National Taiwan University of Science and Technology (NTUST)

Department of Civil and Construction Engineering

Structure Test

Final Project: Wooden Stick Structure

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1. Introduction

The **wooden stick structure** is a practical model for laboratory testing of building designs, analyzed under different shake levels and applied top structure loads. The primary objective is to build and design a wooden structure for a water tank that can resist loads at various shake levels. We used a diagonal bracing structure because it efficiently resists lateral loads and supports the deck weight. Additionally, it provides lateral racking strength along with the horizontal transverse.

In the Design and Construction of Structural Models for **Seismic Resistance Testing** project, each team was working with designing and building a structural model using wooden sticks and other provided materials. These models had to support mass blocks and withstand artificial earthquakes generated by a shake table in the structural laboratory.

2. Design Concept

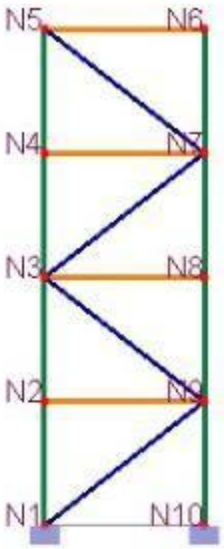

Figure 1. Original design.

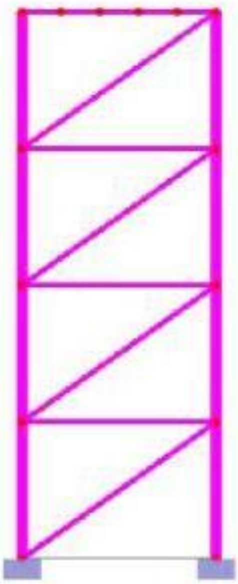

Figure 2. actual design.

The original design of the structure was like the Figure 1, because the first thought was that the structure could have better behavior with the tension and compression forces if the braces were in opposite direction on each floor. However, with more investigation and help of the Teacher Assistant, the actual design was decide as the Figure 2, using **single diagonal braces.**

- Total height of the structure = 560 mm
- Number of stories = 4
- Height of each story = 140 mm
- Dimension of each floor = 196x196 mm^2

- Number of wood stick for each column = 3
- Number of wood stick for beams and brace = 1
- Cross sectional area for each wood stick (beams and braces) = 5.5x5.5 mm^2
- Cross sectional area for the columns = 9.53x9.53 mm^2

3. Load Testing

3.1 Loading

For testing the wooden stick structure in the shake table, it is necessary to put mass at the top of the structure, as is show in the figure 3.

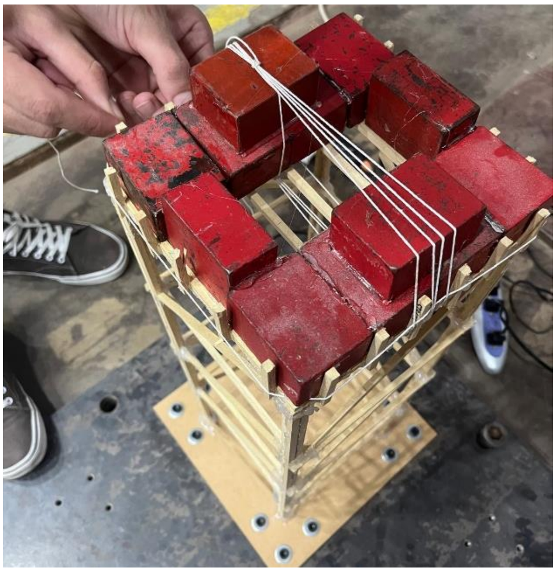

Figure 3. The 12 blocks at the top of the structure.

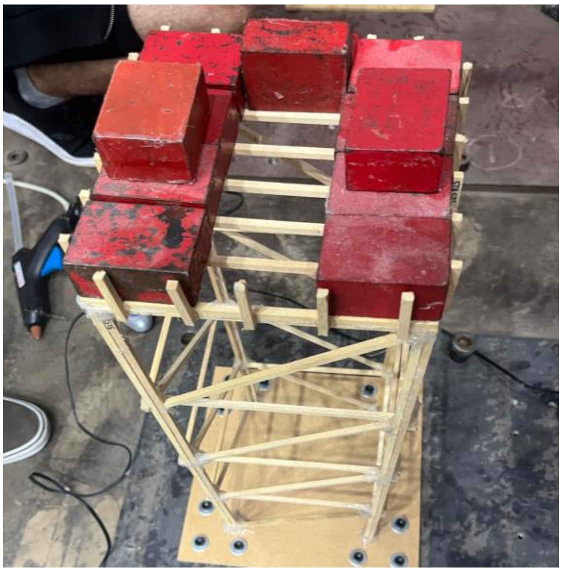

Figure 4. Placing the 12 blocks at the loading platform.

It was necessary to secure the blocks with the cotton rope because two of the blocks were higher than the small wall prepare for the blocks. Those two block were stick together with hot glue to the blocks bellow, but not the blocks to the loading platform.

3.2 Mass Distribution

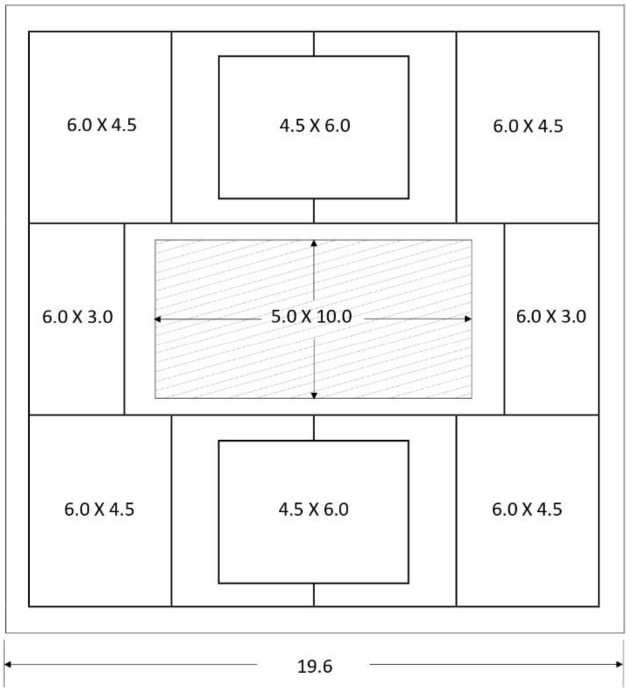

Figure 5. Mass block distribution.

