton, 2019). This dynamic model assumes that the bars are rigid and the strings are linear elastic.

According to Palmieri *et al.* (2021)'s study, by combining an arch-supported membrane system and a diamond-type tensegrity system, it will result a tensile-integrity system that is a nature of cables and membrane in addition to the arches' so-called "floating-bending." It was observed that in addition to compression and bending, the arches also experience torsion. Although arches do not actively bend, they have a curved shape at rest and experience minor deformations at the prestressed equilibrium state. In the initial attempt to merge these two structures, the traditional triangular tensegrity prism, or T3, was said to be "patched" with three arch-supported membranes. This demonstrated the transformation process and the finished system that consists of three arches suspended against one another by membranes and cables to create a free-standing structure. In comparison to typical tensegrity systems, especially those with few struts, they can be generated from traditional diamond-type tensegrity systems and used as deployable or transformable structures enclosing a wider space. In this study, the first process serves as a first step to demonstrate the viability of the floating-bending concept, while the second procedure offers a strong tool for constructing a floating-bending structure in an interesting practical case.

A study was made by Singh *et al.* (2020) wherein buildings and infrastructures must provide sufficient protection for site condition earthquake excitations with limited levels of damage to optimize the seismic performance prescribed by modern structural codes. The study discusses the computational modeling of a bracing system with tensegrity architecture that acts as a compact mechanical amplifier of longitudinal displacements in the transverse direction, trying to limit interstory drifts while dissipating energy. A rhomboidal shape comprising Shape-Memory Alloy (SMA) tendons together with D-bar tensegrity structure, the brace was proposed. To account for re-centering capabilities, SMA components within bracing systems have been extensively studied. Moreover, the objective of the study is to create a seismic bracing system with tensegrity architecture that can be used as a passive energy dissipation (PED) device by merging noticeable displacement amplification qualities with the superelastic response of SMA tendons. This structure incorporates a distinctive strategy, and a system with D-Bars has been formed, displaying the Scissor-Jack damper device equipped with SMA tendons. This design allows us to operate in a way that enables the element to

be stretched while trying to move vertically.

A study conducted by Fernandez-Ruiz *et al.* (2022) that the Octahedron family's topology is displayed in tensegrity structures. Based on their topology, new tensegrity structures that fit into this family are identified. The procedure for determining a self-equilibrated configuration (also known as the form-finding process) is critical in the design of tensegrity structures. Tibert and Pellegrino conducted a review of tensegrity form-finding methods. In a recent paper, the authors proposed an analytical form-finding method for tensegrity structures based on the FDM (Force Density Method). This method entails locating a set of force:length ratios in a symbolic space. The analysis results in a tensegrity structure with an equilibrium shape. The DR (Dynamic Relaxation) method is said to be based on a pseudo-dynamic process that considers tensegrity structures to be a collection of nodal masses and damping elements. Another critical aspect in the design of tensegrity structures is stability. Superstability is a stability criterion for tensegrity structures with which, regardless of the level of self-stress, the tensegrity is always stable and material properties are taken into account. Geometric intuition or topology can be used to build tensegrity structures. The Octahedron family is made up of three octahedrons: the expanded octahedron, the double-expanded octahedron, and the triple-expanded octahedron. The connection presented by Fernandez-Ruiz *et al.* for the Octahedron family can only be used to define the first three members of the family. This work defines the topology of the family by studying the folding process from one member to the next.

