ORIGAMI - Folded Plate Structures, Engineering

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Summary

In conjunction with Hans-Ulrich Buri’s research, this thesis project addresses the engineering part of the folded Origami structures. The material employed for this type of structure is not necessarily defined. Therefore metal, concrete and timber realisations are widely spread. A relatively new product on the market of derived timber products is cross glued timber panels. This project employs this material to design the folded structures. The main goal is to determine appropriate details for the folded joints and establish a static model to calculate real scale structures. Therefore experiments with specially developed joints are tested in the laboratory to enter the results obtained into the numerical static model.

1. Preliminary study

1.1 Folded structures and Origami

Folded structures have a long tradition in construction. A common example for an application is shed roofs for production or stocking buildings. The particularity of folded structures is the additional rigidity due to the inertia introduced by erecting the surfaces.
In this work, Origami folding is extended to a structural scale and application. Adapted methods are developed and analysed to generate a variety of feasible designs.

1.2 Material

As mentioned above, folded structures are not restricted to any particular material. On the other hand, there has been a relatively new product on the market for a little over a decade. Its name has not yet been definitively determined. It is referred to as cross glued timber panels, massif timber panels or massif wood boards. These panels are widely used in timber housing construction. Here they replace traditional 4 x 4 framework constructions.
Firstly, the decision was taken to realise the Origami structures with these laminated cross glued timber panels. This decision was taken because the application and use of this product can be easily expanded and the producers are looking for such new applications, since they are interested in broadening the range of their product.

2. Numerical pre-dimensioning

2.1 Set-up

In this case, a simulation of a fictive, but realistic, tennis hall was undertaken. A numerical design of a tennis hall, supplied by the architect, was modified in a way to import the file into the static software. The aim of this simulation was to know and better understand the internal forces at the edges for which the joints and assemblies must be designed and developed. Furthermore, it was important to examine the presumption that the internal forces in the panels' surface might be of less importance in the global view of the entire structure. Since the simulation was effected in three dimensions with the idea to calculate exactly the given design, there were theoretically six internal forces into which the results could be divided. A differentiation between the edges and the surface was made, because some items were of less importance at the edge and others of less importance in the surface. In particular, there were three forces at the edges:

- F_x (axis parallel to the edge)
- F_y (axis perpendicular to the edge and within its surface)
- F_z (axis perpendicular to the edge and perpendicular to the surface)

and three moments at the edges:

- M_x (around the above-mentioned x-axis parallel to the edge)
- M_y (around the above-mentioned y-axis perpendicular to the edge and within the panel's surface)
- M_z (around the above-mentioned y-axis perpendicular to the edge and perpendicular to the surface)

From these six forces actually present, only three were further examined and analysed. The other three forces were considered less interesting further to the following studies that justified not taking them into account:

1. F_x – the panels have bearings at all four edges, i.e. the four neighbour panels. Since there is close contact between each element, a movement parallel to the edge will, in the first instance, be blocked by contact before any assemblers are activated.
2. M_y – this type of moment plays an inferior role because of the folding at each edge. It cannot be neglected entirely, because the destruction of the prototype showed that panels moved in a way revolving around their y-axes.
3. M_z – this movement is blocked in the same way a movement along the x-axis is blocked.

Concerning the form, the architect delivered the design, and two geometries were analysed. The first one is a repetition of ten arcs that form a symmetrical structure with two planes of symmetry. Fig. 2.1 shows the initial design.

