IASS 2018 BOSTON, JULY 16-20
CREATIVITY IN STRUCTURAL DESIGN

Proceedings of the IASS Annual Symposium 2018
Creativity in Structural Design
July 16-20, 2018, MIT, Boston, USA
Caitlin Mueller, Sigrid Adriaenssens (eds.)

Parametric Design of Drone-Compatible Architectural Timber Structures

Sébastien GOESSENS[1], Nicolas ROGEAU[1], Gaëlle DE BEUSSCHER[1],
Caitlin MUELLER[2], Pierre LATTEUR[1]

[1]Université catholique de Louvain UCL
Louvain School of Engineering EPL, Civil and Environmental Engineering,
pierre.latteur@uclouvain.be

[2]Massachusetts Institute of Technology, Building Technology Program, Department of Architecture

Abstract

The additive manufacturing of real scale structures using drones (or UAV = Unmanned Arial Vehicle) is a new discipline with challenges as broad as the opportunities it opens up for the future. This research, carried out jointly by MIT and UCL since more than 3 years, has investigated several aspects related both to the UAVs flight behavior while transporting heavy loads and the development of "drone compatible" construction elements, in particular masonry systems [1] [2] and timber systems [3]. The challenges that such a construction process require are numerous but mainly:

- The possibility of building large scale structures composed of elements with a mass < 100 kg;
- The precise positioning of the drone. A maximum inaccuracy of 5 cm around a theoretical point is possible according to lab tests made with a big drone at the UCLouvain Dronezone.

In this context, using timber makes sense since the ratio between its weight and its mechanical characteristics is very good. Furthermore, ancient wood-to-wood connections, such as the ones inspired from the Japanese architecture, are a good source of inspiration for this research [3].

This article will focus on various complex architectural shapes of timber space structures that show the interest of combining parametric design with the drone-based construction. The structures are generated using Grasshopper and Rhinoceros 3D software in order to standardize the connections despite the complex shapes.

Keywords: drone, UAV, timber, drone compatible, additive manufacturing

1. Introduction

1.1. The "Robonumerization": building with robots linked to numerical models

The digital revolution combined with the robotic revolution bring new opportunities for the construction sector and pushes us to rethink the way we build. As already explained in [2], the "robonumerization" of the construction should improve the profitability of the projects, as well as the execution time, the mankind working conditions, and the quality of execution.

The increasingly widespread use of BIM (=Building Information Management/Modelling) allows for a better information flow between stakeholders at the design phase. However, the execution remains a critical step at the time of interpreting what has been drawn on the computer in order to build it on site. This phase is still more critical when the complexity of what needs to be built increases. Still today, workers have to open paper plans when working on construction sites, even if the quality of the digitalization of the project is high. Using robots makes it possible to create a direct link between the design phase and the execution phase, since the numerical model can be translated directly into instructions for robots.

This involves rethinking not only the way we build but also the way we design buildings. Since it is no longer necessary to draw a plan, we can think about the project directly in terms of spatiality. Architecture is no longer the extrusion of a 2D plan, but a three-dimensional object defined by constraints and parameters. This object can be described geometrically and translated into numerical instructions. This is further developed in §2 and §3 below.

1.2. About drones

The use of drones is part of a biomimetic approach. Like birds flying back and forth to bring twigs and mud for the construction of their nest, a swarm of drones could quickly assemble a huge number of small and light elements into a real scale structure with a complex shape. The use of drones has the advantage that the complexity of the structure does not matter, since the assembly is based only on the coordinates of the points extracted from the computer 3D model. This is where the interest of linking drones and parametric design appears (figure 2).

In addition, drones can quickly fly in all directions, reach high heights and avoid the use of slow and cumbersome cranes. However, the future of construction is surely not only linked to flying robots. Indeed, future construction sites, in the next decades, will probably see the combination of several types of robots: flying robots, but also climbing robots, humanoid robots, crane robots, etc.

