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Design and construction of the ReciPlyDome, a lightweight modular reciprocal dome

Ellen LEEMANS[a,*], Ahmed SOLIMAN[a,b], Stijn BRANCART[c], Niels DE TEMMERMAN[b], Lars DE LAET[b]

[a,*] Department of Architectural Engineering (ARCH),
Vrije Universiteit Brussel (VUB), 1050 Elsene, Belgium
ellen.leemans@vub.be

[b] Department of Mechanics of Materials and Constructions (MEMC), Vrije Universiteit Brussel
[c] Faculty of Architecture and the Built Environment
Delft University of Technology (TU Delft), 2628 BL Delft, The Netherlands

Abstract

In the event sector, where there is a search for architectural constructions with an innovative morphology, reuse is key to strive towards more sustainable events. Designing modular structures and detailing them for easy disassembly and re-assembly is an ideal way to encourage and facilitate reuse. This way a longer lifespan is assured for the used components. However, temporary (event) structures are often hard to assemble, which can compromise their reusability. The difficulties of assembly are usually induced by the morphology of the modules or by using certain types of connections. Therefore these structures require optimization in terms of assembly while remaining resource efficient. The main objective of this research is to reimagine a developed structure, the ReciPlyDome, and optimize it in terms of assembly. The ReciPlyDome is a reciprocal dome structure based on a rhombic triacontahedron, whereby all elements are identical (except for the five elements that touch the ground). During the assembly phase of the first version of the ReciPlyDome, torsion in the components appeared to hinder efficient construction. To eliminate this, the dome was reviewed, which led to the development of a new connection system and an improved shape for the beams. A new full-scale version of the dome has been built, showing the positive effect of the improved connection system and the optimised beam position. In-situ measurements were made after construction, illustrating good correspondence between the digital and built model. Further research will focus on the covering of this modular reciprocal dome for outdoor use.

Keywords: optimization, modularity, prefabrication, material efficiency, prototyping

1. Introduction

As events only last for a couple of days or maybe a few months, their structures are usually designed for short-term use. Afterwards, they are thrown away and generate about 20.4 kg/m² waste per year [1]. For events in France, except for travel and accommodation, the carbon emissions related to space design and production are the largest, reaching up to about 55% of all emissions for the average events [2]. To resolve this, reuse is key. A study of Catalan covered trade fairs has proven that when 75% of stands are reusable, the waste generation is 3.5 times lower than when none of the structures are reusable. In these cases, gluing all parts of the structure together was the main factor making them non-reusable. Since the useful life of the stands are on average 4.3 days, changing the connection systems to make the overall structure reusable could already significantly prolong the life of these stands [1]. Thus, in these type of structures reuse can mainly be obtained through providing an easy assembly and disassembly phase. Additionally, designing the structures to be easily compacted allows for a smoother transportation.

Modularity can play an important role to provide this easy assembly and disassembly. Because of the standardization of the used elements, modularity often helps to simplify the process. This standardization often even makes place for flexibility to create several designs with the same 'module', as in the case of the ReciPlyDome.

The ReciPlyDome, a reciprocal plywood dome, is a structure designed and prototyped by VUB researchers Stijn Brancart, Lars De Laet and Niels De Temmerman and by Olga Popovic Larsen of the Royal Danish Academy of Fine Arts, School of Architecture, Design and Conservation. Its identical elements are composed of two beams, with different lengths, connected at the ends. This not only allows pre-tensioning of each module but also increases the cross-sectional thickness, both elements that lead to a higher overall stiffness [3]. Only at the bases , the elements have a shorter length to provide a stable connection to the ground. In total four type of beams were designed which allow to create six different structures. Although its modularity already increases the easy for assembly, the torsion that occurred during this phase makes it still challenging. Therefore, some optimizations are needed.

Figure 1. The assembled ReciPlyDome, version 1.

2. Rethinking the structure

To eliminate the torsion occurring during the assembly phase, a stress-free alternative was required. This is obtained through rotating the beams by 90 degrees.

