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TIMBER PAVILION CONSTRUCTED IN COMBINATION WITH PARAMETRIC DESIGN AND THE ZOLLINGER CONNECTION SYSTEM

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ABSTRACT: The engineering workflow in the pavilion project in Belgium has combined a particular connection / joint strategy to fulfil the architect's organic design intentions in a timber pavilion. The client and the architect set high artistic, cost, and environmental ambitions. The goal was to develop a grid-shell mesh consisting mainly of straight beams and continuous for both flat and double-curved surfaces. The structure was created by a combination of parametric engineering design and a grid-shell system called the Zollinger system, invented by Friedrich Zollinger in the 1920s. The paper describes the requirements and limitations set for the timber shell and gives specific features of the timber roof that influenced the design process. To consider all factors in the parametric workflow, a Grasshopper algorithm was set up and used in combination with the design software RFEM to analyse and optimise the grid shell structure efficiently. The paper shows that timber construction with high design ambitions by organic look can be achieved if the parametric design is combined with the Zollinger system. An outlook is provided on how using a parametric design tool can simplify the detailed design and generation of drawings.

KEYWORDS Zollinger system, timber structure, pavilion, parametric design

1 INTRODUCTION

A wooden pavilion for a private client should be designed mainly for the art exhibition. A gallery where the roof should be part of the exhibition, a work of art itself. Therefore, it will be exposed internally and some parts also externally. The Oslo-based architectural firm Snøhetta designed an organic shaped roof with flat, double-curved surfaces. Thus, a structural system needs to be created which sets not only high ambitions on aesthetics but also on the structural efficiency, costs, and environmental impacts. Consequently, the Zollinger system was chosen as a basis for designing a structural grid shell made of mostly straight beams with the help of parametrical design tools.

Figure 1: *Exterior views ©Snøhetta*

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2 THE PAVILION

2.1 THE ZOLLINGER SYSTEM

The Zollinger system is named after the German architect Friedrich Zollinger who patented the structure during the recession in the 1920s. Rhombical arranged lamellas form a grid shell that can span large spans, using timber beams with a limited length and simple connection details. Both factors make prefabrication possible and an easy installation process on site. Mostly single-curved arched vaults were built for which the benefits of using the Zollinger structures show in general additional material savings.

Figure 2: *Interior view ©Snøhetta*

The main pattern of a Zollinger lamella roof is shown in figure 3. Beams are arranged at angles to each other so that two lamellas meet in the middle of one continuous lamella, forming a rhombus. The pattern enables the lamellas to be connected without moment transfer and still provides a stiff system. While the forces are transferred in several directions, the Zollinger system allows for large openings.

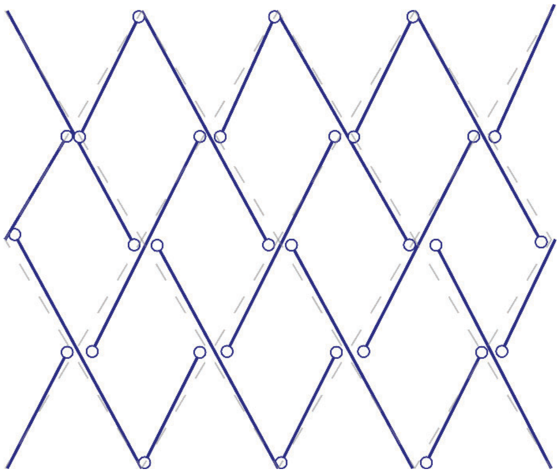

Figure 3: Principal pattern of the Zollinger lamella structure

The Zollinger system is not limited to the structures mentioned above, but it also allows to form double-curved structures out of straight beams while keeping the connection details simple. The system's disadvantages are that the installation process takes longer due to the many details. Therefore, it will be necessary to prefabricate larger elements in the workshop and assemble them on the construction site.