Figure 1 shows lab tests with masonry and timber elements, assembled with a custom-made drone capable of lifting masses up to 30 kg.

Figure 1: The drone used for the lab tests (Drone Zone UCLouvain/Belgium). On the left: assembling of masonry elements. On the right: assembling of timber beams.

1.3. About timber

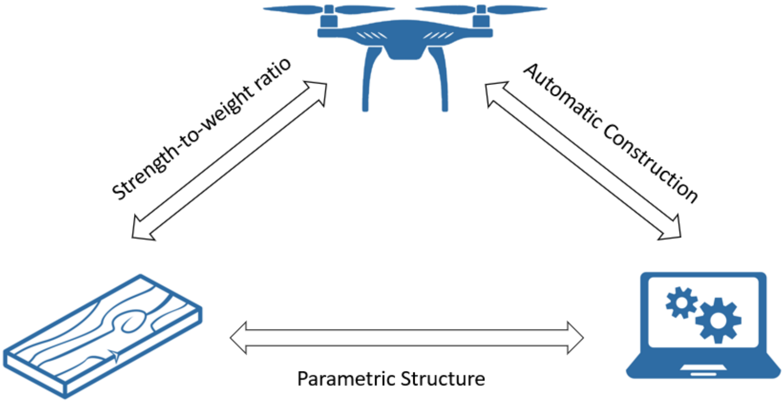

Figure 2: Development of "drone-compatible" timber structural typologies using parametric design

In addition to the fact that timber is an abundant natural resource, it has an excellent strength-to-weight ratio (comparable of that of steel) which makes it particularly well adapted for the drone-based construction.

Previous research [3] focused on adapting traditional Japanese joints in order to develop “drone compatible” timber connections, allowing a connection despite a position inaccuracy of the drone of 5 cm around the theoretical point. This paper this time investigates not only the connections, but mainly the possibility of creating drone compatible complex structures via a parametric design.

2. Stacked timber structures

The first structural topologies that were investigated are the result of the stacking of timber beams, generated with Rhinoceros 3D via the plug-in Grasshopper. An algorithm, that allows creating different iterations of stacks by varying the position of the beams relatively to each other, has been developed.

The position of each beam compared to an arbitrary fixed point in space is given by the computer code and allows a direct translation into flight instructions for the drone(s). This allows a much faster construction than with classical means, since the geometries are very complex, which shows the interest of the drone in this precise case. Here, the connections don’t exist since the elements are just stacked. Adding connections is possible but would involve their parametric design combined with a CNC machine (CNC=*Computer Numerical Control*) capable of producing many different connections and with an adequate and ordered storage of the beams.

