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Comparative feasibility and structural analysis of redesign Zollinger system in a doubly curved lamella *gridshell*

SERRA URETA, M., SOLÀ DE LOS SANTOS, A., BERTOMEU FARNÓS, G., SORIANO BOTELLA, E., TORNABELL TEIXIDOR, P.

Universitat Politècnica de Catalunya
Passeig de la Creu, 25, 3er 1a, Sant Cugat del Vallès (08173), Barcelona, Spain
marc.serra.ureta@upc.edu

Abstract

The Zollinger structural system, introduced by Fritz Zollinger at the beginning of the 20th century, is a three-dimensional single-curved system based on a diamond-shaped lattice. It is characterised by simplified joints with a passing-through plank between two other plank ends, eliminating the need for four beams that meet at one point. The system's advantages include simple connections, cost-effective manufacturing, easy transportation, and quick construction. However, it has some drawbacks, requiring bracing systems due to low stiffness and number of connections and applicability of the system in single curved roofs (barrel shape). When adapting the detail to double-curved, the system's connection ends are non-perpendicular to the element axis, increasing manufacturing time and costs. This study aims to design a node inspired by the original Zollinger joint, restricting machinery to a 3-axis CNC milling machine, to maintain the system's advantages while overcoming its limitations. The research process involved case studies of four recent projects with different re-designed connection details base on the Zollinger, followed by the prototyping of newly designed connections. Empirical and digital studies assessed the rotational stiffness of each joint, considering the implications for the overall construction behaviour. A chosen joint prototype was then used in a 1:1 real-scale construction of a doubly curved lamella grid shell to address structural verification and fabrication plans. The redesigned connections eliminate the need for additional bracing systems and offer a simpler and effective solution for stabilising the structure considering the joint as first factor.

Keywords: Zollinger system, lamella *gridshell*, timber, node design, rotational stiffness, optimization.

1. Introduction

The Zollinger system was first introduced in the early 1900s by Fritz Zollinger [1]. It’s conceived as a three dimensional curved structural system based on a diamond shaped lattice. The core of it design was to have a plank going through in all the joints, so there are never four beams meeting at one point.

The system initially failed due to lacking moment capacity in the joints [2], so the structures had larger deformation. In further revisions, the joining system was improved and started being used in Germany, and F. Zollinger proceed with his patent of this roof creation in 1921[3].

The brilliance of this solution lies in two key aspects: firstly, an efficient joint system reduces shared meeting points, facilitating straightforward assembly and secondly, the strength of the structure is derived from the interwoven beams, ensuring robustness and stability[4].

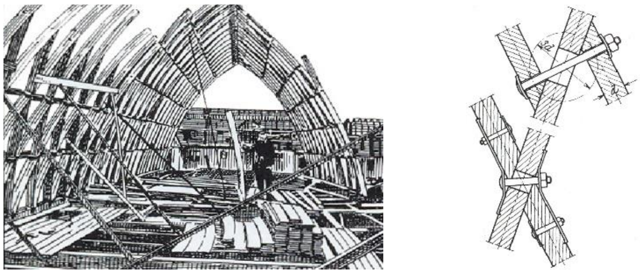


Figure 1: The Zollinger system construction, and a close look on the joint. [5]

The rapid adoption of the Zollinger roof construction stemmed from its significant advantages over traditional designs of the early 20th century. Its efficient use of materials was particularly vital in post-World War I Germany, where there was a shortage of wood [6]. Additionally, the Zollinger roof offered standardized components, facilitating simple dismantling, repair, and assembly. Its support-free design and pleasing aesthetic appearance further contributed to its popularity, alongside its simplified joint structure, uniformity of components, cost-effectiveness, ease of transportation and fabrication, and approximately 40% reduction in wood consumption compared to conventional construction methods.

This system had also a few drawbacks. Despite the simple node, the great amount of joints appearing on the overall structure and the low-stiffness them, lead to high deformation, requiring additional bracing elements like cladding or horizontal beams to ensure to provide global stability of those construction [7]. The system was limited to a single curvature roofs, commonly known as a barrel vault shaped, which did not give much freedom on the designer, and compared to other systems, it typically required more assembling time on long span roofs [7].

As aforementioned, due to the extensive number of node connections, the understanding of the stiffness of these connections is essential for calculating the entire structure accurately [8]. Consequently, experimental investigations were conducted on both the traditional Zollinger connection and a newly devised alternatives. These experiments aimed to analyse and contrast the load transfer and deformation characteristics of these connections.

