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Reciprocal Frame (RF) Structures: Real and Exploratory

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Abstract The paper presents the opportunities and challenges of reciprocal frame (RF) structures. These are discussed through some recently built, innovative examples such as the Mount Rokko-Shidare Observatory in Japan and the Kreod Pavilion in UK, as well as through the explorations with physical models in both small and full scale carried out over the last few years at The Royal Danish Academy of Fine Arts School of Architecture in Copenhagen. The RF structure gives the potential for achieving novel and expressive curved three-dimensional complex forms, using straight members. At the same time, it offers the possibility for fast and simple construction using low-tech techniques and simple joints. This makes it a possible solution for many types of applications, ranging from short-span canopies, to geometrically complex structural forms, to rapidly constructed emergency shelters after disasters. No other structural system can offer the same level of variability and scope for different applications.

Keywords Reciprocal Frames · RF configurations · Physical models · Full-scale RFs

Introduction: What are Reciprocal Frames and Why Use Them?

In their simplest configuration Reciprocal Frames (RFs) can be defined as structures consisting of linear flat or inclined elements which support each other and are arranged in a way to form a closed circuit or unit. The assembly formed in such a way is a stable geometrical configuration and forms a spatial structural system, most

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commonly used for roof structures, where the members share the load and transfer it down to a ring beam, columns or supporting walls (Fig. 1).

RFs and RF related structures are clearly not new. They have been used throughout history in various forms—as flat and inclined configurations, as simple one-unit structures and as more complex forms consisting of several interwoven and combined single units (Fig. 2).

Typically, in simple inclined RF configurations loads are transferred by combined axial and bending action, while in flat assembles they work mainly in bending. In both the flat and inclined RF configurations there is shear at the point where the RF beams rest on each other. RF structures are less efficient compared to gridshell structures, which work mainly through axial action. Despite this, there are some important benefits of using RFs:

- RFs are formed by short members;
- In complex RFs there is a large degree of built-in redundancy;
- In symmetrical configurations all joints are identical;
- In symmetrical configurations all members are identical.

These advantages, together with the extremely large scope of possibilities for creating new spatial configurations, make them a structural system unlike any other. RFs are varied in the configurations that are possible and as such are an interesting system to use for building applications. The different structural forms offer possibilities for different applications. This paper discusses some explorations with full-scale models as well as innovative applications of RFs recently constructed.

RFs in the Past: Fulfilling a Need

As with many inventions, the RF principles have emerged from a need. The flat configurations by Leonardo da Vinci of both simple and complex RFs from the fifteenth century (Popovic 1998), the RFs by the architect Sebastiano Serlio from the sixteenth century, four-beam assemblies or the stairwell configurations were all structures finding a solution for spanning a longer distance than the length of the available timber elements. A further development were inclined RF structures, such as the complex forms found in Leonardo da Vinci's *Codex Atlanticus*, for creating RF grid roofs as well as his designs for temporary bridges (Popovic Larsen 2008). Chinese bridges were also constructed using similar principles; furthermore, in his book *Opera Mathematica* John Wallis studied the complex RF configurations using three-, four- and six-member RF complex assemblies (Wallis 1695).

The German engineer Friedrich Zollinger (1880–1945), developed a system of lamella domes constructed from short timber elements using RF joints. The system was developed to achieve ease and speed of construction. The short timber members do not meet in a single point—instead they form a RF joint with beams that are offset (Fig. 3). The system was developed after the first world war to serve a need for housing and allow for fast, inexpensive construction. At the time, there was a serous lack of housing and deficit of funding and the Zollinger system helped fulfill this very important need. Lamella domes were later used by Pier Luigi Nervi for the aircraft hangers in Orvieto,