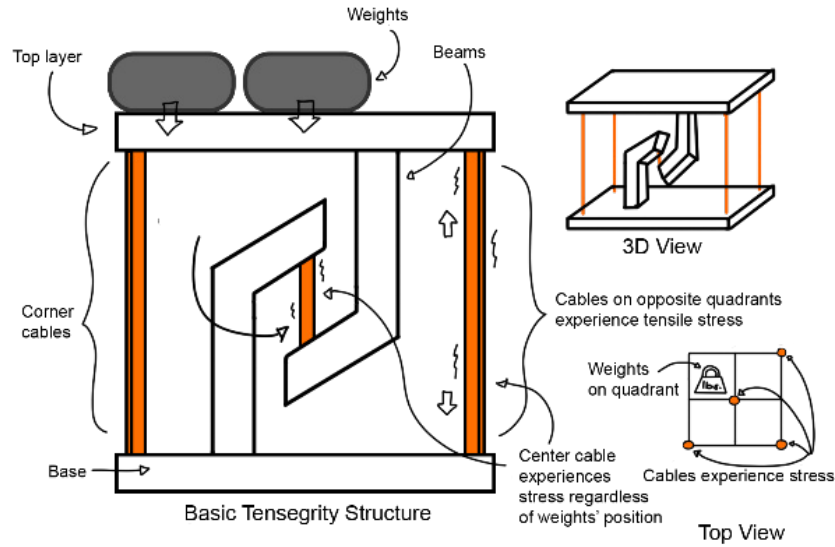
## METHODOLOGY

The researchers made use of the true experimental research design, which gave them access to the scientific method in making the designs for the furniture. The experimental approach allowed the researchers to reach the most optimal procedures and troubleshoot any procedures that did not work. According to Bevans (2022), the experimental design makes use of systematic procedures in testing the hypothesis of a study through the manipulation of the variables present.

As for the procedures of the project, the researchers conducted the experiment in four (4) phases. The phases are denoted as the research phase, the design phase, the experiment phase, and the evaluation phase.

The research phase mainly consisted of figuring out the basics of tensegrity, and how the tension holds up the structures. After observation of existing models and the structures that exhibit this principle, the researchers were able to make a figure showing how it works.

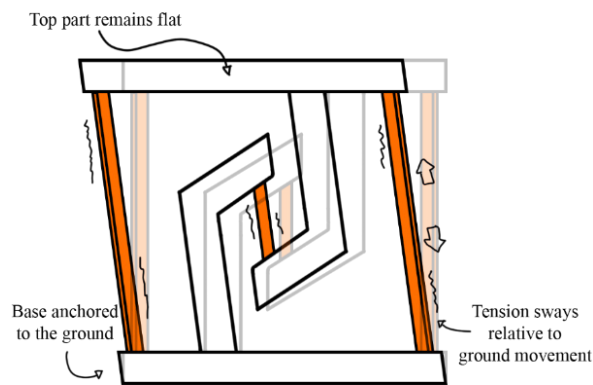
The observations of existing tensegrity builds led the researchers to figure out the main components of a basic tensegrity structure and how they behave together. The structure has layers that include the base and the top layer. Beams are attached to the layers and cables connect them all to make the structure. The central cable serves as the cable that carries the weight of the table whilst the corner cables'