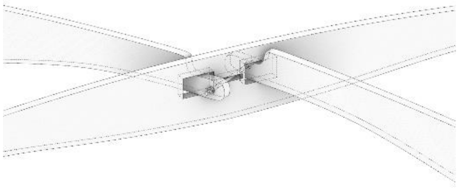
2. State of the art

Although, as previously mentioned, reciprocal frames roofs are often associated with barrel o single curved shape roofs, the innovative work developed in the recent years together with the development of new machinery demonstrates the versatility of the system creating multiple shapes [9].

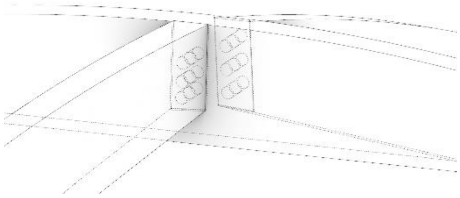
The majority of the projects developed during the early 2000s, are a re-interpretation of the Zollinger node enabling the overcome the limitation of the geometry, and mainly increasing the stiffness of the node and consequently get rid of auxiliary bracing elements, and reduce the overall deformation.

Even though those re-designed solutions vary between projects, a classifications of the node type can be done by looking at the material and machinery involved in the construction process and geometrical principals.

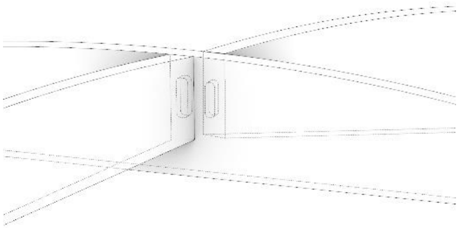
1. Timber thin planks, parallel cut, bolted connection.
2. Timber beams, oblique cuts, pre-drilled holes, dowels, tightening screws.
3. Timber beams, oblique cuts, male-female end pre-drilled dowels, tightening screws.
4. Timber beams, oblique cuts, pre-drilled holes, steel bolts.



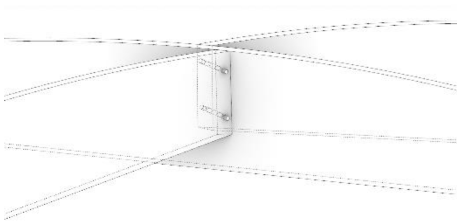
KÄNOPII, 2016, London (UK) by University of Edinburgh



TIJ Bird Observatory, 2019, Stellendam (NL) by Ro&Ad Architecten, RAU Architects and Geometria.fi



Pudelma Pavilion, 2011, Turku (FI) University of Columbia, University of Oulu, University of Aalto and Geometria.fi



ZoLink Wave, 2015, Amsterdam (NL) by University of Leipzig

Figure 2: Axonometric view of each node type based on built projects.

The node type 1, is the simplest solution by manufacturing each piece using a 3-axis machine, every piece could vary on dimensions to adapt to doubly-curved roofs, but it lacks stiffness, requiring auxiliary bracing system. In contrast, both node type 2 and 3, boast highly stiff joints, manufactured with 5-axis CNC milling machine, increasing the production cost and time. In both cases each piece is done separately, reducing the importance of clustering uniqueness off pieces, and they require of pre-drilled holes for dowels or bolts. Node type 3, required also of pre-drilling, even though the final detail is simpler requiring a 5-axis CNC milling machine just for adjusting the oblique flat edges at the beams ends.

