



Universidad de Valladolid



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SCHOOL OF INDUSTRIAL ENGINEERING

Final project (TFG) / International semester

Conception of multifunctional joins for
configurable 3D building scale model

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Abstract

During my studies in the international semester at the University of Valladolid, I had the great opportunity to carry out a final project related to my speciality of mechanical engineering.

This project deals with a 3D building model with the ability to move in all horizontal directions, including bending in two planes and torsion.

The model simulates a multi-storey high-rise building and should serve as a teaching resource to understand the effects of bracing in tall buildings and its consequences on their dynamic behaviour.

In order for the different configurations (number of floors and bracing arrangements) to be easily reconfigured, the connecting elements (joints) between columns, slabs and bracing elements must meet some requirements.

Thus, I was in charge of the conception and prototyping of new multifunctional joints, as well as the assembly of the model in several configurations, collaborating in the modal analysis and proceeding with the numerical simulation.

Key words

Multifunctional joins - 3D building model - Prototyping - Bracings - Dynamic behaviour



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1 / Introduction and objectives

Currently in my fourth year of engineering school at Tarbes, in France, I have made my international semester at the university of Valladolid, at the industrial school of engineering. In this context, I have chosen a final project with 12 ECTS credits linked with my mechanical speciality.

The main issue of this project was the conception of new joins to improve and simplify the behaviour of the 3D building of the structural laboratory.

- One to **introduce and adjust external bracings** for all floors of the building. In this case a previous system existed but it needed improvements.
- One to **keep the column tight inside the building**, no one existed before I arrived.

The report begins with a presentation of the old system which was currently used before I arrived. Then, I will present the methodology which led me to my idea of new joins with drawing, 3D models with CATIA V5, and prototypes of joins made by 3D printer.

Objectives of the project

So, the mains objectives of this project were :

- To imagine and create a new multifunctional join that enable the addition of bracing on the 3D building model of the structural laboratory.
- To improve the dynamic behaviour of the current 3D model of the laboratory by the addition of bracing thanks to new joins.

But on a more general point of view, the mains objectives of this project were :

- To know and master conception guidelines and methodology applied to any kind of engineering project, for instance, in a company.
- To know the prototyping guidelines and methodology with a 3D printer.
- To know the experimentation guidelines and methodology on a real system, at the scale of the laboratory
- To work in autonomous way with a free schedule like an engineer in a company



GANTT Diagramm of the project

In order to have a relevant aspect of the time I have decided to make a GANTT diagram.

Project phases	Week															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Presentation and comprehension of the project and objectives	█	█	█													
Readings of bibliography	█	█	█													
Conception process Joins		█	█	█	█	█	█									
Prototyping			█	█	█	█	█	█	█	█						
Experimentation											█	█	█	█	█	█
Written report				█	█	█	█	█	█	█	█	█	█	█	█	█
Oral presentation														█	█	█

Table 1 : GANTT board

2 / Problems statements : search of the existent

Overview of building models in the market

In this part, we are going to search previous models of building used in schools and solutions to add bracings. Indeed, these buildings are used to study the dynamic behaviour of buildings. So, we have found 2 relevant ones :



Figure 1 : Different buildings model for dynamic behaviour study [12]

So, we have 2 solutions in order to add bracing into the building's model.

The first one uses a screw device in order to be fixed to the building with pre-manufactured bracing. Indeed, we have pre-made horizontal holes in order to put these bracings.

The second one uses a nut object with premade holes inside it in order to add a thin plate of metal that represents the floor of the building as well as bracing or even columns.



Figure 2 : Current solutions of building model in order to add bracings

So, on the one hand the **problem of these solutions is that they don't allow other bracing configuration** (for example V or K bracing) and on the other hand their systems **don't allow the introduction of bracing when we change the height of the floor**. In fact, all their bracings are the same length. Because, in these buildings we have the same height between each floor.

So, our system should introduce all configurations of bracing we can make and to be adaptable to the height of each floor as well.

Previous system of the structural laboratory

So, at the beginning, when I arrived at the laboratory the first week, joins which were used to introduce the bracing inside the building model were made by a previous student [2] as follow:

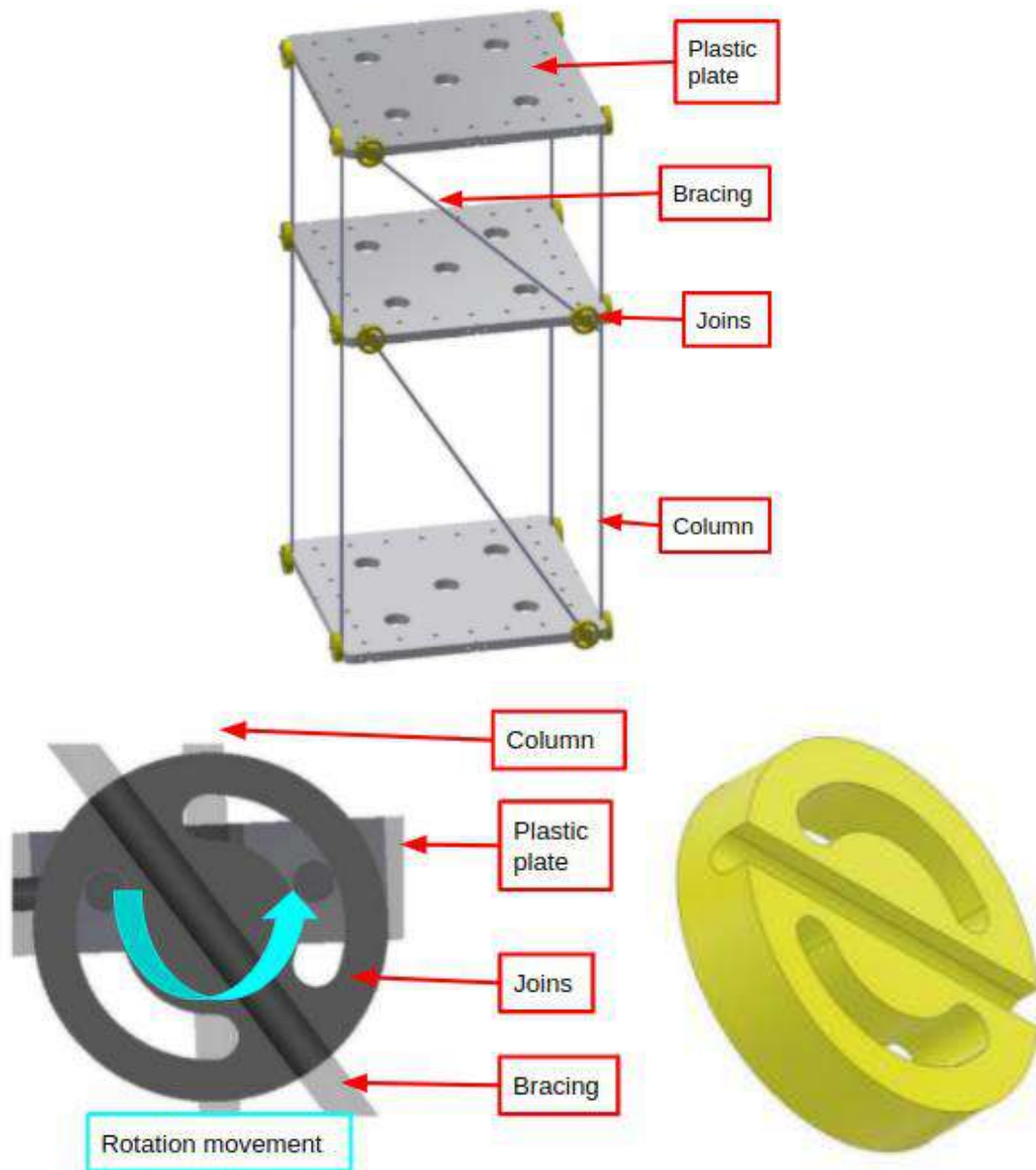


Figure 3 : Previous joins used for the 3D model building

As we can see, the product has 2 holes with circular shape to change the position of the angle of the **bracing (diagonal stick)** if the floor changes its height (moves up or down) by the rotation of the joints itself. In addition, these **parts were done by the 3D printer** of the structural laboratory.

His product has qualities but at the same time, a lot of problems. The joints were fixed into the plastic plate with only cut metal screws, but no nuts or no washers as well. So, one of the main drawbacks of the system is that we need to drill the plastic plate with a drill in a horizontal way. So, it is hard to manufacture them manually.

In addition, **introductions of other bracing configurations are not possible with this join.**

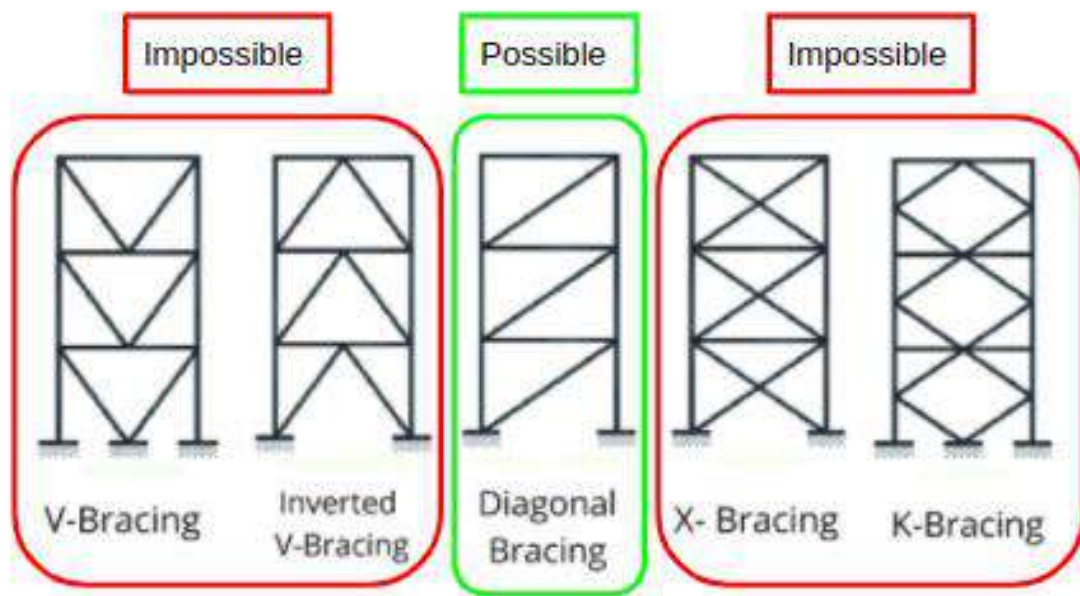


Figure 4 : Possible bracing configuration of the previous joins [9]

As we can see, there are different types of bracing, currently previous joins can only make the diagonal bracing. In theory, and according to the plastic plate, the building can also hold V and inverted V-bracing as well as X bracing or K bracing. So, we have to bear in mind that the next join should introduce all configuration bracings if it is possible (figure 4).

In addition, we have to keep in mind that the joints should also be attached to the first floor directly linked to the ground.



So, let's sum up the **advantages/disadvantages** of this solution below.

Advantages	Disadvantages
<p>Easy to fix and remove from the plastic plate due to standard metal screws and tools (with screwdrivers)</p> <p>Easy and low cost to produce, because this yellow part is made by a 3D printer and uses standard screws.</p> <p>Easy to adjust the angle of the bracing due to semi-circular holes that allow the rotation of the joints when the height of the plastic plate changes (floor level of the building).</p>	<p>Horizontal drill inside the plastic plate is done without good accuracy and it is hard to do (because it is done by a manual way)</p> <p>Need to cut metal screws in half in order to fix the product inside the plastic plate. (not a full screw so it implies a waste of metal)</p> <p>Don't have the possibility to put 2 branching in a single join (for the floor n+1 / floor n-1)</p> <p>Don't keep the column very tight during the earthquake/vibration stimulation due to its shape.</p> <p>Hard connection with the floor. We need something below the building if we want to add bracing at the first floor.</p> <p>Don't allow other bracings configuration</p>

Table 2 : Pros and cons of the previous solution

In addition, we can find an estimated cost of this solution :

Product	Cost
Yellow part	<p>20 € = 1 kg 0,2 € = 10g / part For the all building = 12 x 0,2 € = 2,4 €</p>
Screw	<p>10 cents for 2 metal screws For the all building = 2,4 €</p>
Total	Approx 5 €

Table 3 : Cost of the previous solution

Moreover, we have to take into account that **this solution, which was imagined by this student but was not his principal project**. So, it can explain these drawbacks.



Figure 5 : Old solution with aluminium plate and cut screws

Because, before his creation, they were only rectangular aluminium plates and cut screws to keep the column tight. We can't even introduce bracing at all. (figure 5)

So, these joints need improvements to enhance the characteristics of the 3D building model.

- To allows others bracings configurations
- News joins don't need horizontal drilling to be fix inside the plastic plate
- Add bracing even if we change the height of one floor.

Thus, our project was to imagine, find and create new joins for this 3D building model in order to improve its dynamic behaviour.

3 / Joins to introduce bracings into the building

In this part, we will see the different steps of our work in order to create the new join, with different ideas, as well as 3D printed prototypes and the problems encountered.

Preliminary study with the APTE Methodology [4]

Before we started to design new joins for the 3D building model, we needed to study a little more about the functions that join fulfils. Thus, we have used the APTE method with 2 famous diagrams.

The first one is called “**The Horned Beast Diagram**”

This tool highlights the purpose of the study. It answers to the third following questions :

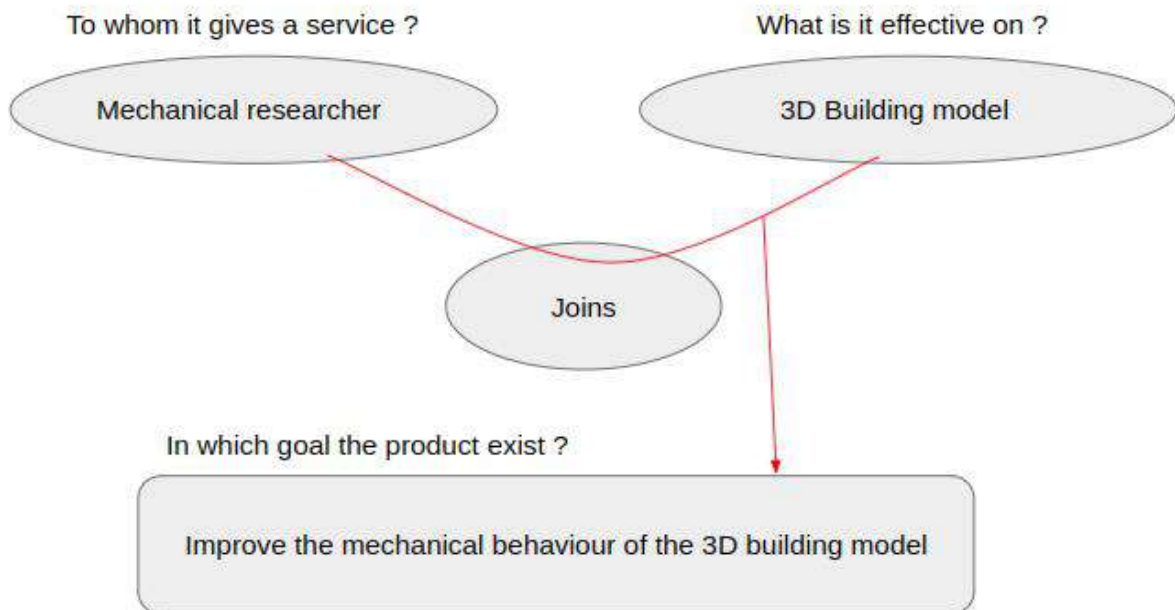


Figure 6 : The horned beast diagram

The second tool that we used is the **octopus diagram or interaction diagram**.

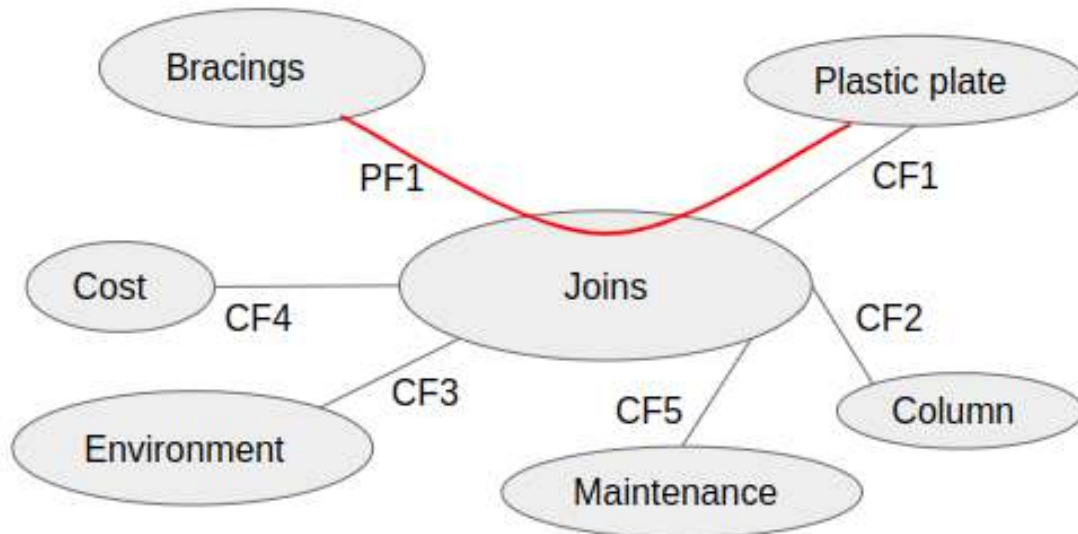


Figure 7 : The octopus diagram

Thanks to this tool, we can identify all the functions that the object needs to answer, and the interaction with its environment. We identify the **principal(s) function(s) (PF)** and the **complementary functions (CF)**. With this diagram, we can make the functional specifications of the product inside a board.

Thus, in these functional specifications, we will have each function listed with its definition, the criteria to respect and the tolerance or the flexibility on this criteria. So, the product has to satisfy requirements and that gives the following tables.

Number	Description	Criteria	Level	Flexibility
PF1	Allow the introduction of bracings on the side of the building	Rotation angle	Allow an adaptable rotation of the bracing due to the change of height of the floor.	F0
		Fix the bracings	Keep the bracings tight to the building during vibrations solicitations	F0
		Introduce other bracing	Allow all the others configurations (if it	F1



			is possible) of bracing to enhance the behaviour of the building.	
CF1	To be fix on the plastic plate	No drill horizontal	Compulsory, because we don't have a good accuracy in a horizontal and manual way	F0
		Use vertical drill (we can to drill other ones with machine)	Compulsory	F0
		Resist to the stress due to the fixation (vibrations, compression)	Compulsory	F0
CF2	Be able to fix the column tight to the plastic plate	Keep enough tight the column during vibration solicitations	Compulsory	F0
CF3	Resist to the environment	Dust	Dust of the lab	F1
		Light	No sunlight, indoor use	F1
		Humidity	Humidity of the laboratory	F1
		Temperature	Temperature of the laboratory	F1
		Earthquake/ vibrations solicitations	Resist to the maximal mechanical stress we can make by hands	F1
CF4	Respect the budget of the project	Cost of the material	Parts of the system will be printed with	F0



		Cost of manufacturing	a 3D printer as much as possible Use standard component (nuts, screws, washer, etc) Estimated price : 20 €/kg Manufacturer processes will be done by laboratory team with the tools available inside the laboratory	F1 F0
CF5	Be maintainable	Assembly and Removing	Joins has to be removable with standard tools (screwdriver, spanner) and components	F0
		Assembly the joins inside the buildings/ Removing time	As fast as possible	F2

Table 4 : functions board, joins to introduce bracings

We have to take into account that :

A flexibility F0 means there is no tolerance on this criteria, the product must answer great to this criteria.

A flexible F1 means there is a little tolerance on this criteria.

And a flexibility F2 means we have to take into account these parameters but the tolerance to meet the needs of that kind of thing is wide.

Thus, we have brainstormed all our ideas for each function and made some sketches of our solutions in order to meet the needs of each function.

For each function, we will introduce the 2 main ideas to satisfy the requirement. Then we will present, in our opinion, the best solution among them we had kept for the project and the final choice in order to build the global part (join) and the entire building as well.

Presentation of solutions

PF 1 : Allow the rotation movement of the bracing

Solution 1 : clips system

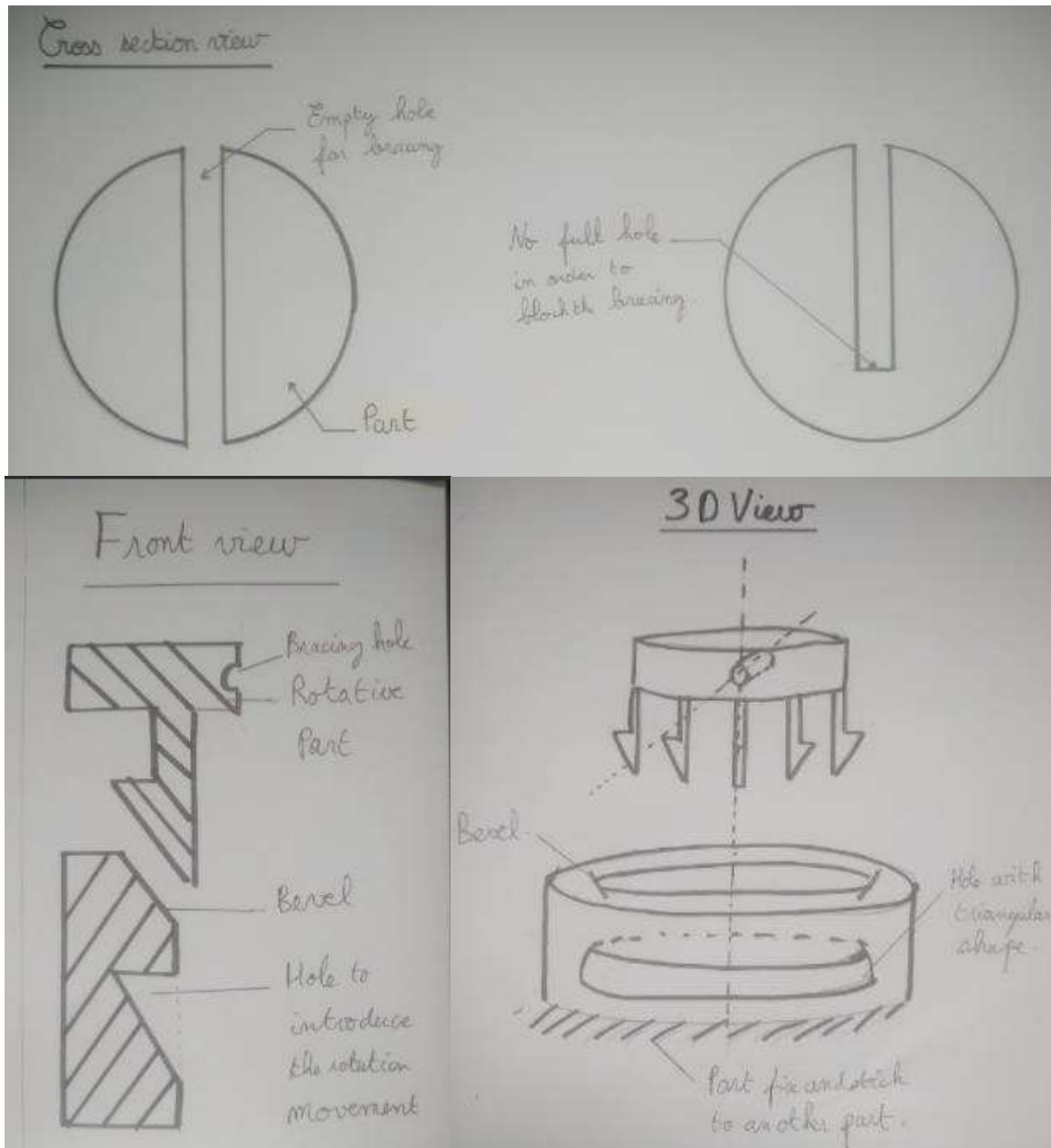


Figure 8 : Different view of the clip system solution

Inspired by a previous project which I did a few years ago, the rotation movement is made by the rotation of a clips part.

The chamfer feet of the clip part are flexible so they are put inside a dedicated triangular hole (front view figure 8). As a result, we put the rotative part with the chamfer foot inside a fixed part by force. So, we can't remove this part after putting it inside. (the rotation system)

In addition, we have two different rotative parts as we can see on the cross view (figure 8) :

- The first one with a full hole inside itself is to put the bracing
- The second one has a semi full hole to block the bracing.

The fixed part of the rotation system will be stuck to an external part made by the 3D printer of the laboratory and fixed to the building.

Thus, this liaison is partial, direct, removable, and made by friction according to [13]

Solution 2 : manufactured nylon screw and nut

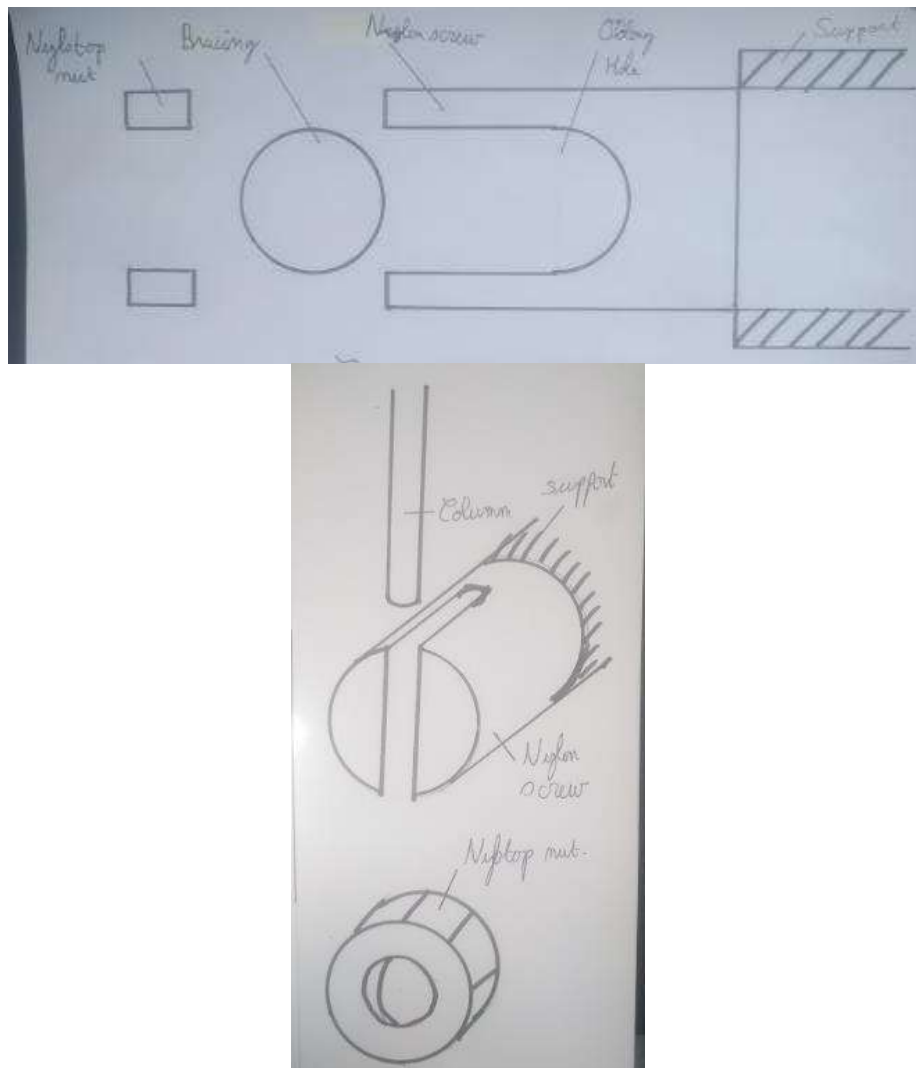


Figure 9 : Sketches of the screw hole solution

As we can see, the rotation movement is done by the rotation of the plastic screw.
 When we have finished adjusting the position of the hole inside the screw, then we put the bracing inside the hole. As a result, we can put and turn the nut to keep the bracing tight to the building by squeezing the nylon screw and the bracing.
 In addition, **the liaison is partial, direct, removable, and made by friction.**

So, there is a **recap of the pros and cons** of each solution.