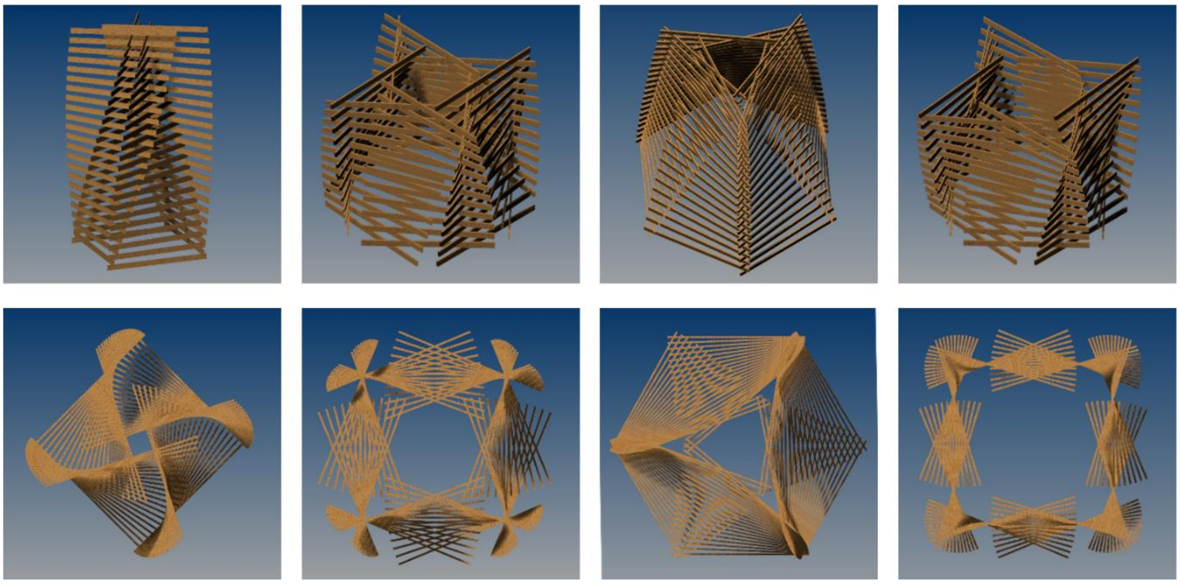

Figure 3: Different iterations of stacked timber structures

3. Interlocking timber panels

3.1. Type of panels

The use of timber panels rather than beams makes it possible to reach larger spans for the same weight by reducing the width of the sections. In addition, they can easily be cut by CNC machines, and they provide the possibility to work with elements with a variable or curved geometry.

Several types of panels are produced by the industry, among which:

- MDF/HDF (Medium/High Density Fiberboard), mainly used for furniture or interior design, it offers few structural applications and reacts very poorly to moisture.
- OSB (Oriented Strand Board) which can be found as bracing panels for walls, roofs and floors.

- CLT (Cross-laminated timber), composed of at least 3 perpendicular glued layers of solid-sawn lumber and can be used in floors and load-bearing walls.
- LVL (Laminated Veneer Lumber), made of veneer layers that offer high mechanical strength and allows manufacturing large elements with high dimensional stability.

MDF and OSB are too sensitive to moisture. CLT panels have a minimum thickness of 60 mm (3 layers of 20 mm). Therefore, LVL panels are the most appropriate choice as they combine the advantages of being available with thicknesses between 21 to 75 mm, very resistant and not very sensitive to moisture.

A source of inspiration can be the Metropol Parasol in Seville, which is composed of a multitude of independent LVL panels connected by metallic wires (figure 4/left).

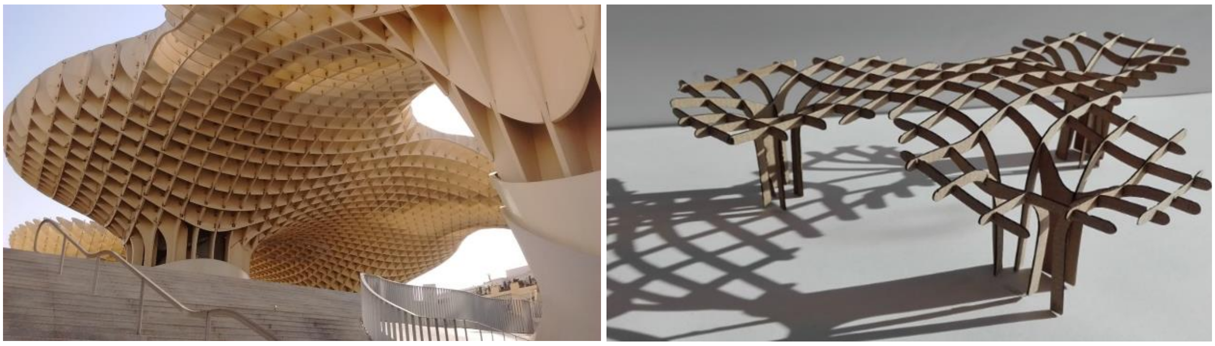

Figure 4: Study of a grid structure inspired by the Metropol Parasol in Seville (left photo: A. S. Branders)

This concept can be extended to a mesh of interlocking panels, as on figure 4/right. The advantage of the grid system is that it reduces the buckling inherent into elements with small thickness. The use of a multitude of thin elements is a major asset for the drone construction since it can lead to a broad variety of architectural and structural shapes.

