Reciprocal Frame (RF) optimized timber truss structure: a design and build case study

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Abstract

The paper describes a project where an optimized timber Reciprocal Frame truss structure was developed to create the roof structure for an agricultural building measuring in plan 32 x 16 meters. The building is a cowshed part of an ecological meat production company. The client strongly believes in sustainable approaches to design and production, thus it was important that the agricultural building design fully followed sustainable approaches. When constructed, the building will be used as a showcase to bring awareness about sustainable production, design and construction. Thus the sustainable approaches are followed through at all levels: from the production to choice of materials for construction, building design principles and the construction process itself. In this context it was important that the timber roof design used locally grown timber, was optimized to minimal use of material, was easy to construct and had a distinct aesthetic. The paper follows through and presents the design ideas and process that led to the roof design. It also points towards possible new ways of working with double-layer RF structures.
Keywords: Reciprocal Frames (RF), local timber, truss structures, efficiency, single-layer RF structures, double-layer RF structures, optimized design, aesthetic expression, simple construction, detailing.

1 Introduction

The site of this project is located on the tiny Danish island of Glænø, located on the west coast of Zealand, with an area of of 5.6 km^2 and permanent population of 57, Wikipedia [1].

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When approached, the client described to us his goal as one where he aimed to develop a new building type that is sustainable, resource saving and energy-creating. He wished for a building that would use mainly local materials, wood from a local forest, fit in the built landscape of the area by externally having the volume and form the same as any other Danish agricultural building – with a 30 deg. sloping roof, but internally the space and structure would have a very distinct aesthetic. Furthermore the construction materials should be used in an optimal way, and the construction methods should be simple, so that other farmers could easily construct their own agricultural buildings without the use of heavy machinery and cranes.

The building was to integrate solar energy panels and explore innovative ways of utilising new forms or renewable energy sources. It was a challenge especially that the design was to be compared in terms of material use to a conventional project, yet it was expected to achieve much more – both in the sense of aesthetic qualities and in terms of simple, almost D.I.Y (do it yourself) form of construction.

The discussion regarding the roof structure went a full circle starting with a Reciprocal Frame (RF), exploring various other options for the roof structure and ending with a form of a double-layer RF truss structure. The roof had to fulfil three main criteria: be structurally efficient i.e. use as little as possible material, be easy to construct i.e. be buildable without heavy machinery except from the machines that farmers would normally have, and lastly – be beautiful both in the overall composition – morphology and in utilising simple jointing methods. Before describing the design and optimization process we need to look at RFs and why they were the obvious choice for the roof structure.

2 Reciprocal frames

Reciprocal Frame structures are a form of a three-dimensional structure formed from mutually supporting linear members organised in a stable interlocking assembly.

The structure can be formed in many different configurations both using members with identical length or members with varied lengths. The different morphologies offer interesting and visually distinct structures. Another advantage of RFs is that in RF configurations because of the offset members only two members are connected at a time. Thus the RF system offers the potential for simpler joints. Had the members not been offset and instead been connected in one point either complex carpentry type of joins or some kind of a metal specially fabricated joint would have been needed to form the connection. Instead by offsetting the members can be bolted through joining only two at a time.

Figure 1: The complex Rokko Mount RF structure.

3 The initial ideas

The first ideas started off with Leonardo da Vinci's form of RF based arches [2] which are easy and simple to construct, yet the interlocking beams offer an interesting sense of spatial weaving, as if one had used giant knitting needles which remained in the knit and formed the roof structure. This idea had several advantages in that it would be very easy to construct it. Had it been a temporary structure – like Leonardo's temporary bridges, one could build it just by interlocking the beams, fully relying on the friction in the joints.

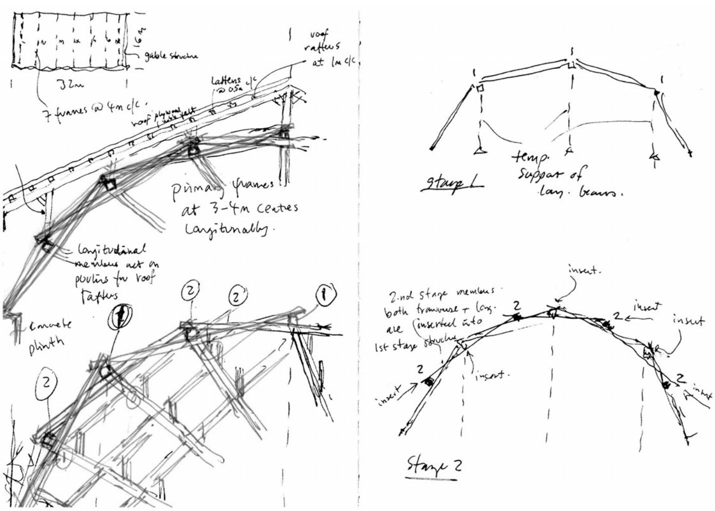

Figure 2: Initial design inspired by Leonardo's temporary bridges.