One of the rules for the loading platform was remain empty a rectangle of 5 cm width and 10 cm long at the center of the loading platform, so the blocks can only be distributed around this empty rectangle.

Twelve block were distributed on the loading platform.

- Mass of each block = 635 g = 6.250×10^{-4} N-s^2/mm.
- Dimension of each block: 60 mm length, 45 mm width and 30 mm height.
- Total height of the structure= 560 mm
- Number of stories = 4
- Height of each storey= 140 mm
- Dimension of the loading platform= 196x196 mm^2
- Unit weight = 7.10×10^{-6} N/mm^3
- Number of wood stick for each column = 3
- Number of wood stick for beams and brace = 1
- Cross sectional area for each wood stick = 5.5x5.5 mm^2

Weight Calculation

Using this formula to calculate the weight of columns, beams and braces.

$$Weight = Volume\ x\ density$$

- **Column weight**

$$Wcolumn = (5.5 * 5.5 * 3 * 140) * 7.10\text{x}10 - 6 = 0.090\ \text{N}$$

- **Beam weight**

$$Wbeam = (5.5 * 5.5 * 1 * 196) * 7.10\text{x}10 - 6 = 0.0420\ \text{N}$$

- **Brace weight**

$$Wbrace = (5.5 * 5.5 * 1 * 241) * 7.10\text{x}10 - 6 = 0.05176\ \text{N}$$

Mass Calculation

To calculate the mass of the columns, beams and braces, we use this formula.

$$Mass = \frac{weight}{9810}$$

g = 9810 mm/s^2

- **Column mass**

$$Mcolumn = \frac{0.090}{9810} = 9.174\text{x}10 - 6$$

- **Beam mass**

$$Mbeam = \frac{0.0420}{9810} = 4.2813\text{x}10 - 6$$

- **Brace mass**

$$Mbrace = \frac{0.05176}{9810} = 5.276\text{x}10 - 6$$

The mass distribution is for the four (4) corners/nodes at the top floor. In addition, each node is supporting three blocks approximately based on the Figure #.

The mass distribution for the nodes are calculated with this formula.

$$Node\ 1-4 = 1\ beam + 0.5\ column + 0.5\ brace + 3\ blocks$$

$$Node\ 1-4 = 4.2813\text{x}10-6 + 0.5 * 9.174\text{x}10-6 + 0.5 * 5.276\text{x}10-6 + 3 * 6.250\text{x}10-4 = 0.001886\ (\mathrm{N}-\mathrm{s}^2)/\mathrm{mm}$$

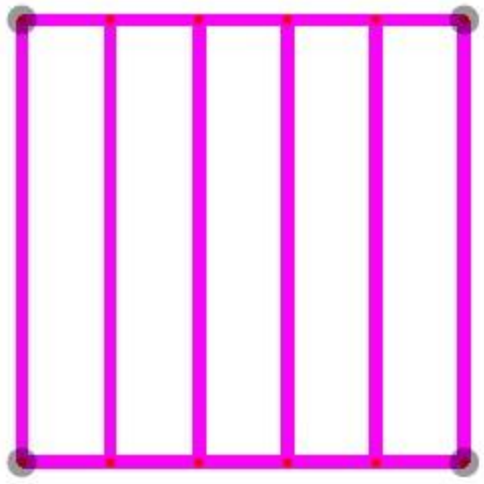

Figure 6. Top view of the loading platform.

4. Transmission of Forces

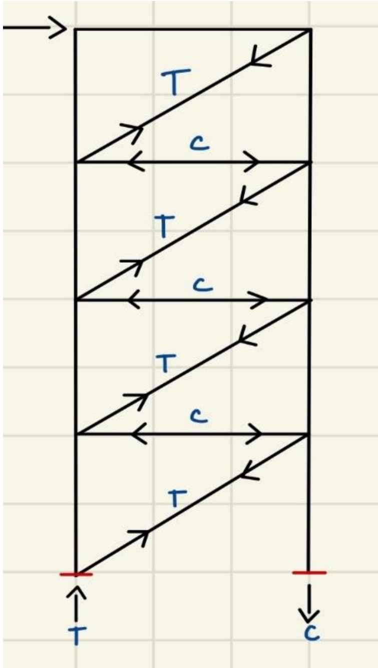

Figure 7. Single diagonal brace.

Single diagonal bracing is designed to resist both tension forces and compression forces. In this, diagonal structural members are inserted into rectangular areas of a structural frame which is good for stabilization of the frame. For fulfilling the requirement of a comparatively efficient system, bracing elements are placed at nearly 45 °. This arrangement is strong and compact.

When lateral load is applied to the braced frame, the diagonal braces are subjected to compression while the horizontal web acts as the axial tension member in order to maintain the frame structure in equilibrium. In this case, the columns on the left-hand side and the diagonals of the braced frame were in tension, while the horizontal beams and the columns on the right-hand side were in axial compression.

In analyzing all the forces working in each member, we used the assistance of SAP 2000 to assess all the **internal forces working**. The internal forces working analyzed are Axial, Shear, Moment, Torsion, and the reaction of the bottom.