However, when rotating these beams, the current connection method would result in eccentricities (Figure 3 (a)). Therefore, incisions were provided on the places of the eccentricities, which also helped fixing the beams (Figure 3 (b)). Another result of the rotation is that the beams needed to be cut out in a curved shape to obtain the same curvature in a stress-free manner (Figure 3 (b)). The curvature of these beams was optimized to obtain a material efficient cutting pattern. Additionally, the elements were reduced to a single layer beam.

This version of the dome was tested with a model, obtained through laser cutting the required beams (Figure 2). The incisions were made slightly bigger to allow for some movement during the assembly of the model. However, this resulted in the structure falling apart halfway through the assembly. Therefore some locking around the connection points was needed to secure the structure. Furthermore, using these incisions would also create weak spots in the elements, causing them to rupture over time.

A solution to these weak points could be to increase the beam height, however it was opted not to do so as this would not be material efficient. Therefore it was decided to eliminate the incisions and create a connection system. (Figure 3 (c)).

Figure 2. Model of ReciPlyDome with incissions to eliminate eccentricities and fix the structure.

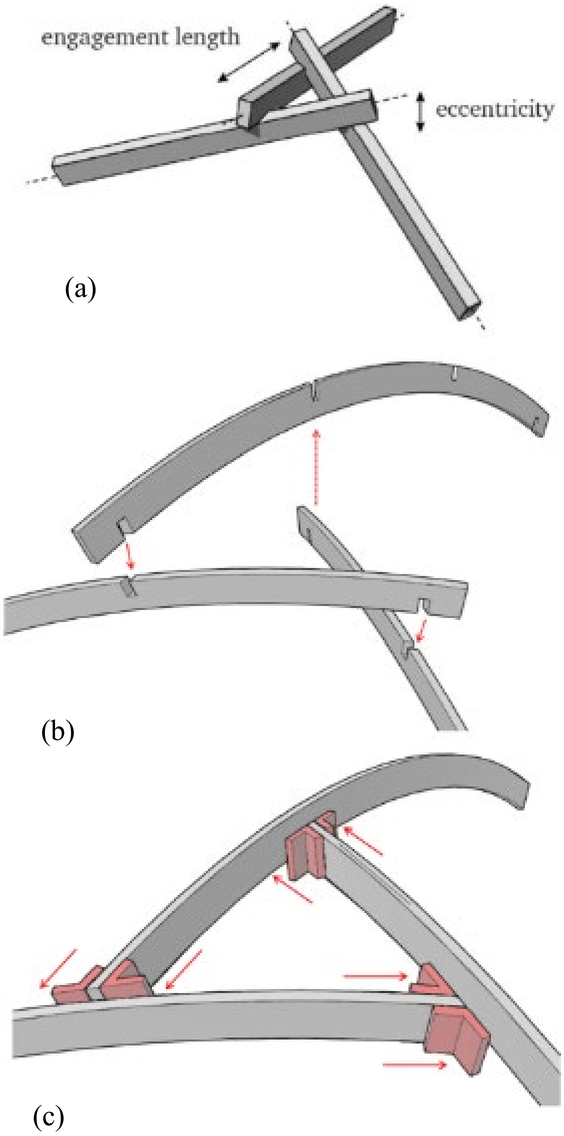

Figure 3. Rethinking the structure. (a) eccentricities occur due to rotation, [3] (b)incisions are provided to eliminate eccentricities, (c) addition of connection system for most ideal assembly.