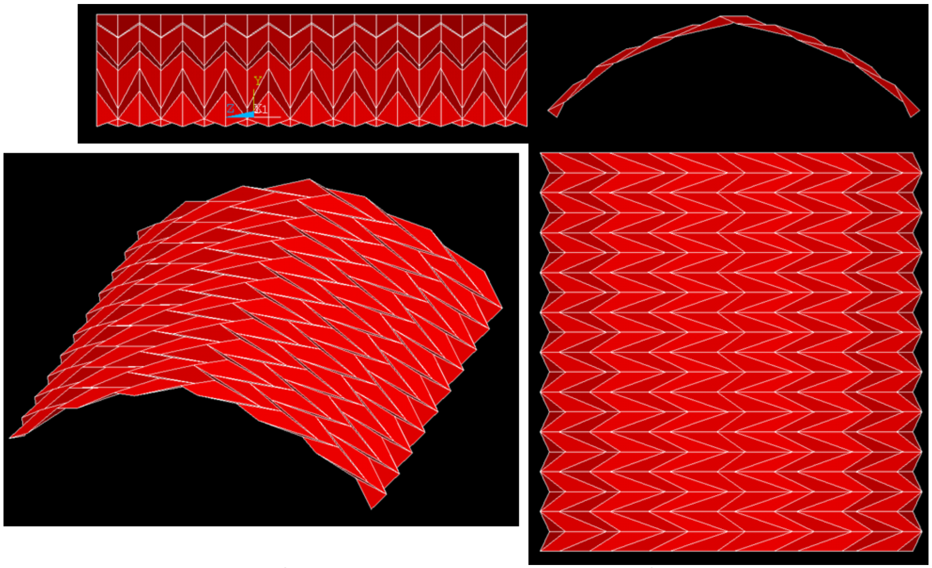


Fig. 2.1 Variant A: uniform structure with two axes of symmetry

Since first preliminary calculations and the prototype showed large deflections on the structures' extremities, i.e. the non-supported ends at the gables, a second variant was adapted where the panels towards the edges were more inclined, with the intention of augmenting the vertical inertia of the folding (see Fig. 2.2). In this case, only half the structure was modelled, because a decision was taken to only apply symmetric loads, whereas a full modelling involves increased work and time without yielding more precise results.

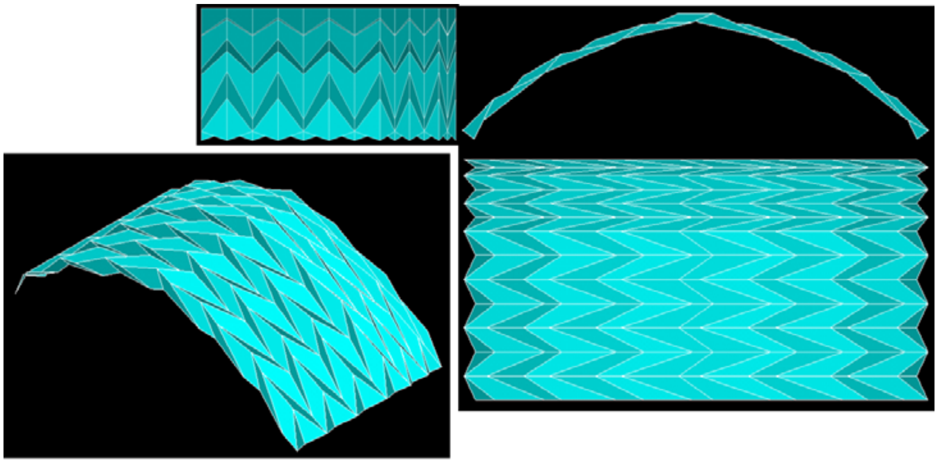


Fig. 2.2 Variant B: one half of the structure with stiffened extremities

2.2 Definition of the edges' rigidity

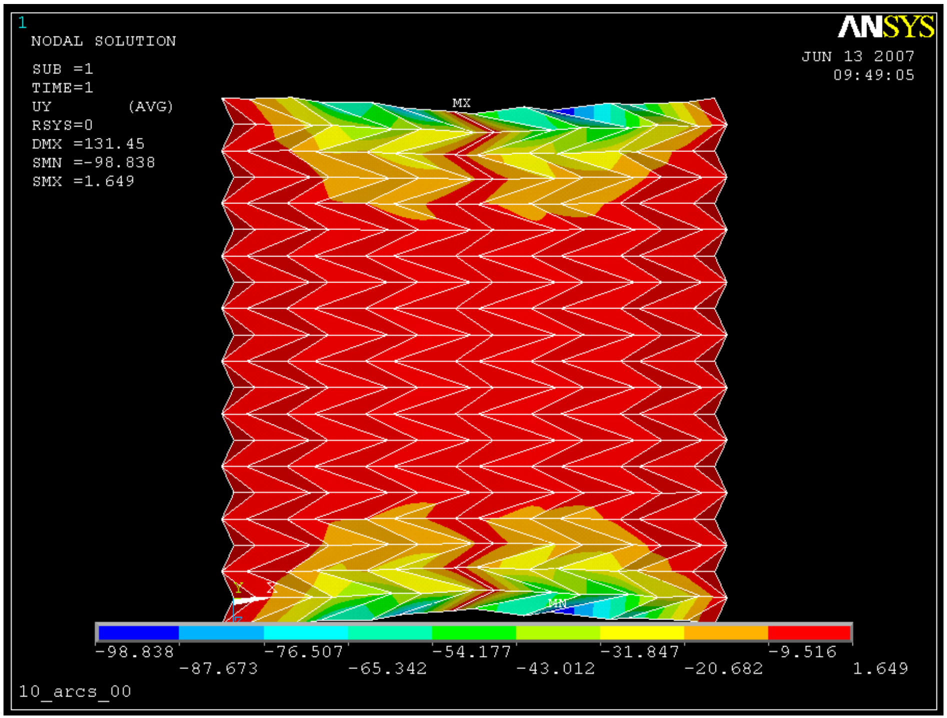
It was interesting to know what degree of rigidity the linear joint required, or to what degree it influenced the resulting internal forces or deformation. Therefore both variants were prepared to be run with three types of joints at the panels' flanges.