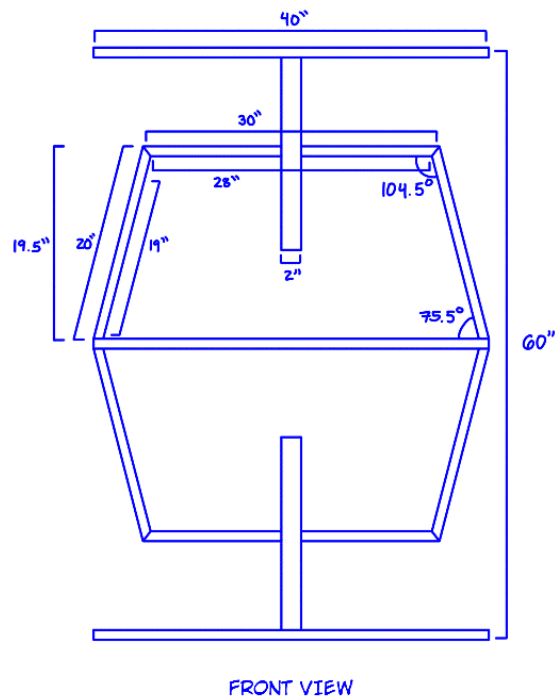
**Figure 1:** Basic Tensegrity Concept

main purpose is to balance the structure and keep it upright. The observations showed that only the tension holds up the weight of the platform and the weights on top, meaning that the initial tension that is present on the ropes must not be too high when constructing the design, to give enough room for more tensile stress that would be applied to the cables when more weight is exerted. The application of force in weight on the structure was also observed to be different from how it is with traditional furniture. Due to the fact that the cables on the four corners are meant to keep the structure balanced, any added weight on one corner of the structure will translate to the middle cable and the three cables outside its quadrant experiencing tensile stress. Researching for the designs also involved observing how tensegrity structures behave in the presence of ground shaking. The researchers were able to make a figure showing how the furniture would act in the presence of ground shaking. As opposed to traditional furniture with a solid foundation that has the chance to topple over or collapse during an earthquake, tensegrity structures have bases anchored to the ground, making it so that the cables hold up the structure, causing it not to topple over during earthquakes, but instead making the top layers move

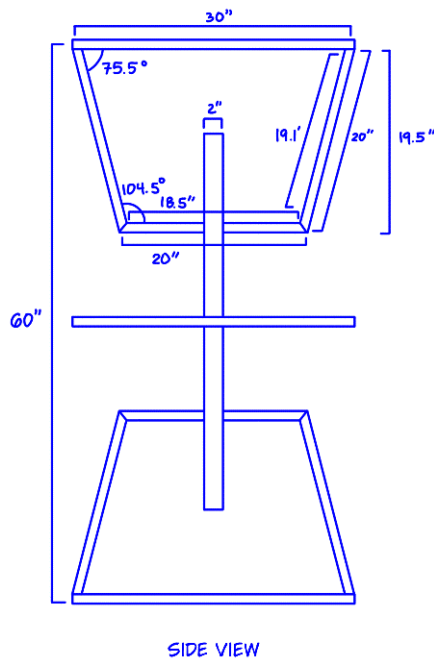
horizontally instead. After understanding the concepts behind structures with tensegrity, the researchers moved on to the design phase in which the researchers made improvements upon the basic tensegrity structure. The factors that needed to be kept in mind concerning the research questions were the dimensions of the structure, the cables to be used, and its earthquake-resistance factor. The longevity had to be considered through the correct amount of tension it initially had. The movements could make it sway too much to the point of it collapsing. This meant that the cables had to not be too loose to add stability to the structures. However, when considering the tensile strength, it also cannot be too tight. The weight that would be placed on top of the structure directly translates to more tension that is needed to keep it



**Figure 2:** Tensegrity in the Presence of Ground Movement



**Figure 3:** Front View of Base Components



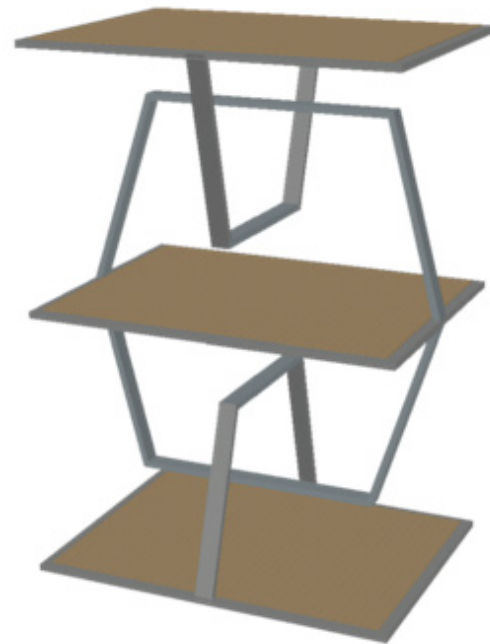
**Figure 4:** Side View of Base Components

standing. Having too much tension initially could make the cables rupture once weight has been added to the system. Due to this, the researchers had to find a middle ground for the initial tension so that it may have room for extra tensile stress, but also so it does not sway too much when there would be ground movement. This was done by using a turnbuckle for each corner cable to not only have adjustable tension but to also make the surface of the layers flat and not tilted.