Technical solutions	Advantages	Disadvantages
Clips system	Easy to adjust the angular angle Easy to put and remove the bracing inside holes	Hard to print due to the chamfer part. No removable rotative part Weak areas inside the part (chamfer)
Manufactured nylon screw and nut	Easy to adjust the angular angle	Manufactured screws and nuts in a manual way => not a good accuracy

Table 5 : Pros and cons of PF1 solutions

Then, we have decided to keep the second solution because it uses standard objects and it is easier to manufacture and print than the other solution. So, in our opinion, it is the best solution to meet the needs of this problem.

CF 1 : To be fix on the plastic plate

Solution 1 : L Shape clamp with stick and pin

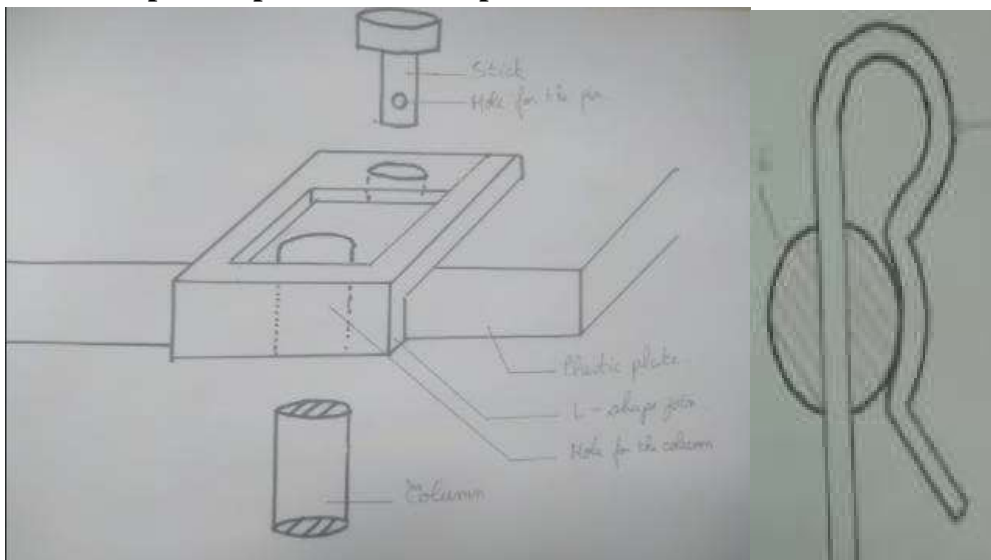


Figure 10 : Drawings of the pin solution

Inspired by an old project as well, the goal here, is to be fixed on the plastic plate with a pin and a soft screw. It is removable if we need it, for instance, in order to disassemble the join. **The liaison is partial, direct, removable, and made by friction.**

Solution 2 : U shape with screw and nuts

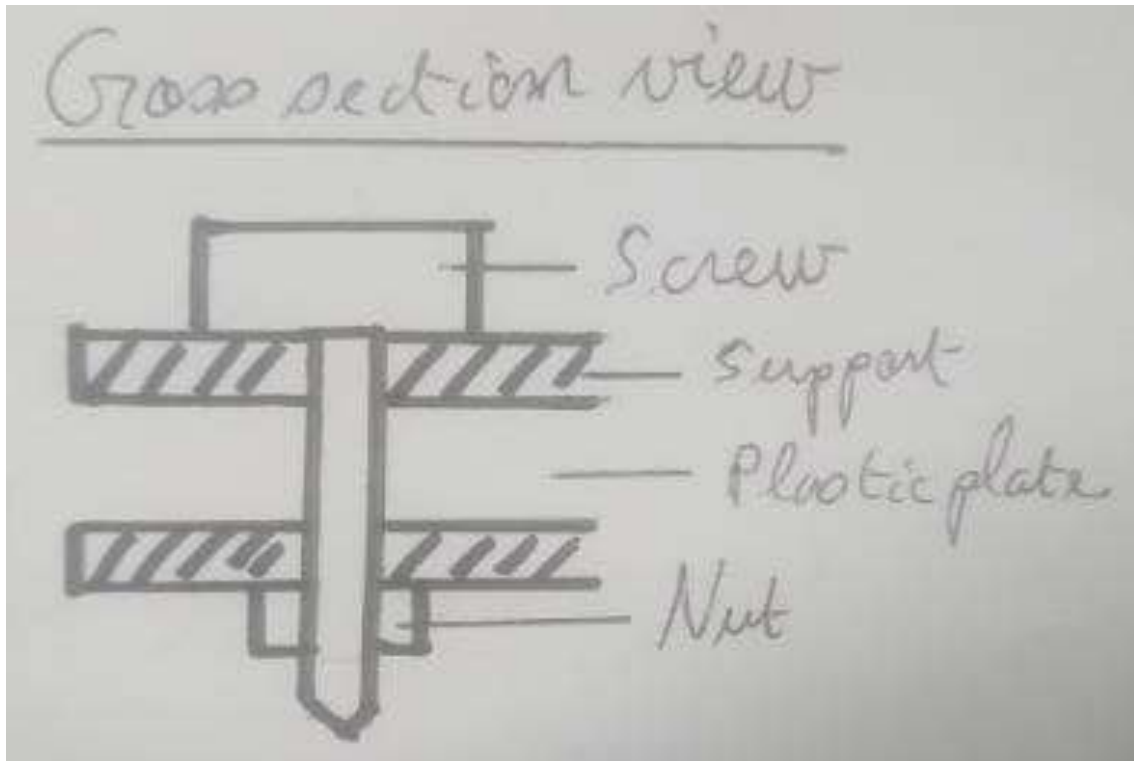


Figure 11 : Sketches of screw and nut solution

Here, we have imagined using standard objects : screw M6 and nut M6 because the holes of 6,5 mm of diameter are already drilled inside the plastic plate (appendix 7). So, as we can see, we put the screw inside the hole already made in the plastic plate then under it we can put our nut in order to keep the support tight to the building. As before, **the liaison is partial, direct, removable, and made by friction** because it will be removable if we need it (change of the height of floors). Let's sum up the **pros and cons of each solution.**

Technical solutions	Advantages	Disadvantages
Stick and pin	Easy to remove and fix due to the pin	The pin is a weak part so it can break easily
Screw and nut	Easy to remove and fix due to standard object	Hard to fix very tight without tools (tight the nut with a spanner)

Table 6 : Pros and cons of CF1 solutions

So, we have decided to keep the solution number 2 because screws and nuts are very easy to find inside the laboratory and easy to fix and remove from the plastic plate. And it uses previous holes from the plastic plate as well.

CF 2 : Keep the column tight to the plastic plate

Solution 1 : Separate plate with the screw

In this solution, we have imagined a pre-stressed part in order to keep the column tight to the plastic plate. The idea is to make the part a bit smaller than the correct dimension between 2 holes. Thanks to the fixation screw behind the column will be tight inside the column.

In addition, the **liaison is partial, direct, removable, and made by friction.**

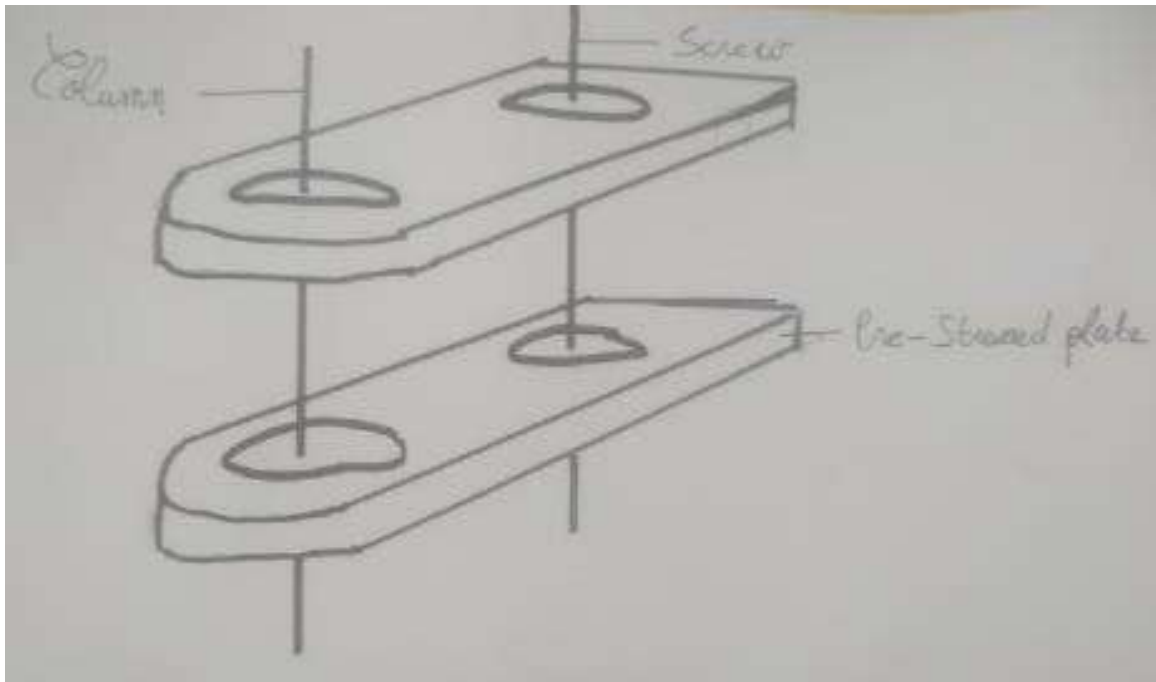


Figure 12 : Solution with separate plate

Solution 2 : Nylon screw with column

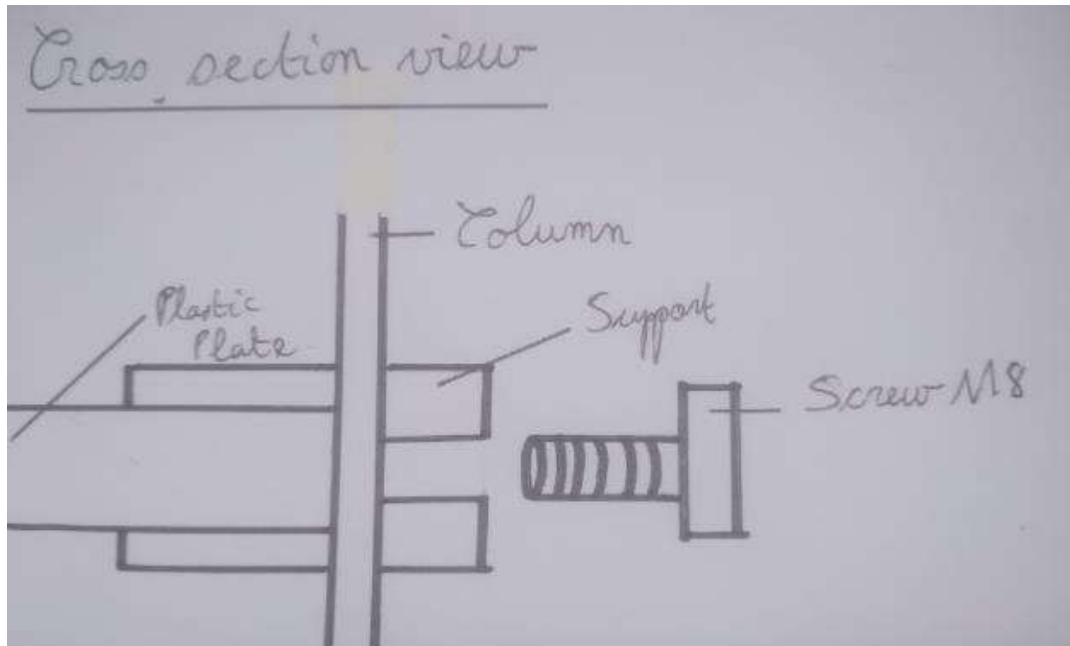


Figure 13 : Cross section view of the nylon screw solution

To do that, we were inspired by the old solution of the aluminium plate which was used before. The idea here is a nylon screw that will keep the column tight when you turn it. In fact, the column is pushed by the nylon screw inside the hole when you turn it.

Eventually, as previous ones, the **liaison is partial, direct, removable, and made by friction in order to disassemble the building if we need it.**

So, let's recap all the pros and cons of each solution

Technical solutions	Advantages	Disadvantages
Separate plate with the screw	Easy to print Easy to fix (2 removable part)	Maybe not enough strong in order to resist to the flexion stress
Nylon screw	Standard object	Can put a lot of stress pressure inside the column

Table 7 : Pros and cons of CF2 solutions

Then, regarding pros and cons, we have decided to keep the second solution to put in regarding other solutions we have chosen before from other function requirements.

All in all, we choose this solution because in our opinion it has the best ratio of pros and cons.



CF 3 : Resist to the environment + CF5 Be maintainable

So, all the pieces will be done by 3D printer of the structural laboratory with PLA plastic.

We have to bear in mind that **PLA is recyclable, so it's eco-friendly but it is weaker than ABS (no recyclable plastic)**. We have also used nylon and metal **standard screws and nuts as well**. Then it is easy to change these components or to find them inside the laboratory or even inside the market.

Recap of the choice of the final solution

So, let's recap, for each function we have decided to keep :

- PF1 : Solution n°2
- CF1 : solution n°2
- CF2 : solution n°2

Finally, we have chosen this global solution. First of all, it uses common components inside the market today. They are very cheap, easy to use and found inside it.

In addition, we can adjust very easily the right angle for our configuration with the screw and then the nylon screw can keep the column tight very well.

Here is a recap of all advantages and disadvantages of the global solution we have chosen.

Advantages	Drawbacks
<p>Easy to put and fix on the plastic plate with plastic screw and nuts.</p> <p>Cheap because the joints will be a 3D printed object.</p> <p>No horizontal drill needed inside the current plate to fix the joints on the plastic plate.</p> <p>Easy to adjust the rotation angle of the bracing due to the nylon screw hole.</p>	<p>More expensive than the previous solution because we have more components inside this solution.</p> <p>Manufacture the nylon screw will be done by a manual way with saw or rotary saw and cutter (with not good accuracy).</p>

Table 8 : Pros and cons of the final solution



CF4 : Respect the budget of the project

According to solutions, we have estimated the cost of the global solution.

We can find websites we have used in the appendix 1 to estimate the cost of this solution

Product	Cost
3 plastic screw M8	0,84 €
2 nuts M8	0,14 €
1 screw M6	0,15 €
1 nut M6	0,11 €
One 3D printed part	20 €/kg 10 g = 0,10 €
Total	Approx 10 €

Table 9 : Cost of the final solution

As we can see the cost of this solution is approximately **2 times more expensive than the previous one.**

But, contrary to the old system, this solution will allow :

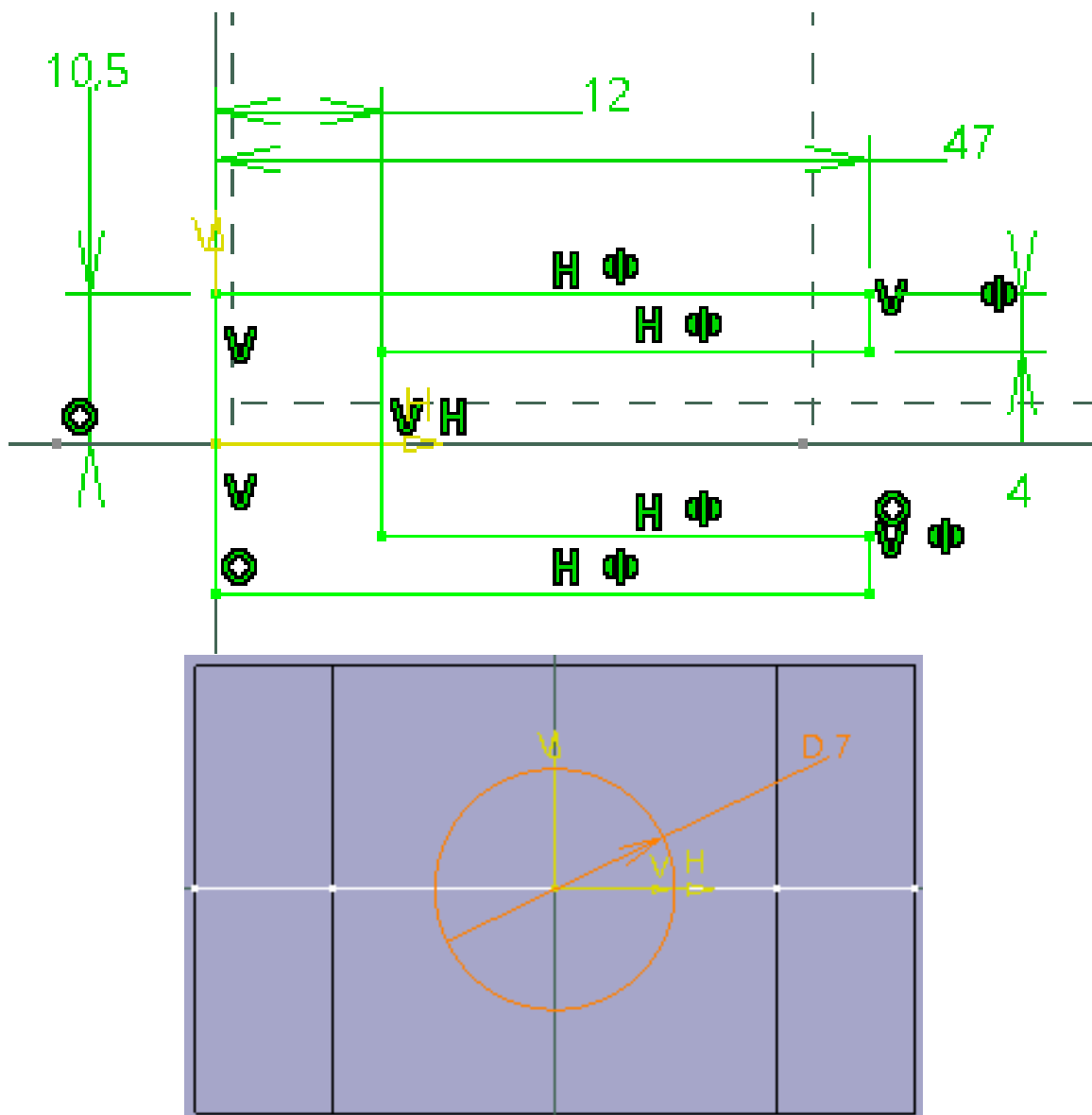
- More bracing configurations
- Adjusted to the altitude of each floor

Implementation of solutions in CATIA V5

After choosing our global solution we have to put it into a 3D model software in order to print it after thanks to the 3D printer of the laboratory.

In order to do that, we have decided to use a very well-known french software, **CATIA V5**.

So, we can find below the ultimate version of the joints we have made so far. But we will show different prototypes that lead us to this solution. First, let's see our drawing in CATIA.



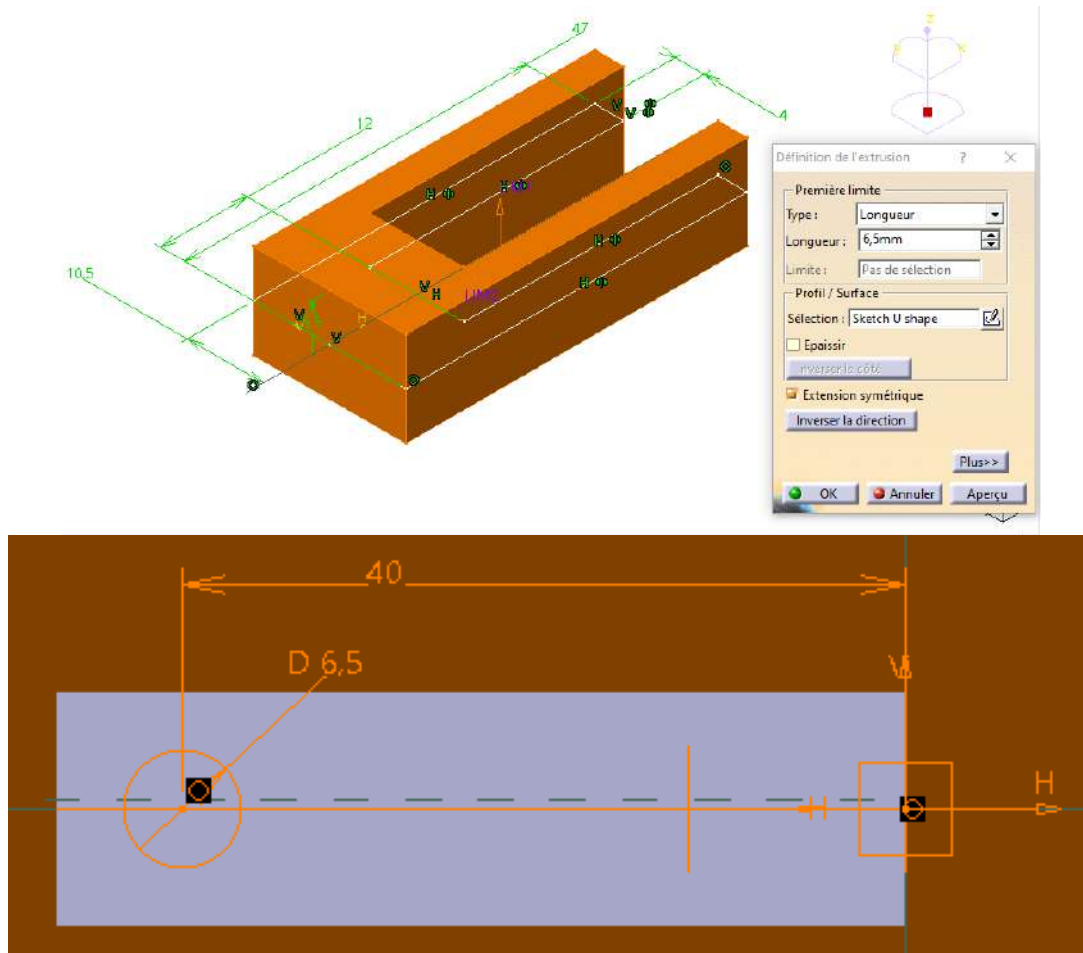


Figure 14 : Sketches of the 3D part in CATIA

To make the drilling part, a rule says that we should have a width of plastic equals to 1,5*of the diameter of the screw in order to put the screw inside [11]. Then, we put 12 mm for the extrusion for the M8 nylon screw.

We have put a diameter of 7 mm for the M8 screw because the hole will be drilled in a manual way [10]. In addition, we have put 13 mm of width in order to take into account the width of the head of screw and the nut as well. Then they will have enough space to rotate each other if they are at the same position. To make the part easy to do, we have decided to use symmetry plans for our part.

In addition, we have put a fillet on the corner of the part in order to consume less plastic. And we have put a chamfer in order to increase the flexion stress of the product. It is useful because the drilling part of the holes will be done in a manual way (compression of hands when we hold it).

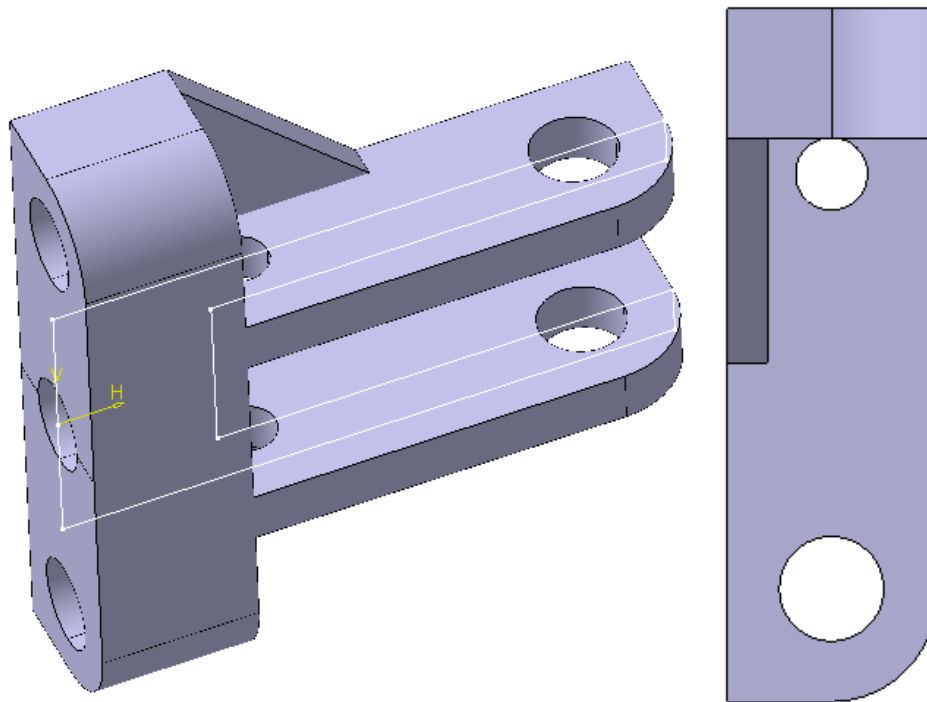


Figure 15 : Views of the final part solution

Then, we have the final 3D joins made in CATIA V5.

We can find the 3D model of these joins in the appendix 12.

N.B : We have to open the file with Adobe Reader otherwise we will not be able to see the 3D joins inside this PDF file.

3D model building preview

Now let's build the global system with the 3D building model.

To do that, we have taken measures of all the components present inside the 3D model building model. We can find all the components in order to make the building (appendix 7) below. Thanks to the 3D mode we will have a good idea of the position of bracings and joins in the real model as we can see below.