1. free pinned ($ux = uy = uz = 0$, $rx = ry = rz \neq 0$)
2. perfectly stiff ($ux = uy = uz = rx = ry = rz = 0$)
3. elastic

For the third run, rigidity had to be initially defined, then adjusted later with the realistic experimental values.

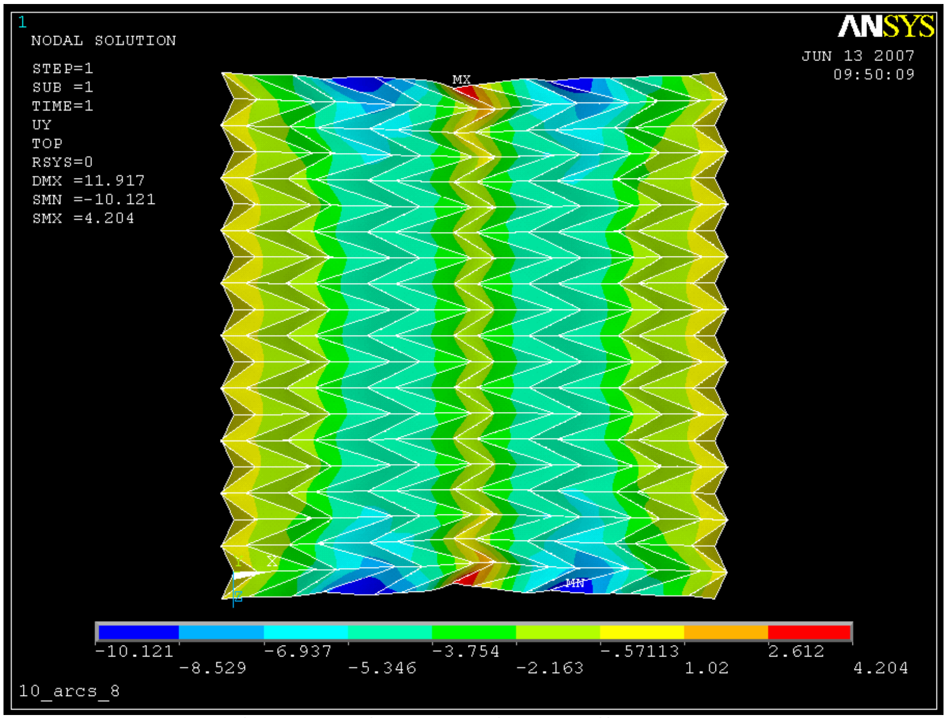
2.3 Results and conclusions from the simulations

The following figures show the results observed for the vertical deformation, comparing the free pinned and stiff variants.



Large deflection can be observed at the free edges of the structure

Fig. 2.3 Vertical deformation for the freely pinned variant



With stiffened panel edges the deformations are more equally distributed over the structure

Fig. 2.4 Vertical deformation for the perfectly stiff variant

Presumably, fewer deformations, due to higher rigidity, came along with rising internal forces. In this particular case, a differentiation between the edges and the middle part had to be made when interpreting the results obtained. The edges were more influenced by irregularities, whereas the middle part was undisturbed. Table 2.1 and Table 2.2 below compare the numerical extreme results. These appear at the edges.

Table 2.1 Comparison of the extreme vertical deformation [mm]

	Variant A	difference [%]	**Variant B**
pin-jointed	**98.8**	-71	**28.7**
difference [%]	-90		-65
stiff	**10.1**	-1	**10.0**

Table 2.2 Comparison of the extreme bending moments along the panels' edges [Nmm/mm]

	Variant A	difference [%]	**Variant B**
pin-jointed	**10212**	-73	**2738**
difference [%]	-33		7
stiff	**6866**	-57	**2925.0**

The observation to be made is that the large bending moments at the edges diminished by changing the joint rigidity for variant A, and did not change significantly for variant B, while for both variants the deformations diminished considerably. In general, the stiffened variant's internal forces can be considered as more equally distributed over the surface.

3. Experiments with joints

3.1 Experimental set-up

Four types of joints were tested in a bending and transversal set-up at the same time.