For a permanent structure one would need to use simple connections with bolts, but they would be easy to construct. To simplify the joints and optimize the construction process it was envisaged that the proposed design would use interplay of one, connected to two, connected to one element-structural members in the RF arch structure (see figure 3).

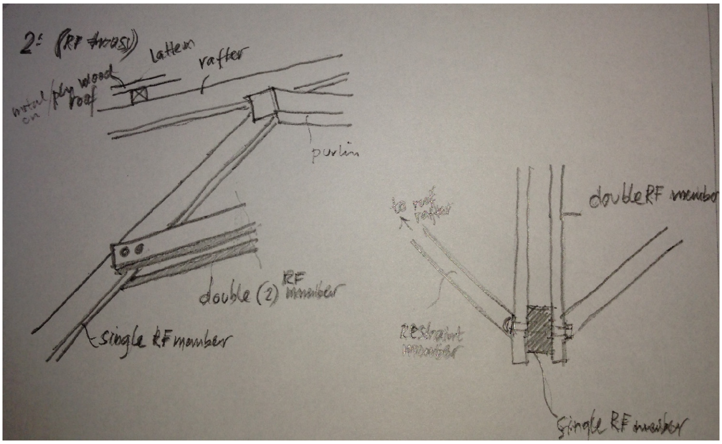

Figure 3: Alternating “one” and “two-rafters” for the structural members simplifies the connections and gives an enhanced aesthetic simplicity.

We all agreed that such a structure would be easy to construct, we all liked the aesthetic appearance, but as expected, when we analysed and calculated the amount of wood needed to construct it – it used about 50% more wood than if we had used a simple prefabricated timber truss structure. It was clear – we were back on the drawing board!

4 The next steps

One of the important next steps was to look at why our initial idea was inefficient in terms of amount of material – wood needed to build it. It is clear that an arch would be less efficient to a truss, but there was more than that.

To form our “Leonardo inspired RF arch roof” we had to build a secondary structure supported on the arch for attaching the cladding and forming the enclosure of the roof. The secondary timber structure was adding unnecessary additional load to the main RF arches. As the initial idea fulfilled the constructability and aesthetic criteria, an obvious suggestion was to propose cladding the arch. This in essence meant exposing the arched form externally instead of having a sloping 30 deg. roof appearance. Despite the obvious material saving due to the reduced load from the removed secondary structure, this solution was not acceptable because of the external form of the building, which would have not fitted in the expected Danish agricultural building landscape. So, we were back to the drawing board again! We went back to looking at trusses, which were efficient but quickly left that idea due to the lack of aesthetic qualities. Then, an idea suddenly came up.

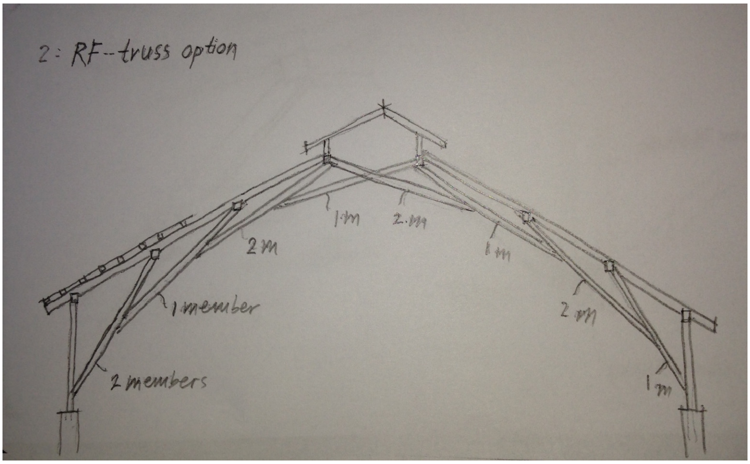

Figure 4: One of the designs with optimised RF truss.

If one works with depth a structure becomes more efficient. Furthermore if one uses the upper cord of the structure to support the cladding and form the required 30 deg. roof appearance, one avoids the unwanted inefficient use of secondary structure. After this real break-through and after several iterations with different RF morphologies – we arrived at the concept design for the roof.

5 Structural analysis

A three-dimensional model of the structure was constructed to analyze the overall stability of the structure under the combinations of loads, including wind and snow loads. In this, all elements-members are assigned to pinned support condition (free to rotate at ends). Though the actual timber connection may transfer the moments between the elements, it will become loose over years due to the local compression deformation of timber and eventually no moments can be transferred; thus it is calculated as pinned supports.