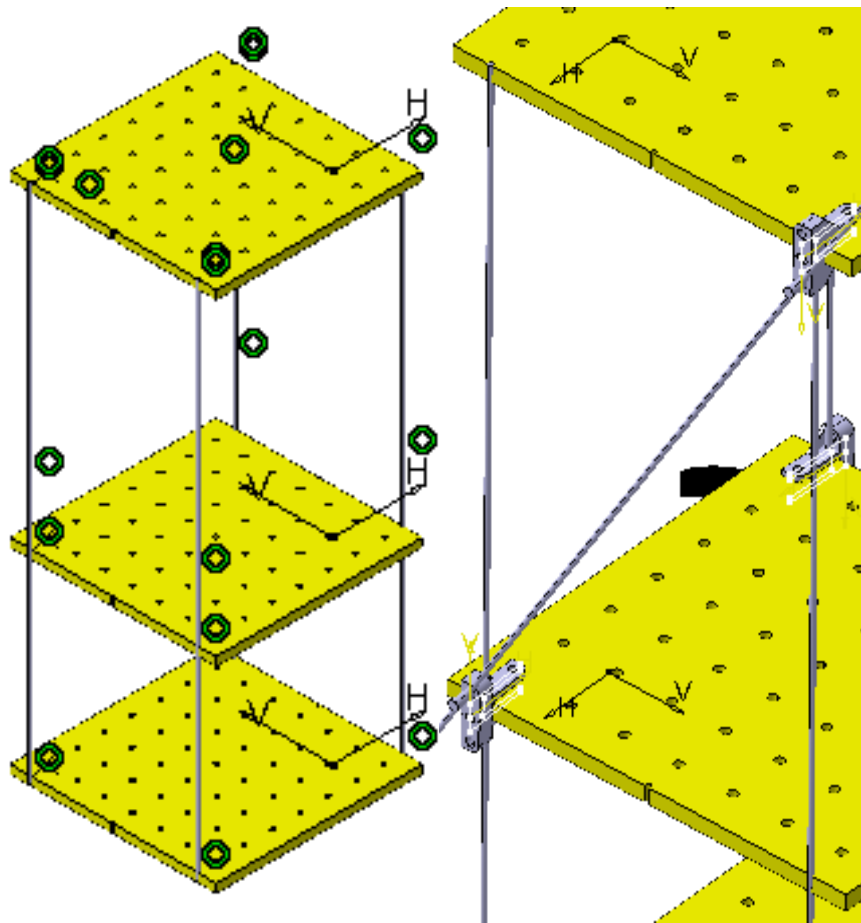


Figure 16 : 3D model building in CATIA V5 without and with diagonal bracing

As the joins, you can find the 3D model of this building in the appendix 13 below.

Prototyping with 3D printer

Now, after having imagined the new joins, we have printed it with the 3D printer of the laboratory.

But before printing the prototype we have to set the parameters of the 3D printer (appendix 6). In order to print it, we have decided to print the prototype as fast as we can (appendix 4 and 5), because the accuracy of the prototype is not compulsory here because we have to check the dimensions and the resistance of the part first.

Altura de la capa	
● Altura de la capa:	<input type="text" value="0,3"/> mm
● Altura de la primera capa:	<input type="text" value="0,35"/> mm

Información del laminado	
Filamento Usado (m)	2,76
Filamento Usado (mm ³)	6630,41
Tiempo estimado de impresión: - modo normal	46m

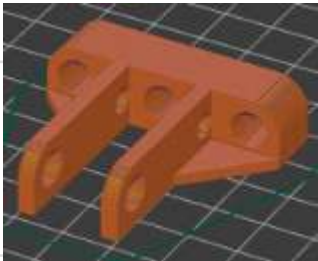


Figure 17 : Parameters of the 3D printer and printing time of the final prototype

So, in this part, we will introduce the 3 mains prototype and the final version we have made, their advantages as well as their drawbacks and to finish improvements for the next prototype we should do. But we have to take into account that we have printed more than 3 prototypes but we have decided to show the most relevant ones.

Manufacturing of prototypes

So, we will print all prototypes with the 3D printer of the laboratory. But we should be aware of the way of printing. Because, when we try to print a prototype in a vertical way (drilling holes are vertical), it doesn't resist the flexion stress as we can see figure 18.

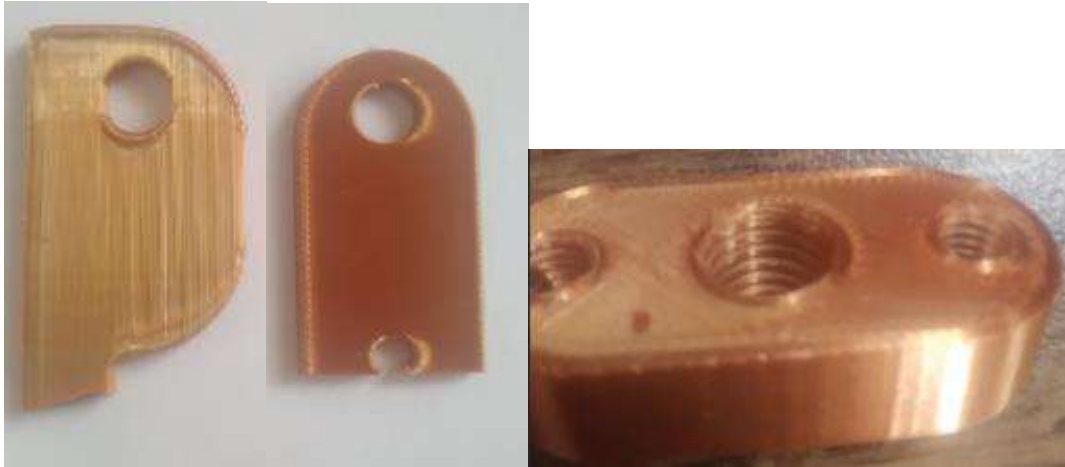


Figure 18 : Configuration of the 3D printed part inside the 3D printer and parts break

So, for every prototype we have printed, we printed the part horizontally then the prototype, even if it is not the definitive version in order to increase the flexion stress resistance when we are going to manufacture them with our hands.

In addition, the accuracy of the printer is not very good, so we have decided to print the part with soft holes and to drill them manually after in order to put screws into it.

So, for all prototypes, **we have drilled holes for the screw in a smarter way.**

Indeed, we made 2 or 3 rotations with the tool and we came back in order to break shavings inside the plastic hole. And we have repeated the drilling process 2 times for each hole in order to have no problem when we put the screw inside the hole.



Figure 19 : Drilling holes of the 3D printed part

We can see here the drilling part of the 3D part after manufacturing as well as what we have inside the part. As we can see, the part is not full of plastic due to our way of printing.

Prototype 1

Here, the first prototype was printed in order to see if the dimensions and the shape made in CATIA were correct or not. Eventually, it was not the case.

So, we have taken into account the drawbacks to enhance the next prototype we will print.

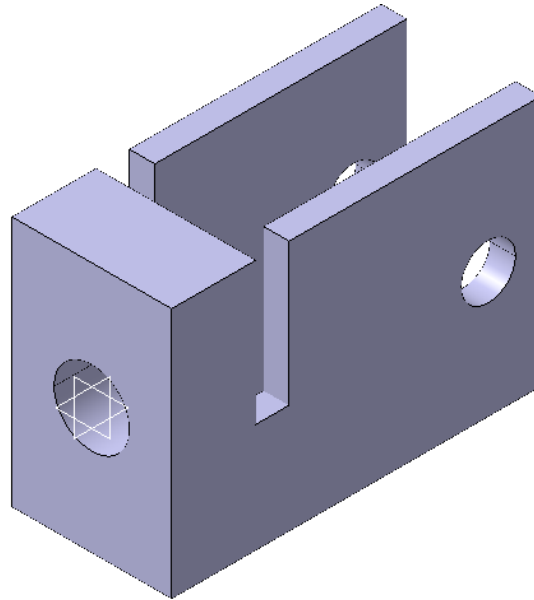


Figure 20 : 3D model of the first prototype

So, below we can find a recap of the aspects of this first prototype :

Table 10 : Pros and cons of the prototype 1

Advantages	Problems	Solutions
<p>Almost all dimensions are correct (screw, column).</p> <p>Making the drilling inside the 3D part is ok for the M10 screw.</p> <p>Time printing is less than 1h so it is convenient here.</p> <p>Drilling holes are well made in order to put screws into it.</p>	<p>The gap to accept the plastic plate was a bit tiny, in fact some areas of the plastic plate were too big for the 3D printed part. (12mm of gap, need 13mm instead).</p> <p><u>Right angle</u> all around the part, <u>it is a localisation of stress concentration</u> which is not good at all.</p> <p>We don't have something to really keep the column tight.</p> <p>The middle cut inside the nylon screw in order to introduce the bracing damage to much the screw</p>	<p>Add 1 mm for the gap in order to put it on the whole plastic plate.</p> <p>Put fillet instead of right angles in order to decrease the stress concentration and the plastic consumption too.</p> <p>Need 2 or 3 screws, 1 or 2 to keep the column tight and 1 for the bracing.</p> <p>Make a hole of the diameter of the bracing instead of the cutting hole inside the screw</p>

Prototype 2

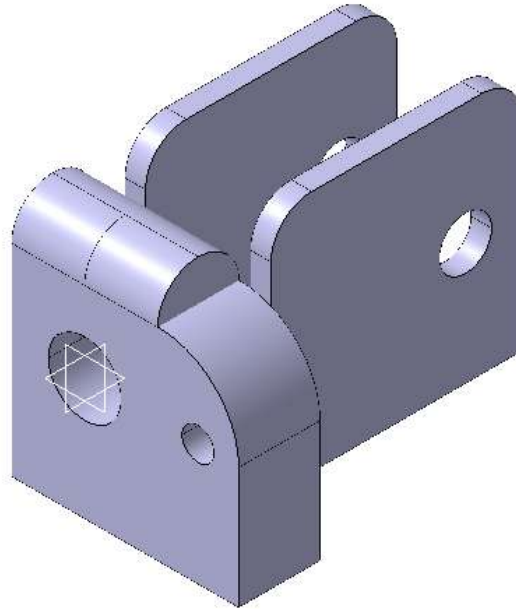


Figure 21 : 3D model of the second prototype

So, let's recap aspects of this second prototype

Table 11 : Pros and cons of the prototype 2

Advantages	Problems	Solutions
<p>1 screw to keep the plastic plate and the other to introduce the bracing. (the most biggest one)</p> <p>All dimensions for plastic plate are correct now</p> <p>Easy to make the hole inside the screw with the drill and a nut.</p>	<p>Flexion stress is too huge for the part when we turn too much the middle screw Thus, it broke the part (figure 18)</p> <p>Width of U shape part is too tiny</p>	<p>Put chamfer on one side to increase the flexion resistance when we manufacture the part.</p> <p>Remove the U gap for the column in order to make the product stronger. Just make a hole for the column.</p> <p>To introduce X bracing, we have to determine the role of screws, the central screw is going to keep tight the column and the 2 others are to introduce bracings</p>

Prototype 3

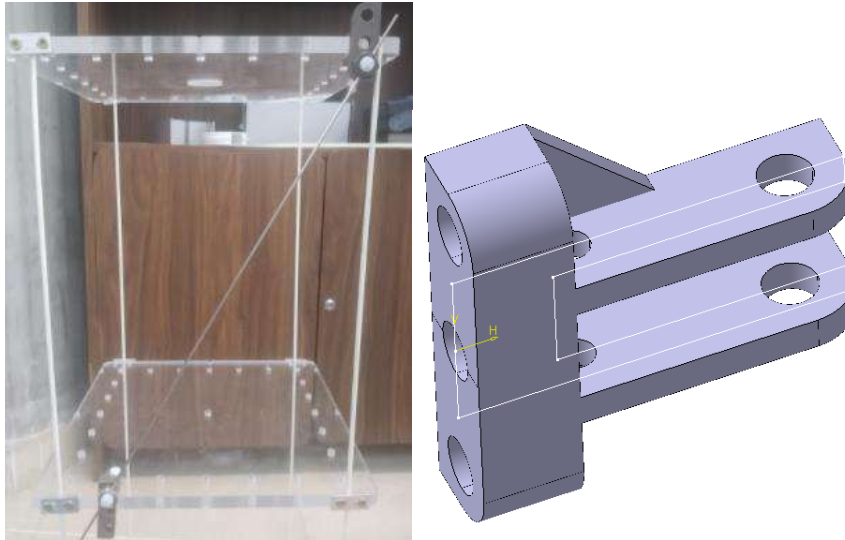


Figure 22 : Prototype 3 on the 3D building model of the laboratory

The prototype 3, is the final version which we have seen before. There is the recap of problems and solutions of this prototype.

Table 12 : Pros and cons of the prototype 3

Advantages	Problems	Solutions
<p>Resistance of the flexion stress is ok now.</p> <p>Use of the column building in order to make the bracing with them.</p>	<p>Too much matter around drill holes for screw (approx. 4 to 5 mm around the drill)</p> <p>Too much plastic consumption here.</p> <p>We didn't let enough space for the rotation of screw and nut M10 at the same place</p> <p>M10 is too tiny for current bracing, should be M12 screw. Or we can change the bracing it self</p> <p>It breaks when we turn the screw too much to keep the column tight due to mechanical stress.</p>	<p>Put M8 nylon screw instead of M10 screw in order to reduce plastic consumption as well as make the bracing closer to the plastic plate</p> <p>Use new type of bracing (tiny diameter 2,3 mm of iron stick available inside the laboratory)</p> <p>Reduce between 2 and 3 mm for drill holes matter around then there is less plastic consumption for the 3D printer and the printing time will decrease as well.</p>

Final prototype

Finally, to make it possible we have taken into account all previous drawbacks as we saw before.

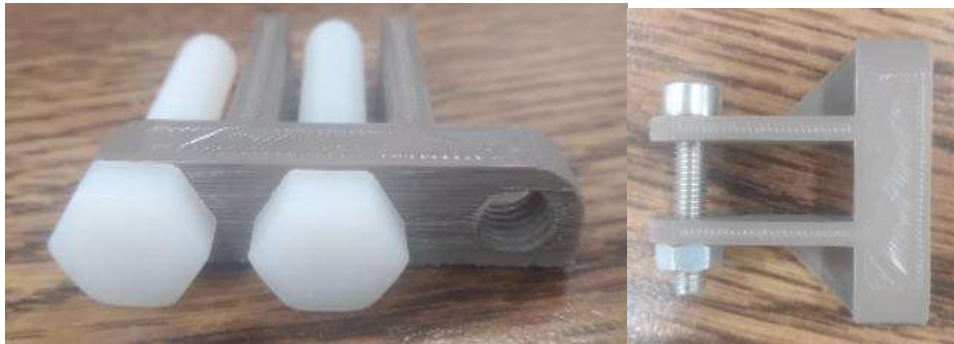


Figure 23 : Head screw and nut not interfere between each other and fixation with M6 screw

As we can see the last prototype is much thicker than the previous one because it has to deal with the compression stress as well. The screws can rotate between each other without interference (figure 23). In addition, we have to create joins for the first floor so we have decided to cut almost in half the join as we can see below (figure 24 and appendix 12)

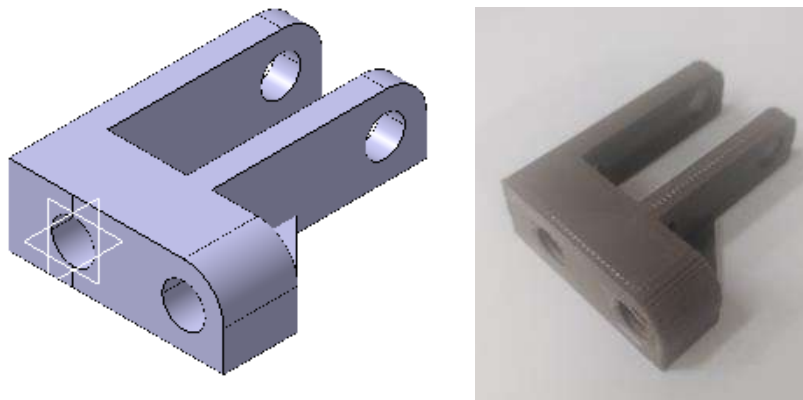


Figure 24 : Join for the first floor linked directly to the ground

As we can see, this last prototype takes into account all the possible improvements of the previous prototype. Now, the only improvement we can do so far is to tackle plastic consumption and stress resistance. We can reduce the width for the screw rotation which is 12 mm to 8 mm and reduce 0,5 mm the width for the screw part fixation into the plastic plate.

Building construction process

First of all, we have to drill and manufacture M8 nylon screw in order to keep tight the column as well as introduce bracing all around the building.



Figure 25 : Drilling nylon screw process

So, in order to drill a hole inside the M8 nylon screw we use a M8 nylon nut with a 3 mm hole previously made as we can see above. We can see, one half will be used to keep the column tight and the other to introduce bracing with a hole in the middle of the screw.

It's in order to have enough length to put the screw inside the joins as well as for the nut which keeps the bracing tight to the building. So, we don't have "screw" waste like the previous solution.

We can find the tools used in the manufacturing process in the appendix 8.

1 nylon screw M8 (cut in 2 parts) = 1 for bracing + 1 to keep the column tight.

So now after having printed and manufactured the joins as well as the M8 nylon screw we need, we can now build the building.

You can find in the appendix 7 all the components used in order to build the building.

So now, let's begin the building process of the entire building.

The step in order to build the building are :

1. Put a plastic plate (that represents the floor of the building vertically).

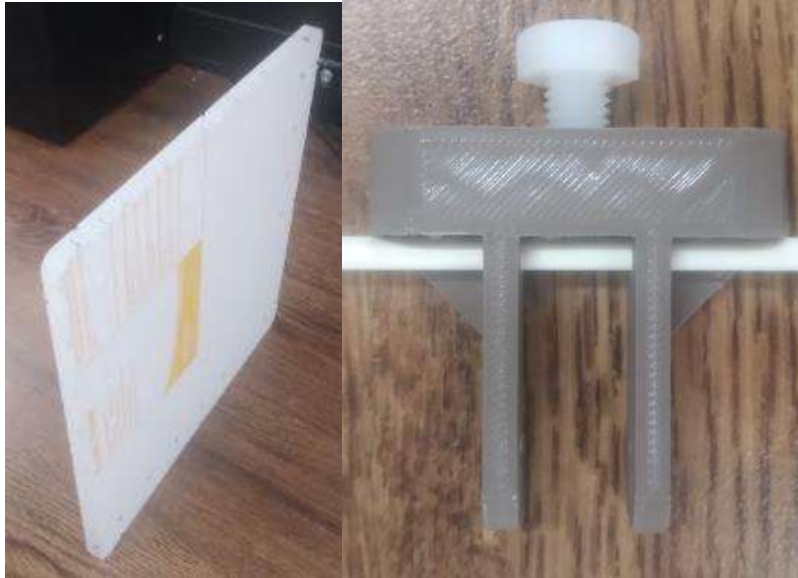


Figure 26 : Building assembly process part 1

2. Prepare the joins with a nylon screw inside as well as a column inside the join.
3. Locate where you have these holes at the extremity of the plate.



Figure 27 : Building assembly process part 2

4. Put your joins here

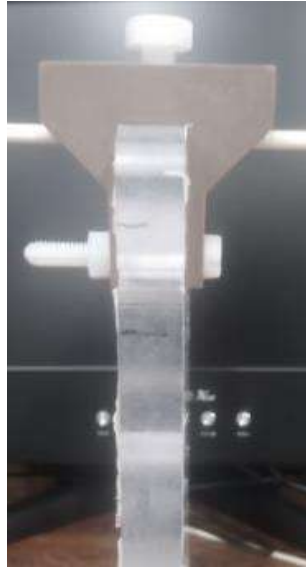


Figure 28 : Building assembly process part 3

5. Put the M6 nylon screw inside the hole and fix the screw with an M6 nylon nut.
6. Repeat the operation for each side of the building
7. Put new join inside the column and repeat the operation with another plastic plate

If we want to add bracing, the explanation to do it will be explained at the end of the next chapter with the other system.

Final building construction



Figure 29 : Building and cross section view

As we can see, we have a M6 nylon screw to keep tight the joins into the plastic plate.
In this building configuration, we can have different configurations.
These configurations will be study in a dynamic way in another chapter

- Without bracings
- With diagonal bracings
- With X bracing

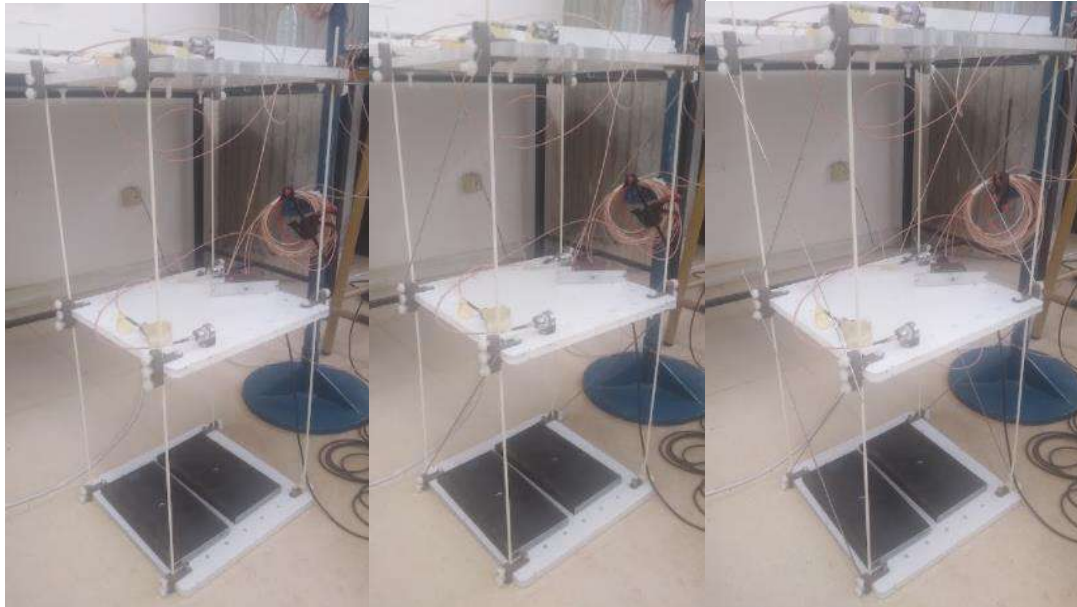


Figure 30 : Different configuration of the building

Other configurations

So, in this part we will find **other configurations, V bracing, inverted V and K bracing**. Unfortunately, we don't have the time to develop these solutions but we have thought about these configurations.

As we said, we have no time to print them but we have made the CATIA part in order to demonstrate that this configuration is possible if the laboratory staff want to study these bracing configurations as well.

So, to introduce the V bracings configuration, we have decided to keep the same strategy as before, but here the join is horizontal and we put it at the bottom of the V and we keep our joins previously printed for the extremities of the V bracing.

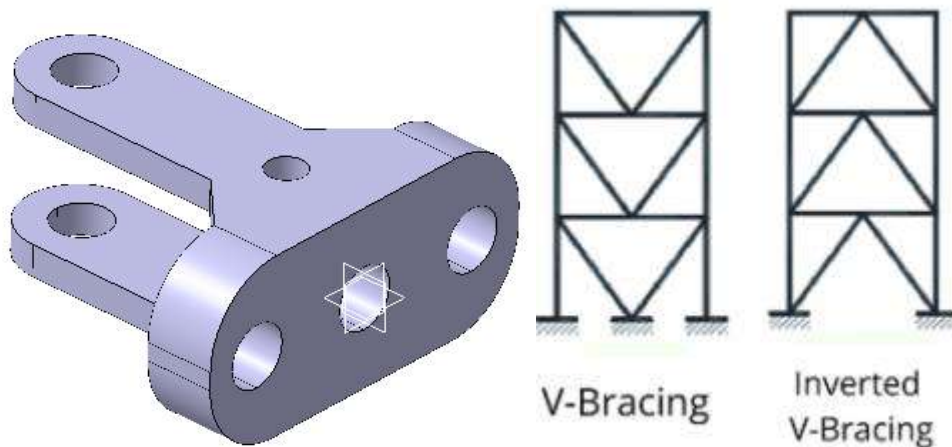


Figure 31: 3D view of the V join

For the K bracing, we have kept the previous joins. We just have to put the join directly to the column and put a V join on each floor as we can see below in order to have the K bracing configuration.

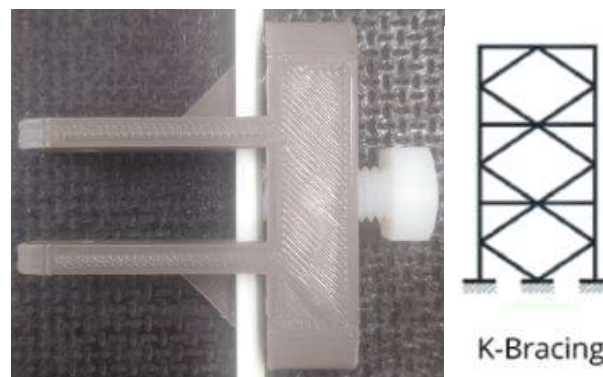


Figure 32 : K bracing principle

Improvements of the prototype

So, after building the building we have seen different possible improvement we can made for the joins we have made :

- Reduce 12 mm to 8 mm of the width for screw holes.
- Reduce 4 mm to 3,5mm for the U shape.
- Reduce 2,5mm of chamfer to 2 mm

In other words, **thanks to CATIA and Prusa slicer** software we can evaluate the plastic and the time saved.

As a result, we can decrease the total volume of the joins and then it's time printing. In fact, we have a **diminution of 25% of the volume**

Caractéristiques		Caractéristiques	
Volume	9,706e-006m3	Volume	7,093e-006m3
Aire	0,006m2	Aire	0,005m2
Masse	0,01kg	Masse	0,007kg

Figure 33 : Before/After the change of the CATIA part.

As a result, with this 2 changes, we can reduce plastic consumption as well as time of printing :

Información del laminado		Información del laminado	
Filamento Usado (m)	2,76	Filamento Usado (m)	2,36
Filamento Usado (mm ³)	6630,41	Filamento Usado (mm ³)	5668,13
Tiempo estimado de impresión: - modo normal	46m	Tiempo estimado de impresión: - modo normal	40m

Figure 34 : time comparison of printing 12mm and 8mm configuration

In total we have **decreased 5 min the time of printing.**

If we have to print 12 joins for an entire building, we will save 1h of printing so it is more than 1 single join printing time.

Conclusion

So, to conclude **in 3 months we have reached the main objective of our project.**

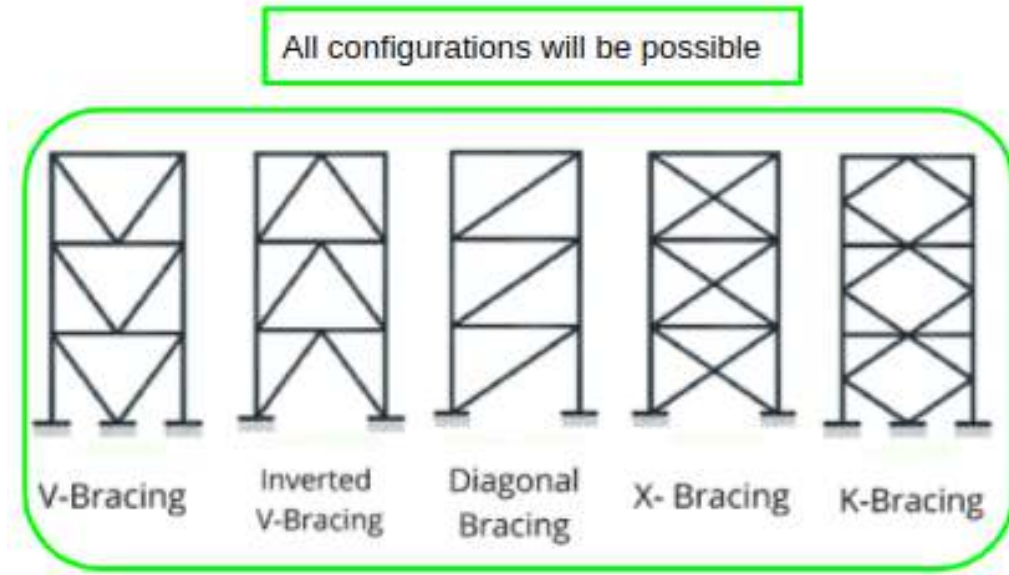


Figure 35 : Bracing building configurations available

Thus, we have to stop here the search for improvement because **we have lost a lot of time to reach the “perfect prototype”** and we don't see at first glance the improvement we could have made in the first one.