3.2. Half-lap joints

These panel joints are inspired from the connections developed in [3] and only require one planar cutting plan. They should thus be compatible with an industrialized production, without increasing the overall manufacturing cost of the structure. Tests have been conducted for an accuracy of positioning set to 5 cm around a theoretical fixed point at the center of the joints, as shown in figure 5 (dimensions in cm).

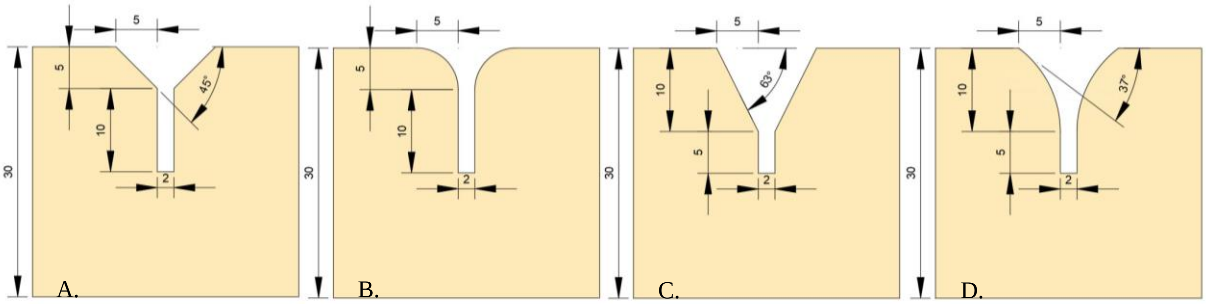

Figure 5: 4 variants of the "drone-compatible" half-lap joint (dimensions in cm).

The minimum slope required for sliding is 35 ° as demonstrated in [3].

With the Type A joint, the pieces tend to abut against the corner formed by the flared opening and the vertical cut as shown in figure 6 (left), which is not the case for the Type B. However, Type B reduces the tolerance with respect to the inaccuracy of the drone because the slopes decrease to zero at the beginning of the assembly, which sometimes prevent the sliding of the two pieces into each other.

The Type-C joint is an improvement of Type A joint, however the same inconvenient appears, even if it is much less frequent than with Type-A. This joint has a smaller notch, which makes the connection less rigid. The Type-D joint combines the advantages without the inconvenient of the previous ones by maintaining a tolerance of 5 cm with a minimum angle of 37 ° at the extremities, which is sufficient to ensure the sliding between the two panels. Finally, multiple half-lap joints can be assembled at the same the time, as shown in figure 6 (right) with Type-D joints.

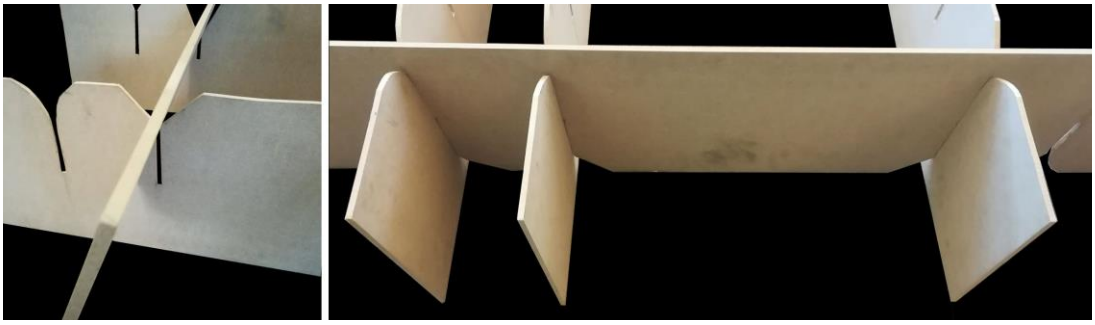

Figure 6: Type-A joint (on the left), multiple half-lap Type D joints (on the right)