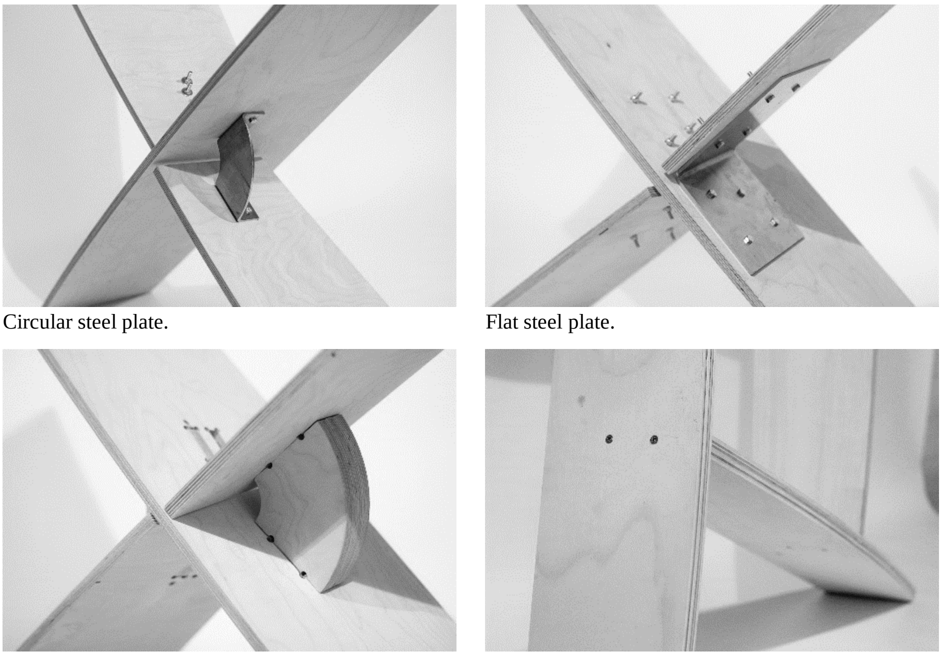
As depicted from these node types, the increment of the stiffness is closely related to the complexity of the geometry and thus higher level of sophistication in the milling machinery.

3. Node Design

The overall goal from this research is to provide a solution of a joint inspired on the Zollinger joint that satisfies the following requirements. Firstly, the node must enable the structure to have global double curvature, since the elements need to be kept straight and flat, that curvature must be provided by the joint. Secondly, both joints and elements must be manufactured by a 3-Axis CNC milling machine, and mass produced to reduce the total cost of production and time. Lastly, the joint needs to provide enough stiffness to ensure no additional bracing system will be required to provide stability and serviceability to the final structure.

Taking into account these three targets, we designed four types of joints.

- Circular steel plate.
- Flat steel plate.
- Circular wooden dowel.
- Doubly-screwed T-joint.



Circular steel plate. Flat steel plate. Circular wooden dowel. Doubly-screwed T-joint.

Figure 3: Built mock-ups of each designed joint type.

Both circular and flat steel plate come from the same principal; the oblique angle of the beam (elements ending faces are not parallel nor perpendicular to any of beam axis) is provided by the shape of the steel plate and not by modifying the beam itself. The circulate steel plate is created by finding a perpendicular plane to the intersecting of two adjacent faces. As a result, all folding of the plate are in 90 degrees, and just the obliquity of the plane of the plate and the circular opening will be unique in each joint.

The creation of the flat plate is simpler, since what will make each plate unique and provide the obliqueness is the angle between the faces of two adjacent elements.

Both cases connect to the planks through three bolts on the folded part of the plate. The holes will be created directly at the same time each plank is milled, since the axis of the bolts are perpendicular to the face of the planks.

The design of the circular wooden dowel follows the same principle as the circular steel plate but aiming to keep all constructing materials equal in timber. Since the strength of timber and steel are not the same, the thickness of the wooden dowel is increase by gluing several layers. The connection to the planks is done through a hole on the plank and insertion of the dowel in those. Since the dowel is perpendicular to both faces of the adjacent elements, the dowel and holes can be manufactured and drilled using the a 3-axis machine. In this joint, the complexity is not anymore on the geometry, but on the assembling process, which the insertion vector is not perpendicular to the elements.

The designed joint is the doubly screwed T-joint which is a simplification of the Zollinger joint by detaching opposite planks and having individual connection to the passing-trough plank with two wood screws. In this scenario, there is still need for oblique cuts at beams edges, by 5-axis machine, but can be removed by replacing the screws with threaded fasteners and double-side nuts.

4. Experimental Investigation

As previously noted, the static system of the construction becomes indeterminate as a result of the numerous node connections [10]. Therefore, comprehending the stiffness of these connections is vital for precisely evaluating the entire structure.

The experiments conducted aim to establish a unified characteristic value for each node to facilitate comparison between them. These values are subsequently incorporated into a structural analysis model to evaluate each node's impact on the overall construction performance.

The study is structured into three parts. Firstly, explanation and obtention of the characteristic value of each node. Secondly, a comparative analysis is conducted to assess the rotational stiffness values obtained digitally versus those obtained empirically. Thirdly, all designed joints undergo a comprehensive study to determine their empirical and digital rotational stiffness. Finally, the results are plotted to provide an overview of the properties of each designed joint.