2.2 THE PAVILION'S GEOMETRY

The roof of the pavilion is a composition of double and single-curved surfaces; therefore, a definition for the grid must have been found, which allows a smooth transition between the different types of surfaces, see figure 4.

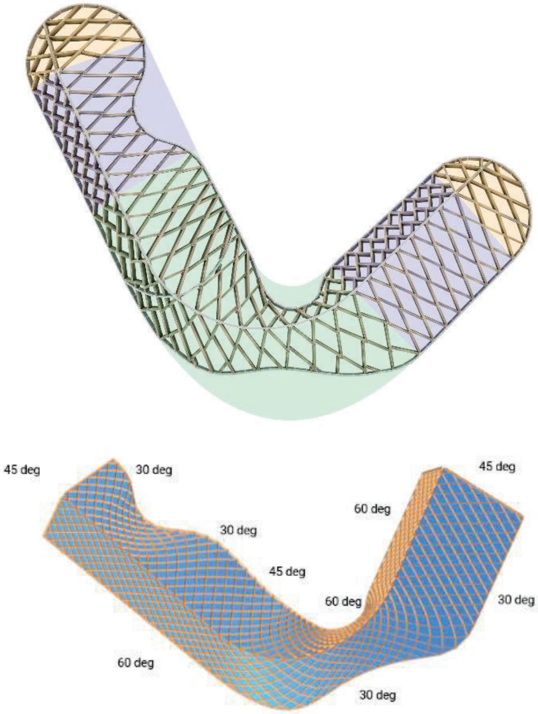

Figure 4: *Different types of surfaces (top) and roof angles (bottom). Top figure: blue: flat surface; green: double-curved surface; orange: double-curved, ellipsoid*

The roof can geometrically be split up into 3 different types. The first type, marked in blue, is a flat surface above the glass-roofed greenhouse and partially above the exhibition/living area. The second type is a double-curved structure marked in green. It represents the entrance area and parts of the residential/ exhibition area. Both pieces will be covered with timber plates and finished with the traditional Japanese shou sugi ban method to make it weather resistant. The areas at each end are part of an ellipsoid with a strong curvature. In addition to the double curvature, the geometry is not symmetrical to the top beam, and the vertical angles differ. This challenge could only be solved with the help of the parametric design described in chapter 3. Several geometries were studied to find an alternative meeting all requirements and limitations.

The requirements and limitations to design an efficient roof structure were:

- Straight beams for the whole roof structure.

- The grid should be as regular as possible to avoid many different node details and different types of beams

- The number of nodes should be kept to a minimum while still being able to establish the Zollinger system and the curved surfaces. With a denser mesh, the surface better approximates the curved architectural geometry, but requires more nodes and, in some areas, more complicated details.

- Simple design detail

- The maximum edge length of the rhombus is given by the glass elements and the plates of the roof membrane

- For each rhombus, a mostly flat surface must be established to mount the timber plates

- Double curved edge beams should be avoided due to the costs and complexity of the production

- The structure must be supported on rigid foundation walls

- The Zollinger system should be applied to all parts of the roof

2.3 SPECIFIC FEATURES FOR THE DESIGN PROCESS OF THE MESH

Specific features of the pavilion's geometry influenced the solution for the mesh.

2.3.1 Double curvature

The nodes in the areas of double curvature will have several different angles, which will influence the detail design. In addition, the mesh must be chosen, such as the timber plates for the roof membrane can be primarily flat or split up into triangulars.

2.3.2 Transition between cold (entrance and glass house) and warm (residential/ exhibition) area.

The roof above the exhibition area will be heated and therefore insulated, while the entrance area and the greenhouse will be uninsulated. Therefore, the thickness of the roof built-up differs. The offset should not be seen, and the top roof surface should be kept at one level. Therefore, the offset in the roof between the cold and warm areas must be handled in the structural system. The beams will be split and moved horizontally apart. Due to the vertical eccentricity, a moment-rigid connection is required, which is made using slotted steel sheets. To avoid complex details, the mesh was chosen so that the façade line (break line) generally does not go through a mesh node but through a continuous system beam.