Note:

Red: Indicating Compressive

Blue: Indicating Tension

Axial Force Distribution

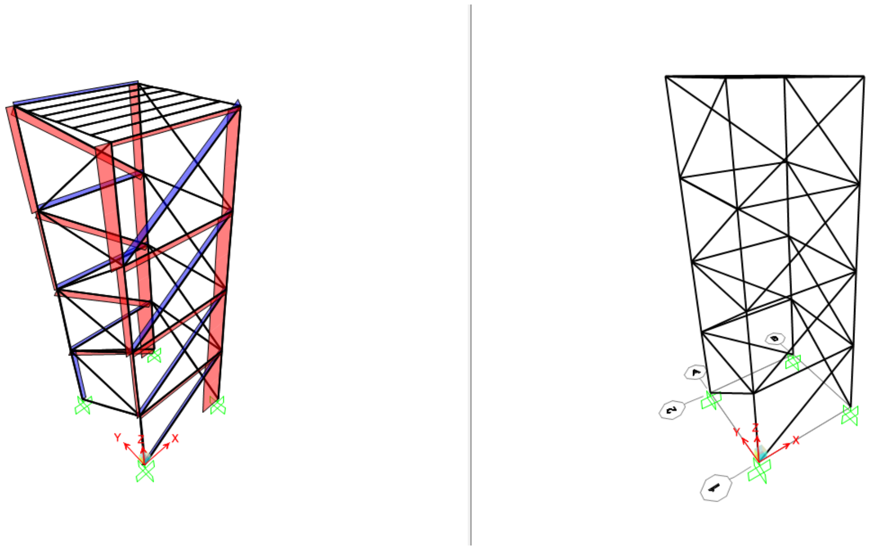

Figure 8. Axial Force Distribution

Shear Distribution

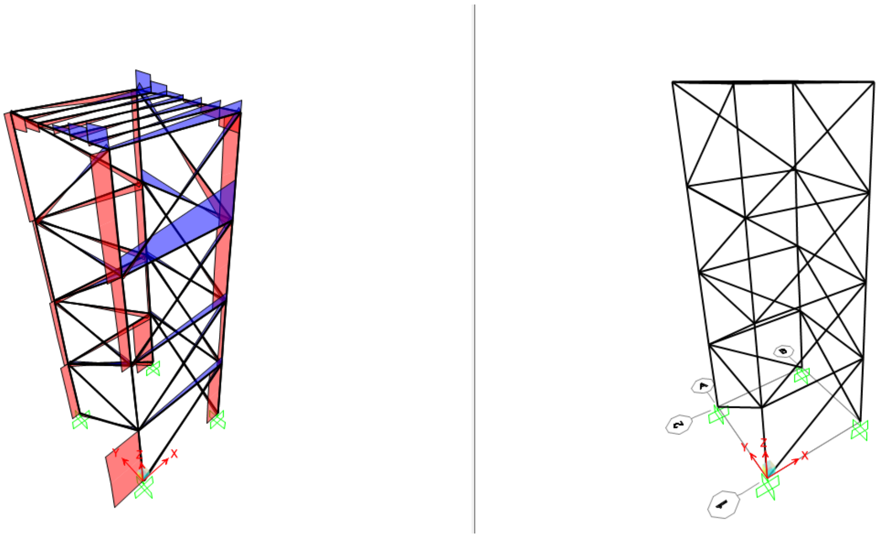

Figure 9. Shear Distribution

Moment Distribution

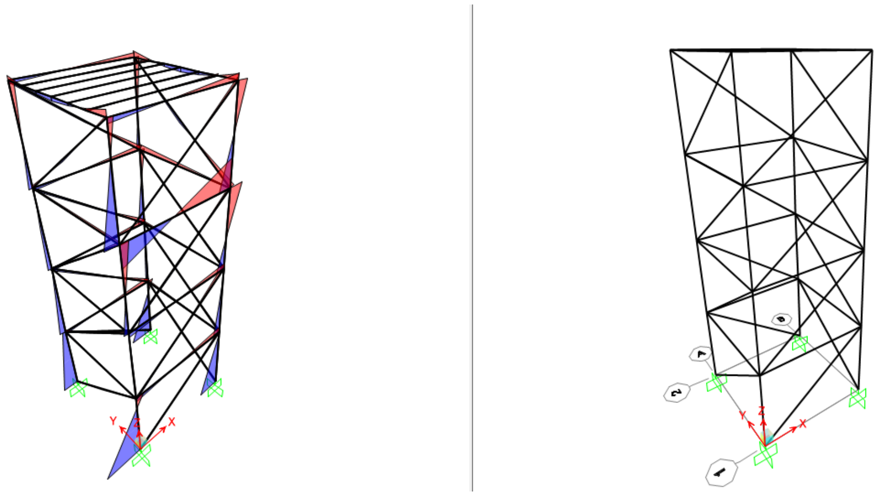

Figure 10. Moment Distribution

Torsion Distribution

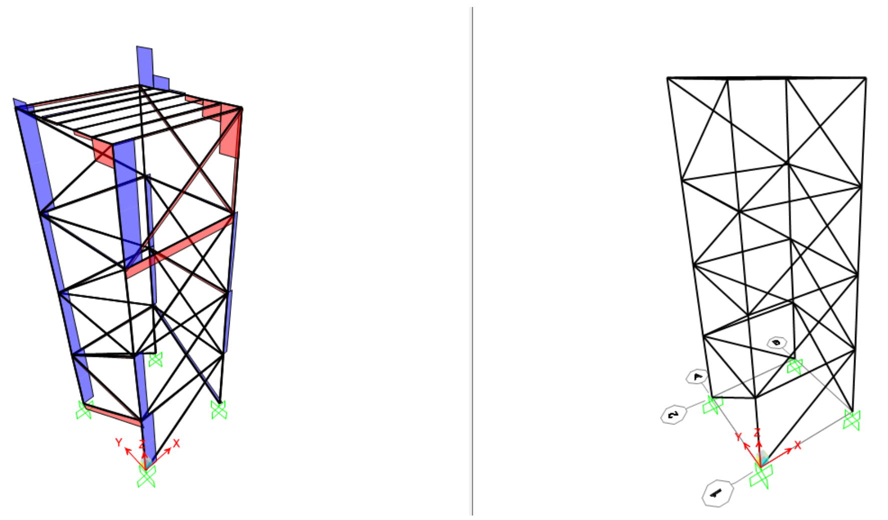

Figure 11. Torsion Distribution

Bottom Fixed Joint Reaction

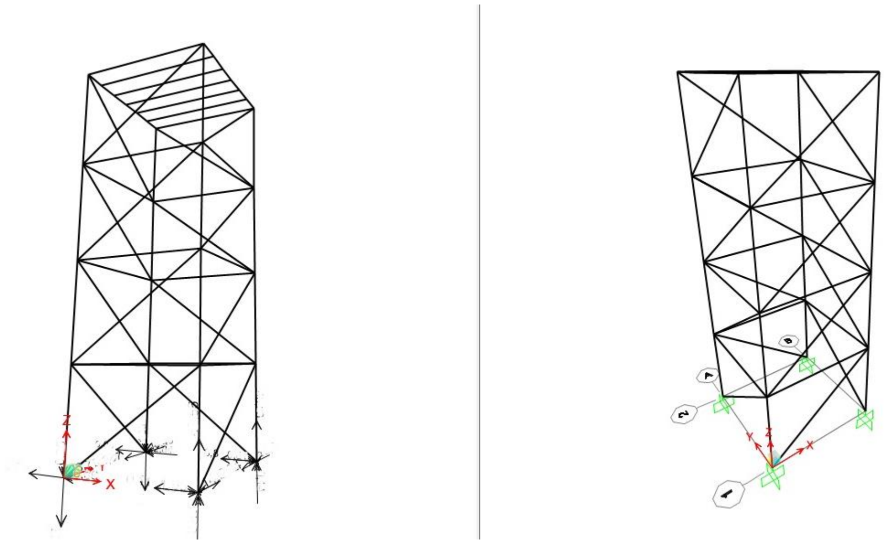

Figure 12. Bottom Fixed Joint Reaction

5. **Modal Analysis**

Once we manage to define the dimensions, we proceed to start entering the data required to start modeling.

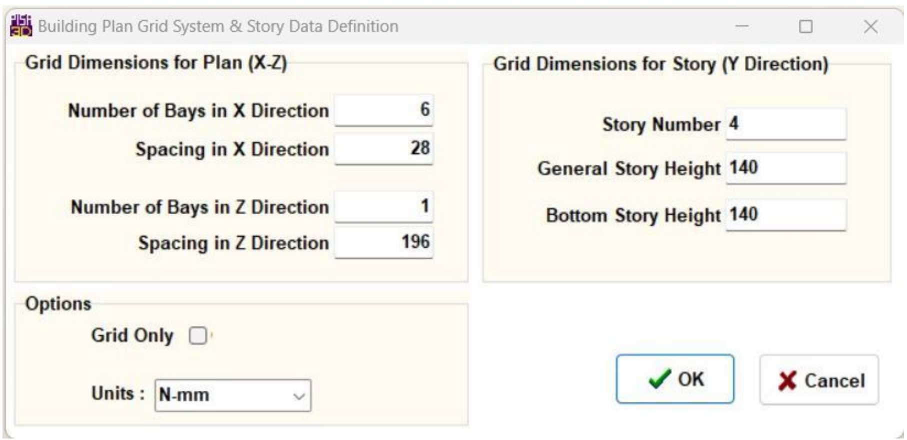

Figure 13. Direction and dimensions in PISA 3D.

Is show in the Figure 13 we enter the data in the corresponding boxes to be able to obtain the first model made at once, thanks to the fact that we have the option to deselect (grid only), this helps us so that at the end of the data entry, the columns and the beams are already made by the software.