All in all, the 3D printer of the laboratory is not perfect so our prototype will not be perfect. But we think we would have reached this result at the end of April because we printed the first prototype at the beginning of march.

So, we think we **are 2 weeks late in this project from our point of view** and according to our own objectives. We have also to take into account that the 3D printer has broken down a lot during this semester, (almost 1 month during the semester) so we couldn't print what we were supposed to do when we want.

4 / Joins for inside column

The other aspect of the project is to make **joins for columns which are put inside the plastic plate**. Thus, we have to create a new part for the 3D building.

For that, we have to **take into account that holes are already inside the plastic plate**. Eventually, this join also has the same function of the previous joins for the bracing but with a focus to keep the column tight during vibration solicitations and no introduction of bracings.

So, we have the same hornest beast diagram as the previous joins but a different octopus diagram as we can see below.

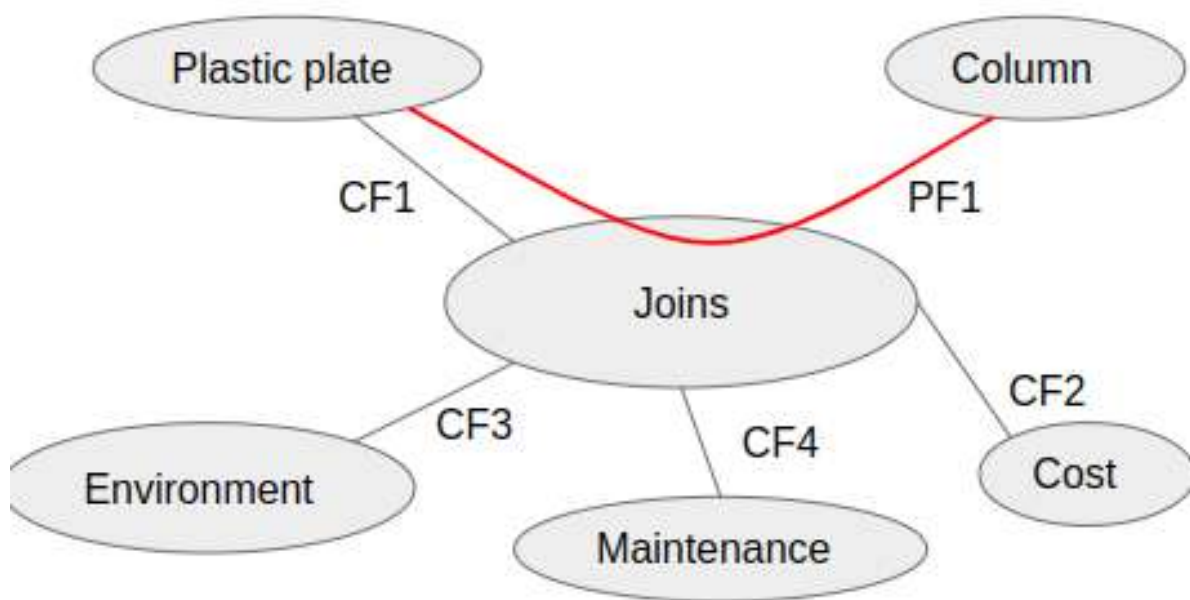


Figure 36 : Octopus diagram

Number	Description	Criteria	Level	Flexibility
PF1	Be able to fix the column tight to the plastic plate	Keep the column tight to the plastic plate during vibration stimulation	Block translation movement	F0
			Block rotation movement	F2
CF1	Be able to be fix on the plastic plate	No drill horizontal	Compulsory	F0 F0

		Drill vertical (only if we need it with a machine)	Compulsory	F0
		Resist to the stress due to the fixation (vibrations, compression)	Compulsory	F0
CF2	Resist to the environment	Dust	Dust	F1
		Light	No sunlight, indoor use	F1
		Humidity	Humidity of the laboratory	F0
		Temperature	Temperature of the laboratory	F2
		Earthquake /vibration stimulation	Resist to the maximal mechanical stress we can do in a manual way	
CF3	Respect the budget of the project	Cost of the material	The part will be print with a 3D printer Estimated price : 20 €/kg	F0
		Cost of manufacturing	Manufacturer processes will be done by scholar team	F1
CF4	Be maintainable	Assembly and Removing	With standard tools	F1
		Assembly time	As fast as possible	F2

Table 13 : Functions board, joins with inside columns

Here, the column is put inside holes in the plastic plate and we need to find a solution to keep it tight. Then, **the main issue is to block the translation movement of the column.**

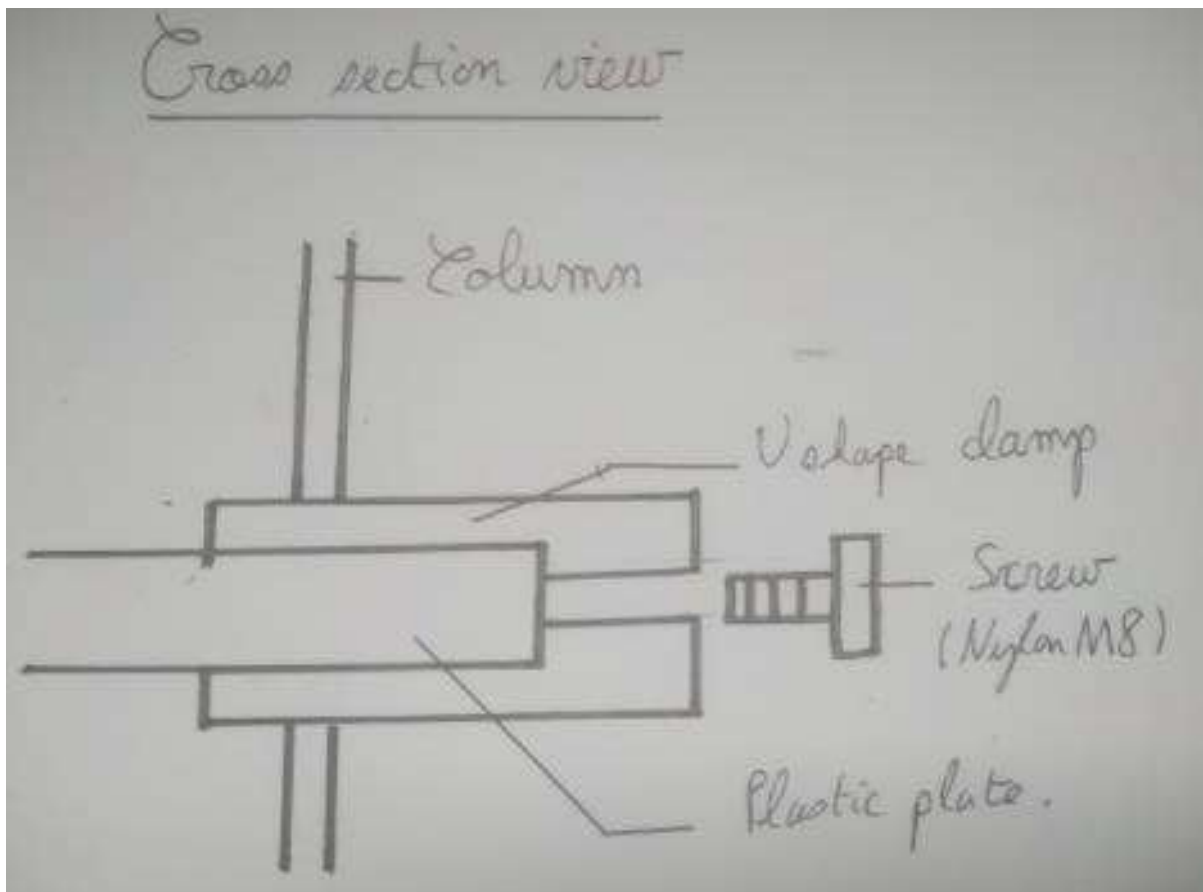
Then, the rotation movement of the column itself is not a problem, it could be allowed.

So, **at least we have a pivot liaison between the column and the plastic plate.**

According to this data, we have imagined 2 solutions to tackle this issue.

PF1 : Be able to fix the column tight to the plastic plate

Solution 1 : Flexion stress



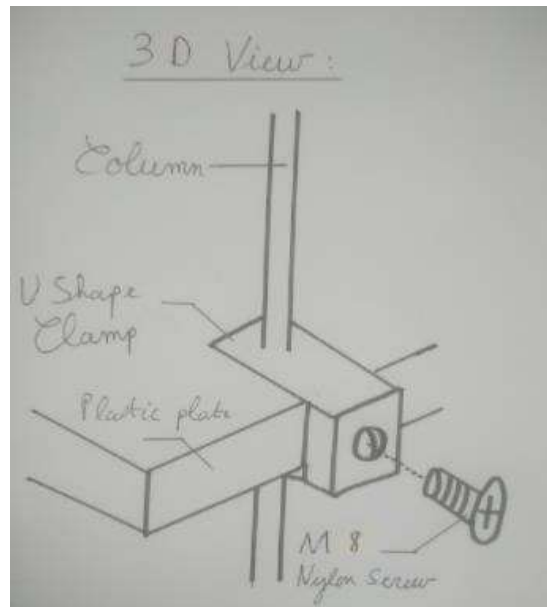


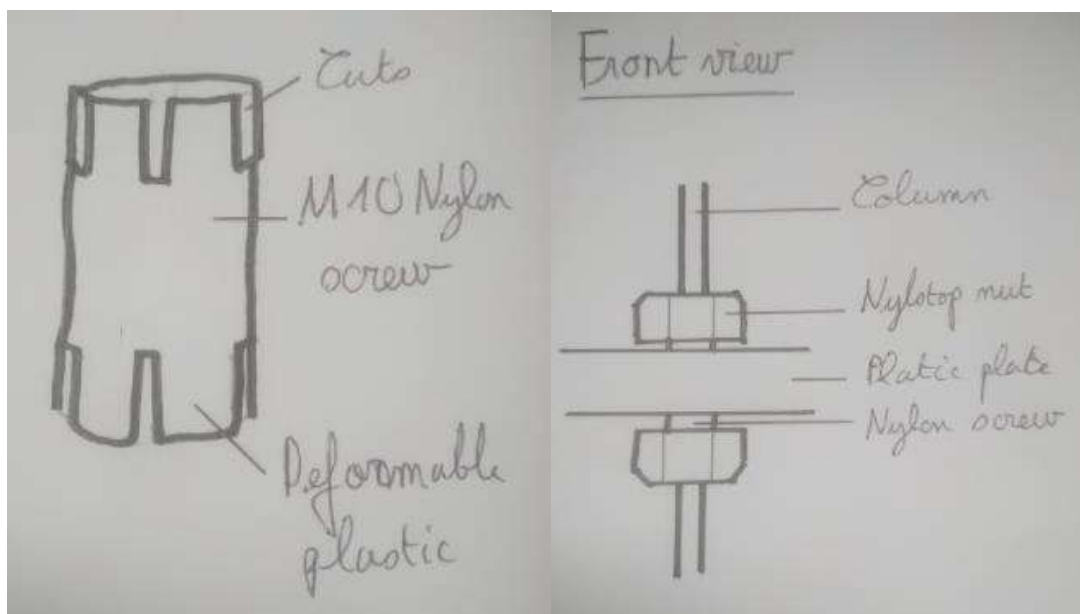
Figure 37 : Sketches of the flexion stress solution

Here, the idea is to use the previous solution for the bracing and **to keep the column tight by adding a perpendicular force to counter the translation movement.**

Indeed, we have changed the screw of the previous solution by the column itself.

To do that, we have imagined a flexion stress made by the screw as we can see, the screw puts effort on the plastic plate and to the column as well. Thus, the column is not able to move up or down. So, as before, **the liaison is partial, direct, removable, and made by friction.**

Solution 2 : Mandrel drill system



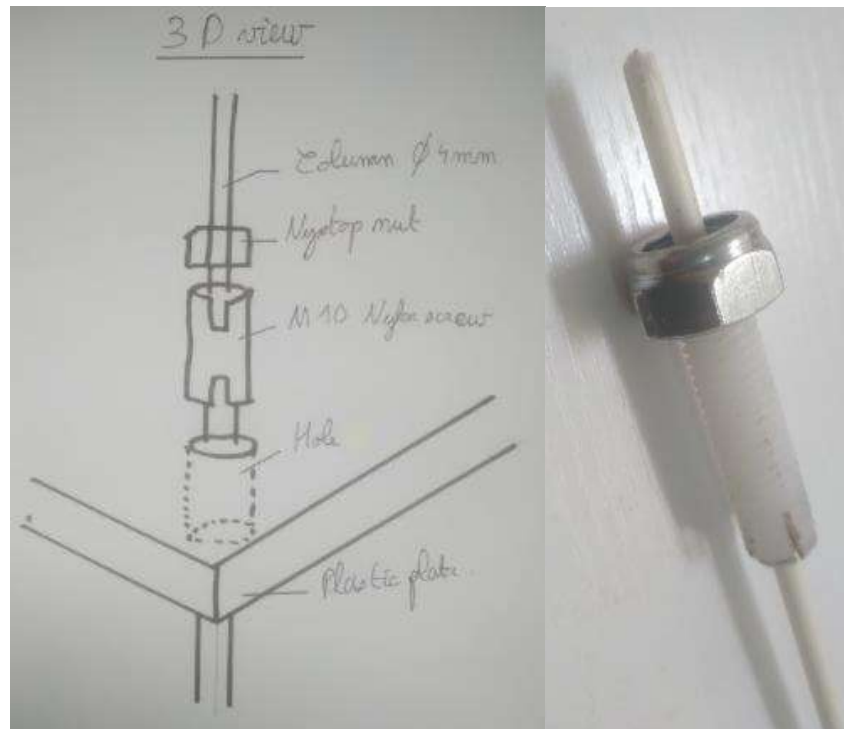


Figure 38 : Sketches of mandrel drill system

This solution is **inspired by the system inside a drill with a mandrel** and the rotative system which keeps tighter and tighter the column inside the screw when we turn the nylstop nut again and again. So, the idea here is to put the column inside a manufactured M10 screw and then according to holes inside the screw we can put a nylstop nut that will compress the screw as well as the nut. To put the system in, we have to manufacture current holes that are present on the plastic plate with a diameter of 6,5mm to 10 mm in order to put the nylon screw fixation. **The liaison is partial, direct, removable, and made by friction.**

We can find below a sum up of all previous ideas, the pros and the coins of each solution.

Technical solution	Advantages	Disadvantages
Flexion stress	<p>Allow to add bracing even if the column is inside the building</p> <p>Use reversible deformation of the plastic and fibreglass</p> <p>Use a previous solution, we don't need to print other part</p> <p>Keep the column tight well</p> <p>Easy to fix and remove with standards objects (screw and nut)</p>	<p>If we put too much effort on the screw the 3D printed part can break because flexion stress can be very huge or the column breaks.</p>

Mandrel drill system	<p>Easy to put and fix on the plastic plate</p> <p>Standard nuts and plastic screw used</p>	<p>Auto blocked nuts are a bit more expensive than normal nuts.</p> <p>Hole and cuts inside the nylon screw are difficult to manufacture (made by manual way)</p> <p>Need to drill the plastic plate with a screw to make the fillet.</p>
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Table 14 : Pros and cons of PF1 solution

Finally, **we have chosen to keep the previous solution we have found before** because it is easy to fix on the plastic plate due to the screw system, keeping the column very tight. It's also the same part as before so we don't need to buy or print something else.

As a result, **we will have almost the same process in order to build the building.**

CF 2 Resist to the environment + CF4 Be maintainable

Pieces will be done by 3D printer with PLA plastic.

We have to bear in mind that **PLA is recyclable**, so it's an eco-friendly material. We have also **used metal or nylon standard screws and nuts as well**. Then it is very easy to change those components.

CF3 Respect the budget of the project

It is the same cost as before for the previous system because it is the same product.

Implementation in CATIA V5

It is the same part as before for the previous system.

We have kept exactly the same system as before :

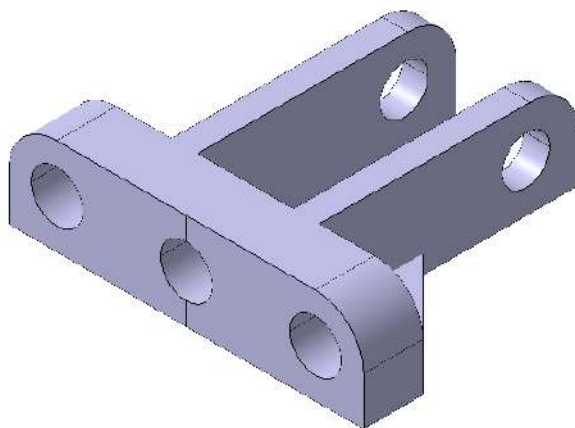


Figure 39 : 3D and real model of the join for inside column

Building construction

So, we don't make another prototype, we just use the part we have done before. We have used the same prototype as the previous chapter, but here we have the column inside the hole of 6,5 mm of diameter instead of the M6 nylon screw.

So now, after printing and manufacturing all the joints as well as nylon screws, we can build the entire building. You can find all the components of the building in the appendix 7.



Figure 40 : Stuff needed in order to build the building

So, in order to build the building, we have at our disposition :

1. Rubber in order to increase the friction stress between the joints and the column.
2. Plastic plates that represent a floor level of the building.
3. M8 screw in order to add bracings as well as keep the column tight to the plastic plate
4. M8 nylon nut in order to keep bracings tight to the plastic plate.
5. Multifunctional joints in order to add floor level as well as introduce bracing to the entire building (for the first floor and for other floors).
6. First floor joints.
7. Columns of the building.
8. Bracings, component that improve the dynamic behaviour of the building.

So, if we want to build the building we have to follow these steps below :
(we will explain how build a floor of the building).

1. Put the plastic plate (that represents the floor of the building) vertically
2. Put 2 joins on the upper part, the nylon screw which keep the column tight is already inside the join

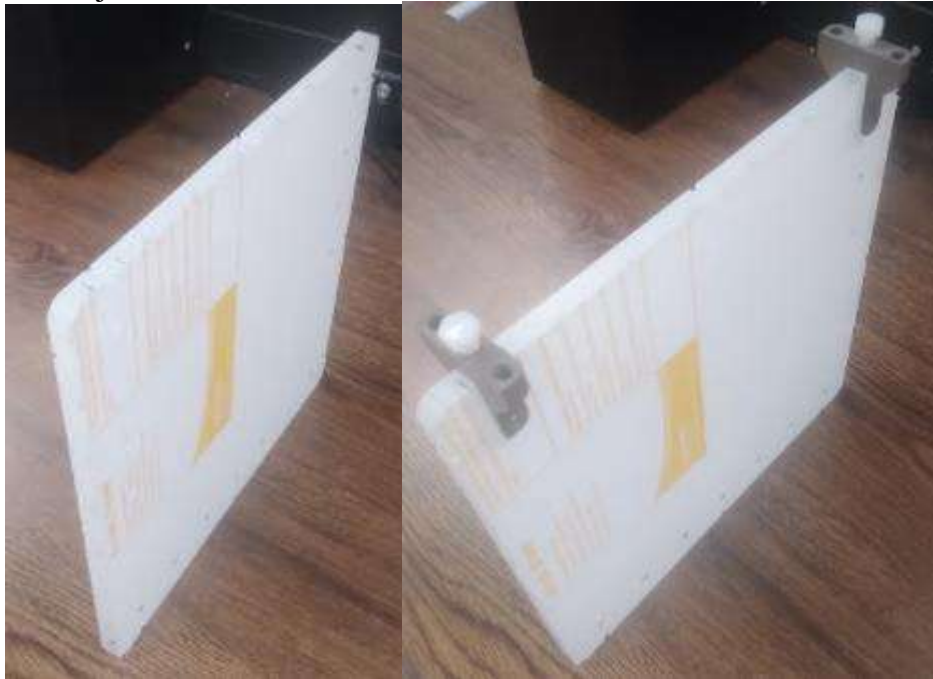


Figure 41 : Building column inside configuration assembly part 1

3. Make sure that the hole of the joins is aligned with the hole of the plastic plate



Figure 42 : Building column inside configuration assembly part 2

4. Put the column inside the holes of plastic plate
5. Turn the screw in order to keep the column tight

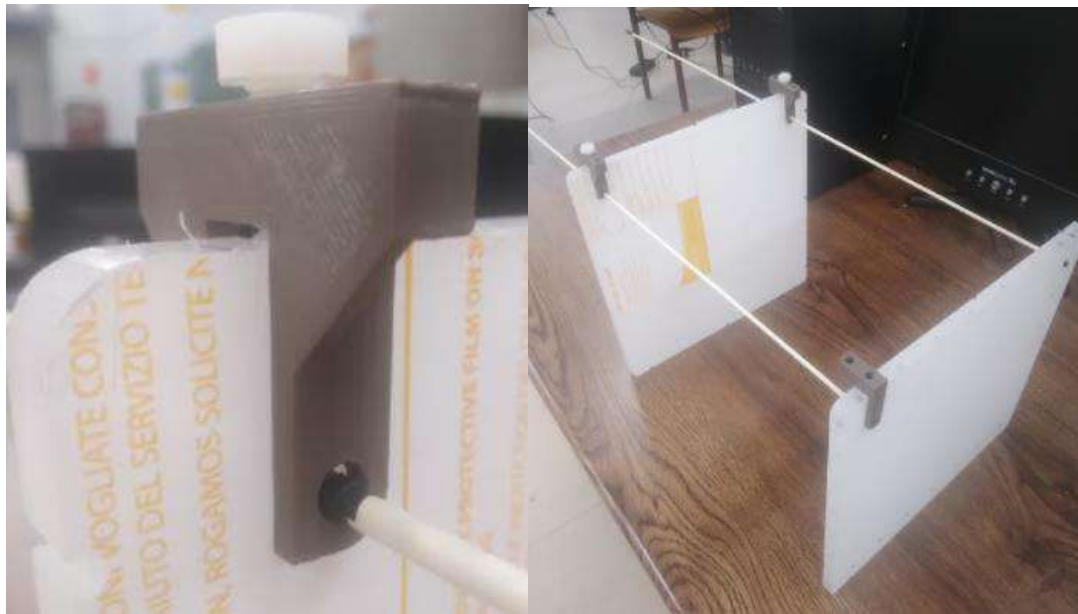


Figure 43 : Building column inside configuration assembly part 3

6. When you have done it, you can repeat the process with the next floor.
7. Return the previous building configuration system and repeat at the second step of the process in order to add the 2 next joins.

Now, after having put all the joins we need, we can introduce bracings.

In order to introduce bracings, we have to follow the step below. In this case it's to introduce diagonal bracing but you can follow all the steps again if you want to introduce X bracing.

1. Put the other half of the M8 screw with the hole inside one join.

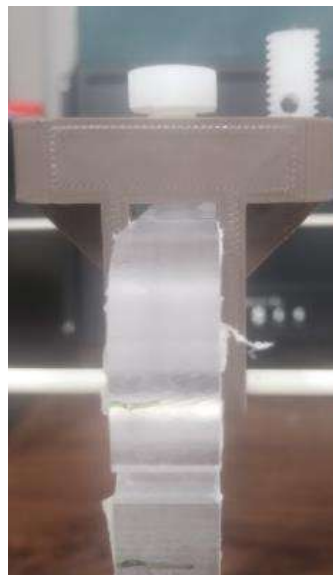


Figure 44 : Introduction of the bracings part 1



Figure 45 : Introduction of the bracings part 2

2. Do it again on the other side of the building, adjust by turning the screw.
3. Put the bracing, here this is a diagonal bracing configuration.

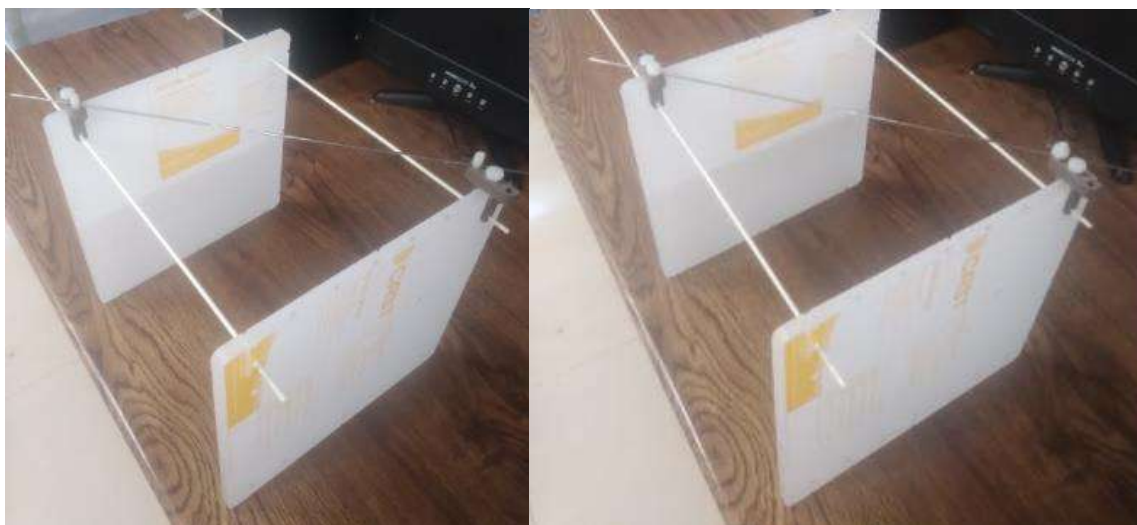


Figure 46 : Introduction of the bracings part 3

- Put nuts on each side in order to keep tight the bracing into the building.

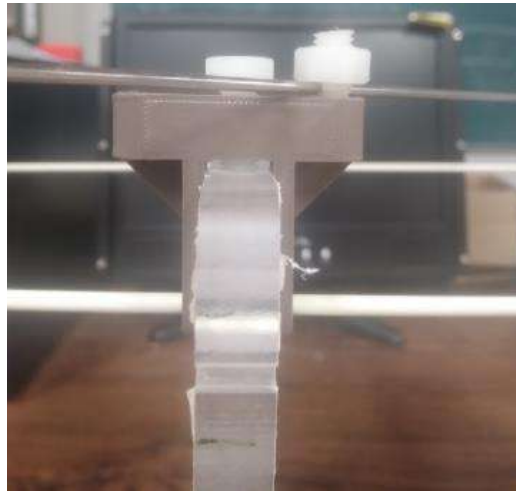


Figure 47 : Introduction of the bracings part 4

Final building

So now, let's see the final result of the building construction.