2.3.3 Foundation

The timber roof will be based on cantilevering concrete walls. The influence of the horizontal deformations of the walls during the lifetime of the pavilion (creep) is considered in the support conditions in the calculation model. Those deformations will lead to vertical deformations of the roof and affect the force transfer.

2.3.4 Edge beams

The edge beams must gap the unsupported areas over the entrances. A double curvature of the beams should be avoided while, at the same time, their geometry should align with the architectural geometry. In addition, the edge beams must be contributed enough stiffness to the roof structure to avoid big deformations. This concerns mostly the long-spanning beam with big curvatures at the entrance area.

Therefore, an alternative geometry was developed that is close to the architectural geometry but only with single curved edge beams.

2.3.5 Half cones

Figure 5: *Alternative for ellipsoids with single curved beams*

The half-cone-shaped surfaces have a small radius of curvature which is challenging for the Zollinger system. Several alternatives were analysed in terms of the complexity of the details, the transition to the other roof areas, the curvature of the beams, the installation process, and the deviations to the architectural geometry.

The Zollinger system is applied but with single-curved beams. The advantages are that the same details can be used, and the visual impression of the main roof is retained. Using single-curved beams can keep the deviation from the architectural geometry to a minimum. Other alternatives were, e.g., a reciprocal frame with pinned connections or solutions with double-curved beams or straight beams spanning between the top and the edge beam.

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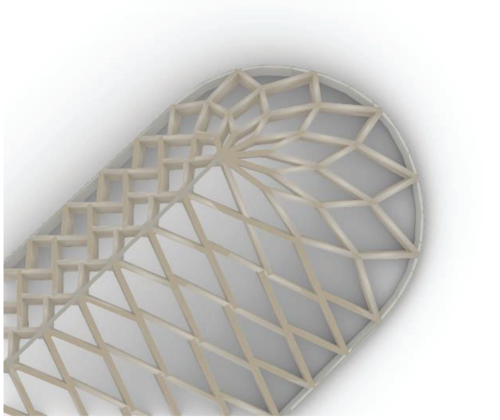

Figure 6: Alternative for ellipsoids – reciprocal approach

2.3.6 Unsymmetrical roof geometry.

Both parts of the roof must be split up in the same number of pieces to guarantee that the beams meet at the same position at the top beam. Since the outer edge line is longer than the inner one, the size of the mesh, especially over the double-curved entrance area, differs a lot. It needed to be ensured that the mesh of the inner part gets manageable since this will lead to many complex details and an enclosed look of the surface. At the same time, the mesh must be dense enough to establish rhombuses on the outer part. Several alternatives were studied. Two alternatives are shown in figure 7.

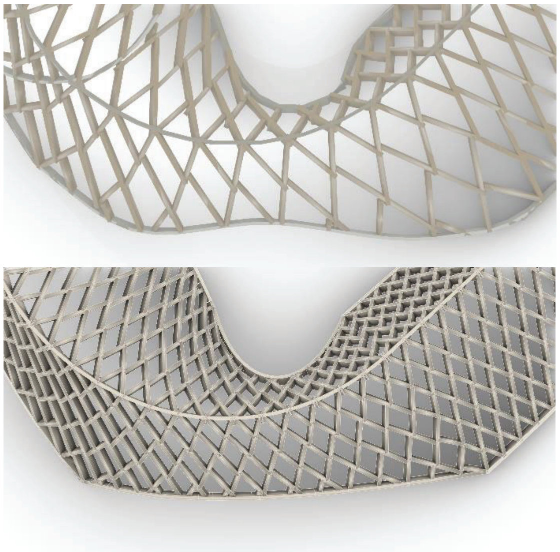

Figure 7: Mesh above the entrance area – Top: wide mesh – Bottom: dense mesh with a single curved edge beam

2.4 NODE DETAILS

Joints and connections are crucial points in timber structures and are generally critical to the structure's design. The strength of the connectors in the joint will dictate the strength of the timber structure [1].