Thanks to that data, we obtained the structure below:

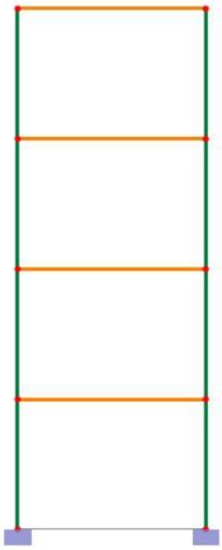

Figure 14. X-1 Direction

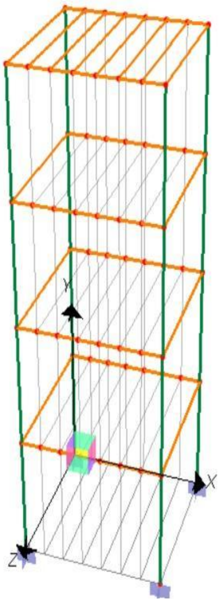

Figure 15. Structure with the dimension

We have the structure this way, as we can see, it is incomplete, so we will have to build the braces one by one.

The base of the structure has a fixed degree of freedom.

The structure rises 560 mm from the base to the roof, divided into 4 floors, each floor is separated by 140mm in height and each floor, like the base, maintains an area of 196x196mm².

Once the structure is obtained, we proceed to define the material to be used, the modulus of elasticity and the Poisson Ratio.

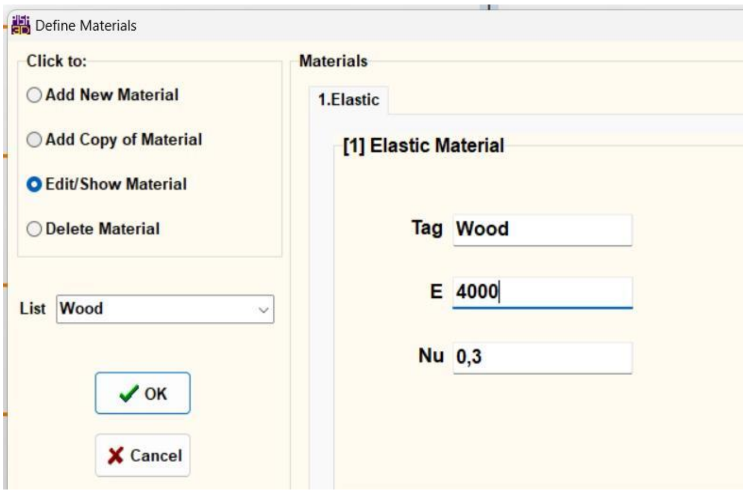

Figure 16. Elasticity modulus and Poisson ratio.

The material is wood, so it is an elastic material. Investigating we managed to find that this type of wood has a modulus of elasticity of 4000 N/mm and Poisson ratio of 0.3

By entering the values that are closest to real life, we expect results and more precise behavior of the structure.