3.3. Parametric design

While designing a new structure, its perimeter is first drawn with Rhino, and then transformed into a grid thanks to the Grasshopper code (figure 7/1). The grid is then projected against a NURBS (Non-Uniform Rational Basis Spline) surface whose shape can be modified with Rhino by moving the control points (figure 7/2). This makes it possible to generate, thanks to the Grasshopper code, a grid of 2D beams (figure 7/3), which geometry can be graphically modified by moving only a few points. At this stage of the process, one already has a first preview of the structure, and many different architectural possibilities can be explored easily.

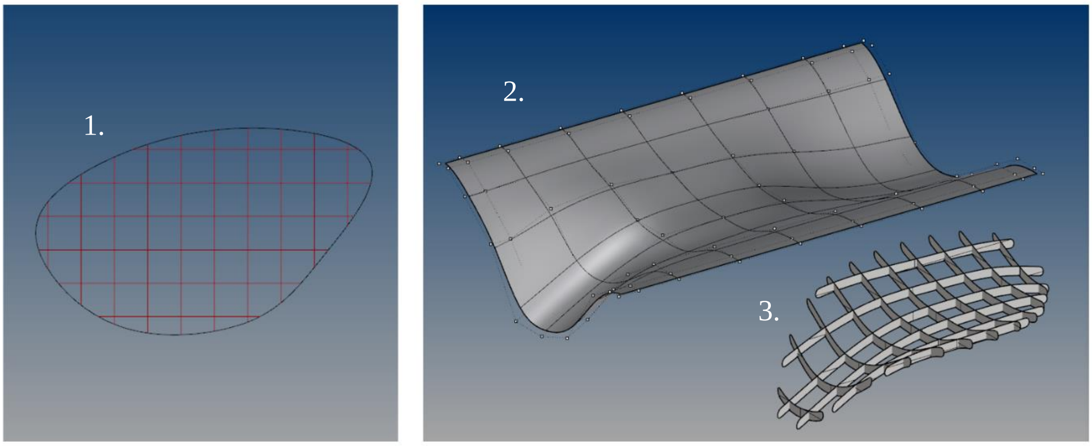

Figure 7: First steps of the parametric design of the structure

The next step concerns the determination of the 2D geometry of each beam and the position of the Type D joints notches (figure 8/right), thanks to an integration of the Type-D joint exact geometry into the Grasshopper code. A parametric shape for the supports of the grid is also generated (Figure 8/left). The same joint Type D is used for the supports, which dimensions can automatically be modified according to the thickness of the panels, the height of the structure and the shape of the NURBS surface.

The last step is the flattening of the pieces in order to export the cutting file, thanks to the grasshopper code. This methodology allows generating various 3D rendering of the structure, giving the possibility to test plethora of geometry before construction (figure 9).

