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Proposal for a lowtech wooden space truss

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Abstract

It is well known that wood is difficult to assemble; complex steel system is often used as technical solutions. The solution proposed in this paper is to limit the use of steel connection by using a specific shape of element to take the shear force and link the top and bottom layers of the space truss. The structure was designed by the laboratoire Navier/GSA, crafted and erected by the Compagnons du tour de France (fédération compagnonique), tested by the IUT (institute for higher technician) and sponsored by the laboratoire GSA and the company Wurth. The structure is 9 m by 9 m span and has a height of 1.5 m. The elements that link and brace the top and bottom layer are hyperboloids that are simply screwed; no complex steel assembly was required. The structure was tested under symmetric and asymmetric load. The deflections and a detailed of observation of the connection during loading was performed using photogrammetry. A dynamic analysis was also performed showing a natural frequency above 10 Hz. The behavior of the structure was then compared to the numerical model. Finally, the authors conclude on the economic and environmental aspects of such structures.

Keywords: Space truss, low tech construction, wood construction

1. Introduction

For many years, the Navier research lab investigates on the construction aware structural design [1][2] and [3]. The wooden space truss proposed (Figures 1 and 2) in this paper tries to limit the use of steel connection by using a specific shape of element to take the shear force and link the top and bottom layers of the space truss. The structure was designed by the lab. Navier/GSA, crafted and erected by the compagnons du tour de France (fédération compagnonique), tested by the IUT (institute for higher technician) and sponsored by the lab GSA and the company Wurth. The structure is 9 m by 9 m span and has a height of 1.5 m. The elements that link and brace the top and bottom layers are hyperbolic paraboloids (hypar) that are simply screwed; no complex steel assembly was required.

Figure 1: A 3D view of the structure model

Figure 2: The structure built

The space structure is a classical configuration based on a concatenation of tetrahedrons and half octahedrons (Figure 3). It can be seen from Figure 3 that 4 hypars (asymptotic lines) create a "humbug" shape ("berlingot" in french) which can be viewed as a tetrahedron with curved faces. Section 2 describes the way the structure was built. Section 3 details the numerical model. Section 4 describe the loading test and compare the results of the observed deflection and the one found by the numerical model. In this section, a dynamic analysis was also performed using a specific device. In Section 5, the authors conclude on the economic and environmental aspects of such structures.

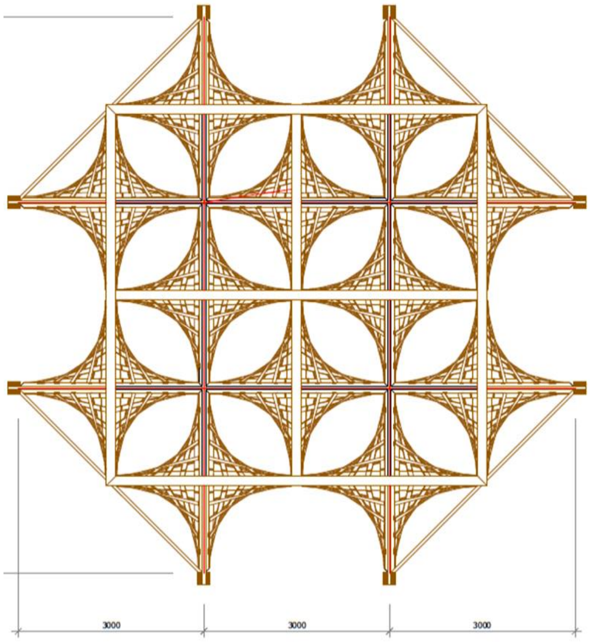

Figure 3: Plan view of the structure

2. Details and assembly of the structure

The structure is composed of 48 (Figure 4 a and b) units assembled on two specific jigs (according to their orientations) acting like a mold. Each hypar is made of:

- Edge beams shaped according to a curve due to the nature of hyperboloids. Those where fixed to the jig during the assembly the units.
- A first layer of 6 battens linking the top and bottom edge beams by double threaded screws.
- A second layer of battens crossing the firsts and strutted to them by bolts. This layer's goal aims at stiffening to stiffen the hypars.

Each batten is twisted to 90°. In order not to break those while the molding operation it was essential to do experimentation to find its optimal dimensions and to choose a premium quality material with a linear fiber and as few knots as possible (as in lute-making).
Once hypars are assembled, they kept their shapes. Elastic movement due to the energy of torsion of the elements was hardly observed.
The crafting and assembly of the units was the longest part (159 hours). The rest of workshop time was saw cut and screw work (16 hours).