Define Sections

After having defined the material, we proceed to define the sections, these sections area: columns, beams and braces, each with its respective dimensions. Only the columns have a larger section than the beams and braces, this being 9.53x9.53mm².

Beams and Braces have a section of 5.5x5.5 mm².

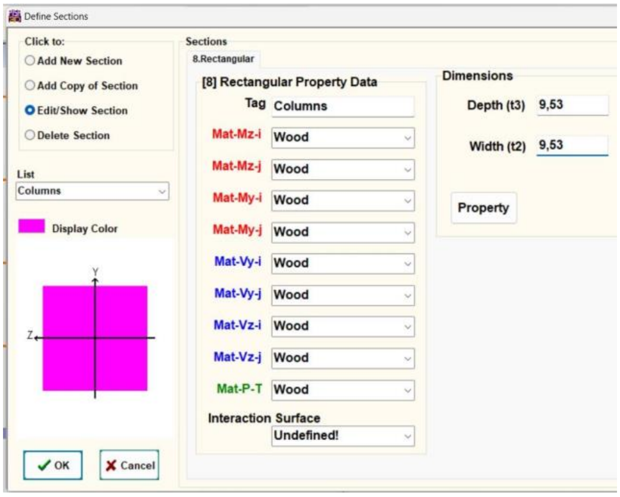

Figure 17. Adding the cross-sectional area of the columns.

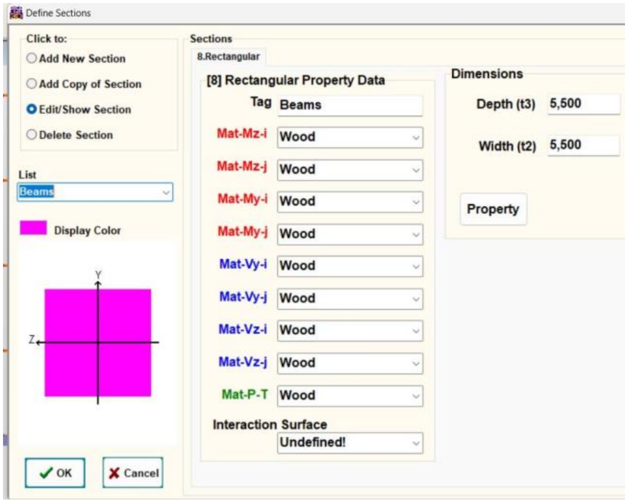

Figure 18. Adding the cross-sectional area of the beams.

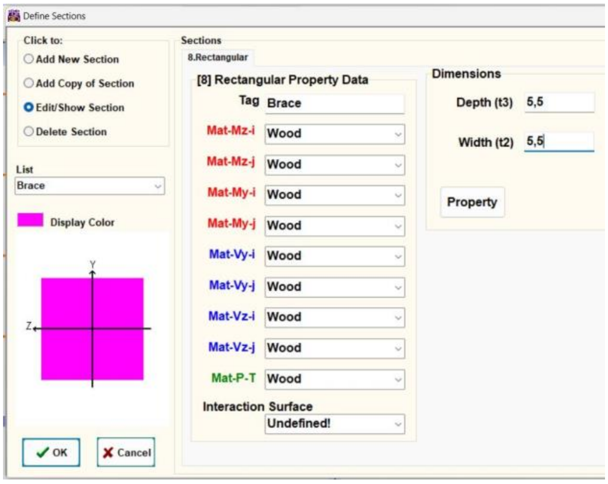

Figure 19. Adding the cross-sectional area of the brace.

The sections were applied to each element of the structure, thus obtaining the final model.

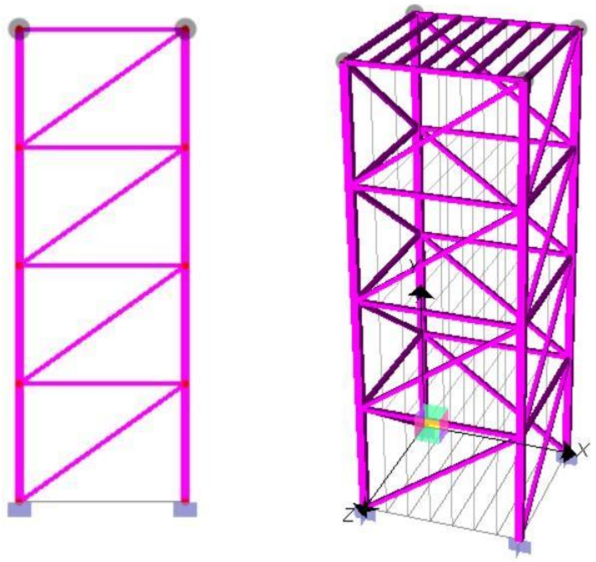

Figure 20. The structure with all the cross-sectional area.

Once the structure is finished, we can see that at the top of the structure, to 4 of the corner nodes, the previously calculated masses were applied. The nodal mass was 0.001886 N-s²/mm.

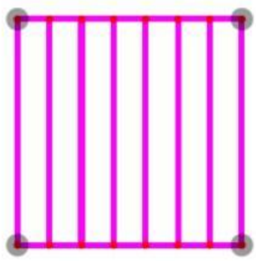

Figure 21. Top view of the top floor.

To finish configuring the behavior of the structure, we proceed to configure the Set Analysis Option.

Name: DynamicAnalysis.

- SpLength: 0.001953125
- Ana Steps: 56321
- Ground Acceleration Record: 2500 ,4000 ,5000, 6000,7000 or 8000 gal, depending on which one you want to analyze.
- XFactor: 1
- TimeFactor: 1

- MagnitudeFactor: 9810 mm/s².