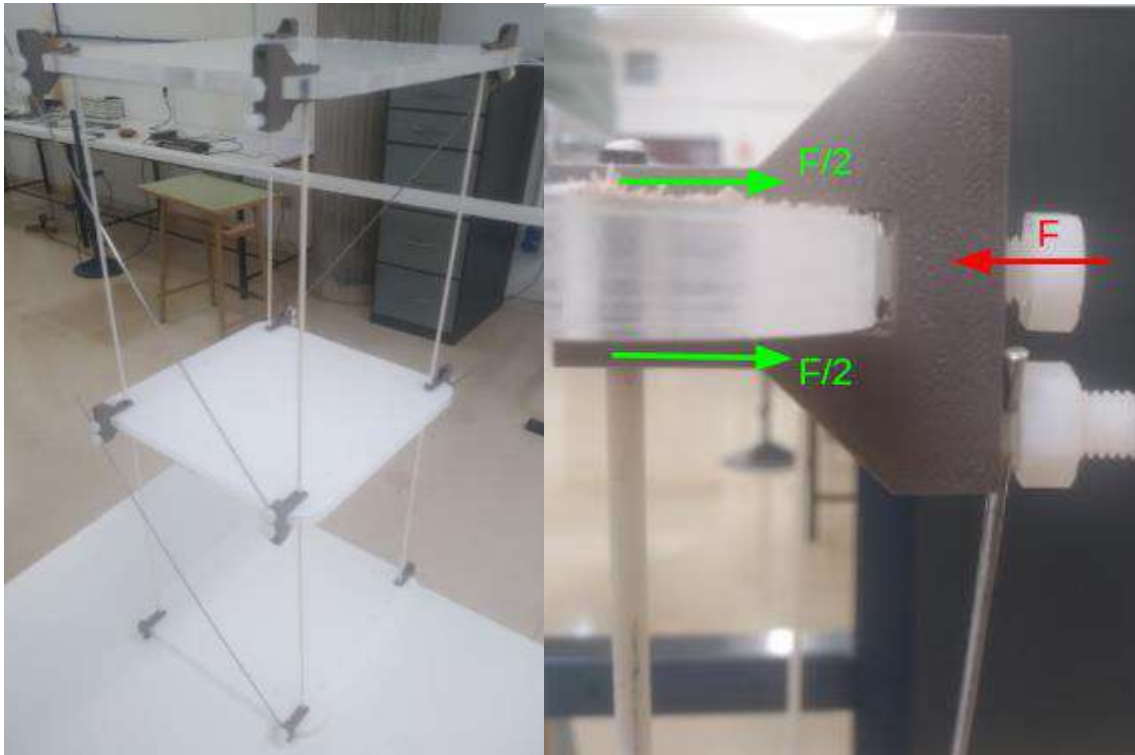


Figure 48 : 3D building model with compression screw and diagonal bracing

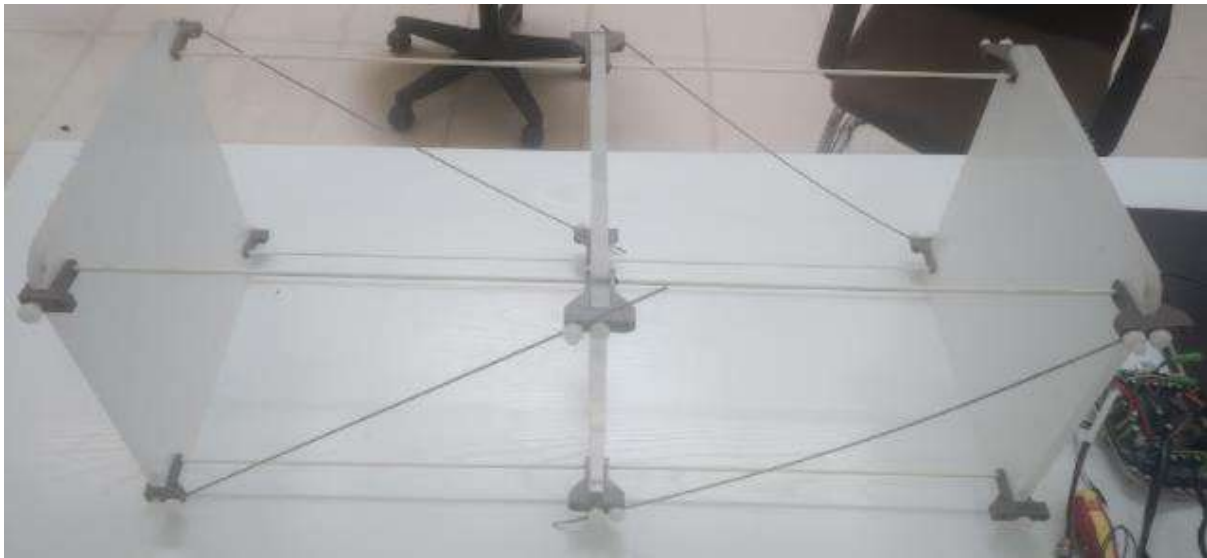


Figure 49 : Diagonal configuration of the 3D building

As we can see here, bracings are the same but the middle screw keeps the column tight by adding 2 perpendicular forces into it. ($F/2$). Plastic plates are kept horizontally with this same force as well (F)

In addition, we have decided to **add extra rubber on the column**. Indeed, we have more flexibility and **we have more friction between all components when we have vibration solicitation**. Thus, we have more dissipation of energy that causes an increased shock absorption of the building.

So, let's recap all the aspects of this solution

Advantages	Drawbacks	Solutions of improvement
<p>Rubber on columns adds more friction force between all parts of the building. Consequently, the building resists more vibration solicitation.</p> <p>Mechanical behaviour is close to a 2D dimension building model when we put vibration in a manual way due to bracings.</p>	<p>The friction link between all the parts is a bit weak. As a result, the building tends to rotate around itself or floors change height.</p> <p>Hard to put the plastic plate into the column in a vertical way in order to build the building.</p> <p>Joins can make a 90° rotation if the screw is not tight enough to the plastic plate.</p>	<p>Reduce the width of the joins of 12mm to 8mm in order to have a range of motion of the screw wider than before. Then, we can put more flexion stress in order to keep the column tight.</p> <p>Building it horizontally is easier than the vertical way.</p>

Table 15 : Pros and cons of the final prototype



Figure 50 : Joins at the bottom of the structure which can rotate

Conclusion :

This building is a bit weaker than the previous one because of the lack of stress for keeping the column tight and the plastic plate as well. Of course, there are some drawbacks of these joins but you have to take into account that **these joins can be used in 2 different cases (columns inside and outside the plastic plate).**

One, with the column inside the building and the other when columns are outside the building. That's why the join is a bit too strong in the previous case (columns outside).

Then, these joins work well for both uses.

Indeed, **the building is used to illustrate the dynamic behaviour of the building to students of the university.**

5 / Vibrations behaviour analysis

The goal of this part is now to study the dynamic behaviour of the building when we have vibration solicitation and also to see how bracing influences its dynamic behaviour and response (natural frequencies)

Theoretical part

First of all, we are going to **approximate the behaviour of the building b) by the 2 models with mass and spring a)**. So, we are going to have 2 natural frequencies. So, it's a system with 2 degrees of freedom.

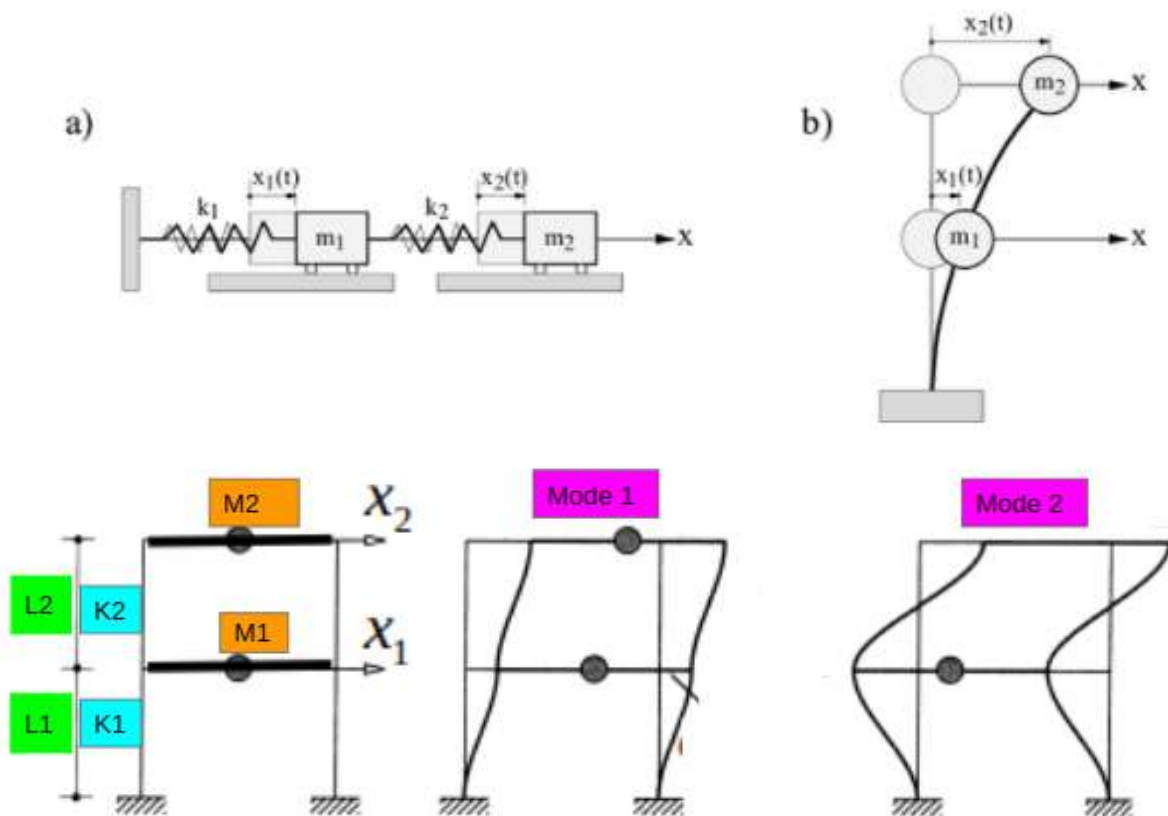


Figure 51 : Simplification of the dynamic behaviour of the building [6], [7]

In order to find the K_1 and K_2 we have assimilated the column as a spring with stress. So, in this situation and according to the [8] documentation, the K for a column is equal to :

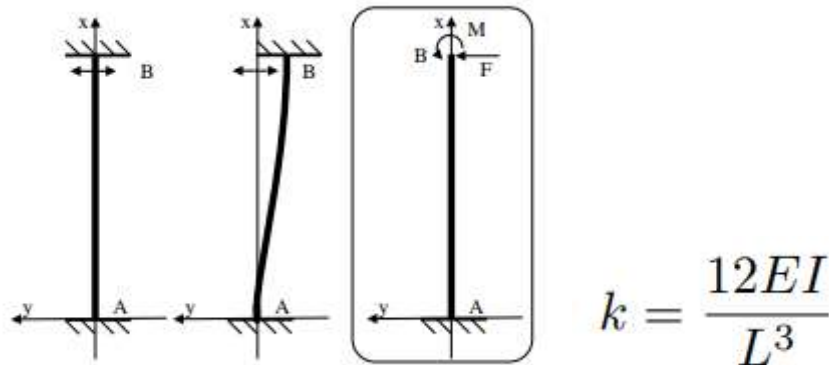


Figure 52 : Simplification of the column behaviour [8]

First, let's calculate the masses of the system (recap of masses in the appendix 7)

$$M1 = \text{mass plate} + 4 \times \text{mass of one join} + 4 \times \text{mass of one bracing} = 1,57 \text{ kg}$$

$$M2 = \text{mass plate} + 4 \times \text{mass of join} = 1,50 \text{ kg}$$

So, according to [8] document and theoretical equations, we have the theoretical value of k for one column above (figure 52) as we said before.

But in our case, **we have 4 columns for each floor so the equivalent spring is 4 times the K of a column.** (springs in series)

$$K1 = \frac{4 \cdot 12 \cdot 46 \cdot 10^9 \cdot 1,02 \cdot 10^{-11}}{0,38^3} = 411,86 \text{ N/m}$$

$$K2 = \frac{4 \cdot 12 \cdot 46 \cdot 10^9 \cdot 1,02 \cdot 10^{-11}}{0,33^3} = 628,87 \text{ N/m}$$

So according to physics laws we have the system below :

$$\begin{cases} M1 \cdot \ddot{x}_1(t) = -K1x_1 - K2(x_1 - x_2) \\ M2 \cdot \ddot{x}_2(t) = -K2(x_2 - x_1) \end{cases}$$

$$\Leftrightarrow \begin{cases} M1 \cdot \ddot{x}_1(t) + K1x_1 + K2(x_1 - x_2) = 0 \\ M2 \cdot \ddot{x}_2(t) + K2(x_2 - x_1) = 0 \end{cases}$$

$$\begin{bmatrix} M1 & 0 \\ 0 & M2 \end{bmatrix} \cdot \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} K1 + K2 & -K2 \\ -K2 & K2 \end{bmatrix} \cdot \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix}$$



Finally, we have :

$$\det([K] - \lambda[M]) = 0 \Leftrightarrow \det \begin{bmatrix} (K1 + K2) - \lambda M1 & -K2 \\ -K2 & K2 - \lambda M2 \end{bmatrix} = 0$$

$$[(K1 + K2) - \lambda M1] * [K2 - \lambda M2] - [-K2^2] = 0$$

$$M1M2\lambda^2 + (-M1K2 - M2K1 - M2K2)\lambda + K1K2 = 0$$

So we have these numerical value :

$$M1 = 1,57 \text{ kg}$$

$$K1 = 411,86 \text{ N/m}$$

$$M2 = 1,50 \text{ kg}$$

$$K2 = 628,87 \text{ N/m}$$

$$\text{Then, we have : } 2,51 \lambda^2 - 2640,14 \lambda + 259009,18 = 0$$

$$\Delta = b^2 - 4ac = 4367861,152$$

$\Delta > 0$, so we have 2 distinct reals values :

$$\lambda_1 = -b + \sqrt{\Delta} / 2a = 941,50$$

$$\lambda_2 = -b - \sqrt{\Delta} / 2a = 109,52$$

We have two values :

$$\omega_1 = \sqrt{\lambda_1} = 30,68 \text{ rad/s}$$

$$\omega_2 = \sqrt{\lambda_2} = 10,46 \text{ rad/s}$$

$$\text{So, frequencies are : } f_1 = \frac{\omega_1}{2\pi} = \mathbf{1,66 \text{ Hz}}$$

$$f_2 = \frac{\omega_2}{2\pi} = \mathbf{4,88 \text{ Hz}}$$

So, now we are going to see if these natural frequencies are good ones by making a software simulation and a real experimentation as well.

We have to take into account that we have assumed a behaviour of building in the plan (2 dimensions). But in the software, we are going to have 3 dimensions. Then we are going to have more degrees of freedom for building on the software.

Software part

Hypothesis and configuration of the model

Now, we have decided to see the dynamic behaviour of the building with different joints with the **french software RDM 7** [5] and to compare results with the practical experimentation. We just look at the vibration behaviour of the building for the same movement and for a particular mode of vibration. (natural frequencies)

So in order to build the building we have made some simplifications :

- We have neglected the dimension of the joints (but not their weight)
- We put the column and bracing at the same point

Because these simplifications are commonly used in structural engineering

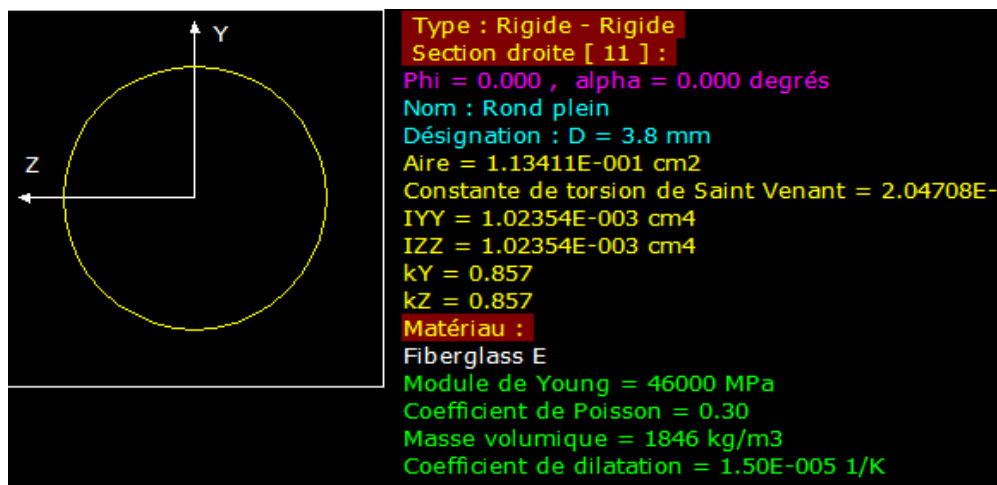
So, below we can find the **building in 3 configurations** :

- without bracings
- with diagonal bracings
- with X bracings

The material used are the same in 3 cases

- Red part (building floor) : Methacrylic with a square of 12 mm of section.
- Blue part (column) : E fiber glass column with a diameter of 3,8 mm.
- Green part (bracing) : Steel bracing with a diameter of 2,3 mm

N.B : Characteristics of these materials are in the appendix 7



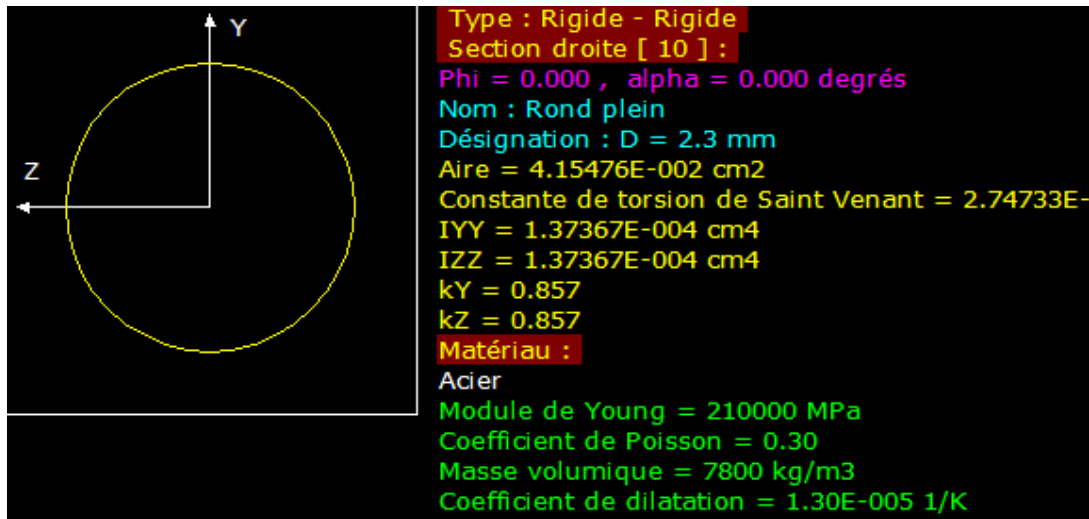


Figure 53 : Section view description on RDM7

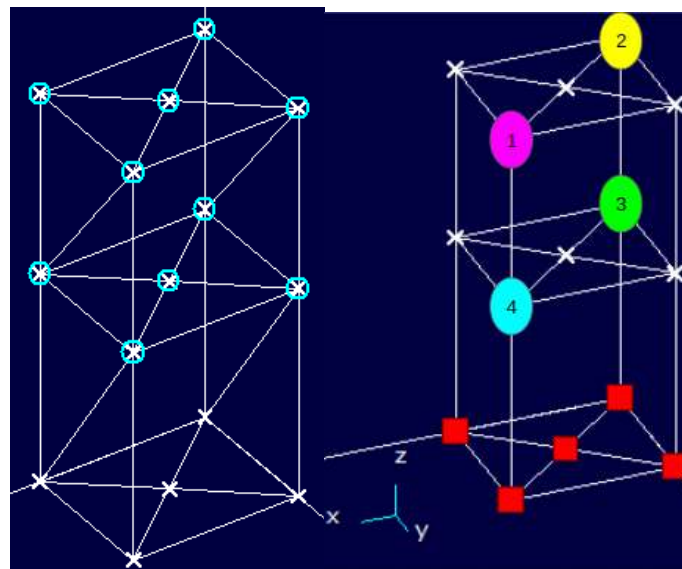


Figure 54 : Nodal mass and fixed points on the building and section view

The red parts are fixed liaison points directly connected to the ground and to simulate the behaviour of a rigid plate we have put a point in the middle of the square for each floor.

And on points in blue, we have added the extra mass in order to have the same mass as the real system. (mass of joints and accelerometers on points 1, 2, 3, 4 as the real system experimentation). So, in order to adjust the right mass for each node of our system we have put additional mass.

The side of the rectangle has a length of $L=0.25$ m and the other one has a side of $l=0,3$ m We know the area $A = 1,44e-4$ m^2 and a density of 1165 kg/m^3 as the [3] document provides.

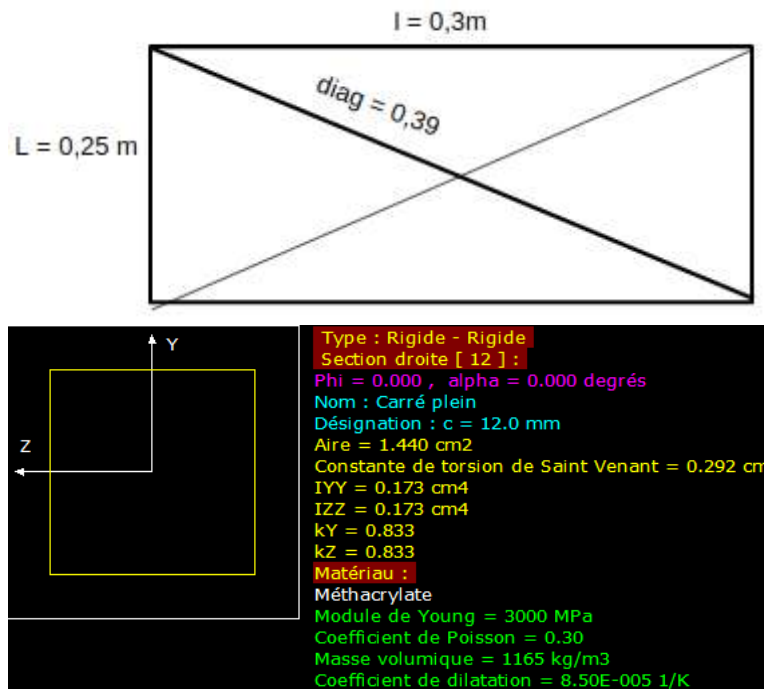


Figure 55 : Rectangle plastic section characteristic

We know that : Mass (kg) = V (m^3) x Volumic mass (kg/m^3)

So, let's calculate masses ml, mL, m diag.

$$M l = 2 \text{ (number of sticks per plate)} \times 1165 \times 1,44e-4 \times 0,25 = 0,0838 \text{ kg}$$

$$M L = 2 \times 1165 \times 1,44e-4 \times 0,30 = 0,1 \text{ kg}$$

$$M \text{ diag} = 2 \times 1165 \times 1,44e-4 \times 0,39 = 0,130 \text{ kg}$$

$$M \text{ to divide} = \text{Total} - (Ml + ML + Mdiag) = \text{approx. } 1 \text{ kg}$$

So, for each point we have to put in 0,2 kg.

In addition, we have to have the weight of the joins, **each joint has a weight of 12g.**

But **we don't have to add the mass of bracings on nodal points.** Next, we have to take into account the weight on the accelerometer of the experimentation.

We have a big one that has a weight of 54,9 g and a small one of 43,3 g.

So for each point we have :

- Point 1 : 2 smalls ones = 0,0866 kg
- Point 2 : 1 big = 0,0549 kg
- Point 3 : 1 small = 0,0433 kg
- Point 4 : 1 small and 1 big = 0,0981 kg

Then, we've put all the weight for each point.

Eventually, we have to set up the accuracy of our simulation

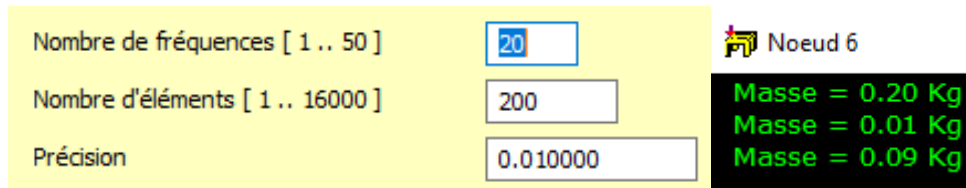


Figure 56 : accuracy of the software mode and weight (+/- 0,01 kg)

So, we can calculate the 20 modes of the system with 200 elements on the system to determine its natural frequencies. Finally, our system can be simulated.