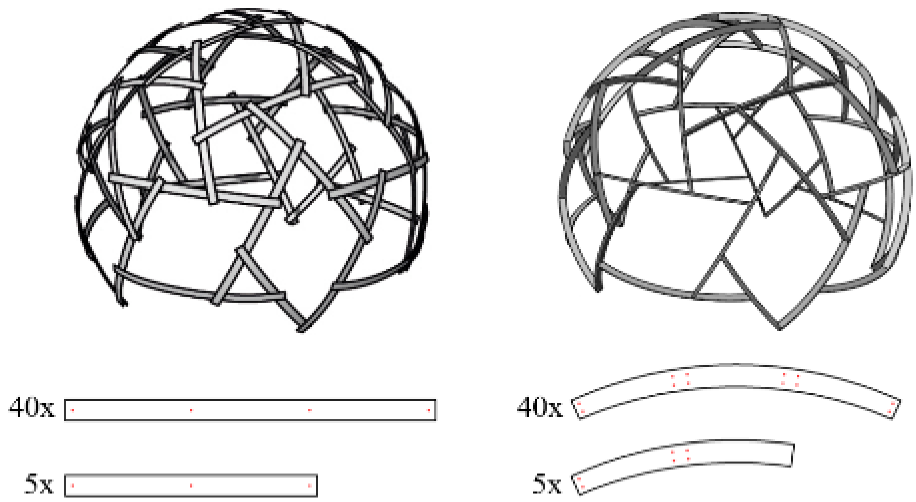

Figure 4. (a) 3D model of the original single-layered ReciPlyDome and the needed elements (source), (b) 3D model of a new version of the ReciPlyDome, whereby the elements are rotated over 90°, resulting in curved beams.

3. Connection system

3.1. Model scale

To connect the unstrained curved beams with each other, without creating cut-outs, a connection system was designed. With this system the beams were able to lean on each other in a reciprocal manner (Figure 5). It also allowed for sidewards movements to facilitate the assembly.

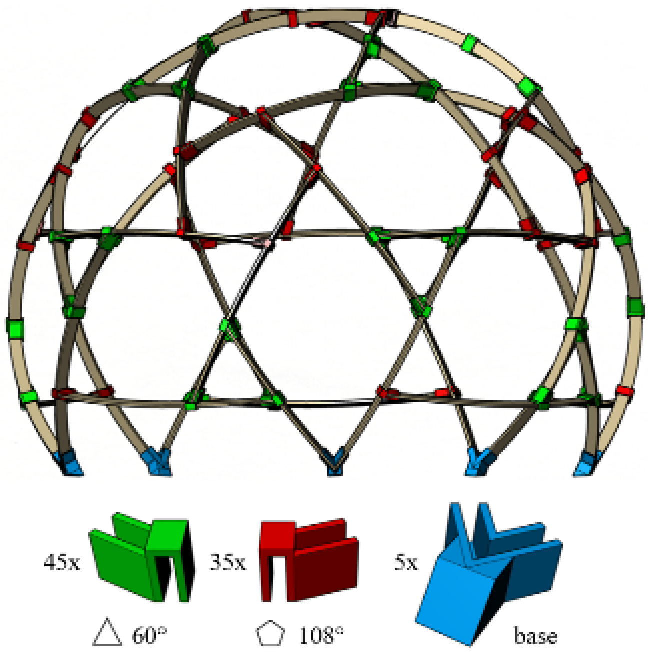

Figure 5. Connection system for the unstrained version of the ReciPlyDome with curved beams, consisting of three types: Type 60° for the triangles, Type 108° for the pentagons and Type base for a connection to the ground.

In total, three different type of connectors were designed, two for connecting the beams to each other and a third to connect them to the ground. Within the first-mentioned, a distinction was made based on the geometries that can be found in the dome. When looking closely, it can be seen that the dome consists of rhombuses and equilateral triangles and pentagons. The connection system was thus based on the corners of these equilateral triangles and pentagons, resulting in respectively a 'Type 60°' connector and a 'Type 108°' connector.

To test this connection system, 3D models were made and 3D printed. The design allowed for the Type 60° end Type 108° to be easily slid over the beams, while the adjacent beam can lean on the side of the connector (Figure 6).

To connect the dome to the ground, a base type was designed where two beams come together under an angle of 60°. By incorporating this angle in the connection piece, the base was able to touch the ground on a stable flat side (Figure 7).

Figure 6. The (a) Type 60° and (b) Type108° connection system, which can be respectively used to create (a) triangles and (b) pentagons.