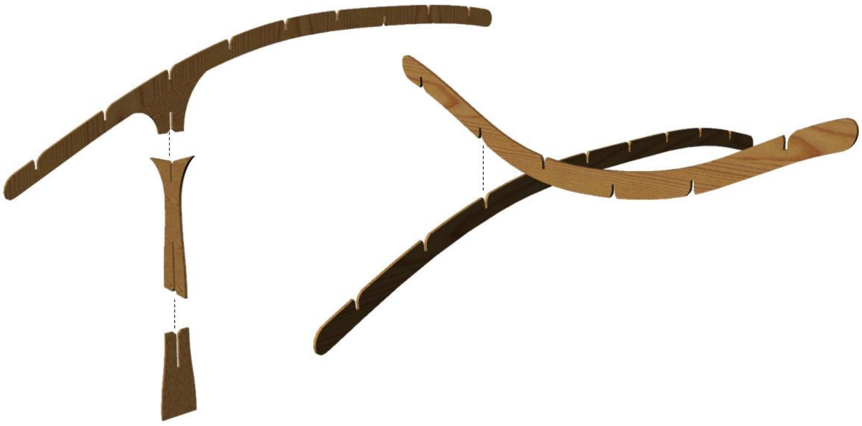

Figure 8: Positioning of the half-lap joints

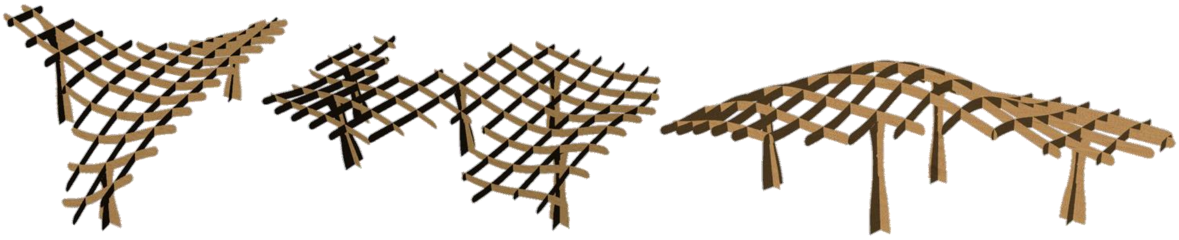

Figure 9: Multiple iterations generated by the algorithm

3.4. Assembly sequence

The orientation of each notch on the panels depends on the assembly sequence of the beams. Therefore, the assembly sequences must be determined beforehand. The construction process must begin with the placement of a first bearing structure on the supports. Then all the other beams are put in place in order to conserve the global equilibrium of the structure at each step of the construction (figure 10).

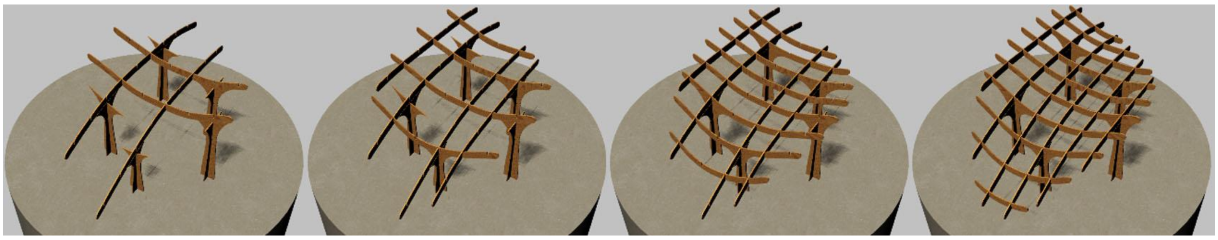

Figure 10: Assembly sequence

4. Global and local resistance

Several failure modes have been identified for the interlocking timber panels system. The following analysis is based on the Eurocode 5 (Design of timber structures).

4.1. Resistance of the Type D connections

The resistance of the joint to a compression stress can be evaluated assuming the friction forces are neglected, according to the following design criteria: $N/A \leq f_{cd}$ (1), where “A” is the area subjected to a force N, as shown in figure 11-a, and f_{cd} is the characteristic yield strength in compression of the LVL, security factors included.

The resistance to a lateral load such as wind can be considered by applying a load on the vertical edge of the notch as shown in figure 11-b. The maximum force F is also given by equation (1).

For panels with a thickness “t”, and with notches of height “h”, the resistance to a torque M due to the rotation of one panel into another as represented on figure 11-c can be evaluated by balancing the forces around the center of rotation of the connection: $M=Rh/2=th^2f_{cd}/4$.