We have 3 configurations to study with the software as well as with the real model :

1. Without bracing
2. With diagonal bracing
3. With X bracing

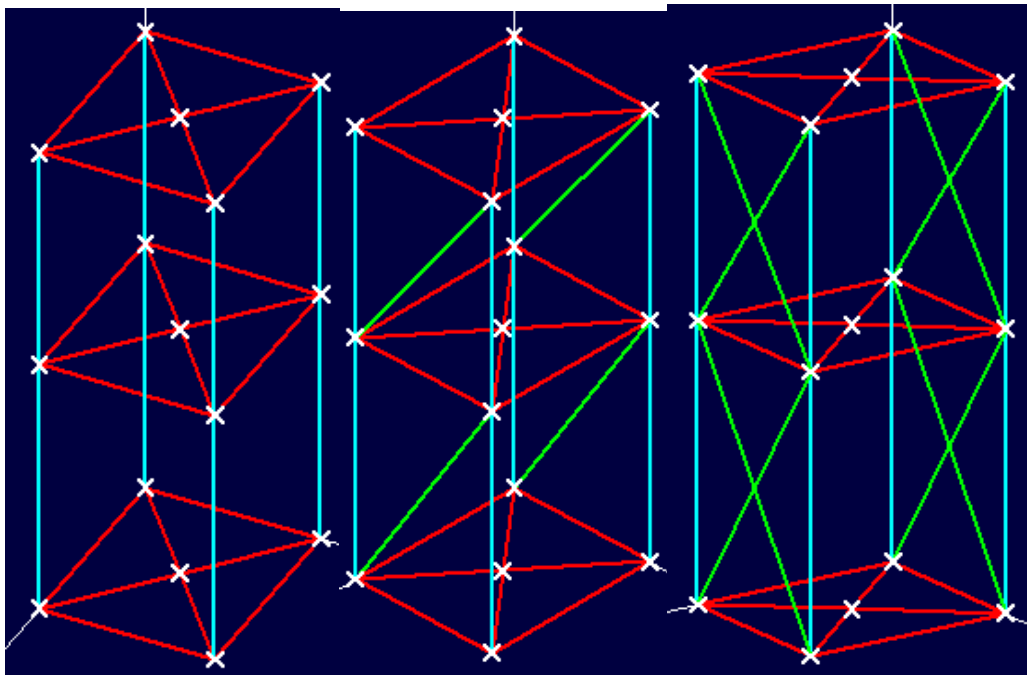


Figure 57 : Software building configuration

Configuration without bracing

In this configuration we have **6 degrees of freedoms (natural frequencies)**

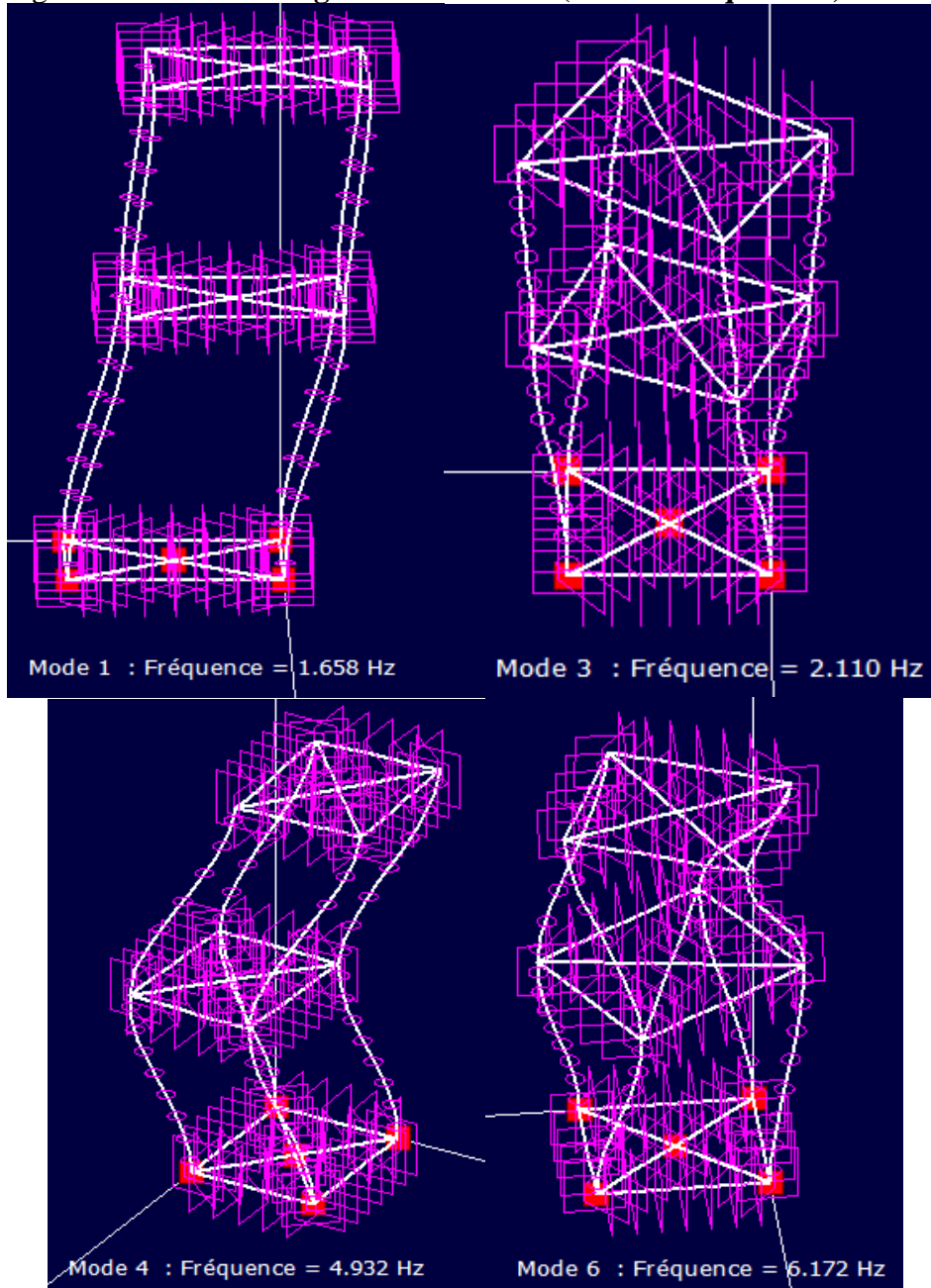


Figure 58 : Without bracing configuration in RDM7

The modes 1 and 2 are almost the same but in different directions (x and y) as well as the modes 4 and 5. So, for mode 1, we just keep the x axis mode translation/flexion and for the 4 as well. Indeed, we can see that **we have 6 degrees of freedom**, 2 translations/flexions for each floor (x and y). And two degrees of freedom in torsion (around the z axis).

Configuration with diagonal bracing

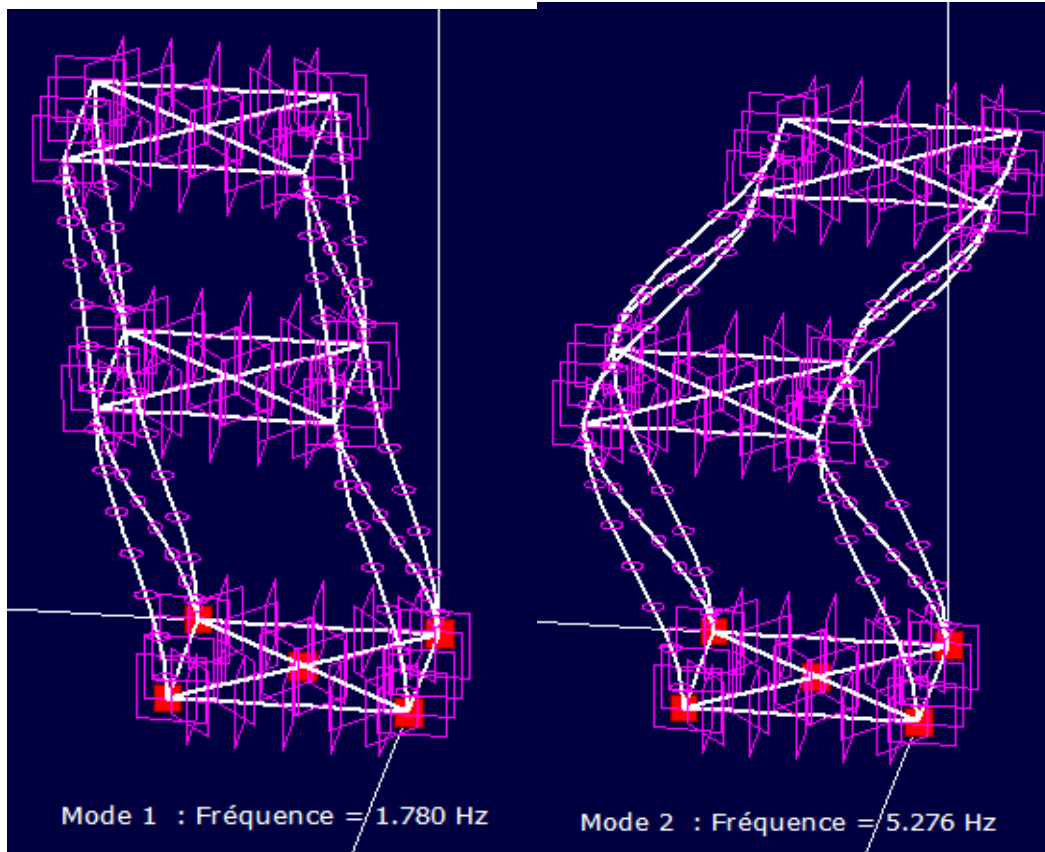


Figure 59 : Diagonal bracing configuration in RDM7

So, we see here that the addition of bracing changes the behaviour of the building. Instead of having 6 degrees of freedom as the previous model, **we now have just 2 degrees of freedom (natural frequencies) due to the addition of bracings.**

We can also see that **the natural frequencies of the system increase with the addition of bracings.**

Configuration with X bracing

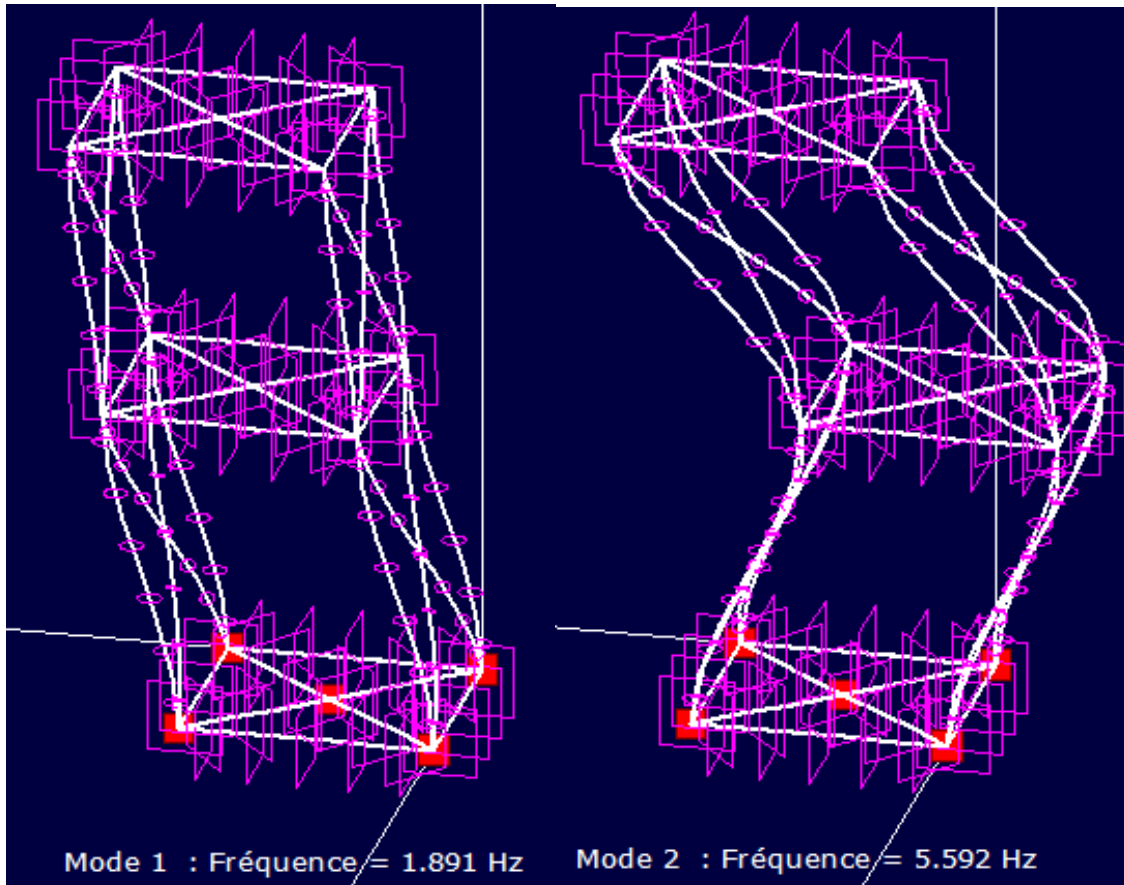


Figure 60 : X bracing configuration in RDM7

So as before, we have 2 natural frequencies provided by the software. They are more important than the previous configuration (diagonal bracings).

So, now let's compare our result with the theoretical part :

Configuration	Software values	Analytical values	Relative error
Mode 1 (Hz)	1,891	1,665	11,95 %
Mode 2 (Hz)	5,592	4,883	12,67 %

Table 15 : Comparison between X bracing software/theoretical part

We can see that we have a small relative error between the analytical part and the software (12 % of relative error approximately) So, we can conclude that our theoretical model of 2 degrees of freedom is valid. In other words, it's a good approximation of the software model.



Recap of result

Configuration	Without bracing	Diagonal bracing	X bracing
Mode 1 (Hz)	1,658	1,780	1,891
Mode 2 (Hz)	2,110	5,276	5,592
Mode 3 (Hz)	4,932	x	x
Mode 4 (Hz)	6,172	x	x

Table 16 : Recap of result of the software between different bracing

We can see that **the addition of bracing increases the natural frequencies of the building.** As a result, the more we have bracings the more the building can resist an earthquake or vibration solicitation for instance. (because its natural frequencies have increased and we have a 2 dimensional movement of the building with bracings instead of having a 3D without bracings). Indeed, we need more energy to make a vibration on the building.

So, we can see that **the addition of bracings decreases the number of degrees of freedom of the building.**

As a result, the building is more stable because we have decreased the number of freedoms.

Others bracing configuration

So, in this part, we are going to see if the addition of bracing in other configurations also affects the behaviour of the building as well as its natural frequencies.

We have to take into account that due to a lack of time during the project, we are not going to do the real model experimentation of these configurations.

We are just going to have a closer look at these configurations with the software and check if the 2-dimensional (2D) model is valid for these configurations as well.

So, below we can find the 2 natural frequencies of these other configurations.

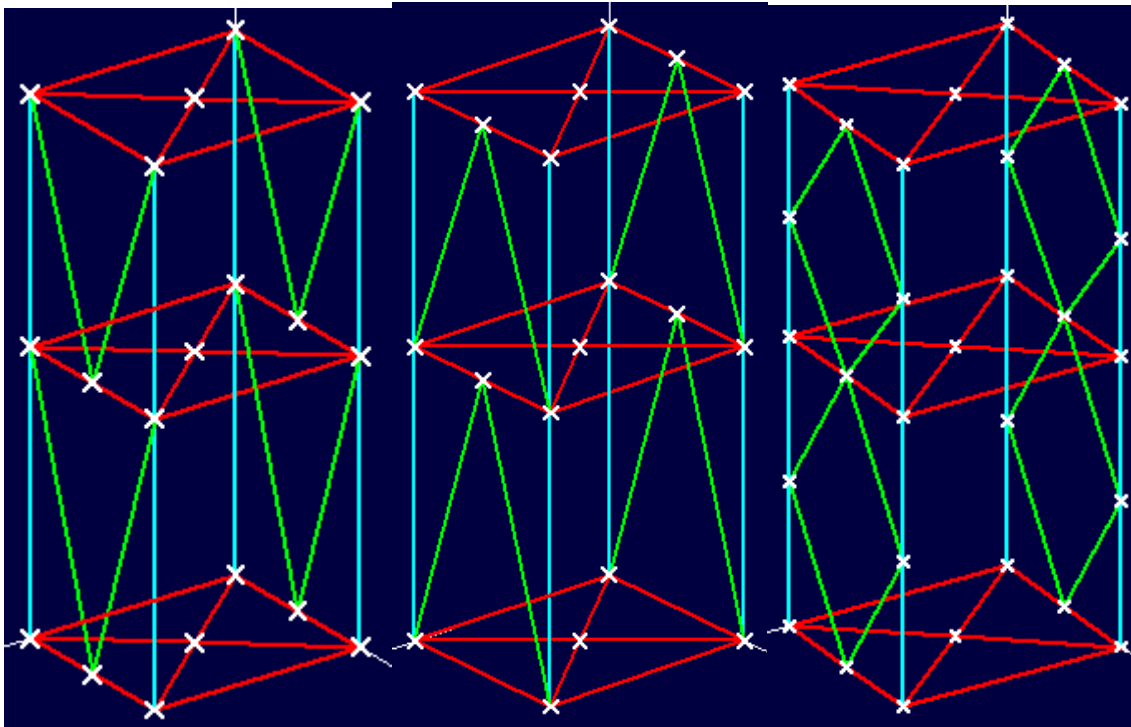


Figure 61 : Other bracing configuration

V bracing configuration

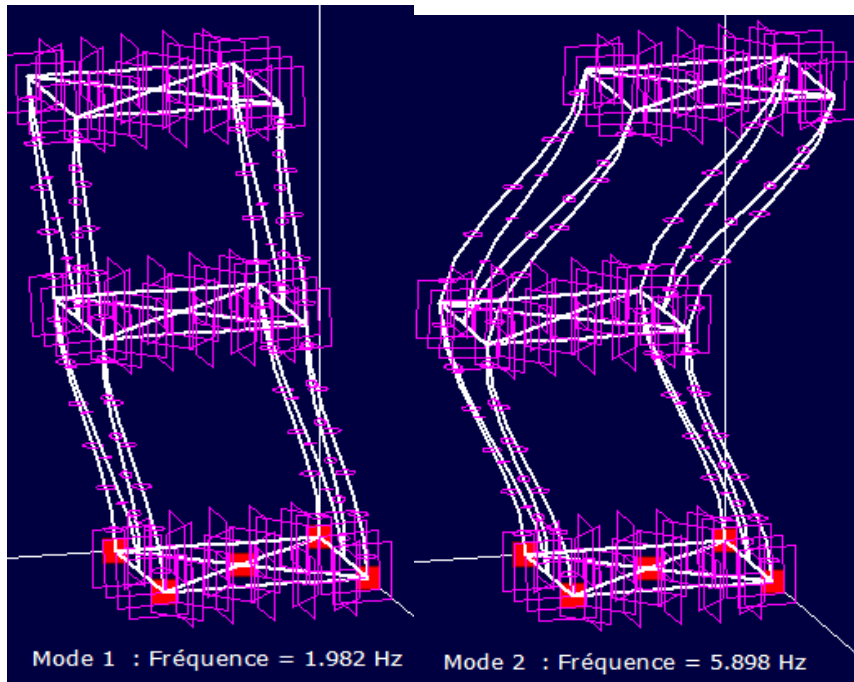


Figure 62 : V bracing configuration in RDM7

V inverted bracing configuration

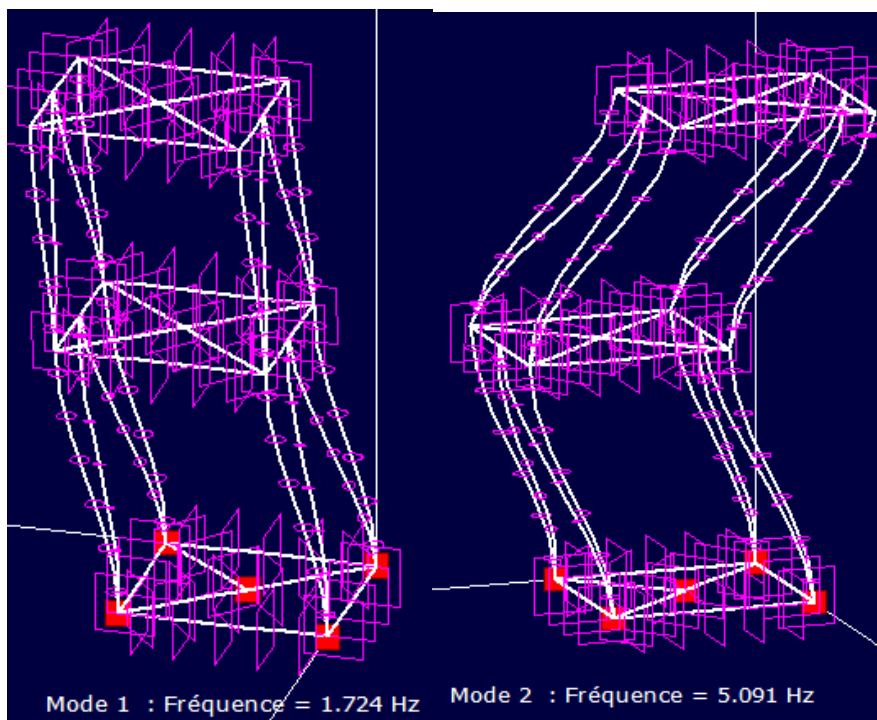


Figure 63 : Inverted V bracing configuration in RDM7

K bracing configuration

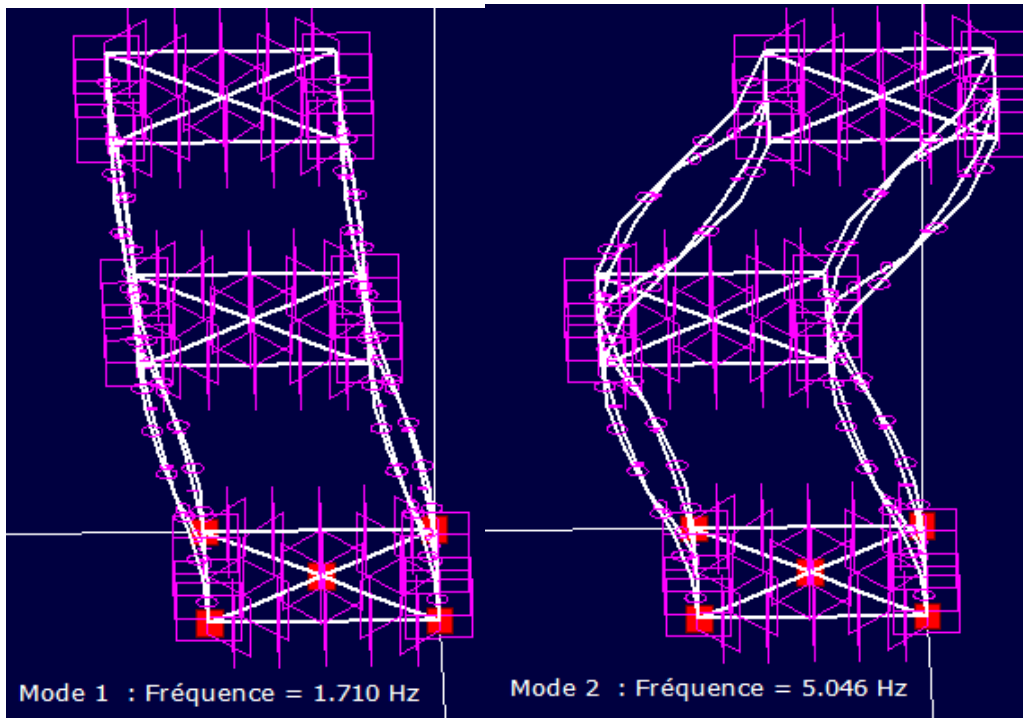


Figure 64 : K bracing configuration in RDM7

So, in any bracing configuration, we can see that the addition of bracing changes the dynamic behaviour of the building (its natural frequencies as well as its degree of freedom).

In addition, we can see that natural frequencies of the K and inverted V configuration are close together. And the V configuration is close to the X configuration (natural frequencies).

This is normal because they have almost the same weight as the X configuration.

So, the 2D model is also valid for other bracing configurations.

Experimental part

So, now let's **check if the results from the software are correct in the real world.**

In this part we are going to check the dynamic behaviour of the system in the laboratory. We have put accelerometers on the building to measure the frequencies of the building.

Setup of the system and acquisition of data

We can find below the system configuration (column outside the building). We have chosen this configuration because the building is more rigid in this situation.

We don't have the same origin in the software but we have the same axis system (x,y,z).

Thanks to the help of the laboratory staff, we have put 6 accelerometers (4 in the x direction and 2 in the y direction) in order to check the frequency response of the building (appendix 9).

All the data are collected and injected to the Dewesoft software (acquisition of data)

For the axis system we have :

- In red X axis and point of application force
- In blue Y axis and point of application force

In addition, the points where we gathered the data were :

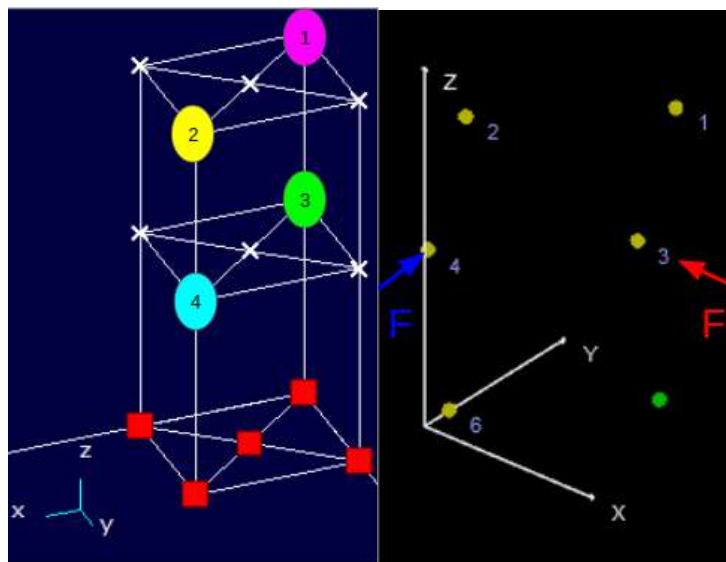


Figure 65 : Acquisition points of data of the software

We have only knock :

- Point 3 in order to see the x direction, knock with a certain F force in x direction only
- Point 4 in order to see the y direction, knock with a certain F force in y direction only

So, in total we have done 6 experiences. We have repeated each experience 5 times on average in order to avoid errors of measurements and then we keep the average values of frequencies.

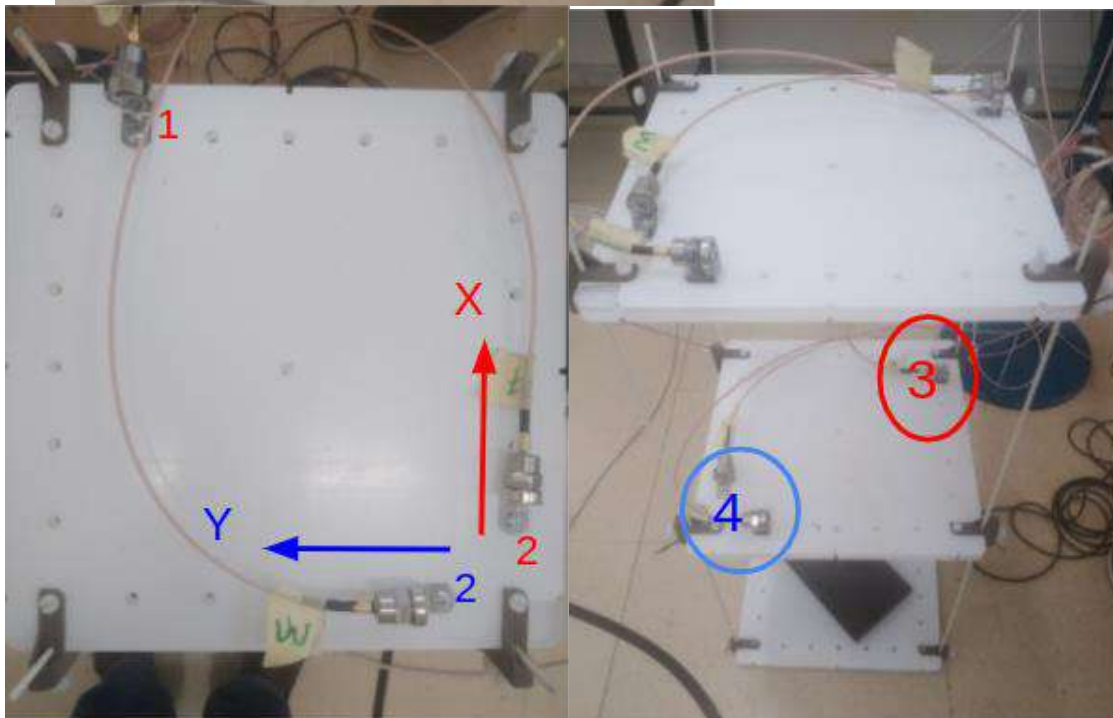
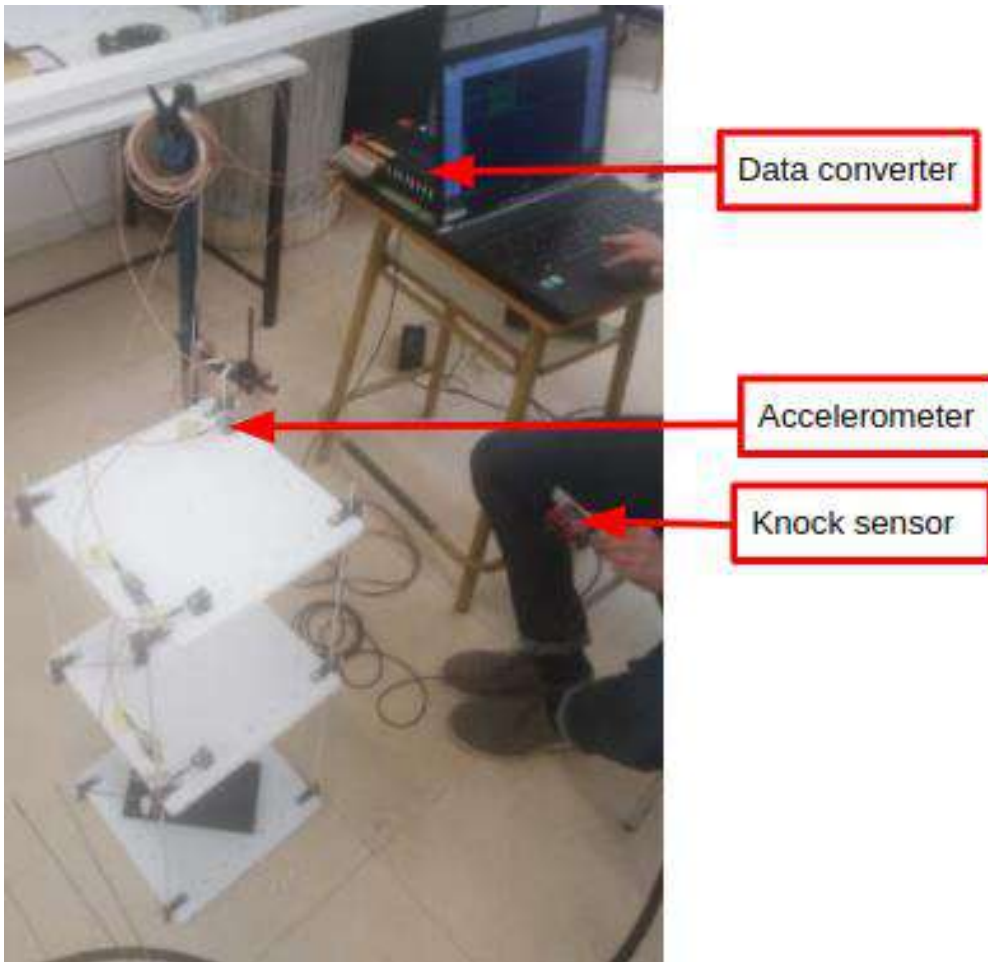


Figure 66 : Building with accelerometers set up

Configuration without bracing

So, here we don't put any bracings on the building as we can see below :



Figure 67 : Without bracing configuration building

The weight at the first floor represents the red point (fixed part of building) of RDM7.