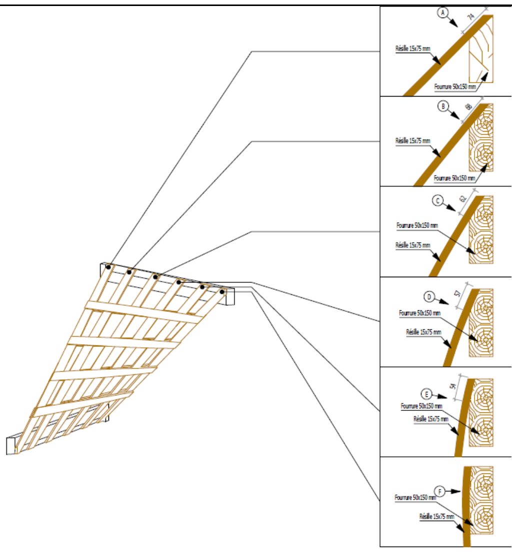

Figure 4: a) Hypars built independently b) Connection with the top and bottom edge beam

The whole structure was erected within 2 days with a team of 4 students who were novices in carpentry (48 hours). The hypar were then connected to the top and bottom chords by bolts as shown in Figure 5a and 5b.

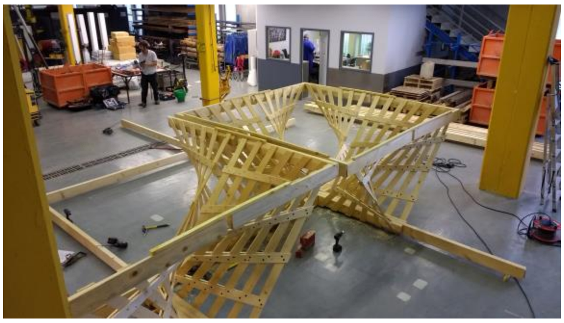

Figure 5: a) Hypar assembled to the top and bottom chords b) Detail of the connection

The structure was finally entirely assembled and put on its support (Figure 6) with the help of a crane.

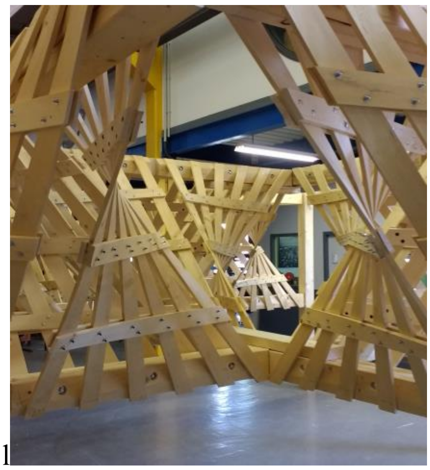

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Figure 1: Inside View of the whole structure

3. Numerical model

The numerical model was first done using Karamba and then using Autodesk Robot Structural Analysis (Robot); only elastic linear calculation was performed. A 3d view of the structure is pictured in Figure 7.

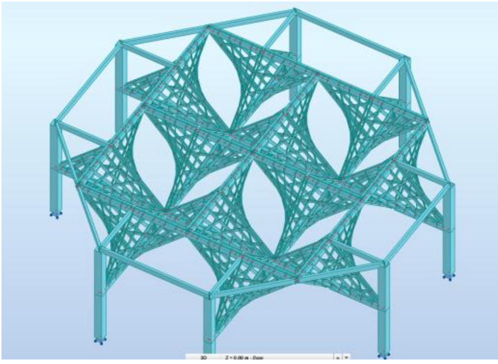

Figure 7: View of the initial model

3.1. Details of the model

In the original model the hypars were connected directly to one another and with the chords, in other word the edge beams of the hypars were ignored. In the real structure the hypars were bolted to the main chords. A more advanced model was created to take into account these eccentricities. To link these different beams, it was decided to link them with 10 mm diameter bars representing the bolts as shown in figure 8. In reality, the bolts have only to take shear forces but in the model they also had to take bending as the thickness of the wood is not represented in the model. Also frictions forces between the edge beam of the hypar and the chords were ignored in the model.

So we decided to make a second model with diameter bars 30 mm to be able to see the influence of the bolts in the stiffness of the structure.