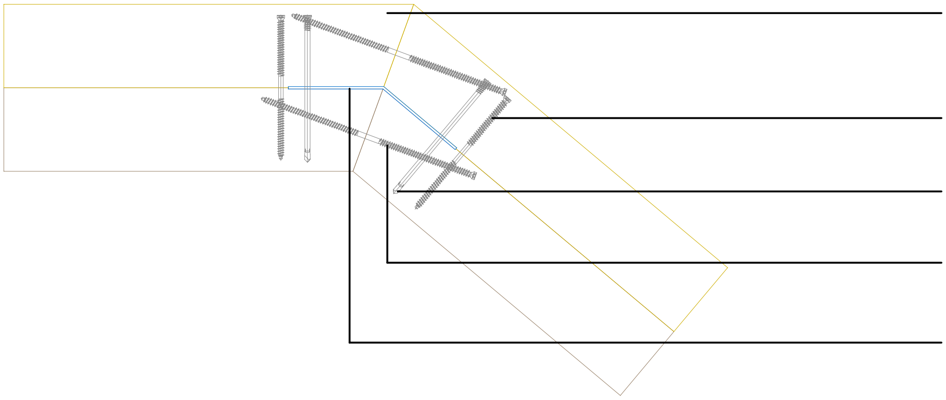
1. Single layer with one SFS WT connector (300mm)
2. Double layer with 2 x 2 SFS WT connectors (300mm and 190mm)
3. Double layer with 2 SFS WS self-drilling dowels (190mm) and metal plate
4. Type 2 and 3 combined

For each type, three parameters were varied:

1. The distance between the connectors
2. The thickness of the metal plate
3. The angle between the surfaces

The experiments were designed following the method of designed experiments, which guarantees a maximum of information obtained with minimal cost, time and material.

Fig. 3.1 shows exemplary type 4 with the bended metal plate in the interface between the two timber layers and the screws and dowels.

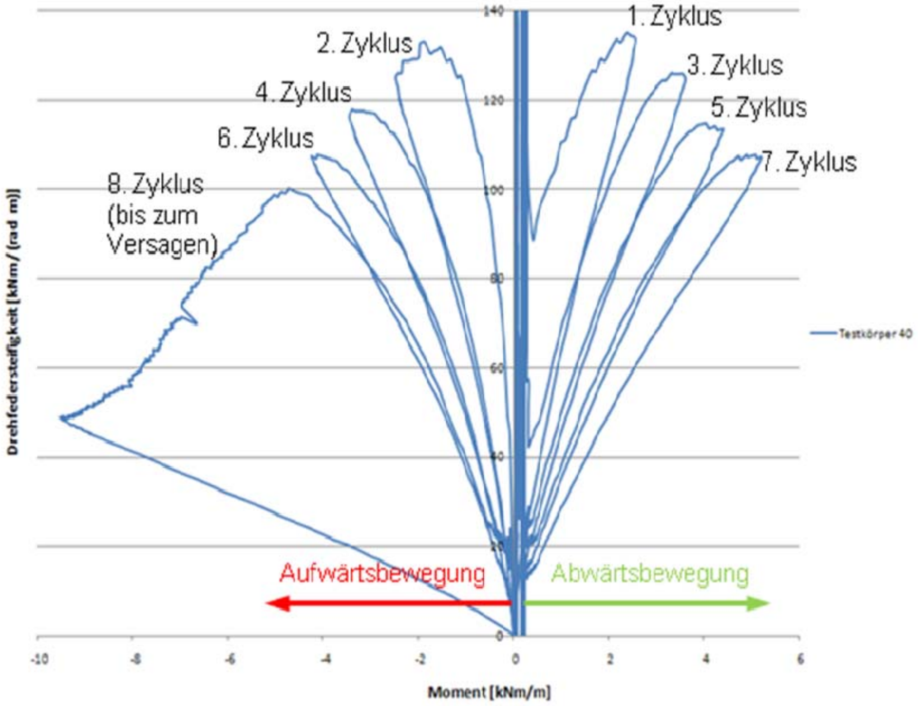


1. Two layers of cross glued timber panel, 110mm
2. 2 x SFS WT, 190mm
3. 2 x SFS WS, 190mm
4. 2 x SFS WT, 300mm
5. Metal plate, 3mm

Fig. 3.1 Type 4 of the tested joints

3.2 Results

With the data analysed, the rigidity of a torsion spring can be determined as a function of the parameters introduced. Fig. 3.2 shows a typical curve of a rigidity / moment diagram.



Parameter setting:

1. Connector distance : e = 250mm
2. Angle : α = 40°
3. Metal plate t = 3mm

Fig. 3.2 Rigidity / introduced moment diagram

The tested joints showed:

- Bi-directional behaviour, i.e. the rigidity differed for the two possible moment directions
- Plastic deformation behaviour
- Ductile fracture behaviour.

4. Conclusions

The results obtained will define a torsion spring element for the numerical simulation. With this, the results will improve in accuracy and reliability.

The simulation will be automated and a user interface developed to ease the exertion.

Further efforts have to be made in order to optimise the suggested joints. The optimal distance and distribution - and therefore the number of connectors - will be determined with the spring element introduced.