Figure 7. The Type Base connection system, to provide a stable connection between the lower beams and the ground.

3.2. Prototype scale

To translate this connection system to the prototype scale, some alterations had to be made. First, to make the system more efficient in terms of material use and fabrication, the design was simplified. The first result of this was a connection system consisting of a pre-drilled 2 mm U-shaped steel plate welded onto a another pre-drilled 2 mm steel plate. However, since it still included a lot of operations, cutting out the right shape, drilling, folding and welding, it was simplified even more.

Figure 8. First version of the connection system Type 60° on prototype scale.

The next version consisted of two 2 mm L-shaped stainless steel plates of 60° and 120° for the Type 60° connector and 108° and 72° of the Type 108° connector (Figure 10). However, although equilateral triangles and pentagons are used in the dome, there corners turned out to be slightly different. Due to the three dimensional spherical shape of the structure, the connection angles are turned inwards as can be seen in Figure 9. Therefore more correct angles would be 60.77° and 119.23° for the Type 60° connectors and 70.18° and 109.85° for the Type 108° connectors.

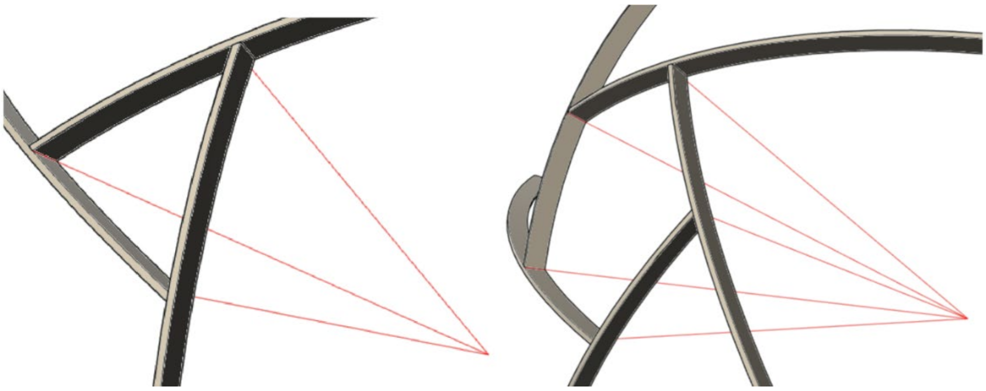

Figure 9. Inclined connection angles due to the sperical shape of the structure.

Another change was elongating the holes in the steel plates on the side that would be connected at one third of the beam length (Figure 10). This allows for some flexibility during assembly, but still sufficient stiffness once fully assembled. Lastly, some smaller holes were added onto the plates to allow a future cladding system.

(a) (b)

Figure 10. Second version of the connection system (a) Type 60° and (b) Type 108° on prototype scale.

4. Assembly

4.1. Assembly of the model

For a smooth assembly of the scale model, the laser-cut beams were prepared by attaching the 3D printed connection pieces to the end of each beam. As can be seen in Figure 11, each beam contains a Type 60° connector on one side and a Type 108° connector on the other side. Only for the five beams at the base the Type 108° connector was exchanged for a Base connector. By subsequently attaching the connectors at one third of the beam length, triangles can be created from the Type 60° connectors and pentagons from the Type 108° connectors (Figure 12).

Compared to the earlier model with incisions, this version allowed an easier assembly thanks to the connection system. Additionally, the structure was more secure, whereas the previous version started to fall apart halfway through the assembly. Therefore the connection system allowed for an overall stiffer structure.