So, at first glance, without bracing the system tends to **vibrate very easily in all direction** (x, y) translation and rotation for each floor.

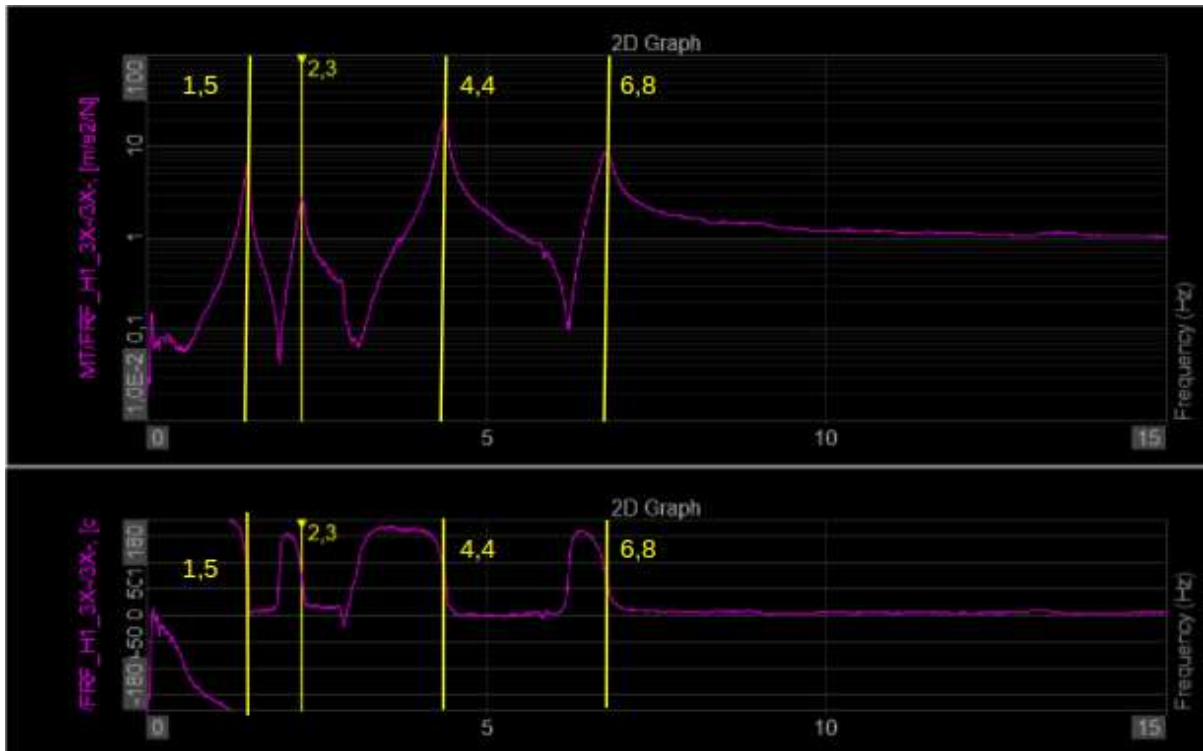


Figure 68 : Screenshot from the Dewesoft software of the natural frequency of the building, without bracing configuration, in x direction

So, as predicted by the software we have natural frequencies, with 4 pics.

In fact, the 4 pics of frequencies represent the 4 degrees of freedom of the system.

Indeed, we have 1 translation in x and y for each floor.

$$f_1 = 1,5 \text{ Hz}, f_2 = 2,3 \text{ Hz}, f_3 = 4,4 \text{ Hz}, f_4 = 6,8 \text{ Hz}$$

In addition, **these frequencies cut the phase diagram at the middle of the decrease curve.** That demonstrates that these frequencies are the natural frequencies of the system.

Indeed, we need to study a 6-degree model in order to approximate its behaviour because we also have natural frequencies in the y axis.

But it is very difficult to do it that's why we use bracing in order to get a system with 2 degrees of freedom. Then, it is easier to approximate the dynamic behaviour of a 2 degree of freedom system than a 6 degrees of freedom system.

Configuration with diagonal bracing

So, here the second configuration is to put one bracing on each side of the building.



Figure 69 : Diagonal bracing configuration building

So, in this situation the addition of bracings almost blocks the translation in the y direction as well as the rotation around the z axis (translation in y and x). (**reduce degree of freedom**).

So, let's see if the decreased number of freedoms is certified by the experimentation.

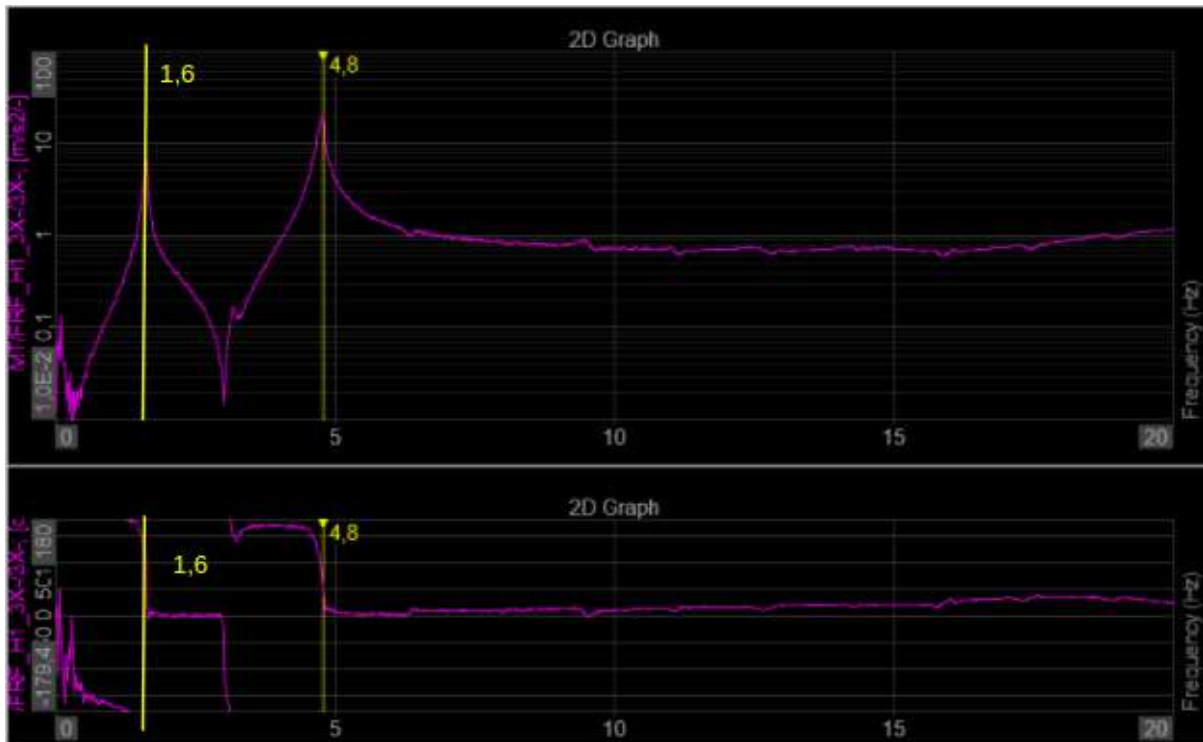


Figure 70 : Screenshot from the Dewesoft software of the natural frequency of the building, diagonal bracing configuration, in x direction

As we can see, we have **2 pics that represent the 2 degrees of freedom of the system** 1 degree of translation in x for each floor.

$$f_1 = 1,6 \text{ Hz and } f_2 = 4,8 \text{ Hz}$$

These frequencies cut the phase diagram at the middle of the decrease curve. That demonstrates that these frequencies are the natural frequencies of the system. As a result, **we have changed the behaviour of the system.** We can see with these graph that we have higher natural frequencies than the previous model (without bracings).

Configuration with X bracing

In this ultimate situation, we have put all the bracing in X, on each side of the building

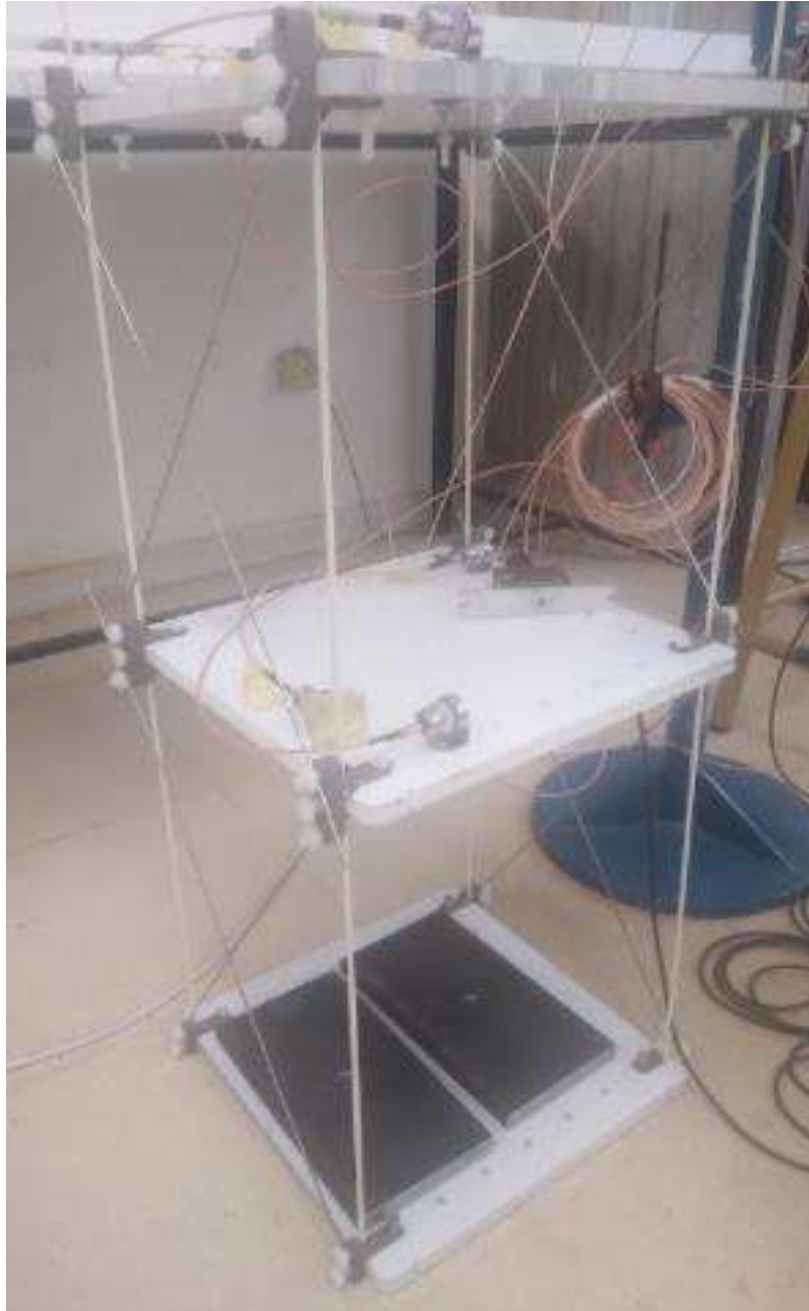


Figure 71 : X bracing configuration building

In this situation, we have put the X bracing configuration. The system is more rigid here. It can only move on the x axis as the diagonal bracing configuration.

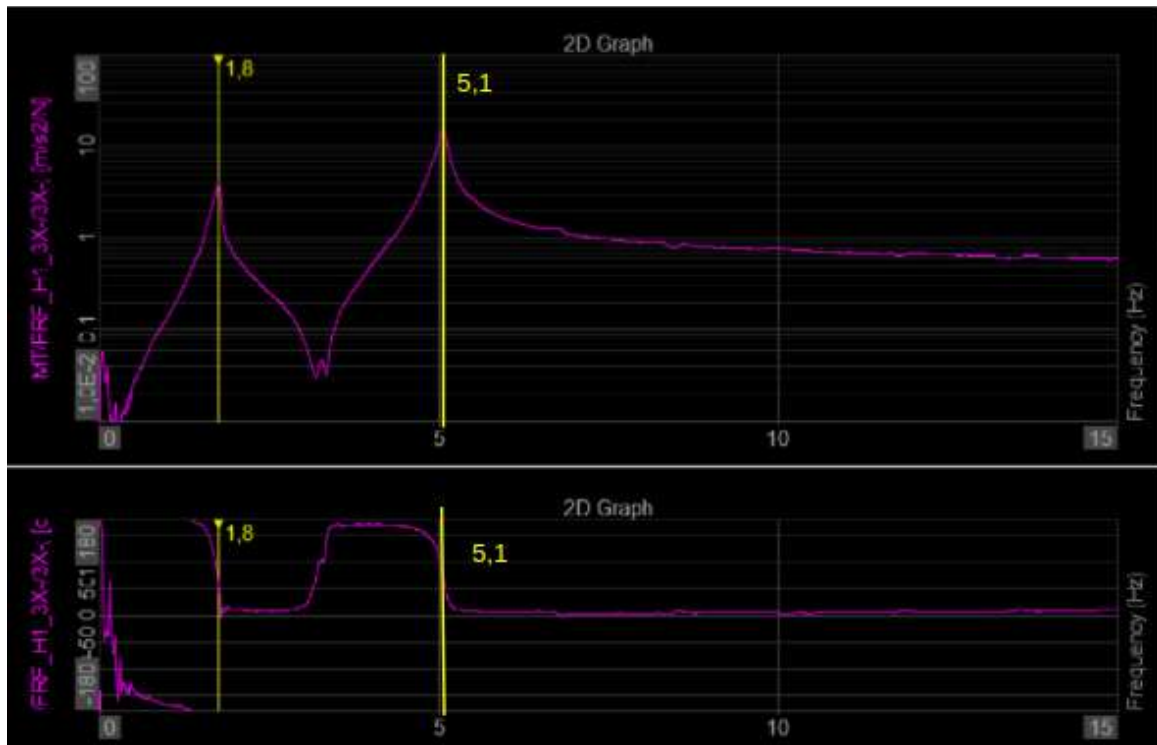


Figure 72 : Screenshot of the Dewesoft software of the natural frequency of the building, X bracing configuration, in x direction

As before, we have 2 pics that represent the 2 degrees of freedom of the system.

$$f_1 = 1,8 \text{ Hz and } f_2 = 5,1 \text{ Hz}$$

And according to the experience, we have a higher frequency response than the previous configuration (diagonal bracing).

Solicitation in the y axis

So, now let's see the answer in the y axis stimulation in these 3 configurations

Without bracing configuration

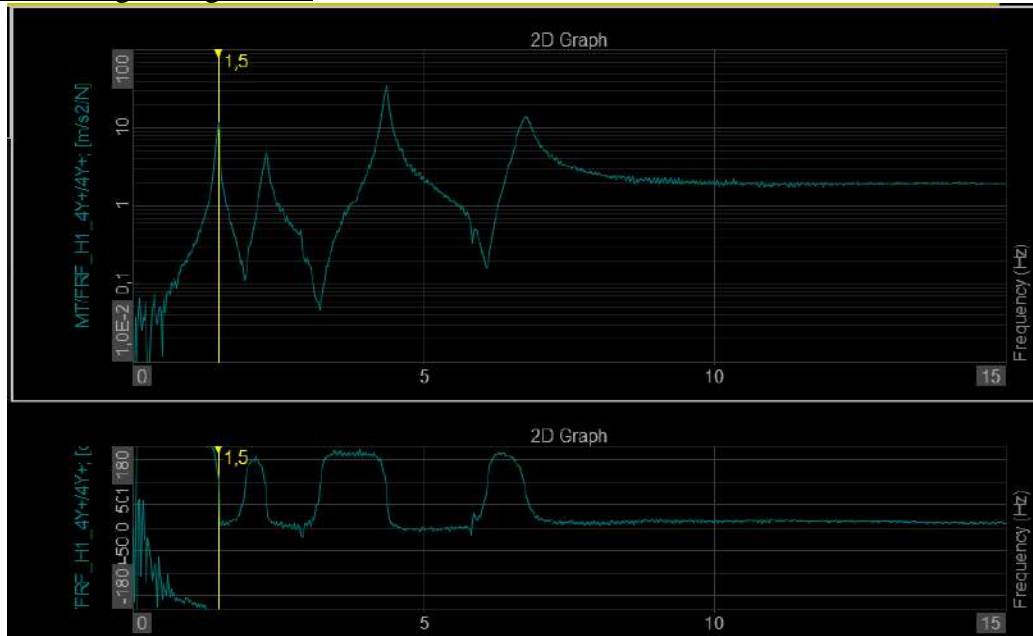


Figure 73 : Y axis response, sin bracing configuration

As we can see in the y direction, we have almost the same natural frequencies response as in x direction. That confirms that we have a 6 degree of freedom system.

Diagonal bracing configuration

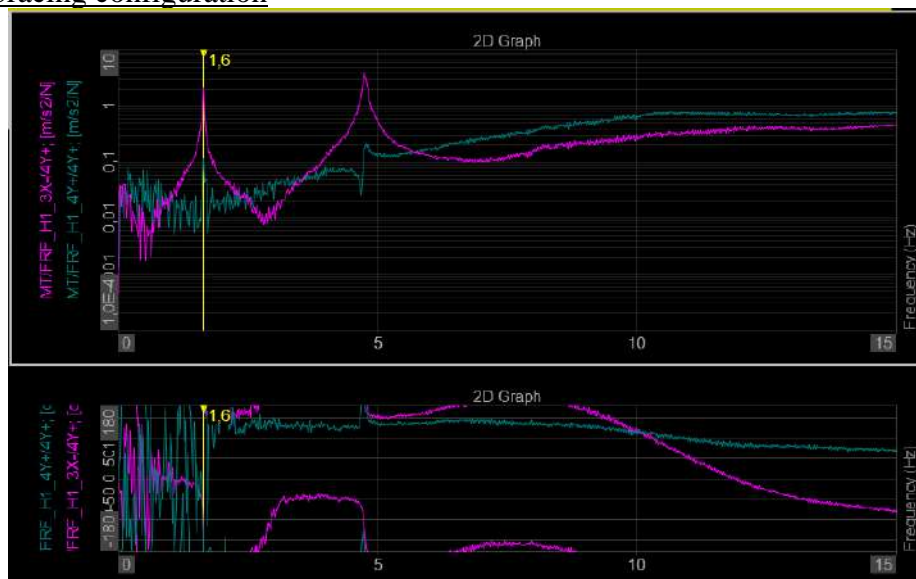


Figure 74 : Y axis response, diagonal bracing configuration

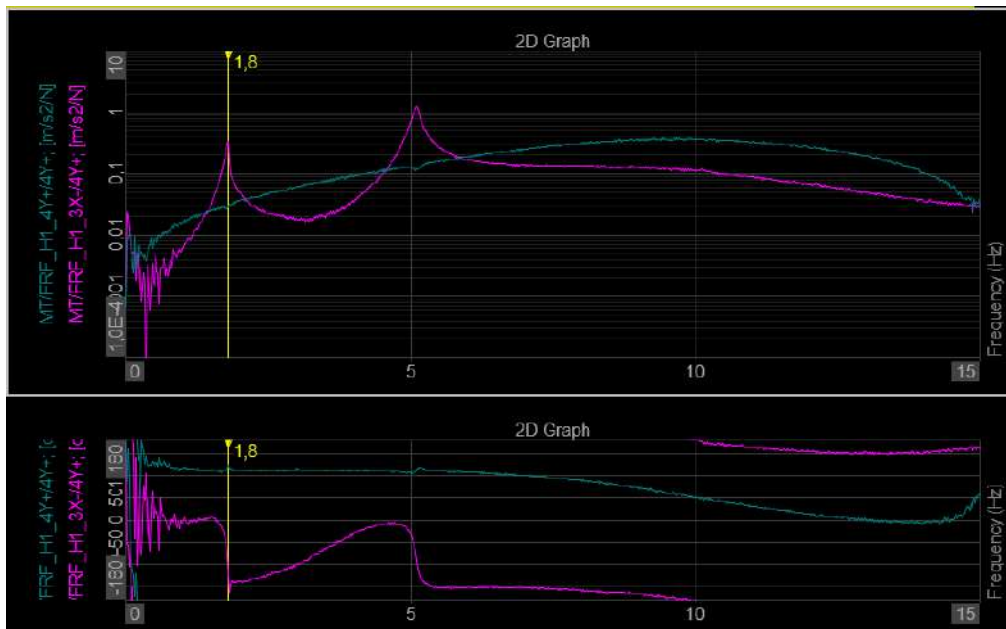


Figure 75 : Y axis response, X bracing configuration

The purple curve represents the response of the accelerometer at point 3 in x direction. We can see that these 2 last situations (diagonal and X bracing configuration) don't have natural frequencies in y axis direction (blue curve) because we don't have pics upwards like in x axis direction (purple curve). So, the movement in y axis direction is almost no existent. Indeed, frequencies are very attenuated in the y axis direction (blue curve)

So, we can conclude that our model of 2 degrees of freedom in the x axis is correct because we don't have natural frequencies in the y direction.



Recap of the result

So, let's recap the results in the x axis, we have gathered in these 3 experiences :

Configurations	Frequency of the software	Frequency of the real model	Relative error (Theoretical-practical)/ theoretical
Without bracing			
Mode 1	1,65	1,50	9,53 %
Mode 2	2,10	2,30	4,76 %
Mode 3	4,93	4,48	9,16 %
Mode 4	6,17	6,8	10,17 %
With diagonal bracing			
Mode 1	1,78	1,64	7,86 %
Mode 2	5,27	4,78	9,40 %
With X bracing			
Mode 1	1,89	1,80	4,30 %
Mode 2	5,59	5,10	8,79 %

Table 17 : Recap of frequencies result software/real model

So, after getting results we can see that **the answers in frequencies are close to the frequencies we get from the software**. We have an average error of **8 % approximately**, we have a **weak error software/practical**. Indeed, that's not a big relative error average.

So, it is a good approximation of the real building dynamic behaviour.

So, we can conclude that our software model is a relevant view of the dynamic behaviour of the real model.

We can explain the difference by the simplification we have made in the software as well as the configuration of the real building.

Conclusion

First, **the frequencies of the building have increased by the addition of diagonal bracing**. That's normal because we have changed the global behaviour of the building.

Second, **the addition of bracings on the building decreases the number of degrees of freedom of the system**.

In fact, before adding bracing the building can move in 6 directions (translation in x and y for each floor as well as torsion) but when we have added bracings, the building can only move in 2 directions (translation in x for each floor). So, it is easier to predict its behaviour with a dynamic equation, for example as the theoretical part we have done before.



6 / Conclusion and future lines

In conclusion, I have managed to imagine and develop a join in order to add bracing to a 3D model building. As a result, with bracings the 3D model has the behaviour of a 2D building model, then **the main objective of the joins was fulfilled**.

But current joins I had made can be improved, especially in plastic consumption and in the printing time. All in all, **this project was very interesting in all its aspects**.

It allows me to undertake a real project like an engineer in a company with a holistic point of view of the conception and prototyping process (appendix 2 and 3). Then, I had the opportunity to develop my skills in conception and in prototyping with a 3D printer.

On a personal side, it was the first time I have worked on a 3D building model in the structural domain. And it was very interesting for me to discover it. Thus, it was interesting to know more about methods that can improve this kind of model. Moreover, I continued to develop my skills in project gestion and methodology, on CAD software and written skills in English too.

In our opinion, the future lines of work will be :

- Print V join in order to add and study other bracing configurations
- To make real experimentations with other bracing configurations in order to have a holistic aspect of the behaviour of the building in all configurations we can make.

Then, we can compare the results obtained with the real system, the software, and the theoretical way. Then we will be able to conclude on the best bracing configuration in order to resist vibration solicitations.

In addition, there is a 2D building of the laboratory that also needs bracing but it is a much bigger building than the previous one. So, we can use the same idea of joins in order to add bracing but in a bigger way than the previous one.