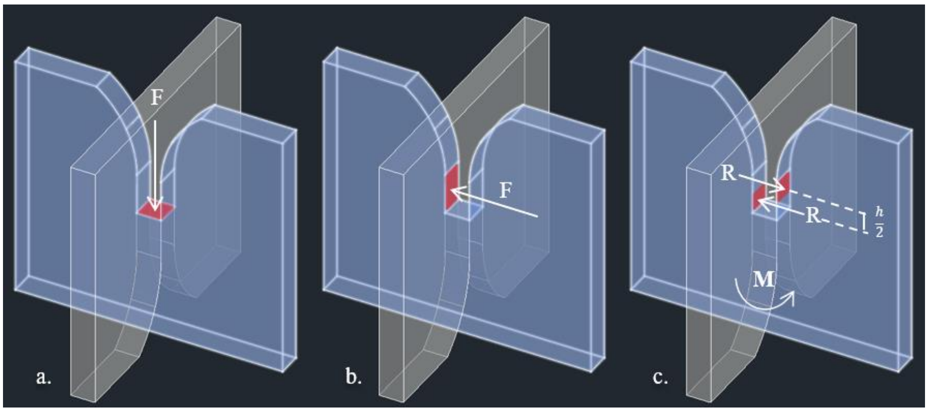

Figure 11: Rupture of the notch due to a vertical stress (a.), due to a lateral stress (b.), due to a torque (c.)

Usually the layers of LVL are oriented in the same direction, which is assumed in this article (wood fibbers parallel to the axis on the beams). One considers characteristic yield strengths equal to, respectively, 3.8 MPa (compression applied on the surface, perpendicular to fibbers), 7.5 MPa (compression along the edge, perpendicular to fibbers) and 40 MPa (compression along the edge, parallel to fibbers). With the assumption h=50 mm (30 mm thick panels) and taking into account a security coefficient of 1.5, an order of magnitude of the resistance is about F=4500 N for case a, F=3800 N for case b, and M=47,500 Nm for case c.

4.2. Resistance of the supports for lateral forces

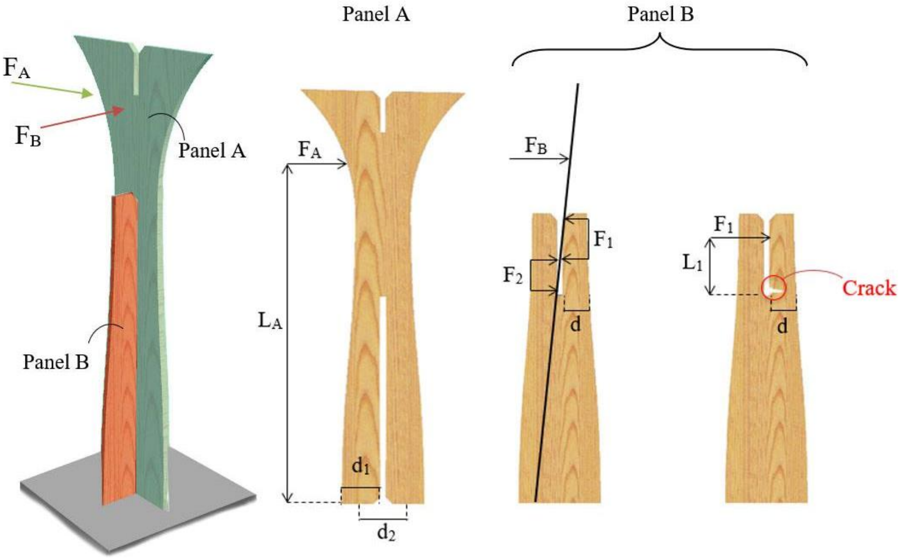

Figure 12: forces transmitted into the connections with supports

The lateral displacements of the grid, due for instance to the wind, introduces bending into the supports (figure 12). The resistance can be checked in both directions. For Panel A, the resistance at the ground level can be evaluated with (note that, this time, f_{cd} is the strength parallel to the wood fibers, security coefficients included, ≈27 MPa): $F_A=td_1d_2f_{cd}/L_A$. For Panel B, the rotation of upper panel A causes a compression stress into the notch. The design criterion is given by equation $6F_1L_1/td^2 \leq f_{md}$ ($f_{md} \approx 30$ MPa, security coefficient included). Note that other design criteria have to be checked such as the shear one or the buckling one.