4.1 Rotational Stiffness

Stiffness is a property of a body which is defined as the resistance to deformation under loads[11]. The stiffness of a body k can be written as the ratio of force applied F to the displacement d produced due to the force as:

$$\mathrm{K} = \mathrm{F}/\mathrm{d} \tag{1}$$

Similarly, rotational stiffness is defined as the property of a body to resist rotation or the ratio of applied momentum M to angle of rotation a. Mathematically, the rotational stiffness equation can be written as:

$$\mathrm{K} = \mathrm{M}/\mathrm{a} \tag{2}$$

1. Modelling the joint in a FEM Software, in this case in Karamba3D. Support points where bolts are connected to the adjacent beam, steel plate and beam as finite elements (meshes), with corresponding properties.
2. Apply a load F at the extreme of the beam in a distance L from the supports.
3. Run the Finite Element Analysis to obtain the deformation df at the extreme of the beam.
4. Obtain the rotation angle through trigonometry.

$$\tan a = \frac{opp.side\ (df)}{adj.side\ (L)} \tag{3}$$

5. Obtain the applied bending moment M with the following formula

$$M = F * d \tag{4}$$

Once obtained the rotation stiffness of the join, there is a second verification in the software modelling the timber beam in a one-dimensional finite element, and applying the value of rotational stiffness on the extreme support. Afterwards, a force with the same value F is applied at the other extreme of the beam, provoquin a deformation equal to the initial FEM model of the steel plate and beam modelled as 2d elements.

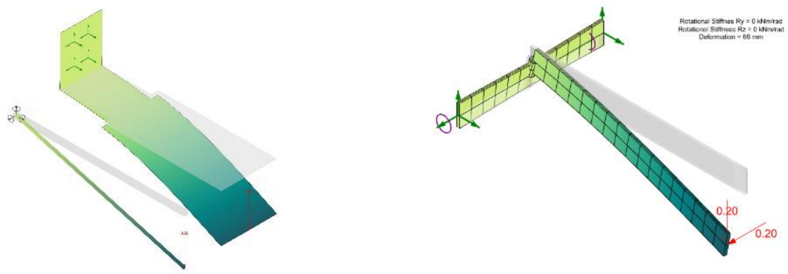


Figure 2: Digital Finite Elements Model of the joint to obtain the deformation, and apply calculated rotational stiffness to the support joint of the straight element. Rotational Stiffness applied in a joint between two beams.

4.2 Empirical investigation

After obtaining the characteristic value of the rotation stiffness of the flat steel plate through FEM digital analysis, we proceed to follow the same steps as the rest of the joints. Unfortunately, not all joints are suitable to be modelled in FEM software, and we proceed to evaluate the rotational stiffness with the 1:1 built mock-ups.

These joints are shaped on what is called a “T” joint, and allow us to run the same test following the same configuration. The horizontal beam is attached to a flat surface to avoid any kinf of movement due to applied force. Then, the vertical beam, perpendicular to the horizontal, is connected to the beam just with each defined joint type. At the extreme of the beam, further to the connection, we apply a vertical or horizontal force and read the deformation of the beam at each step.

When applying a horizontal load, what we call inward force, we obtain the rotational stiffness around the Y local axis of the beam, and when the load is applied vertically, we obtain the rotational stiffness on the Z local axis of the beam.

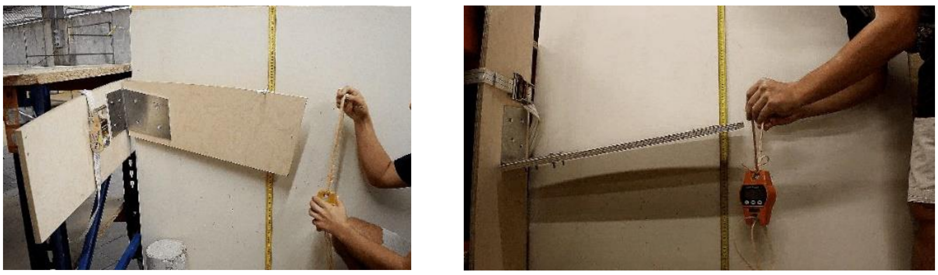


Figure 3: Flat steel plate empirical test applying the load vertically, inward force, horizontal force, down force.

On the following figures we can see how both the Flat steel plate and the Doubly-screwed T-joint are quite stiff when an inward force is applied in the test. The results of the Circular steel plate are cut in the middle of the table due to the fact that its rotation was so big that both beams started touching and prevented the movement of the joint.