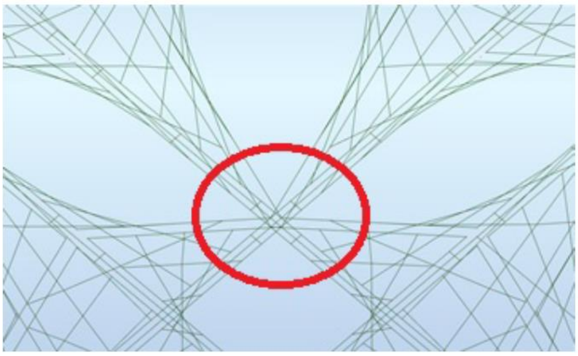

Figure 8: Details of the connection with the hypars and the chords

It was observed that the model included other errors. Indeed, the edge beams were connected to each other instead of being discontinuous (see Figure 8).

Model was then modified by reducing the size of the hypars 5 cm to prevent the transmission of forces through the edge beams and thus modify the stiffness of the structure (see Figure 9).

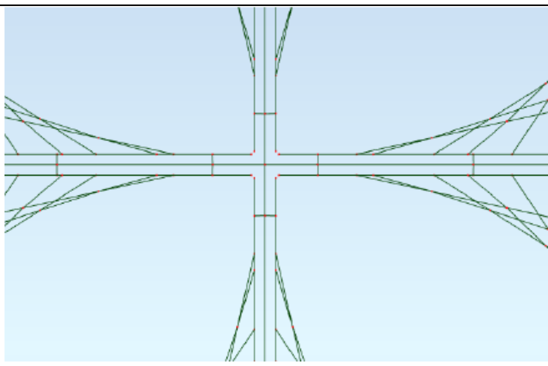

Figure 9: Top view of the connection between the chord and the hypars

4. Structural behavior of the truss

The structure was loaded with equally spaced sand-bags along the lower part of the space truss as shown in figure 10. To study the behavior of the structure, a distributed load of 1.5 T was put on the structure; this represents a load density of 40 kg/m. To do this, we suspended 72 bags filled with 20.8 kg of sand, at bolt locations on the lower chords. As the structure is quite thick (1.5 m high for 9 m span), one can expect that the deflection will be mainly due to shear straining and very little from bending. By analogising the structure as a continuous beam with simplified mass distribution in its section, a simple handmade calculation showed that the deflection due to bending was only 0.73 mm, which represents only 10% of the deflection observed in the comparators.

Figure 10: View of the structure loaded

4.1. Measurement of the displacements and comparison with the model

The measurements of the displacement were done by means of a digital image correlation (DIC) technique. These displacements have been assessed on two different parts of 4.5 m of the lower chord (red and blue ellipses in Figure 12). To be more accurate, the displacements were not tracked directly on the chords because they were sandwiched between two hypars that hide them on the digital images (see Figure 6). The DIC-assessed displacements are represented by the dotted curves red and blue in Figure 11 where the vertical axis represent the vertical displacement and the horizontal axis represent the position along the lower chord. The origin of these positions is set at the link between a chord and an external post.