In the computer model, the loads are applied on each frame as line loads, and the wind load on the gables are applied on pseudo-panels. The calculations are in accordance with the Eurocode with Danish National Annex. Also, the structure is checked against the limit state design criteria, and the overall displacements of the structure are not critical as for the building does not include any brittle components. The material strength of the elements is specified to C18 with Service Class 2.

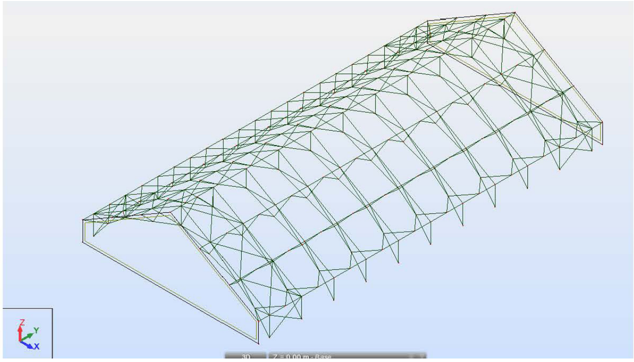

Figure 5: Perspective view of the structure.

Figure 6 shows the wind loads (kN/m^2) applied on the roof. "+" signifies wind towards the structure and "-" wind away from the structure.

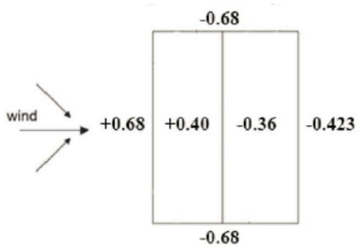

Figure 6: Applied wind loads on the main RF trusses.

The deformations of the structure in a perspective view and elevation are presented in figures 7 and 8 respectively.

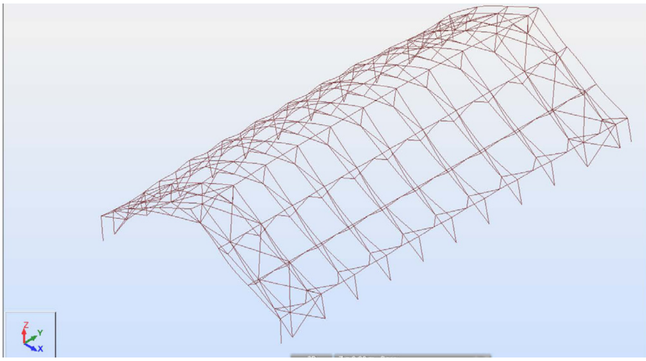

Figure 7: Perspective view of the deformed structure under the wind load.

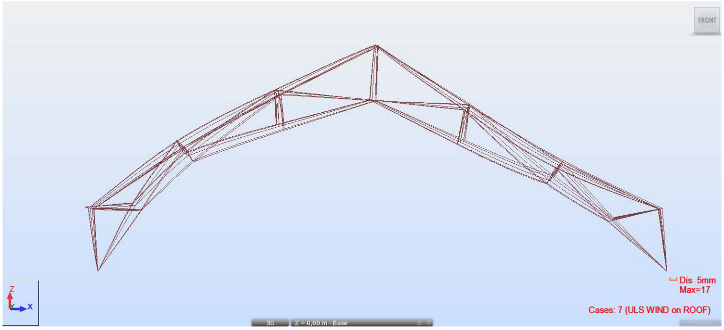

Figure 8: Elevation view of the deformed structure under the wind load.

The wind loads (kN/m^2) applied on the gables, the deformations in a perspective view and elevation are given in figures 9, 10 and 11.

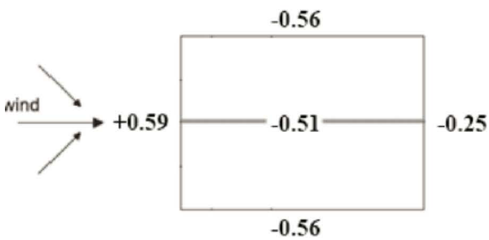

Figure 9: Applied wind loads on the gables.