Regarding the down force, the Doubly-screwed T-joint graph is almost vertical because its rotational stiffness is really low, consequently, under a really low load it deforms a lot. The other three joints are behaving similarly with the Circular wooden dowel as a best performer in terms of deformation.

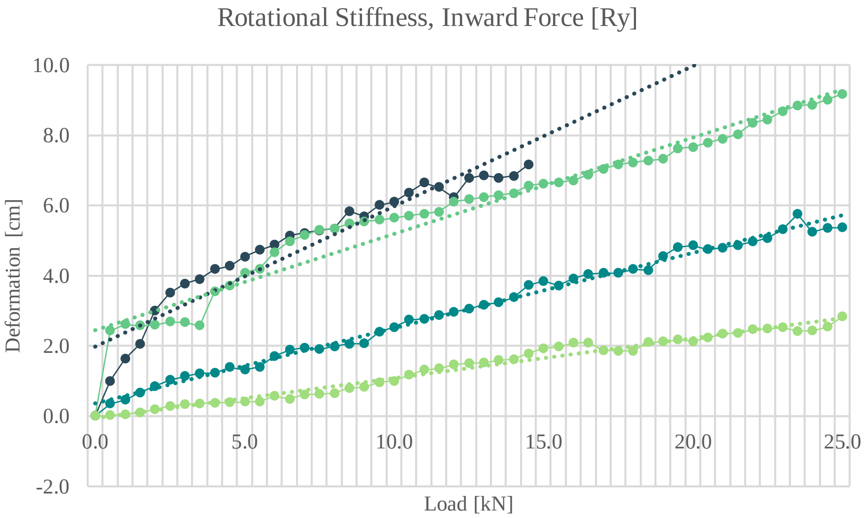


Figure 4: Graph comparing the deformation of the beam vs. the load applied in the vertical direction

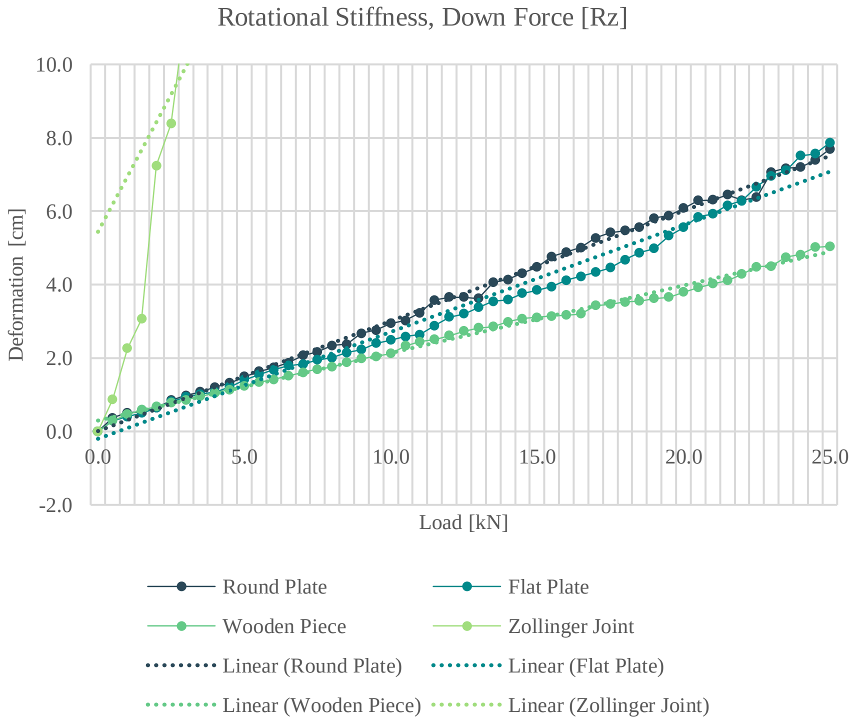


Figure 5: Graph comparing the deformation of the beam vs. the load applied in the perpendicular direction.

From these empirical tests we obtain each rotational stiffness which will be applied to the whole structure of the *gridshell*.

Table 1: **.** Comparison table of the rotational stiffness obtained from each empirical test.