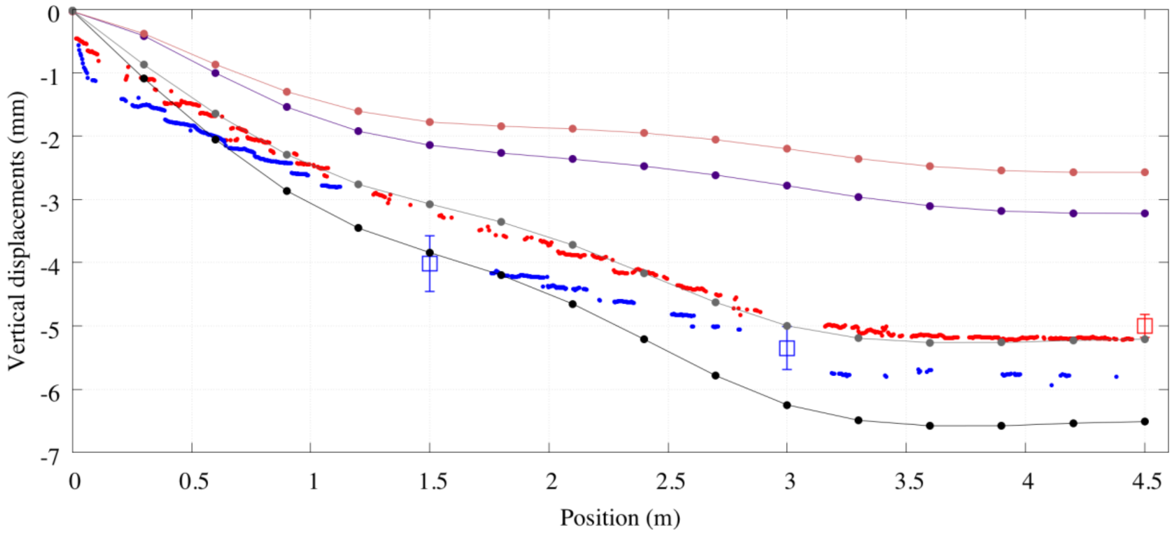

Figure 11: Vertical displacements along half of two lower chords of the structure: (red and blue dots) DIC measurements, (red and blue square symbols) comparator measurements, (black curve) prediction of the initial model, (gray curve) initial prediction rescaled with a factor 0.8, (pink and violet curves) predictions of two models where the interconnection of hypars have been modified.

Although the structure and its loading are symmetrical, it can be seen that the two sections does not undergo the same displacement. Therefore, two elements that are substantially identical do not necessarily behave in the same way. This gap, which is shown to be significant thanks to the accuracy of the optical measurements, can be explained by the discontinuity of the lower chords and the presence of dovetail joints (so called "queue-d'arondes" in french, shown by discontinuities of red lines in Figure 12). Moreover, the natural heterogeneity of wood may also partly explain the different responses of the two chords.

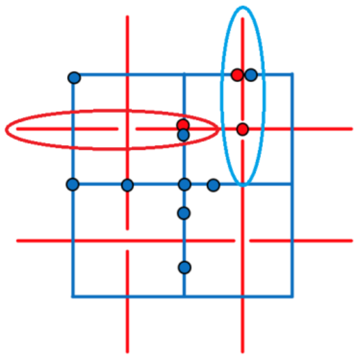

Figure 12: Sketch of the top view of the truss structure: dots define the comparator positions, blue lines are upper chords, red lines are lower chords

Back to Figure 11, the values of the 3 comparators (red and blue) with their estimated error bar are also shown. These results show the reliability of the DIC technique, since there is no considerable difference between the data from the two measurement means. It may be interesting to notice that the implementation of the comparator-based measurements where more troublesome while the number and accuracy of assessed data is significantly less.

In the lower part of the same plot, the black curve corresponds to the displacements obtained on the same section with the initial numerical model (hypars directly interconnected). This model, although geometrically different from reality, seems to fit fairly the deformation of the structure where the *S*-

shape of the curve is preserved. The gray curve is actually a homothetic version of the black curve that highlights the good agreement of the model with the measurements if the stiffness of the wood was slightly increased (higher Young's modulus). Some marked discrepancies appear at the vicinity of the posts; they may be due to a local distorsion of the hypar bolted that is to the chord (see Figure 5b). The measured displacements are actually the displacements of the bottom edge beam of a hypar, and this beam may slightly slip on the inside chord making the chord displacement apparently larger.

Finally, the two curves at the top represent displacements obtained with modified Robot models concerning the way the hypars are interconnected as described in Section 3.1. These two improved models were designed to be more "realistic" since they are geometrically closer to reality as explained in Section 3.1. They both result to underestimated deflection providing that way the upper limit of the actual magnitude of displacements, while the initial model gives the lower limit. Anyway, the relative deflection of the lower chord, defined as the deflection f divided by the total span L of the chord, is rather small (f/L # 7.10^{-4}). Thus, the lowtech space truss can clearly be qualified as a stiff structure despite it is made of wood.