Designing the structure also involved conceptualizing the dimensions. To mitigate the movement involved during ground shaking, the shapes of the base needed to be as equilateral as possible, meaning they needed to have almost equal dimensions for their bases. Having one side longer than the other meant that it would sway more in one axis, potentially causing it to fall over or have the tension rupture.

After figuring out the factors to be kept in mind, the type of furniture also had to be considered. Tensegrity tables were the basis of the study and were easy to design. However, existing tensegrity structures could be made into tables or chairs easily. The researchers therefore focused on shelves as the furniture to be designed.

During the design process, the researchers came up with the design of a three-layered tensegrity shelf with the layer's dimensions having a 4×3 ratio. The exact dimensions of the base and the other layers are 40"×30"×1", with the structure being 60" tall. The base of the structure was made of plywood with steel framing. The design process ended with the researchers picking the best suited material to be used for the cables. The two factors that the researchers kept in mind when choosing the cables were the cables' tensile strength and accessibility. The researchers ended up choosing three possible cables that are most suitable for the project: nylon rope,



**Figure 5:** 3D Render of Structure Base

galvanized iron wire, and low-carbon steel chains. In the end, the researchers used 3/16" low-carbon steel chains for their affordability and good working load limits of 800 lbs. The working load limit of a system is how much weight can be exerted without the risk of it failing. This is determined by getting 1/3 of the product's breaking strength (Halvorsen, 2021).

After figuring out the design, the researchers moved on to the experiment phase. The structure had to be tested for its earthquake endurance, or its ability to remain intact during an earthquake. This meant that the structure had to endure high-intensity earthquakes, intensity levels that would cause traditional furniture to be displaced and collapse.

#### Research Locale

The data collection of the research took place in the office of the Philippine Institute of Volcanology and Seismology (PHIVOLCS) located at Diliman, Quezon City (11.8 km from Manila). The researchers made use of the institute's earthquake simulation device to gather data.

#### Statistical Treatment

Testing the earthquake endurance of the structure involved testing how well it endures higher intensity levels of earthquakes compared to regular household furniture. For reference, the Modified Mercalli Intensity Scale (MMI) was used, which states that heavy furniture tends to be shifted during an intensity 6 earthquake, and collapse or overturn during an intensity 7 earthquake (Wood & Neumann, 1931).

The researchers used the earthquake simulator in testing the structure to have the earthquake intensities be scaled accurately. The earthquake simulator could only go to an intensity level of 8.4, which was already above the limit that the structure had to reach.

In gathering the data, the simulated earthquake intensity was gradually increased until the structure started moving dramatically. The researchers conducted three (3) identical tests on the structure to get the mean score and standard deviation of the earthquake intensity levels endured by the structure.

The data gathered was then tested using a one-sample t-test due to the existing hypothesized value of intensity 7.0. One-sample t-tests are used when a calculated mean from gathered data is compared to a standard value (Bevans, 2020). The t-test used was right-tailed, as the researchers were trying to prove that the structure is significantly more earthquake-resistant than traditional furniture. The data was used to get a calculated t-value using the formula below:

$$t = (\bar{x} - \mu) / (s / \sqrt{n})$$

t – Calculated t value

μ – Hypothesized mean (7)

$\bar{x}$  – Sample mean

s – Sample standard deviation

n – Amount of Observations

Equation 1 - One Sample t-calculated Value Formula

After getting the calculated t-value, it needed to be compared to the sample's critical t-value. The critical t-value is found in the one-tailed P-table by getting the degree of freedom of a population, which is achieved by subtracting 1 from the number of observations, with consideration of the alpha level, 5% or 0.05.