	Circular Steel Plate	Flat Steel Plate	Circular Wooden Dowel	Doubly-screwed T-joint
Rotational Stiff. Inward Force [Ry]	0.01	10.83	1.40	6.32
Rotational Stiff. Down Force [Rz]	1.18	1.15	1.79	0.01

5. Case Study

Charged with the duty of designing and building a lightweight structure which would serve the purpose of being an outdoors classroom or a space to stay, we decided take the advantages of the Zollinger System. Small elements easy to carry, lift and transport. The structure must be able to be built by a force of a small group of people without any other trucks or cranes. The self-standing of the structure during assembling process will be a key point to facilitate the movement on site. To achieve the structure to be self-standing, means that no required bracing system will be used.   build a Zollinger type wooden structure. Since Zollinger structures are characterised by its small pieces, this allowed us to build the structure by ourselves without the need of any mechanical help.

The project was built in Palol de Revardit in Spain in 2021. The covered surface is approximately 45m² with bounding dimensions of 12,58 x 7,63 x 3,21.

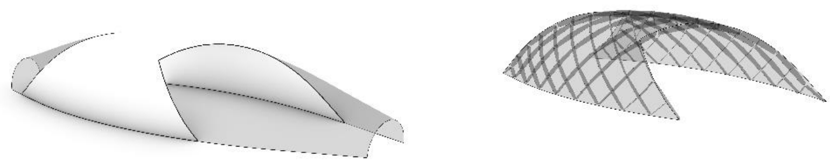


Figure 6: View of the structure including outer membrane layer and inner structure.

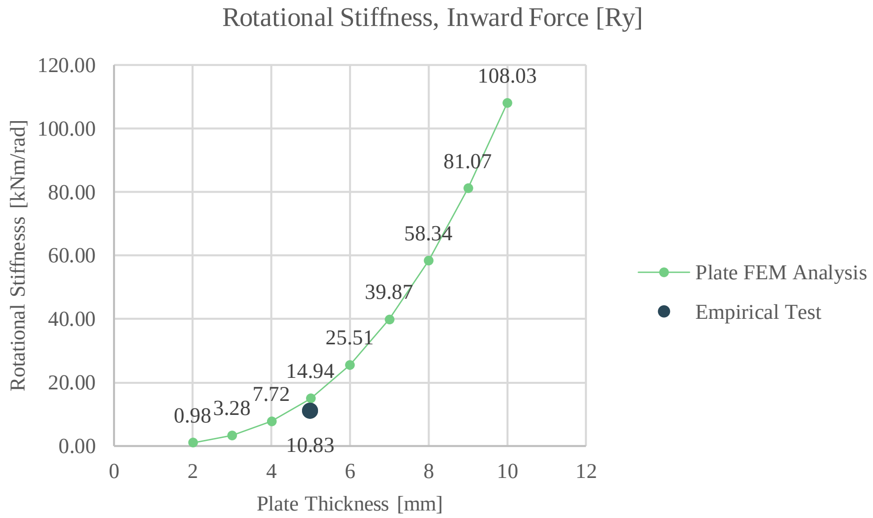
5.1 Node Selection

Taking into consideration the rotation stiffness obtained from the empirical test of each joint, we can introduce those values in the digital structural model obtaining the overall deformation of the structure under in each case. In the following graph we ca see how the flat steel plate gives considerably more stiffness to the overall geometry with an initial deformation of 53mm..

Figure 7: Graph comparing the deformation of the *gridshell* with each different type of joints.

The joint which accomplished with better performance the goals described in the introduction, is the flat steel plate. The mock-up test was done with plates of 150x150 and thickness of 5mm.

Whether this deformation is acceptable, or the joint is suitable to the structure, needs to be defined by a complementary analysis. The main idea is to know which is the performance of the same joint when changing the thicknesses. Through FEM analysis following the method described in previous sections, we can obtain the rotational stiffness in both directions, Ry and Rz.