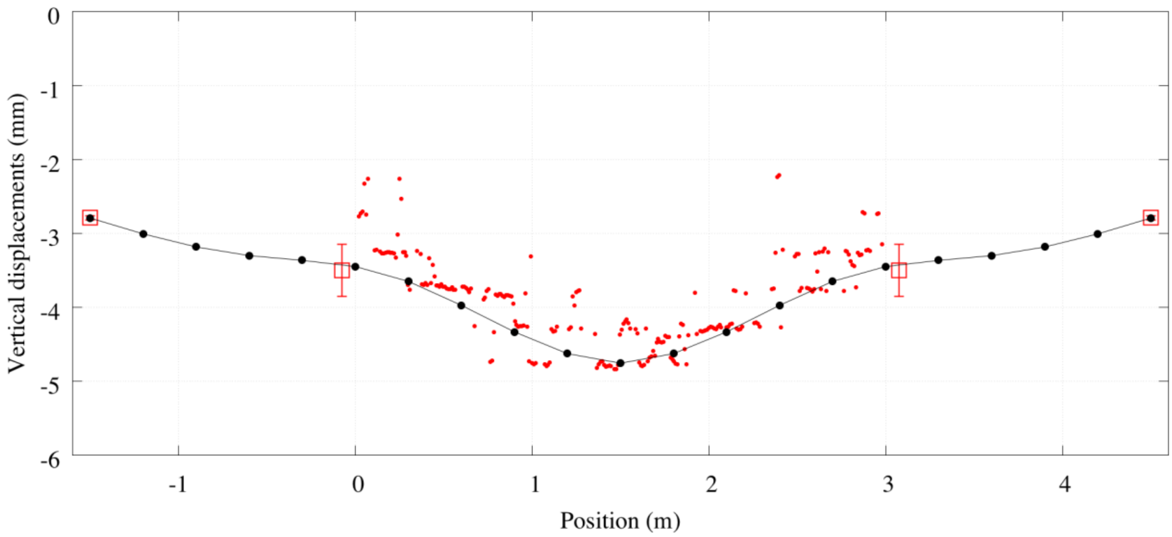

Figure 13: Vertical displacements along an upper chord of the structure: (black line) prediction of the initial model, (red dots) DIC measurements, (square symbols) comparator measurements.

The displacements were also tracked on the central part of an upper chord as shown in Figure 13. We observe a good agreement of the initial model with both the comparator and DIC measurements. The latter data is however more scattered this time because of poorer conditions of shooting, but the order of magnitude and the trend follow quite well the prediction of the model (despite the rigid connexion of the hypars). This better match may be explained by the fact that the loading was applied on the lower part of the truss as shown in Figure 10.

4.2. Natural Frequency

Every structure vibrates permanently because of the natural activities and human beings that constantly generate waves that move through the ground and the works, but that are too weak for us to feel.

Thanks to technological progress, it is now possible to measure this phenomenon called "background noise" and analyze the results to determine the vibration frequencies of the structures. Here is the type of recordings made by the company MIAGE on the structure (then not loaded) with "velocimeters" measuring speeds of a precision from about 10^{-6} to 10^{-7} m/s. In our case, the structure happens to be extremely rigid along its vertical axis since it has a natural frequency of about 10.2 Hz as shown in figure 14.

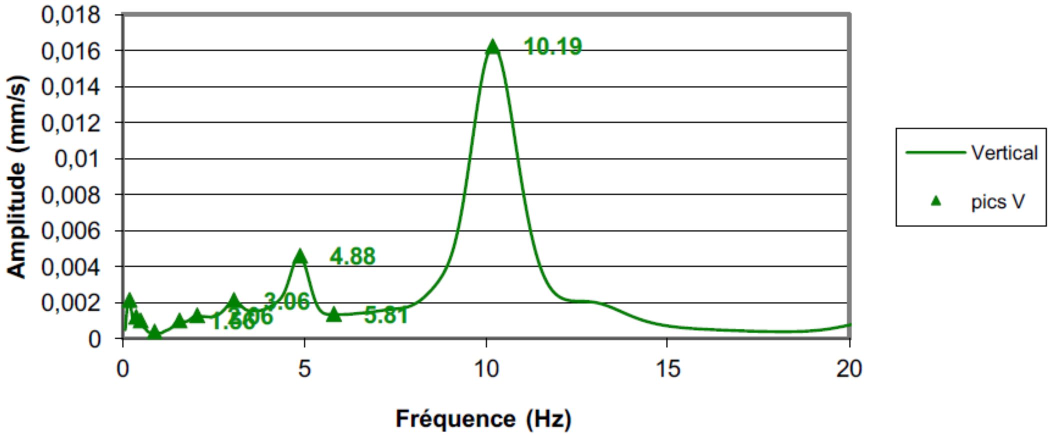

Figure 14: Natural frequency measured with the 'velocimeter'

The calculations from the numerical model gave a frequency of 12,6 Hz for the initial model. Once again, there is a good agreement between the model and the 'on site' test measurement.

5. Conclusions

The paper presented a wooden space truss constituted of hypar separating the top and lower chords. The construction details and the numerical model were detailed. The system is rather simple to build and has the advantage is to spread the connection along the edge beam of the hypars. The loading test showed a good correlation between the model and the real displacement of the structure. Further work is planned, a test showing the maximum load that the structure can support will be done shortly. Also a simpler configuration with no torsion in the hypar is under development.

Acknowledgements

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