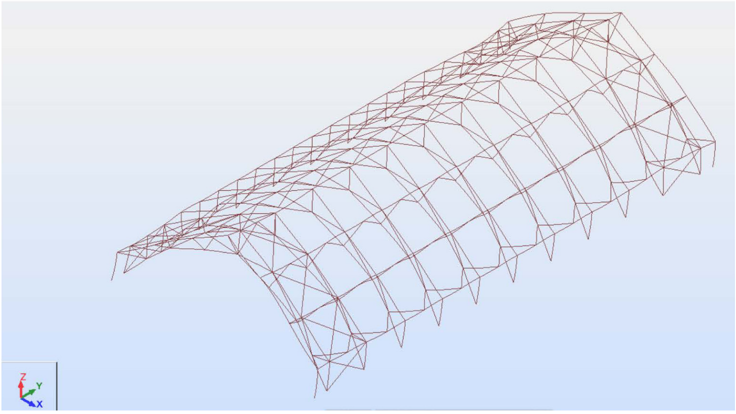

Figure 10: Perspective view of the deformed structure under the wind load applied on the gables

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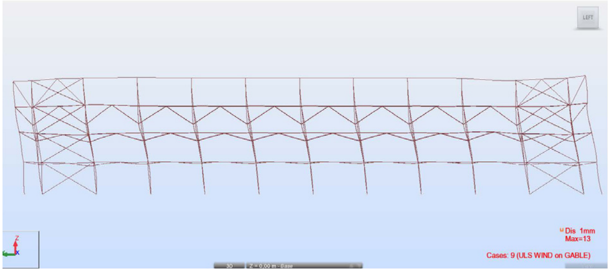

Figure 11: Elevation view of the deformed structure under the wind load applied on the gables.

The deformations due to snow loads are presented in figures 12 (perspective view) and 13 (elevation).

We carried out many iterations and the design was optimized in terms of ease of construction, appearance, detailing, and structural efficiency. Each step in the iteration was compared in terms of material used to a prefabricated truss, which was used as a benchmark. The last RF optimization iteration brought the design very close to the efficiency of the truss structure. The RF design uses only 5–10% more timber than the truss. Yet, this design offers a distinct aesthetic, simple construction methods and an opportunity to use locally grown timber.

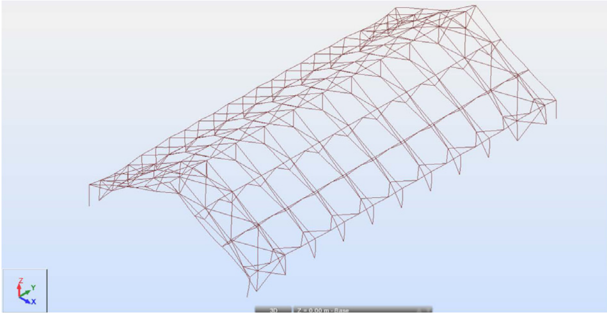

Figure 12: Perspective view of the deformed structure under the snow load.

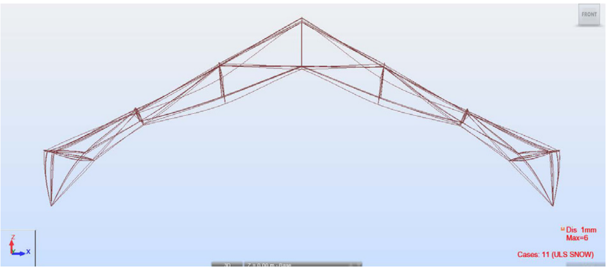

Figure 13: Elevation view of the deformed structure under the snow load.

6 Work in progress

The client has bought the timber from a neighbouring forest on Glænø. The timber – local spruce has been felled. The next step is to cut the timber to the needed timber member sections with correct lengths and to leave it to dry. At present the design of connections is being completed. The connections need to be simple to build and apart from providing safe and reliable details also, need to contribute to the enhanced aesthetic of the timber roof structure. We are hoping to have connections with only one bolt going through the joint. The project will start on site in approximately 6–8 months to allow time for the timber to dry and to fit with the lifecycle of the cows for which it will be providing a home.

7 Research potentials and conclusions

This design project has given an opportunity to try out a new possible research direction for RF structures. Double-layer RFs are a new possibility for optimized minimal structures. The beautiful RF structures constructed to date all use a single-layer RF structure, which in most cases, carries a secondary structure for the cladding creating the roof enclosure to the building. Working with increased structural depth in the double-layer RF trusses makes the structure more efficient. Also, it offers a possibility of using the main structure for attaching the cladding. This also gives the possibility of forming roof structures that externally resemble an ordinary building appearance as in the case of the Glænø roof. It would be interesting to explore further the double-layer RF opportunities in terms of optimised minimal material use, construction simplicity and visually beautiful and distinct structures. This makes sense on every level and is something we are pursuing at present.

Acknowledgement

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References

[1] Wikipedia accessed 5 March 2014 http://en.wikipedia.org/wiki/Glænø
[2] Popovic Larsen, O. *Reciprocal Frame Architecture*, Elsevier, pp. 5-18, 2008.