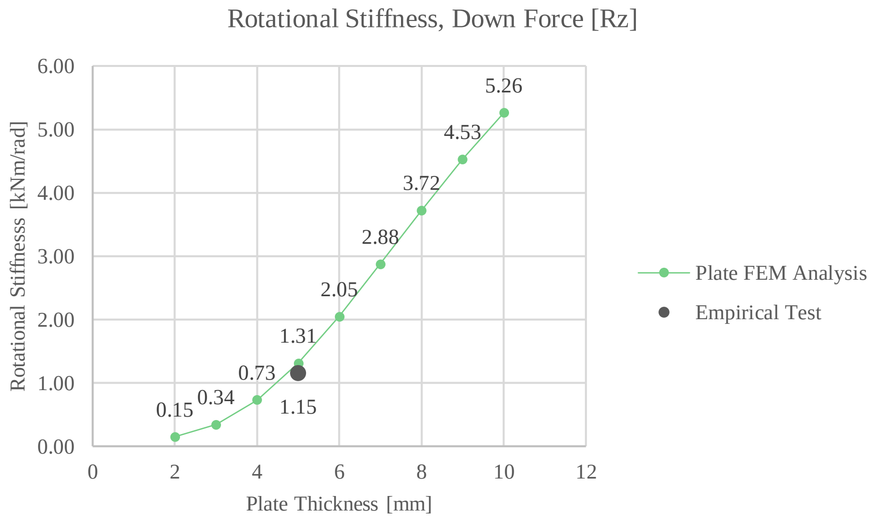


Figure 8: Graph comparing the rotational stiffness around the Z axis with different thicknesses. Figure 29. Graph comparing the rotational stiffness around the Y axis with different thicknesses.

5.2 Thickness selection

Comparing the deformation between a model with and without bracing from pinned to fixed joint, going through 9 times of thicknesses, therefore 9 different types of rotational stiffness, we observe that even though the deformation of the model without braces starts being almost a mechanism, by increasing the thickness of the plate, and by that we mean, by increasing the rotational stiffness of the joint, the overall behaviour gets closer to a completely rigid system, thus stable.

Nevertheless, the aim of a structure is not to be unreformable but deform in a an accepted range. This margin, or limit, is defined by the Eurocode and it is the span of the structure divided by the limit set in the regulations.

We observe that a model with bracing system does not rely on the thickness or rigidity of the joint to achieve a good structure performance, because its deformation is always under the limit.

However, with a *gridshell* without bracing system, the deformation is dependent on the rotational stiffness of the joint. So in our case study, we need a plate with a minimum thickness of 4mm to accept the performance of the structure.

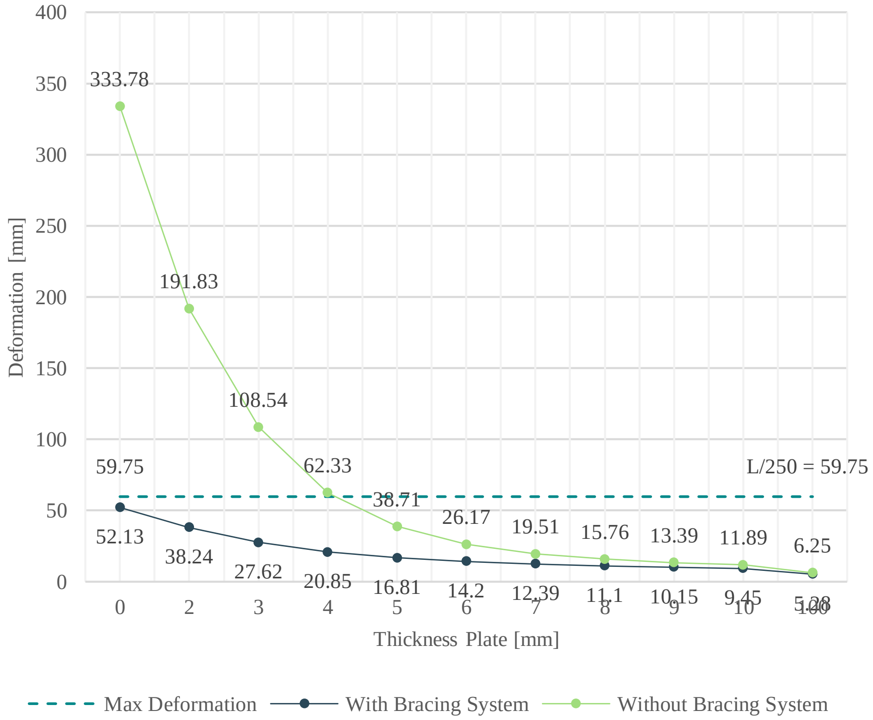


Figure 9: Graph comparing the deformation of the *gridshell* with and without auxiliary bracing system and different rotational stiffness according to plate thickness.

5.3 Digital vs. Empirical

Once the structure was built we did an empirical loading test in order to compare the deformation of the digital test with the real building. We hanged a total load of 250kg from four points of the structure. The same approach we did in the digital model applying four point loads.

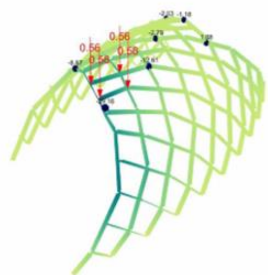


Figure 10: Loading process of the built structure. Figure 43.Scheme of point loads applied to the digital model.