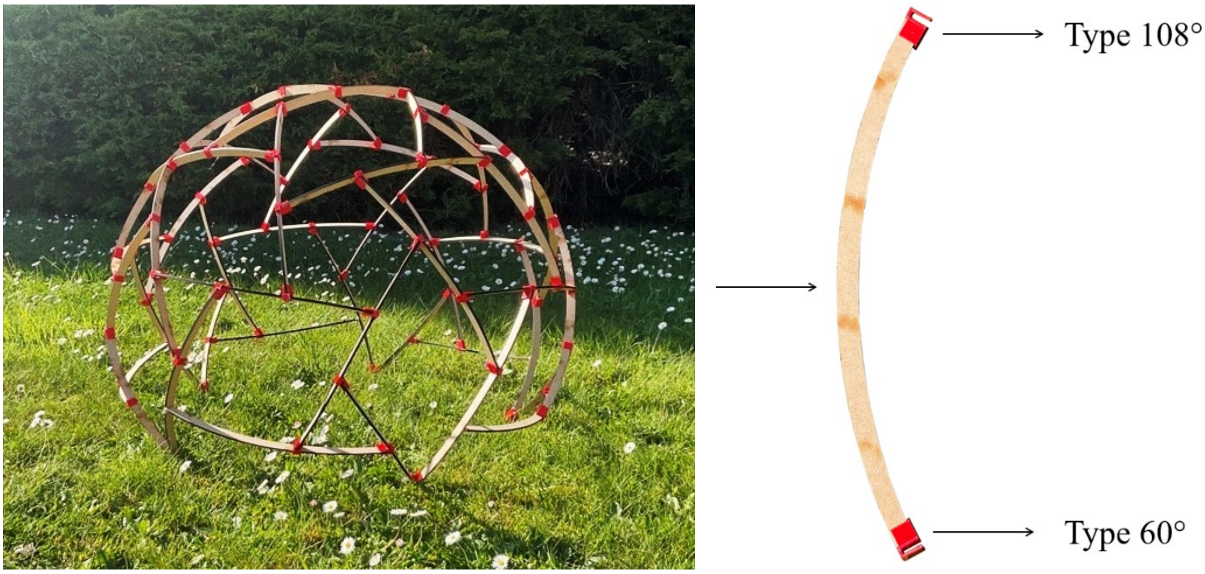

Figure 12. Assembly of the scale model of the rethought ReciPlyDome with modular beams and connection pieces of Type 60°, Type 108° and Base.

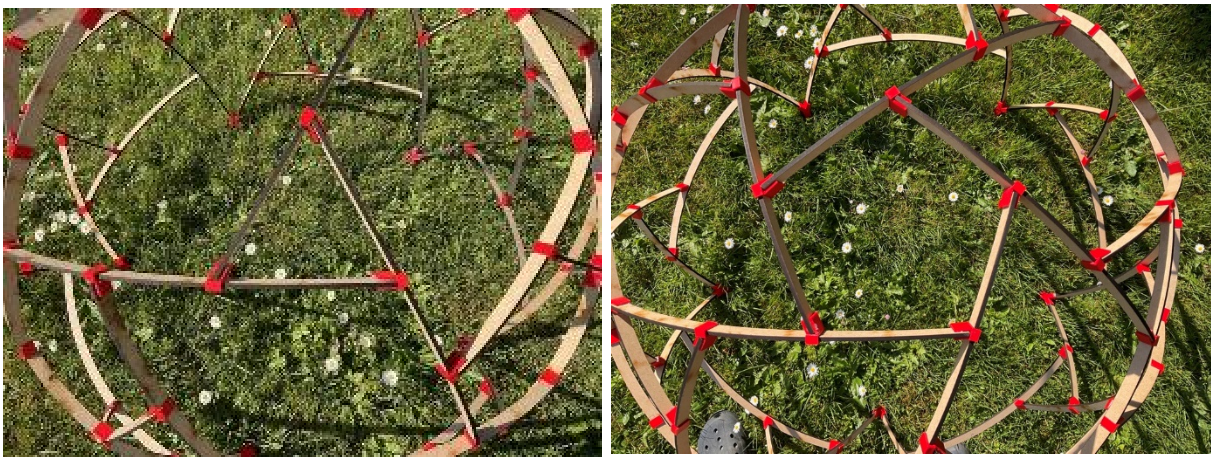

Figure 11. (a) Triangles and (b) pentagons formed by respectively the Type 60° and Type 108° connectors.