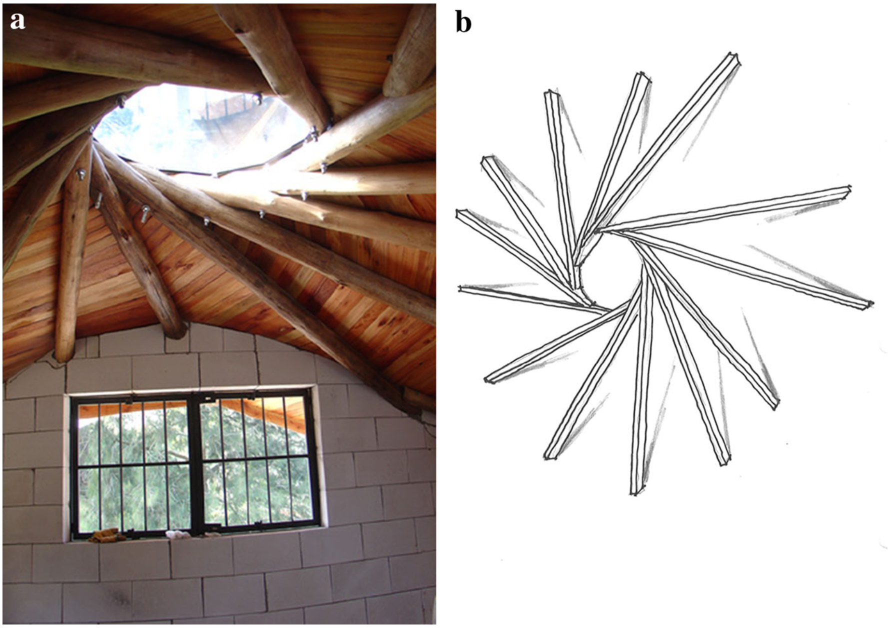


Fig. 1 A simple RF configuration

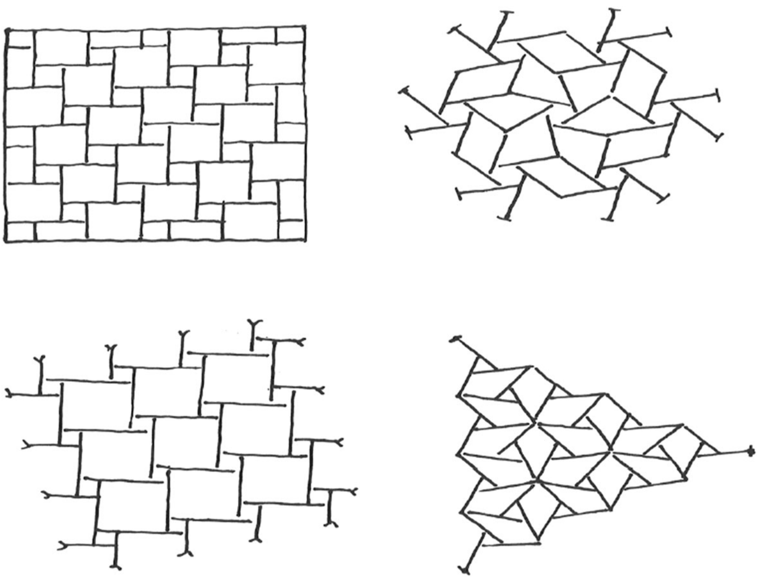


Fig. 2 Examples of complex RF configurations

destroyed in World War II (Fig. 4). Also, a beautiful steel lamella dome is the early-twentieth-century Copenhagen School of Architecture, canteen roof structure initially constructed for and used by the Navy (Fig. 5) (Popovic Larsen 2009).