Several types of details can be considered for the connection of the timber beams. Several factors influence the choice of relationship. Such as

-Types and sizes of internal forces which need to be transferred

-Geometry of the node. There are different angles in different directions, plus a possible eccentricity between the two ending beams

-The installation process. The number of nodes to be mounted on site must be considered, as what kind of angles are present and how much space is available.

- Collision between the connection elements of the two connecting lamellas.

2.4.1 Zollinger pin

The pin can transfer mainly axial forces. Its advantage is that it is easy and fast to install and has only one pin per node. The eccentricity required to install the pins can be large to use the pin for double curved surfaces. Especially at the inner area over the entrance where the mesh is denser, this will be problematic. Due to the shrinking of the timber elements, tightening the pin at regular intervals can be necessary.

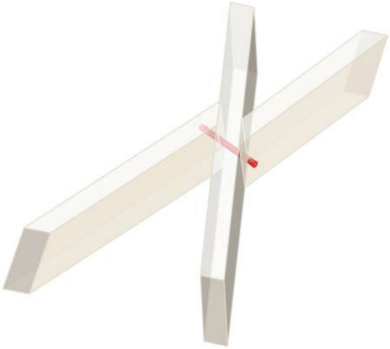

Figure 8: Zollinger pin

2.4.2 Connection with slotted-in plates and dowels / screws

A connection with steel plates will contribute more stiffness to the structure and allow the transfer of axial and vertical forces. Due to the different angles of the surfaces, this type of detail would lead to many different shaped steel plates, leading to a complicated planning and installation process.

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Figure 9: Detail with slotted-in steel plates of Frans Masereel Centrum in Kasterlee, Belgium

2.4.3 Connection with screws

In this kind of connection vertical and axial forces can be transferred. To avoid a possible collision between the screws of the two end beams an eccentricity between the two ending lamellas is necessary. For the double-curved surfaces, the angles for the screws can be adjusted. Several screws will be required per node, leading to more connection elements than with the Zollinger pin.

Figure 10: General detail of Frans Masereel Centrum in Kasterlee, Belgium.

2.4.4 Connection to the pavilion

For all the above connection requirements it has been determined to use a screwed connection for the general detail and where required by geometry or force a slotted plate as shown in figure 9.

3 PARAMETRIC DESIGN PROCESS

Parametric design tools are used to establish the mesh's geometry with the specifications and requirements mentioned in chapter 2. Unlike being designed directly, the parametric design method is shaped according to algorithmic processes. The aim is to be flexible with few basic parameters, to allow for fast analysis of different alternatives.

3.1 PARAMETRIC TOOLS

To define the geometry GRASSHOPPER was used. Once the boundary conditions were defined, an algorithm was set up that easily allows to adjust of the mesh size. It efficiently and quickly contributes to the study and identification of geometrical problems, such as collisions between the Zollinger roof and the facade line or the evenness of the roof membrane.

The definition was based on architectural geometry. The algorithm's input is the roof's outer lines, which represent the edge beams, and the top line, representing the ridge. In addition, the architectural surfaces of the roof were required, to define a mesh which is as close as possible to the architectural geometry. The input geometry was slightly adjusted to optimise the transition between the flat and double-curved surfaces.

In chapters 2.2 and 2.3 the geometrical specifics of the pavilion roof are given.

In the first step, the outer line without the end parts and the top line were split into the same number of segments. The reasons are given in 2.3.6. Also, the surfaces along the top line are split up normally to the plane in a specified number of segments. It applies the same design approach as for the outer and top lines. The designer chooses the number of segments but it must be a number that can be divided by 2 into a natural number. Only then a Zollinger grid can be established.

In the second step, a diagrid is set up. The nodes from the bottom lines are connected with the ridge nodes. In figure 11 the diagrid is shown as dashed lines.