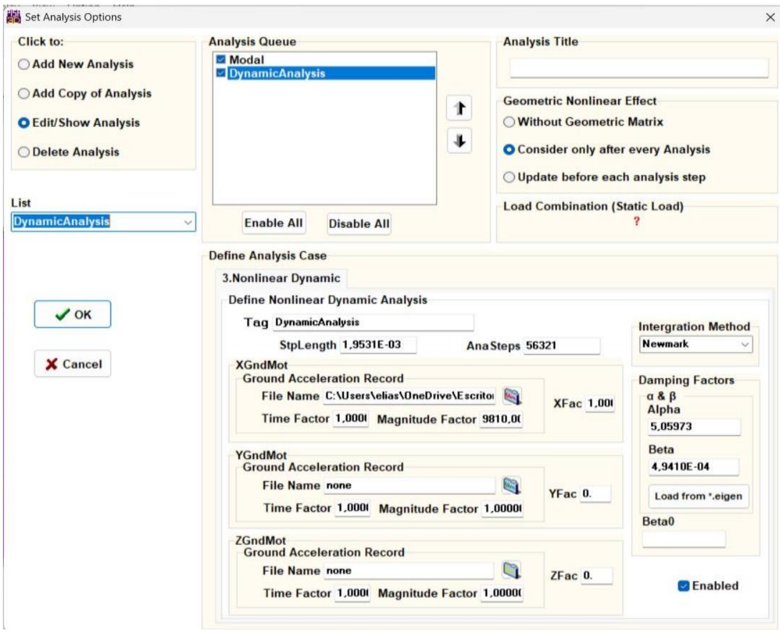

Figure 22. Dynamic Analysis

Once the model is fully configured, we can start to analyze the displacement and acceleration of a chosen node at the top of the structure. In this way, we obtained these results:

Magnitude 2500 mm/s^2

- **Displacement = 0.311 mm**

Figure 23. Displacement with earthquake 2500 mm/s^2.