If t-calc = t-crit, then reject  $H_0$

If t-calc > t-crit, then accept  $H_1$

During the design process, the researchers came up with three (3) setups to possibly further increase the structure's earthquake-resistance. Setup 1 was by replacing the center cable with a tensioner spring to enable the layers to oscillate more freely. Setup 2 was adding 50 kg of weight

to the base or the bottom layer to lower the structure's center of gravity, causing less movement of the base. Setup 4 was combining the two previous setups. The default setup was denoted as 'Setup 1'.

T-tests were also used in comparing the means of the endured intensity of the three setups with the default setup to see if they are significantly more earthquake-resistant. However, instead one-sample t-tests, independent sampling t-tests were used to get the calculated t-values (Bevans, 2022). The calculated t-value needed to be great than a critical t-value to prove that the setup is effective.

$$t = (\bar{x}_1 - \bar{x}_2) / \sqrt{((s_1^2)/n_1 + (s_2^2)/n_2)}$$

Equation 2 - Independent Sampling t-calculated Value Formula

## RESULTS

The section shows the results of the earthquake simulation testing done with the different setups. Each setup was tested three (3) times and their mean scores and variances were given the statistical treatment for the study.

### Setup 1 Earthquake Intensity Testing

**t-calc > t-crit → Reject  $H_0$**

Table 1 deals with earthquake intensity level that the structure endured for three tests to get the mean and comparing it to the intensity level 7 from the Modified Mercalli Scale using t tests to see test if tensegrity-integrated furniture are more earthquake-resistant than regular furniture. The calculated t-value of 35.317 is greater than the critical t-value of 2.56. This makes it fall under the rejection region, meaning that the researchers must reject the null hypothesis and accept the alternative hypothesis. With this, the researchers conclude that tensegrity-integrated furniture are significantly more earthquake-resistant than regular household furniture.

**Table 1:** T-Test (Setup 1)

	Mean	St.Dev	T-Calc	T-Crit	df	P-Value
Setup 1	7.97	0.047	35.518	2.920	2	0.0005935
Traditional Furniture	7					

### Setup 2 Earthquake Intensity Testing

**t-calc < t-crit → Fail to Reject  $H_0$**

Table 2 deals with the means of the earthquake intensity levels endured by the structure before (Setup 1) and after (Setup 2) replacing the center cables with tensioner springs and comparing them to see if it significantly increases the earthquake-resistance of the structure. The

results came back with the calculated t-value of -3.4631 which is less than the critical value of 2.132, meaning that the researchers failed to reject the null hypothesis. The researchers therefore conclude that there is no significant difference in the earthquake resistance of the structure with the center cable being replaced with tensioner springs.

**Table 2:** T-Test (Setup 2 & Setup 1)

	Mean	St.Dev	T-Calc	T-Crit	df	P-Value
Setup 2	7.8333	0.0471	-3.464	2.132	4	0.0285955
Setup 1	7.9667	0.0471				

### Setup 3 Earthquake Intensity Testing

**t-calc > t-crit → Reject  $H_0$**

Table 3 deals with the means of the earthquake intensity

levels endured by the structure before (Setup 1) and after (Setup 3) adding weights to the structure's base and comparing them to see if it significantly increases

**Table 3:** T-Test (Setup 3 & Setup 1)

	Mean	St.Dev	T-Calc	T-Crit	df	P-Value
Setup 3	8.4000	0.0000	15.9217	2.132	4	0.0029326
Setup 1	7.9667	0.0471				

the earthquake-resistance of the structure. The results came back with the calculated t-value of 15.9216 which is greater than the critical value of 2.132, meaning that the researchers must reject the null hypothesis. The researchers, therefore, conclude that adding weights to the base of the structure makes it more earthquake-resistant.