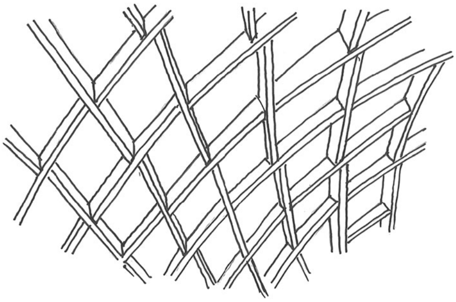


Fig. 3 Zollinger-type lamella structure with offset joints

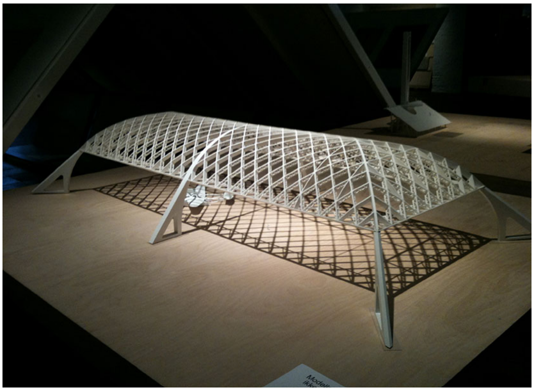


Fig. 4 The Orvieto hangar structure by Pier Luigi Nervi, physical model

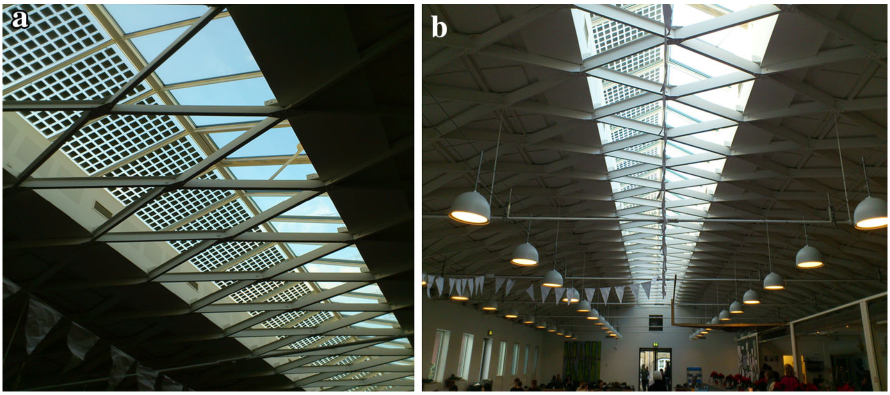


Fig. 5 Steel lamella dome canteen roof structure, Copenhagen School of Architecture

RFs at Present: Some Recently Constructed Structures

In the last few years RF structures have become a more popular structural solution. As a result some innovative RF configurations have been constructed. It is interesting that the examples represent different reasons for using a RF structure.

Fig. 6 Mount Rokko-Shidare Observatory

Fig. 7 Mount Rokko-Shidare Observatory. The RF pattern is interrupted with the bamboo tubes which channel the wind and create a tune

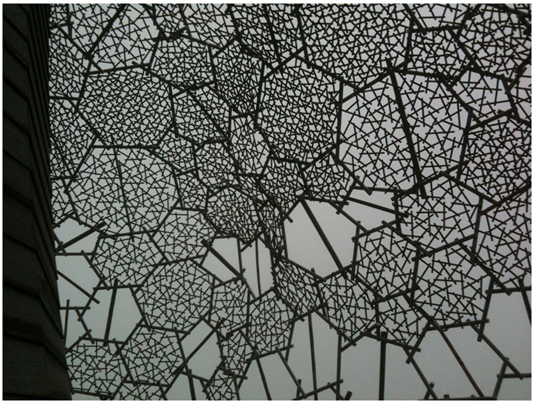


Fig. 8 Mount Rokko-Shidare Observatory. The RF pattern is denser where it needs to provide shading

Mount Rokko-Shidare Observatory, designed by architect Hiroshi Sambuichi and Ove Arup and Partners[1] in Japan, was completed in 2010 (Figs. 6, 7, 8, 9). Built on the top of the Rokko Mountain at 900 m altitude, the observatory is directly above the Kobe

[1] Arup and Partners were responsible for both the structural and the environmental design.

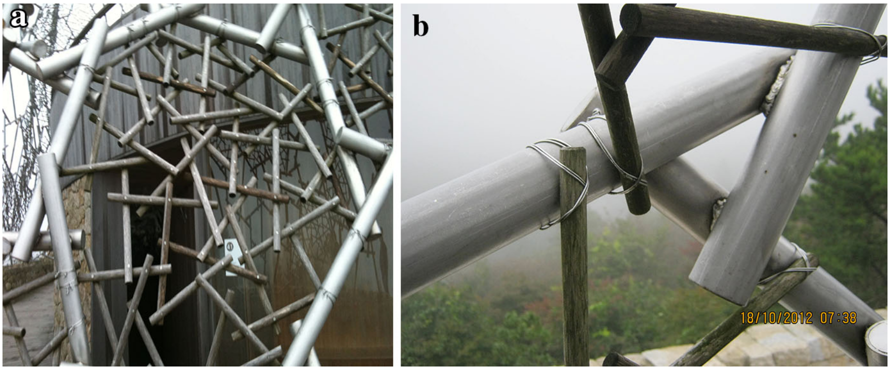


Fig. 9 Mount Rokko-Shidare Observatory. The RF pattern and a detail of the welded connection and tied wooden timber battens