- **Acceleration = 717.020 mm/s^2**

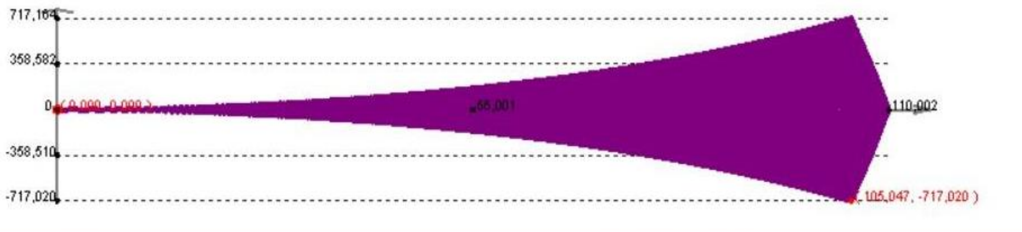

Figure 24. Acceleration with earthquake 2500 mm/s.^{2}

Magnitude 4000 mm/s^2

- **Displacement= 0.497 mm**

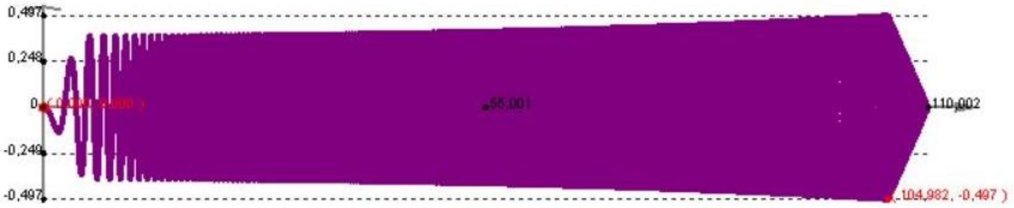

Figure 25. Displacement with earthquake of 4000 mm/s^2

- **Acceleration = 1147.323 mm/s^2**

Figure 26. Acceleration with earthquake of 4000 mm/s^2

Magnitude 5000 mm/s^2

- **Displacement = 0.622 m**

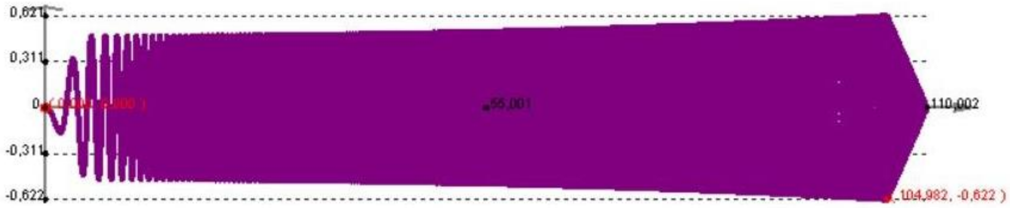

Figure 27. Displacement with earthquake of 5000 mm/s^2

- **Acceleration = 1434.322 mm/s^2**

Figure 28. Acceleration with earthquake of 5000 mm/s^2

Magnitude 6000 mm/s²

- **Displacement = 0.726 mm**

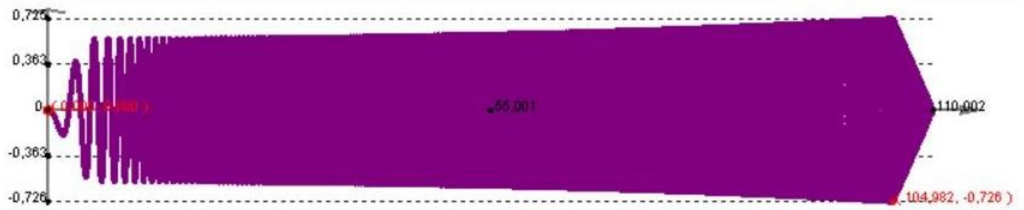

Figure 29. Displacement with earthquake of 6000 mm/s²

- **Acceleration = 1675 mm/s²**

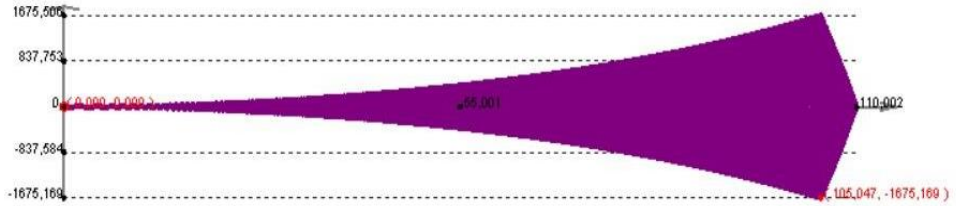

Figure 30. Acceleration with earthquake of 6000 mm/s²

Magnitude 7000 mm/s²

- **Displacement = 0.870 mm**

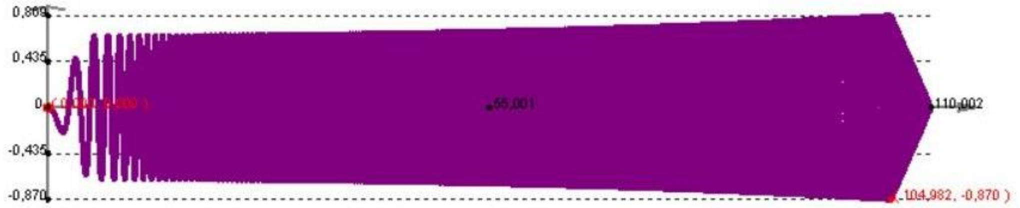

Figure 31. Displacement with earthquake of 7000 mm/s²

- **Acceleration = 2008 mm/s²**

Figure 32. Acceleration with earthquake of 7000 mm/s²

<u>Magnitude 8000 mm/s^2</u>

- **Displacement = 0.995 mm**

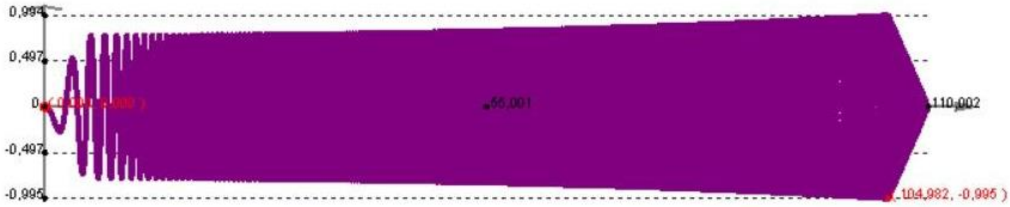

Figure 33. Displacement with earthquake of 8000 mm/s^2

- **Acceleration = 2295 mm/s^2**

Figure 34. Acceleration with earthquake of 8000 mm/s^2

Finally, we find the frequency with the given period of the software:

$$f = \frac{1}{T} = \frac{1}{0.062} = 16.13\ Hz$$

6. Construction of the structure

After modifying our initial design and deciding to put all the braces in the same direction for all the floors we started to join the columns using 3 sticks of wood with a height of 560 mm, with a cross-sectional area of 9.53x9.53 mm^2.

At the base we measured the width and length of our structure and at the corners we made the holes for the support of the base of the structure that would be semi-embedded by the base.

Figure 35. Making the holes to join the base plate with the column.

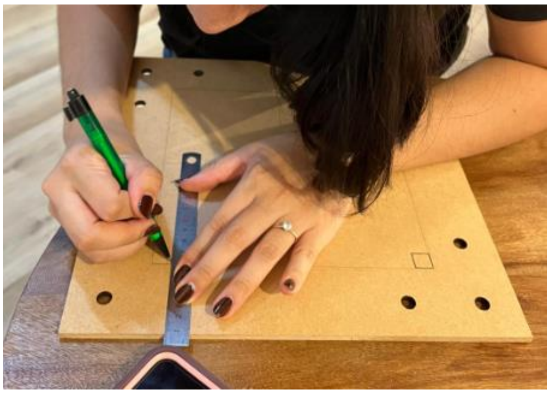

Figure 36. Measuring the dimension of the base.

Then we tested how the columns would be embedded and then we began to measure and cut the beams to join with the columns according to our measurements.

Figure 37. Cutting the beams for the structure.

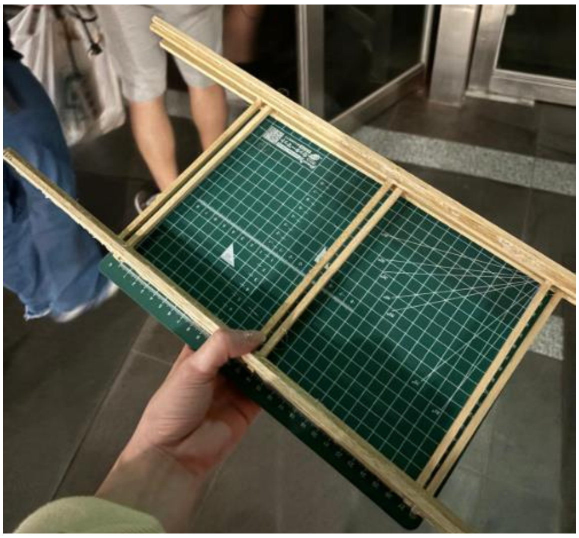

Figure 38. Creating the faces of the structure.

After adding all the side beams we start by measuring and cutting the diagonal beams and then joining with the beams and columns so that we have two superficial veneers made with beams and diagonal braces, and then we join these two veneers together using side beams.

Figure 39. Joining the braces with the beams and column.

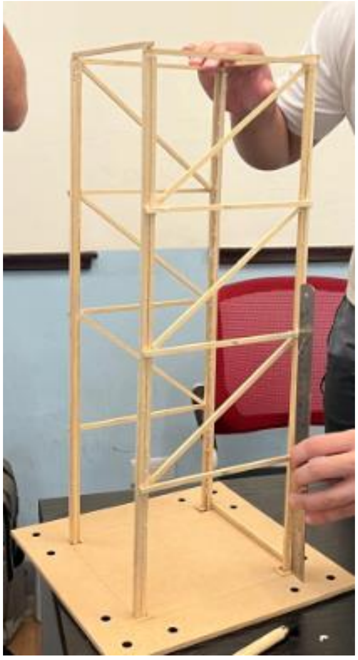

Figure 40. Trying the structure on the base before stick it together.

Then we glued all the diagonal braces of the other two side veneers. We cut, measured and glued the beams of the top of the structure and when we had the whole structure done, we joined it to the base.

Figure 41.The entire structure with lateral beams and braces.

Figure 42. The final structure on the base plate.