5. Application

Figure 13 shows an example that illustrates the structural possibilities offered by the interlocking wooden panel system.

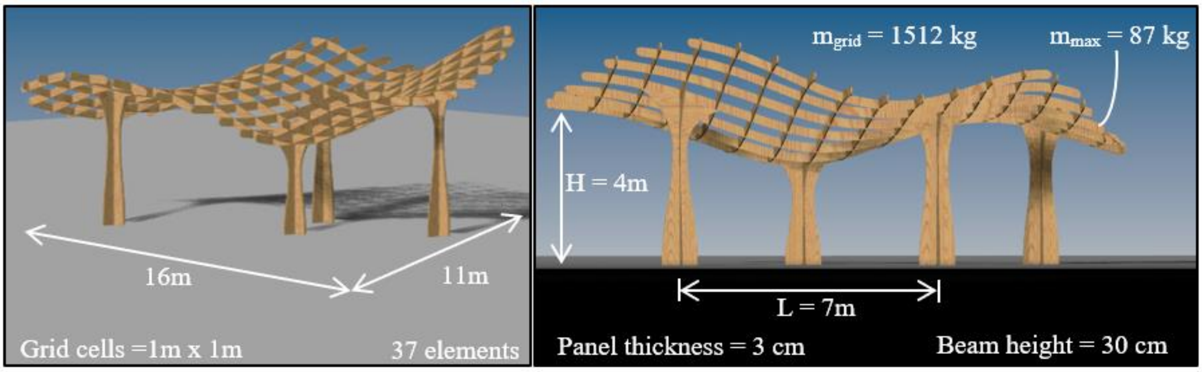

Figure 13: Dimension

This structure has been designed to resist to its own weight and some other solicitations like wind and a light covering. For panels of 3 cm width, the maximum length of the beams is limited to 18 m in order to respect the mass criterion of 100 kg.

6. Conclusion

Drone-compatible timber construction is a new research field whose future applications promise to revolutionize the building process. Exploring the development of drone-compatible structural topologies induces new ways of designing structures via parametric tools. Using flying robots for a building process allows automating the construction of complex shapes while coding the geometry into Grasshopper. This also avoids the long drawing process of all the different connections.

Using a grid of interlocking timber panels allows the development of a broad variety of shapes that can suit to different projects. The integration of the geometric constraints related to the half-lap joints into the algorithm makes also it possible to adapt the structural topology to any construction site and demonstrates the potential of building with a lot of small elements assembled by drones.

Further research should characterize the behavior of such structures and allow to automate the design process and the optimization of the geometries. Some rules could also be searched about the assembling sequences in order to ensure the stability at each construction step and avoid any scaffolding.

Acknowledgements

The authors wish to thank the MISTI MIT-UCL Seed Fund and the Belgian FRS-FNRS (Fonds de la recherche scientifique).

References

[1] Latteur Pierre, Goessens Sébastien, Breton Jean-Sébastien, Leplat Justin, Ma Zhao, Mueller Caitlin, *"Drone-Based Additive Manufacturing of Architectural Structures"*, International Association for Shell and Spatial Structures, Amsterdam, 17-20 August 2015.

[2] Latteur Pierre, Goessens Sébastien, Reniers Milan, Ma Zhao, Mueller Caitlin, *"Masonry Construction with drones"*, International Association for Shell and Spatial Structures, Tokyo, 26-30 September 2016.

[3] Goessens Sébastien, de Furstenberg Tassilo, Manderlier Charline, Mueller Caitlin, Latteur Pierre, *"A Few Aspects of Timber UAV-based Construction"*, International Association for Shell and Spatial Structures, Hamburg, 25-29 September 2017.