To apply the Zollinger system the lines in the defined main direction of the diagrid are split at every second node. The received segments represent the continuous lamellas. The same way the second direction is handled but starting the segmentation at the first node, then every other. Now the principle of the Zollinger system is established.

Dependent on the design of the node detail, the eccentricity of the two ending lamellas is required. To study all consequences of the eccentricities on the mesh geometry and other design aspects, the definition of the eccentricities was included in the GRASSHOPPER definition. Therefore, the vectors of the lines of the diagrid are identified. Depending on the vector's direction, the line's end is moved upwards or downwards from the node on the continuous lamella. The principal can be seen in figure 11.

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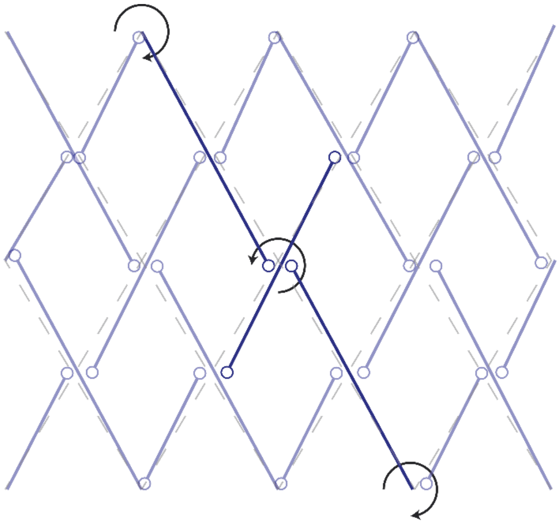


Figure 11: *Diagrid and set up of the eccentricities*

For the ellipsoids, the definition must be due to the strong curvature of the surface and the fact that the meshes of each side of the top line meet adjusted. Dependent on the chosen design approach.

Once the geometry is final, the model can be used to set up a calculation model. For the analysis, the software RFEM from Dlubal was used. Among others are the cross-section, beam hinges, support condition and loads defined in GRASSHOPPER and exported to RFEM.

3.2 CALCULATION MODEL

3.2.1 Geometry, node and support conditions

The geometry defined in GRASSHOPPER was used to set up a calculation model in RFEM. This way, it is possible to make changes to the geometry, such as optimising the curvature of the edge beams or changing the mesh size, without spending much time setting up a new model each time.

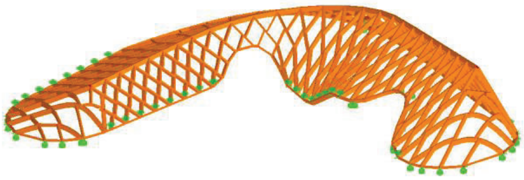


Figure 12: *RFEM Modell*

The connections between the lamellas are assumed as whole hinges. This represents the properties of the Zollinger pin. For other types of details, the stiffness of the connection is determined to check the influences on the roof system and the connection forces.

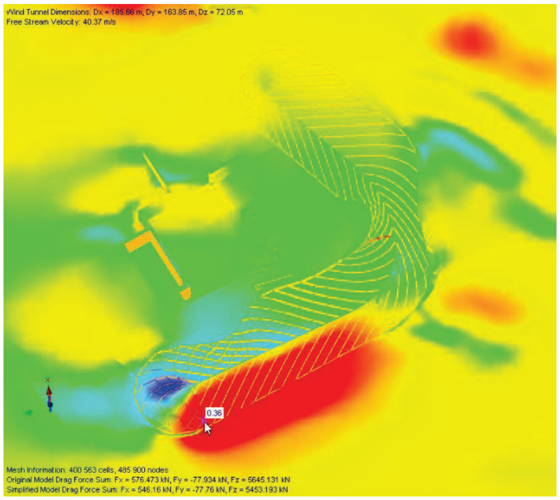
The vertical support is fixed, while the supports in the direction perpendicular to the concrete wall / outer beam are modelled as springs to account for the horizontal stiffness and long-term effects of the concrete wall.