**Setup 4 Earthquake Intensity Testing**

**t-calc > t-crit → Reject H<sub>0</sub>**

Table 4 deals with the means of the earthquake intensity levels endured by the structure before (Setup 1) and

after (Setup 4) doing both measures of replacing the center cable with a tensioner spring and adding weights to the base, and comparing them to see if the two setups combined significantly increases the earthquake-resistance of the structure. The results came back with the calculated t-value of 3.8971 which is greater than the critical value of 2.132, meaning that the researchers must reject the null hypothesis. The researchers therefore conclude that doing both measures of replacing the center cable with tensioner springs and adding weights to the bottom, but not to the same extent as having only the weights added.

**Table 4:** T-Test (Setup 4 & Setup 1)

	Mean	St.Dev	T-Calc	T-Crit	df	P-Value
Setup 4	8.2667	0.1247	3.8971	2.132	4	0.0608450
Setup 1	7.9667	0.0471				

**DISCUSSIONS**

The results of the study showed the effectiveness of tensegrity-integrated furniture as the prototype survived the high-intensity earthquake simulations. However, some may question if its earthquake-resistance can result in the mitigation of earthquake damage in households.

In the event of an earthquake, it is common occurrence for heavy furniture like shelves to collapse on people, potentially leading to loss of lives. With tensegrity-integrated furniture, the risk of the structure toppling over and causing harm is shown to be lower due to the way they behave during earthquakes. And in higher intensity levels where they do collapse, the absence of a solid foundation makes it so that they would not cause severe injuries due to them being lighter in weight. This type of furniture has also extra shown useful features during the simulations. One of them is the fact that the structure oscillates even in weaker intensity levels. This could be useful in scenarios where the occupants of a household see the furniture’s movement, indicating that an earthquake is occurring at that moment. A potential weakness of this system is the chance of the cables rupturing, which is why the researchers chose the most cost-effective cables that are available, which are chains. During the testing, there were no instances of the cables snapping because of the sudden ground movement. The only way that the structure started to fail was when the base started getting shifted. This is the reason why the researchers came up with the three setups to increase the stability of the structure. Setup 2 was shown to have no significant difference in the structure’s earthquake resistance when compared to Setup 1. In fact, this setup managed to perform slightly worse than the default setup without the tensioner springs as the center cables. The researchers initially hypothesized that

the base would move less due to the more free-moving layers. However, the tests showed that the oscillation only caused the base to move more due to the movement of the top layers, adding motion to the inertial base and causing get displaced in slightly lower intensity levels.

Further observations also revealed that this setup would not be practical since the free-moving layers may cause the inertial objects on top of the shelf to fall off quicker than they would with Setup 1 or even just traditional household furniture.

Setup 3, however, significantly increased the earthquake-resistance of the structure. The hypothesized results of the structure having less movement due to the lower center of mass and a more anchored base was observed during the simulations. This behavior can also be observed in traditional household furniture. However, doing it in tensegrity-integrated furniture is more effective due to the structure weighing less overall, thus making it easier for the center of gravity to be lowered. An alternative option exists where future designs are anchored more to the ground through different means such as being bolted or even through adhesion. Overall, Setup 3 ended up being the most optimal setup during the simulations.

Setup 4 served as the middle ground between the previous setups, having both the tensioner springs and the added weights on the base. This was reflected in the results wherein it had greater earthquake resistance than both Setup 1 and Setup 2, but not to the same extent as Setup 3. The added weights at the bottom helped stabilize it but the oscillation of the top layers caused it to move. Overall, the tensioner springs failed to replicate the measures used in seismic isolation.

More factors could be measured or tested with future research and designs of the furniture. Properly testing

factors such as tensile strength, base dimensions, additional layers, friction of the layers' surfaces, and base anchoring could be done as additional ways to make the structure more effective.

## CONCLUSIONS

To summarize, tensile integrity integrated into furniture is a modern take on earthquake safety measures, similar to existing ones like seismic isolation. And with the proper setup and more improvements, its earthquake resistance factor can save lives.

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