4.2. Assembly of the first prototype

The first connectors made for the prototype were obtained through drilling holes through 2mm steel plates, folding the steel plates and finally welding the required edges together. Afterwards a coating was applied to achieve a homogeneous look and protect the connectors from corrosion. The final result were three Type 60° connectors.

Figure 13. First prototype for the Type 60° connection system.

The plywood beams for the prototype were manufactured with the aid of a jigsaw. However, due to the curved shape of the beams, a lot of plate material was wasted. Therefore options to repurpose the leftover materials should be explored.

For the assembly, the beams were prepared in a similar manner as the scale model. At the end of each beam a Type 60° connector was attached. Next, the beams were connected to each other by attaching the connector at one third of the beam. This connection system allowed for a torsion- and stress-free assembly of a triangular fragment of the dome.

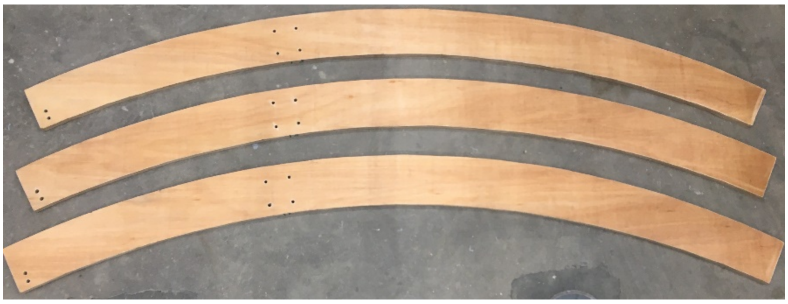

Figure 14. First prototype for the single-layer curved beams.

Figure 15. The prototype of the Type 60° connection system connected to the beams.

Figure 16. Assembly of a triangular fragment of the dome with the first prototypes of the Type 60° connection system and single-layer curved beams.

4.3. Assembly of the second prototype

To make the connection system more material efficient and easier to fabricate, a second version was developed. The beams were already prepared by connecting the adapted Type 60° and Type 108° connection system, now consisting of L-shaped plates, respectively to each side of the beam. Thereafter six pentagons were made by connecting each time five beams with each other through the Type 108° connectors. The central pentagon was then attached to a lift, whereafter the other pentagons could be attached to this central pentagon by raising and lowering the lift. Lastly the remaining beams were attached from top to bottom.

The two beams forming a base of the structure are connected with the L-shaped plate bended over 70.18°, which is part of the Type 108° connection system. To fix it to the ground a U-shaped anchor was used. During future research a better connection to the floor will be developed.

From this assembly it was concluded that the torsion present in the ReciPlyDome with the double-layered beams was eliminated. However the assembly process might still be optimized in the future by working out a smoother plan such as a beam per beam top to bottom assembly starting from the central pentagon, as during the tested assembly process the attachment of the pentagons to each other was still challenging due to their size.