3.2.2 Wind loads

The Eurocode only gives Cp-values for simple geometries of buildings; thus, the pavilion's plan geometry and the Eurocode assumptions do not cover the double-curved surface. Therefore, the add-on module RF-WIND was used to define the C_p-values for the wind loads for different wind directions. RF WIND is an add-on module to RFEM.

With the C_p-values and areas given from RF WIND the wind loads on each node of the structure were calculated within GRASSHOPPER and applied to the structure. The add-on module can also apply the wind loads directly to the structural model. Still, additional surfaces must be defined, which could adulterate the stiffness behaviour of the structure. In addition, the wind loads would need to be newly defined by RF WIND each time something was changed in the model. Using only the C_p- values can better control and check the load size.

To verify the C_p-values of RF WIND, they were compared to values from the EC 1-4 for a simpler roof geometry. It turned out that the values corresponded well and that the values from RF WIND could be used for the calculations.



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Wind Tunnel Dimensions: Dx = 185.66 m, Dy = 163.85 m, Dz = 72.05 m
Free Stream Velocity: 40.37 m/s
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Mesh Information: 400 563 cells, 485 900 nodes
Original Model Drag Force Sum: Fx = 576.473 kN, Fy = -77.934 kN, Fz = 5645.131 kN
Simplified Model Drag Force Sum: Fx = 546.16 kN, Fy = -77.76 kN, Fz = 5453.193 kN
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Figure 13: *RF WIND Simulation*

3.2.3 Analysis

With the calculation model, weak points of the structure were identified and optimised in cooperation with GRASSHOPPER according to the limitation and requirements given in chapter 2.2. For this purpose, among other things, the eigenforms of the roof were studied, and the force flow was analysed.

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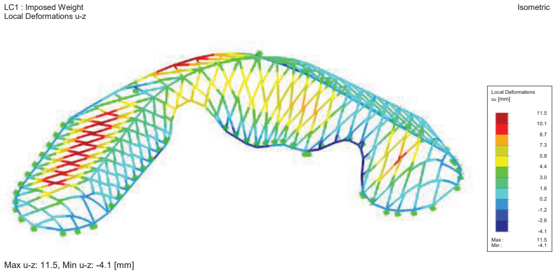

Figure 14: *Deformation print-out RFEM*

4 OUTLOOK

A parametric workflow could be developed to create drawings in a later design phase of the project. This will be especially helpful since, due to the complexity of the double-curved geometry, the length of the different beams and the angles of the connection details will differ. In addition, with the help of parametric tools, clashes of connection elements are quickly identified, and controls to guarantee the feasibility of each node are established.

The forces to transfer at each node can be retrieved from RFEM and checked in GRASSHOPPER for the governing combination. Especially with many different angles, it will take much work to identify manually relevant nodes for the calculation design.

5 CONCLUSION

The studies and analysis for this project show that a combination of a double-curved roof structure and flat surfaces made of straight timber beams using the Zollinger-System in combination with parametric design is possible.

Several factors must be included in the design process for the definition and the setup of the final mesh, such as the design of the nodes, evenness of the roof membrane, types of surfaces, base geometry (symmetrical, unsymmetrical, size of curvature, …), number of nodes, size and regularity of the mesh and the function of the building. All these factors can be included in the parametric design workflow.

The integration of a parametric workflow makes an efficient planning process possible. It helps to identify structural and geometrical problems early and allows quick adjustments in the structure's design.

GRASSHOPPER in combination with the calculation software RFEM from Dlubal allows changes in the geometry easily and therefore an optimised geometry which covers all requirements can be achieved.

REFERENCES

[1] Livingstone, Andrew: *Timber Connection*. Centre for Offsite Construction + Innovative Structure, 2015 A.Livingstone@napier.ac.uk

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