7. Performance in the shake table.

The performance on the shaking table was based on the following rules:

1. The PGA values are 2500 mm/s^2, 4000 mm/s^2, 5000 mm/s^2, 6000 mm/s^2, 7000 mm/s^2, and 8000 mm/s^2, starting with small earthquakes and increasing in sequence.
2. If the model passes the 4000 mm/s^2 seismic test, it meets the basic standard.

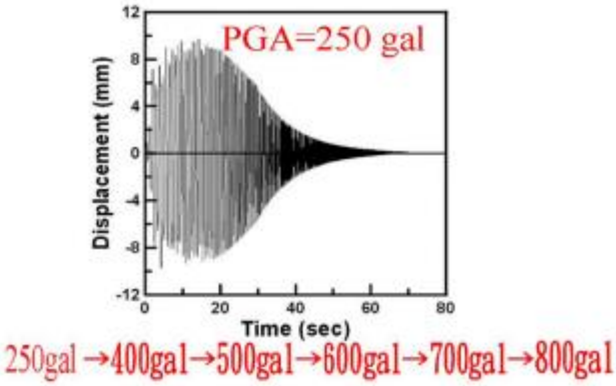

Figure 43.Example of displacement with 250 gal

Figure 44. Installing the structure on the shake table.

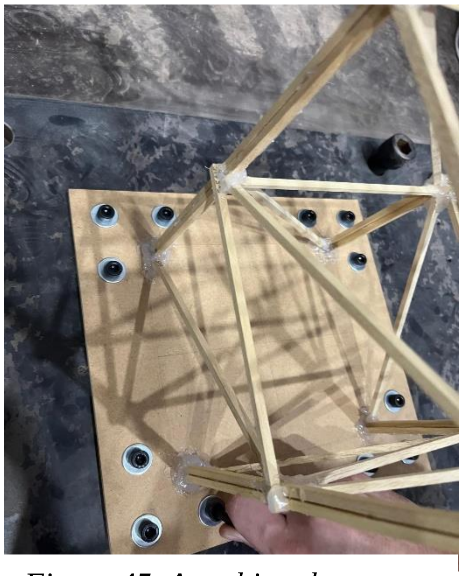

Figure 45. Attaching the screws to the shake table.

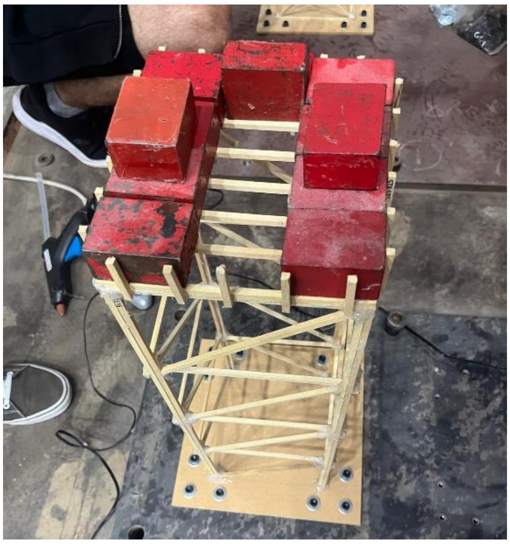

Figure 46. Place the 12 blocks on the loading platform

Figure 47. The final installation before start the first shake.

Figure 48. The four structures before start with the performance.

- **Performance of 0.25 g**

Figure 49. The structure after the earthquake of magnitude 0.25 g

The structure showed a good behavior with the earthquake of 0.25 g, but one the braces on the four floor at the back was already broken with this magnitude, either way was not affecting the equilibrium or behavior of other near elements of the structure. At the end of the shaking, the structure show a high vibration at the four floor; a high vibration in comparison with the other three structures and because of that the blocks and the loading platform were affected, showing a movement within the blocks, the little walls created for the blocks were already affected as it is possible to see in the Figure 49.

- **<u>Performance of 0.4 g and 0.5 g</u>**

Figure 50. The structure with 0.4 g of magnitude.

The structure pass the 0.4 g and 0.5 g magnitude but more vibration at the four floor and on the loading platform due the lack of glue between the blocks and the beams on the top floor.

- **<u>Performance of 0.6 g</u>**

Figure 51. The structure after 0.6 g magnitude.

The structure did not pass the magnitude of 0.6 g due the fall of the blocks, but the whole structure was in a good form even the columns and braces, except the brace that was already broken with the magnitude of 0.25 g.

After the final performance of 0.6 g the structure only show fracture on only one brace at the four floor, maybe because the compression was too much for one wood stick and also because the load of 12 blocks. A mistake during the installation of the structure on the shake table was not placing glue between the blocks and loading platform; if this mistake did not exits, the structure could support even the 0.7 g because the strong columns made of three wood stick ensure a good performance and equilibrium to the structure.

8. Conclusion

Model PISA 3D: it is possible to see in the section of **analysis**, in Figure 24, Figure 26 , Figure 28, Figure 30 Figure 32 and Figure 34 that the acceleration of the structure did not match the acceleration of the shake table; every acceleration made from the software it's around 29% less than the acceleration of the shake table, this is a good explanation of why the structure has high vibration at the end of each test, because the **structure and the shake table were shaking at different values.**

Failure mode:

Our failure on the structure was the top of the building that supports the block on the sides, we only put sticks in vertical directions surrounding the structure but we don't put enough material and also during the table shaking we don't put **enough glue for the blocks.** That causes that the blocks fall in a corner and that we **are disqualified** during the competition.

Improvements:

During the construction of the structure are some things that we could've done better, in the top of the structure we should use sticks in horizontal directions and use more layers , doing that the block will not fall. Our structure is very stiff because we use a column of 3 sticks, so one improvement will be to use less material in each column because one requirement was to use less material and resist more weight. Instead of using 3 sticks in each column we should have used the other materials that the professor gave us. For example the thread , the use of thread in the columns was going to be very beneficial for horizontal and vertical movements and also it doesn't have much weight compared with the 3 sticks that we use. The use of 2 sticks and also the thread will be a better option. Our structure resists each test of the shake table (2500 mm/s^2, 4000 mm/s^2, 5000 mm/s^2), if the blocks had not fallen at 6000 mm/s^2, we think that our structure would continue to resist the shaking and our structure would not be deformed.