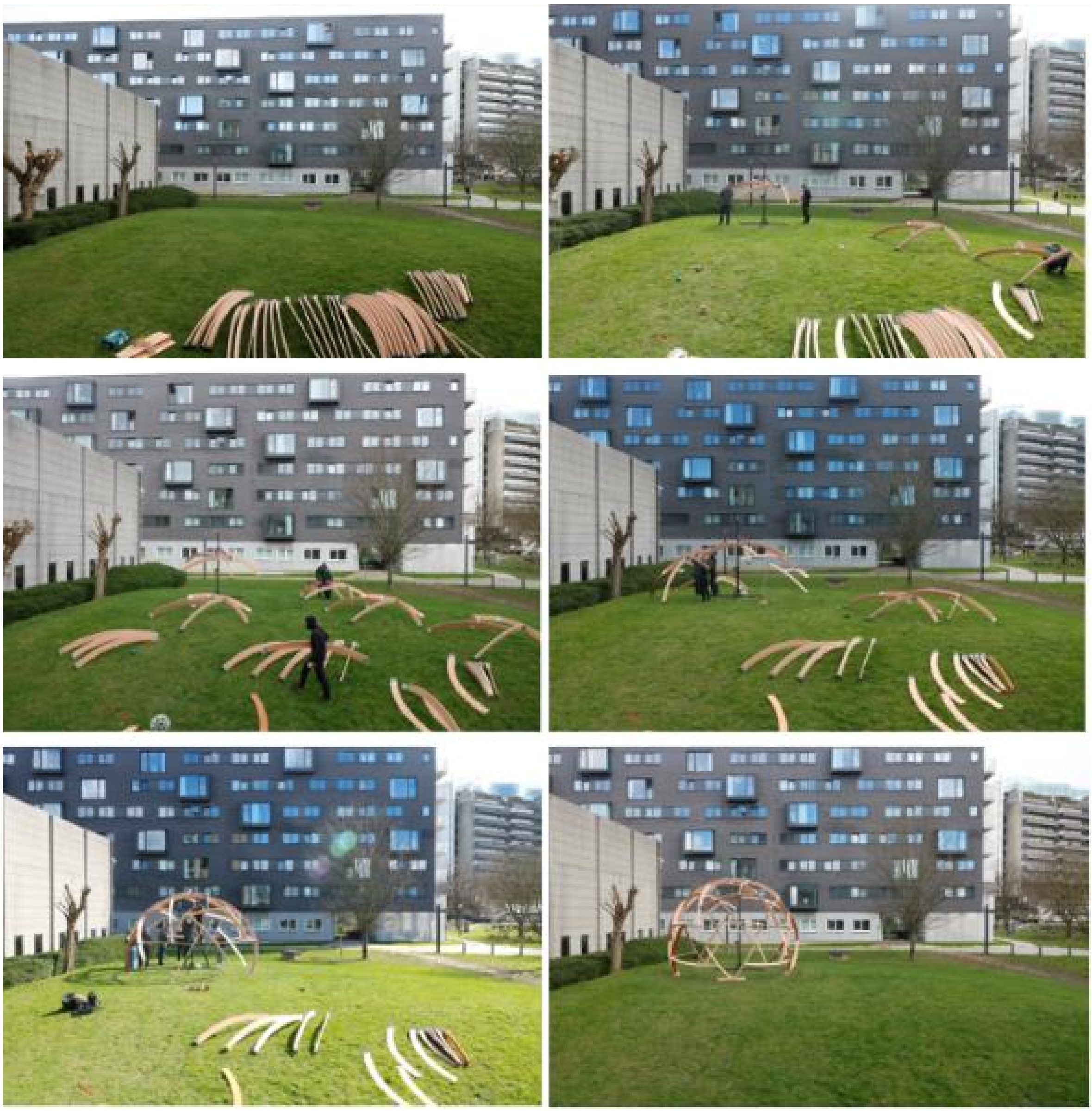

Figure 17. Assembly of the full scale prototype of the second version of the ReciPlyDome.

Figure 18. The assembled ReciPlyDome, version 2

5. Conclusion

While working towards reusable temporary structures, the ReciPlyDome was reviewed to obtain a smoother assembly and disassembly process. To achieve this goal, the torsion present in the assembly process needed to be eliminated. This was mainly achieved by rotating the beams by 90° degrees and reducing them to a single-layered module. However, to obtain the same curvature the beams are cut out in a curved manner, which results in some material losses.

Next to the rotation of the beams, a new connection system was developed that also contributes in the elimination of torsion and a smooth assembly due to the margins provided by the slotted holes. A connection system to fix the dome to the ground still needs to be developed. In future research it will be reviewed if these excess pieces of wood created by the curved shape of the beams can be used in the design for the base connection pieces of the dome.

The hands-on approach during this research allowed for accurate insights in the performance of the developed concepts. Additionally, the prefabrication of the beams and the connection system contributed to an overall smoother assembly. However, for future use a more fluent assembly plan will be designed.

The next step in this research is to conduct both a physical as a digital structural analysis to asses the optimisations. Additionally, a cladding system will be designed to provide more comfort in outdoor usage of the structure.

Acknowledgements

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