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- [11] https://fixation.emile-maurin.fr/custom/docs/gamme/for_b2_f1/regle-implantation-vis-for_b2-lfor3.pdf
- [12] https://blogs.univ-tlse2.fr/ip3a/files/2020/03/Resonance_CONTENU.pdf
- [13] http://bboy78.free.fr/Cours%20TN01/C9_SolutionsTechnologiques.pdf



Appendix

Appendix 1 : Cost of components

Product	Cost per unit (€)	Website
Nylon screw M6	0,15 €	https://es.aliexpress.com/item/1005004335191674.html?spm=a2g0o.productlist.main.85.270e7e76xdekIY&algo_pvid=95ba2ee3-a9a9-4461-8388-63f52ad8b2fc&algo_exp_id=95ba2ee3-a9a9-4461-8388-63f52ad8b2fc-42&pdp_npi=3%40dis%21EUR%212.23%210.98%21%21%21%21%21%21%402145279016854872656773873d0790%2112000028803380070%21sea%21ES%210&curPageLogUid=iDGc54bUN4Zf
Nylon screw M8	0,28 €	https://es.aliexpress.com/item/1005004307521473.html?spm=a2g0o.productlist.main.51.3e2644a9vGk3FB&algo_pvid=70477e59-ca55-49ed-9678-ff7d4c4e6aaf&algo_exp_id=70477e59-ca55-49ed-9678-ff7d4c4e6aaf-25&pdp_npi=3%40dis%21EUR%211.91%210.98%21%21%21%21%21%21%402100b0d116854875242896329d0742%2112000028700365761%21sea%21ES%210&curPageLogUid=XUZGDd6IAcFO
Nylon nut M6	0,11 €	https://es.aliexpress.com/item/1005004307521473.html?spm=a2g0o.productlist.main.51.3e2644a9vGk3FB&algo_pvid=70477e59-ca55-49ed-9678-ff7d4c4e6aaf&algo_exp_id=70477e59-ca55-49ed-9678-ff7d4c4e6aaf-25&pdp_npi=3%40dis%21EUR%211.91%210.98%21%21%21%21%21%21%402100b0d116854875242896329d0742%2112000028700365761%21sea%21ES%210&curPageLogUid=XUZGDd6IAcFO
Nylon nut M8	0,14 €	https://es.aliexpress.com/item/1005004307521473.html?spm=a2g0o.productlist.main.51.3e2644a9vGk3FB&algo_pvid=70477e59-ca55-49ed-9678-ff7d4c4e6aaf&algo_exp_id=70477e59-ca55-49ed-9678-ff7d4c4e6aaf-25&pdp_npi=3%40dis%21EUR%211.91%210.98%21%21%21%21%21%21%402100b0d116854875242896329d0742%2112000028700365761%21sea%21ES%210&curPageLogUid=XUZGDd6IAcFO
3D printer plastic	20 €/kg	Approximately in Spain

Appendix 2 : Times of action

Action	Time
To drill one M8 screw	1 min
Cut one M8 screw	30 s
Fix the column tight	5 s
Put the system inside the plastic plate	30 s
Print a part (3D printer)	Approx 45 min



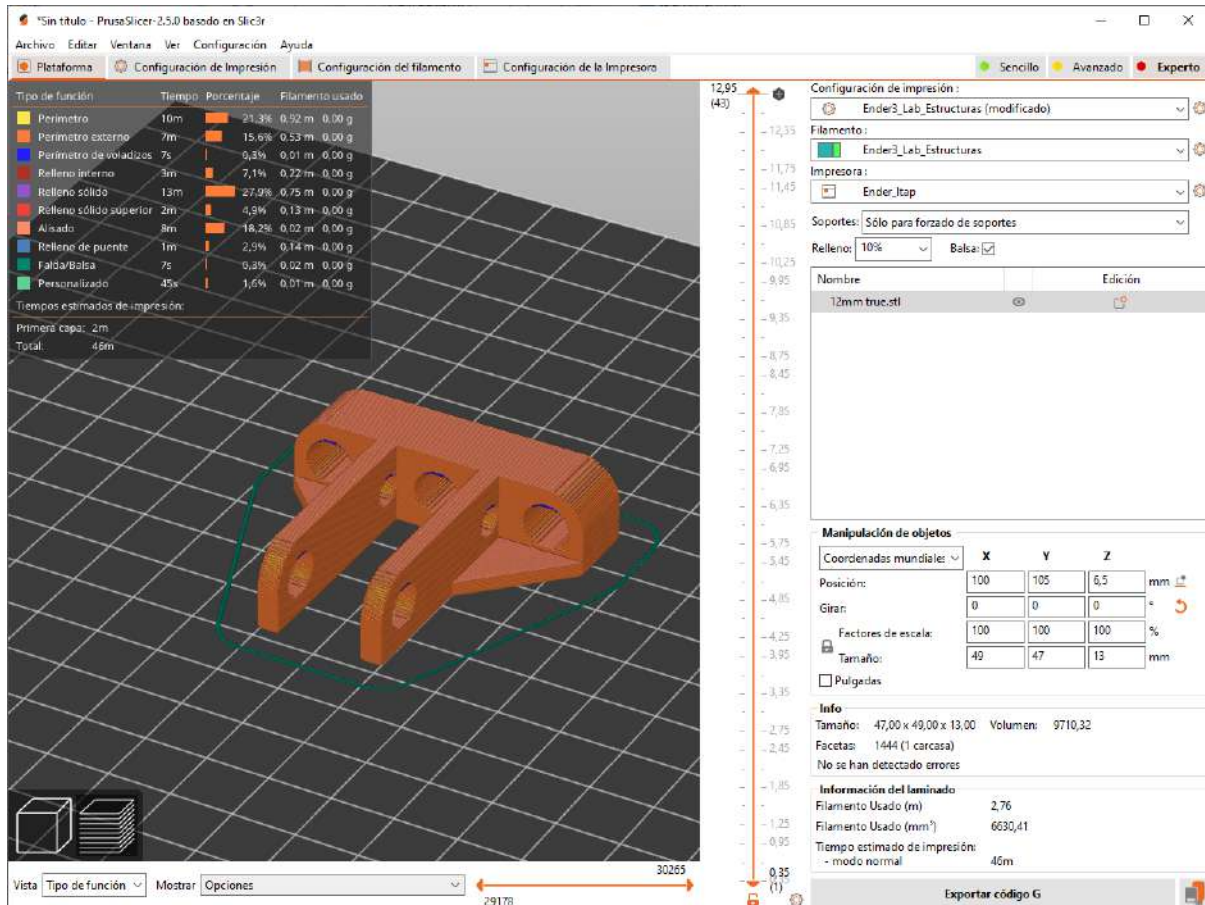
Adjust the bracing completely	Approx 10 s
Building/Disassemble the building with bracing	5 min approx.
Cut the 12 M8 nylon screw	3 min
Drill the 12 M8 nylon screw	3 min
Put the rubber for all the columns	3 min
Make a measure of vibration behaviour	10 min approx.

Appendix 3 : Time costing

We don't really remember how much time we have taken for this project so we have taken the estimated time provided inside the syllabus of this discipline.

Action	Time
Work inside the laboratory/day in average	3h
Week (Monday to Friday)	15h
Total estimated (lab and homework)	300h
Minimum salary in Spain	6,75 €/h
Total cost if I was paid (minimum)	2025 €

Appendix 4 : Interface of Prusa Slicer software

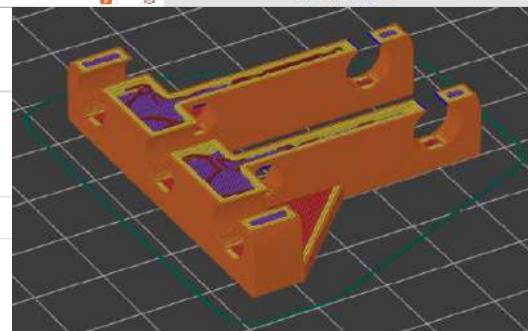


Altura de la capa

- Altura de la capa: mm
- Altura de la primera capa: mm

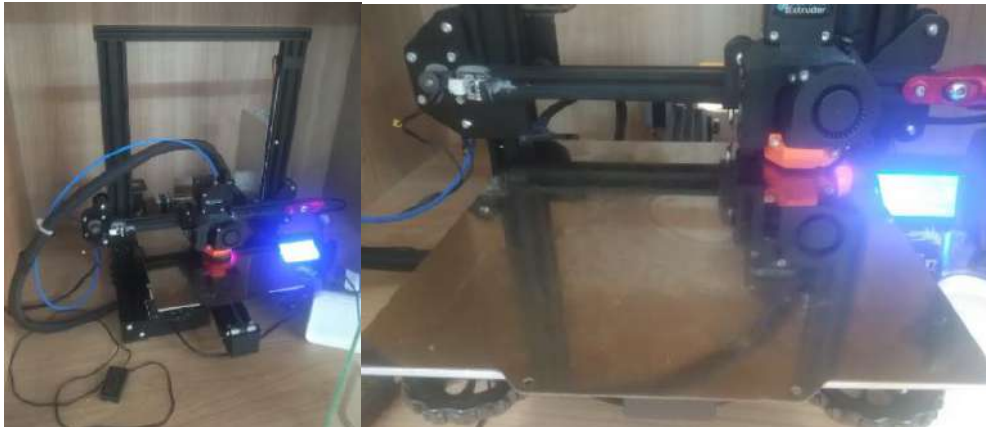
Carcasas verticales

- Perímetros: (mínimo)
- Modo vaso:



There are screenshots of the view of the printed part as well as parameters put inside. **We have decided to print the part very fast because accuracy is not very important here.** But if we print slowly, the part will be more well-made and stronger. In addition, we have to adjust the temperature of the bed and the plastic as well. **The values were 65°C for the bed and 210°C for this plastic on average.**

Appendix 5 : Characteristic of the 3D printer of the laboratory and parameter to print prototype



Accuracy of 3D printer :

Holes : between 0,1 to 0,3 mm less than on the computer dimensions

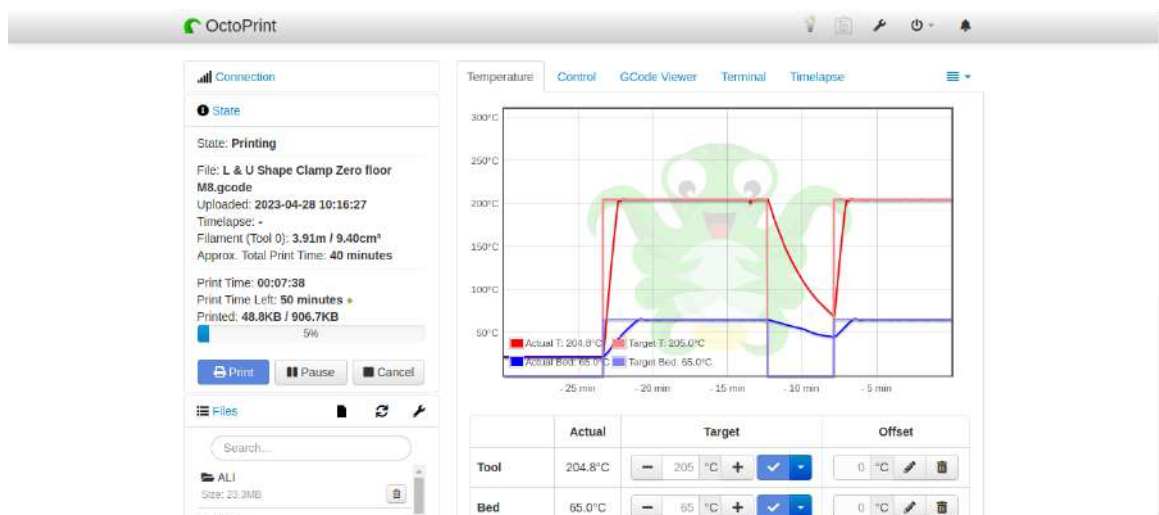
Width : 0,1mm less than on the computer dimensions

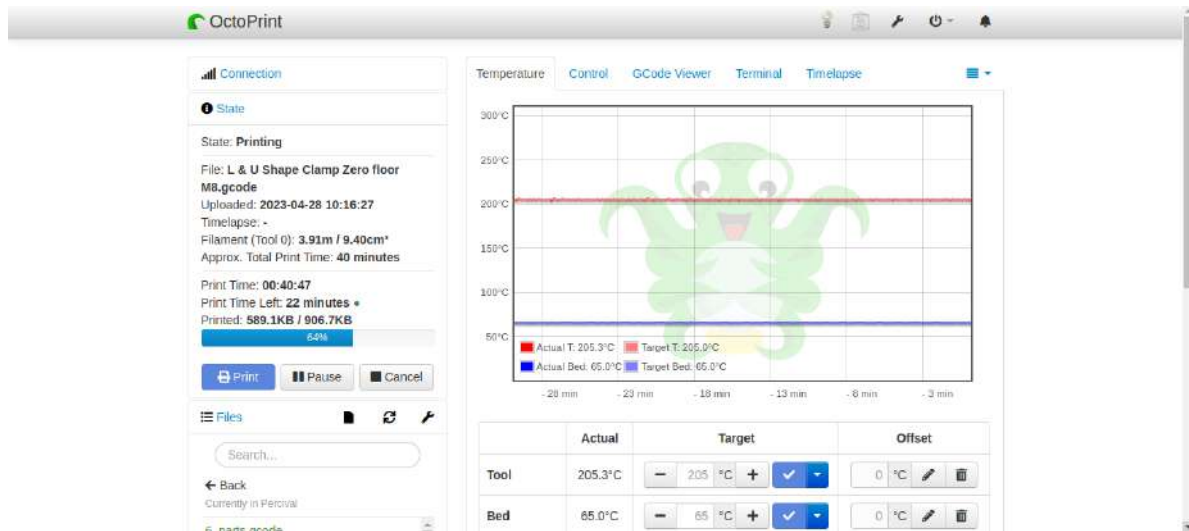
Plastic used : PLA which is recyclable, an eco-friendly material

Appendix 6 : Interface with the computer

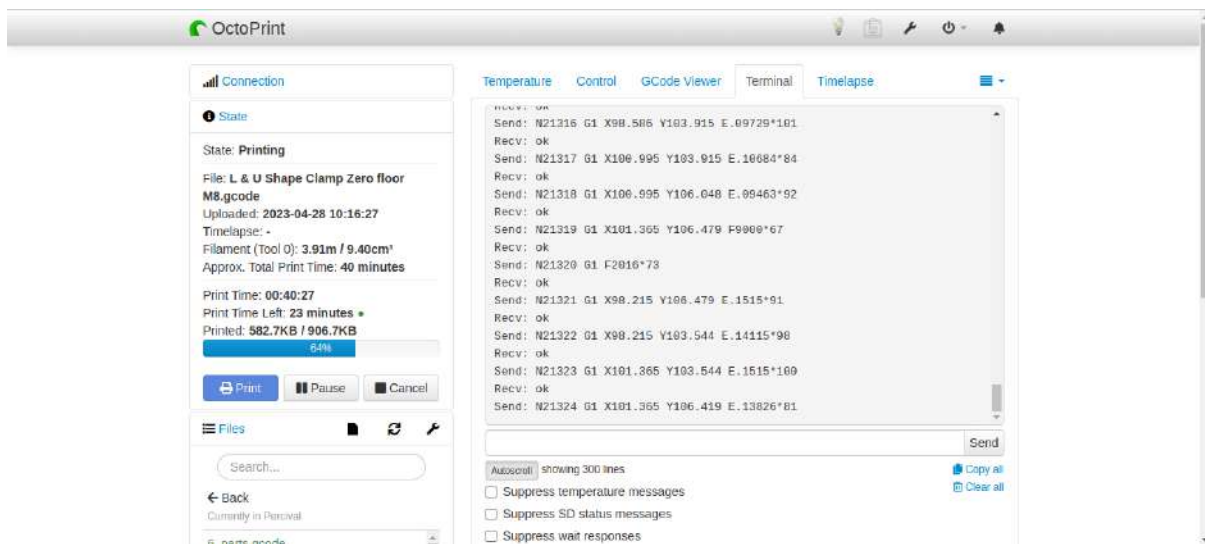
Here, you can find the interface between the computer of the laboratory and the 3D printer. This is an internal website dedicated to the 3D printer of the structural laboratory.

Bed temperature input and response of the system and a stationary situation



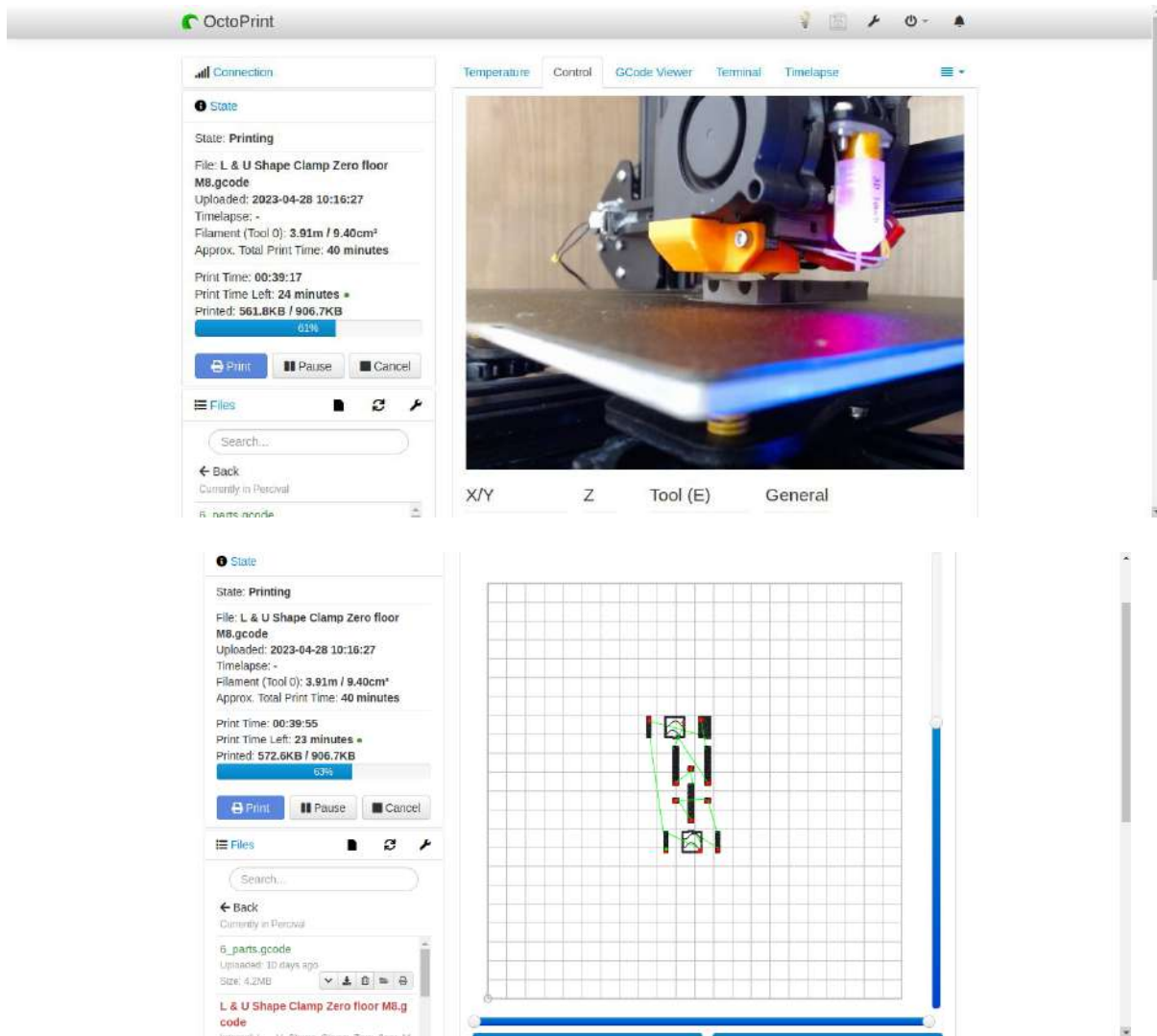


G-Code execution from prusa slicer





Visualisation of the 3D printing part process



Appendix 7 : components of the 3D building model



Column of the 3D building :
 Length approx. 77 cm
 Diameter 4 mm approx. (real 3.8 mm)
 Weight : 17,4 g
 Mater : fibreglass

bar measurements	
Length	750mm
Diameter	4mm
Mass	17.4g

glass characteristics	
Density	1846.2 kg/m ³
Young's modulus	46000MPa

Board extracted from the [2] report (constructor data)



Plastic plate of the 3D model building
 Dimension 30,5 cm x 30,5 cm that represents a floor of the building.
 Weight : 1,310kg
 Mater : methacrylate

plate measurements	
Side Length	305mm
Thickness	12mm
Mass	1310.1g
Surface hole diameter	7mm
Side hole diameter	4mm
methacrylate characteristics	
Density	1165kg/m ³
Young's modulus	3000MPa

Board extracted from the [2] report (constructor data)



Metal bracing with a diameter of 2,3mm length 1000mm
 Total weight : 36g (=> 1 bracing = 18g)
 Mater : steal

Recap of mass of components of the 3D building

Components	Mass
Full joins (3 half nylons screw)	12 g
Mass of one bracing	18 g
Mass of one accelerometer (small)	43,3 g
Mass of one accelerometer (big)	54,9 g
Mass plastic plate	1301 g

Appendix 8 : tools used for the building



Electronic digital calliper with an accuracy of +/- 0,1 mm



Steel tap M8





M8 nylon screw, M8 nylon nut, Saw and rotative saw, drill

The rotative saw was used in order to cut nylon screws in 2 parts.

The drilling tool was used to makes holes inside nylon screws.

The steal tap was used in order to drill holes inside joins in order to put screws inside.

The calliper was used in order to see the dimensions of objects.



Half of a M8 screw, one to keep the column tight and the other to add bracing with a hole inside.

M6 nylon and metal screw with its nylon or metal nut was used to fix the joints into the plastic plate.

The rubber was put on columns in order to add more friction with the joint.

The balance was used to know the weight of all the components used in this project.

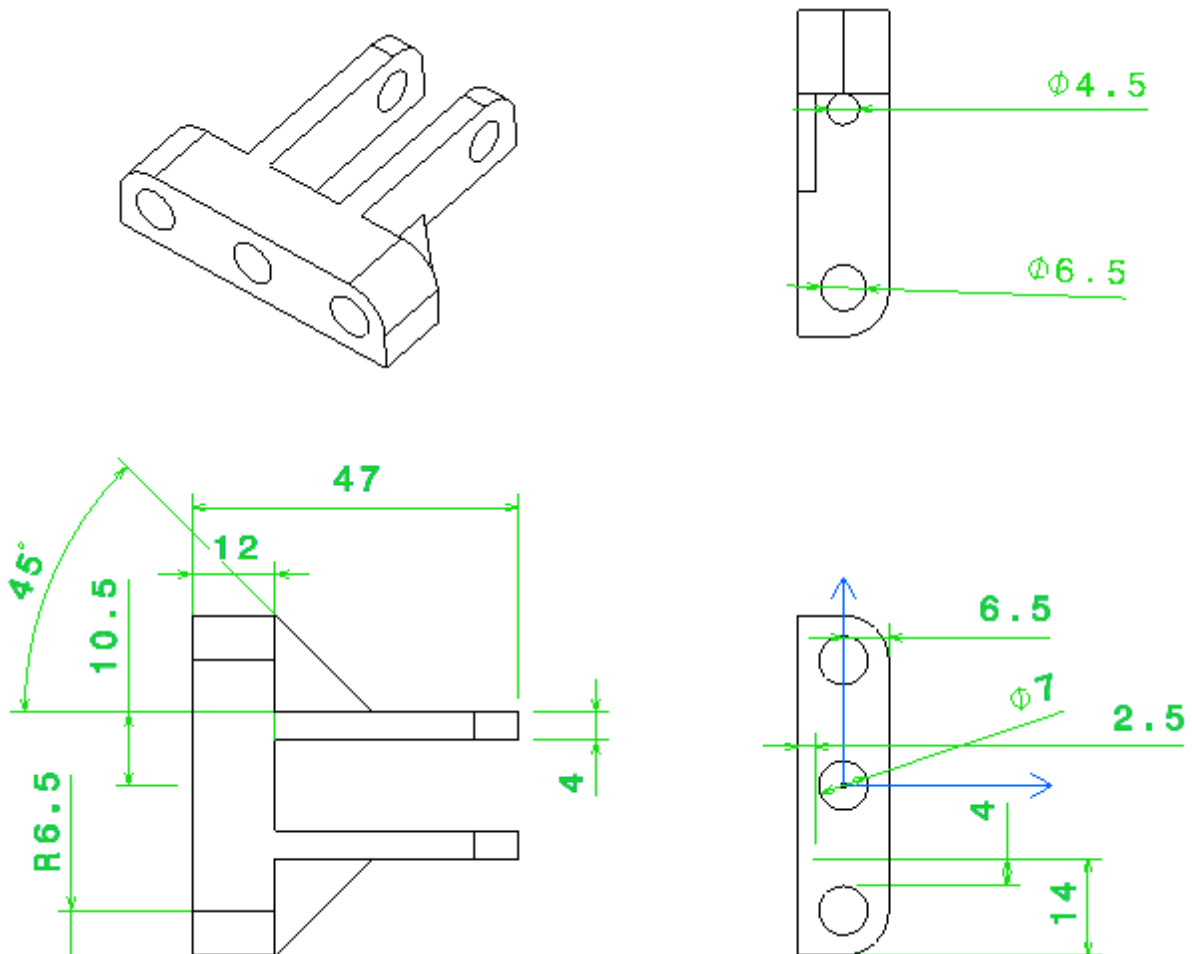
Appendix 9 : tools used for the measurements of the vibrations part



We have here, the data box acquisition (Dewesoft software), the knock sensor, and the accelerometer

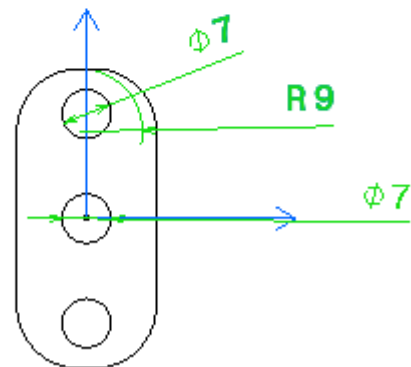
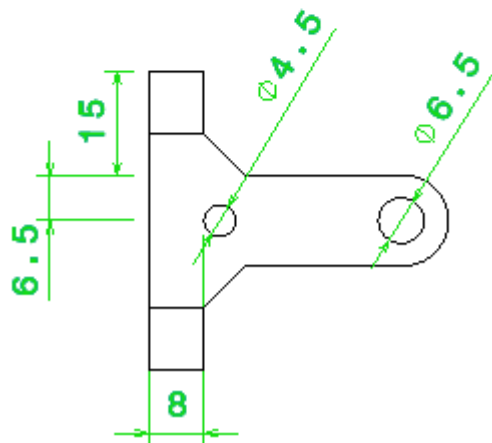
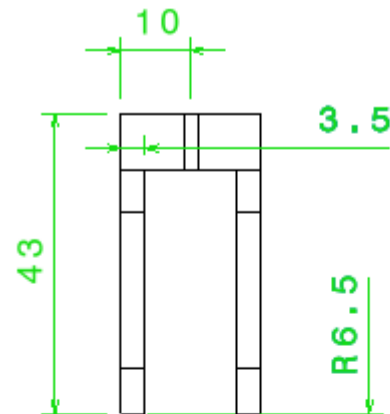
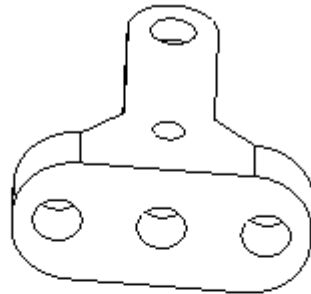
Accuracy of the software acquisition in real time : +/-0,2 Hz

Appendix 10 : plan 2D of multifunctional join in CATIA V5



DESIGNED BY: Percival		<h1>New join</h1>		I	-
DATE: 01/05/2023				H	-
CHECKED BY: XXX				G	-
DATE: XXX				F	-
SIZE: A4		<h2>UVA EII</h2>		E	-
				D	-
SCALE: 1:1	WEIGHT (kg): XXX	DRAWING NUMBER: XXX	SHEET: 1/1	C	-
This drawing is our property; it can't be reproduced or communicated without our written agreement.				B	-
				A	-

Appendix 11 : 2D plan of the V joins solution



DESIGNED BY: Percival		<h1>V join</h1>		I	-
DATE: 01/05/2023				H	-
CHECKED BY: XXX		<h1>UVA EII</h1>		G	-
DATE: XXX				F	-
SIZE A4		<h1>XXX</h1>		E	-
SCALE 1:1	WEIGHT (kg) XXX			DRAWING NUMBER XXX	SHEET 1/1
This drawing is our property; it can't be reproduced or communicated without our written agreement.				C	-
				B	-
				A	-



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Appendix 12 : 3D joins in CATIA

Appendix 13 : 3D building model in CATIA