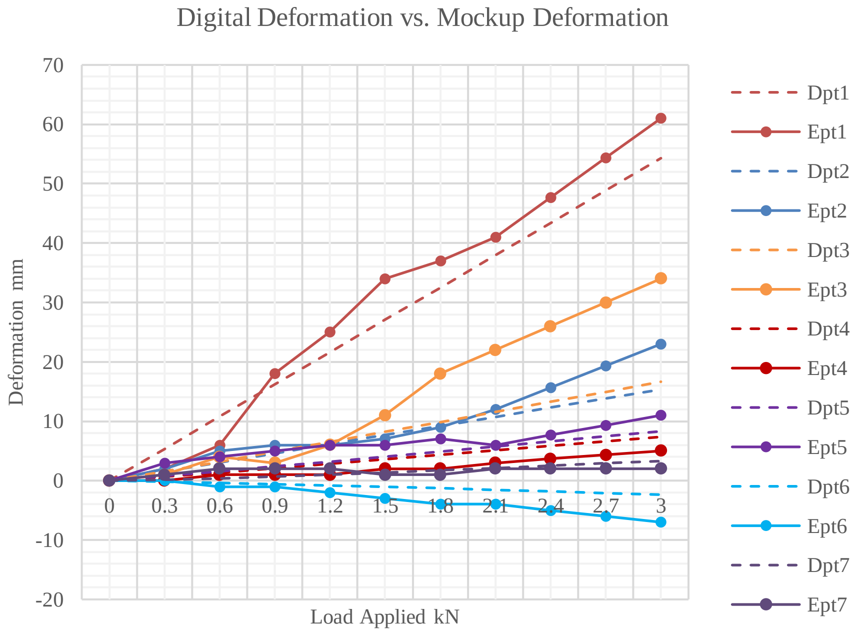


Figure 11: Graph comparing the displacement of each point of the digital model (dashed lines) and the empirical loading test (continuous line).

The results showed us that the structural behaviours in terms of deformation of both digital and real buildings were similar. We obtained an increasing deformation factor of x1.2 applied to the digital model to achieve the real deformations.

Consequently, we validate the results obtained during all this study, and trust the selection and decisions done.

6. Conclusion

The Zollinger structure is an efficient way to cover large spans, however, it must be correctly studied and analysed. We can reduce thickness by replacing the stiffness of the thick beams by using small but still metal plates. The system is flexible enough to de adapted to doubly curved surfaces, which is of great advantage for global efficiency and stability.

Even though the use of bracing helps the structural behavior of the whole structure, we have proven it is possible to build Zollinger inspired structures without the use of it and have it behave correctly according to regulations.

After this in depth analysis regarding structural behavior, price and fabrication constraints, we would like to point out some aspects that could be further developed:

- Mesh density: A further study on how the density of beams affect the structure and comparing with different types of joints could be developed. The density of elements is not only crucial due the extra number of nodes, but if just increasing the number of elements in linear direction, the almond-shaped lattice get acute, and so the loads are transferred more vertically.
- Larger scale building: We've studied how to build on a small scale, without the needs of cranes. How the system would apply to bigger volumes and larger buildings could be studied.
- Use of membrane as bracing: Even though it is not accepted by regulations, it is interesting to study the effect of using the membrane as complementary bracing system..

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Author(s): Marc Serra Ureta
Alex Solà de los Santos
Gerard Bertomeu Farnós
Enrique Soriano Botella
Pep Tornabell Teixidor

Affiliation(s): Universitat Politècnica de Catalunya

Address: Passeig de la Creu, 25, 3er 1a, Sant Cugat del Vallès (08173) , Barcelona, Spain

Phone: 639549117

E-mail: marc.serra.ureta@upc.edu

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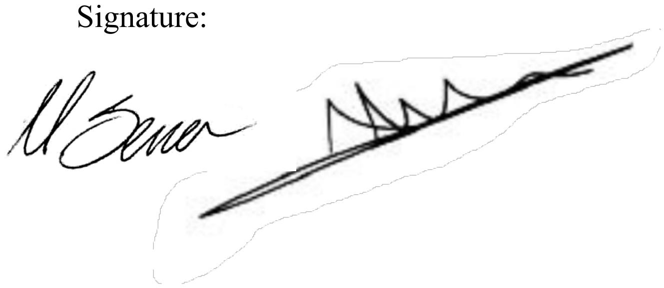

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