bay, and on a clear day offers an amazing view over the sea and coastline. The RF structure forms an open canopy with a complex geometry. It is a meshed irregular dome-like laced RF structure 16 m in diameter. The irregular shape of the complex RF is built from a regular single-unit. The main structure is made of 50 mm welded steel tubes 1–2 m long arranged in an RF pattern in-filled with 15–20 mm thick wooden (Japanese cypress) RFs of varying density. The overall shape was based on the requirement to passively induce air movement facilitating natural ventilation, to be relatively easy to construct and to be built within the constraints of the budget. The choice of the pattern and its density, on the other hand, was based on the necessity for the structure to provide shading (the south) and enable air movement (Figs. 10, 11, 12).

In winter the lace-like RF structure creates a delicate icy roof, just like those we see in Nature. The architect's idea of the lace forms were inspired by tree patterns, which the engineers developed into a RF pattern following ideas from traditional Japanese RF structures. The geometry is based on chop-stick model of single RFs supporting each other that have been associated/overlaid onto a surface of a multi-faceted cylinder that could be manipulated parametrically. The problem becomes quite complex geometrically with the introduction of the depth of the members because the depth has an influence on the overall geometry. A shift frame geometry (SFG) solver was developed by Arup, which had the capacity to incrementally shift all elements simultaneously and find, through an iterative process, the converging geometrical solution for the actual member sizes. Using this approach, the pattern was optimized by the Arup software based on Bentley's Generative Components. The aim of the optimization was to produce a visually pleasing form that complied with the architectural vision, one that is structurally efficient and that could be constructed easily. The contractor developed a method of checking the complex geometry during construction. This was extremely important because had the precision not been high enough—it would not have been possible to construct the RF and to connect the RF members (Goto et al. 2011).

In the complex form, the regularity is formed out irregularity. It is only interrupted by the bamboo tubes added later, across the RF hexagons, which channel the wind and create the tune of the Mount Rokko. The tune is to a degree disturbing. It is the hmm-ing of the mountain. That, together with the RF that lets the wind

Fig. 10 Kreod Pavilion: **a** *up* without cladding; **b** *down* without cladding. Images: courtesy Rambøll

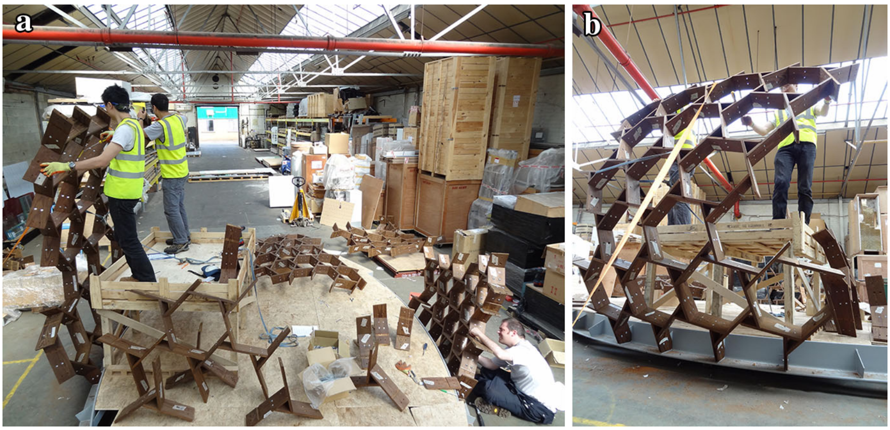


Fig. 11 Kreod Pavilion, test assembly. Photo: courtesy Rambøll

through and catches the icy, lace-forming crystals, creates a beautiful and poetic structure, full of symbolism. As the engineering team at Arup state, 'This design shows new possibilities for architecture in applying high-tech analytical techniques to realizing low-tech design solutions' (Goto et al. 2011).

The potential of the RF to generate complex configurations that support and enhance architectural ideas came together beautifully in this project, which has become a landmark for Kobe and has attracted many visitors since its completion in 2010.

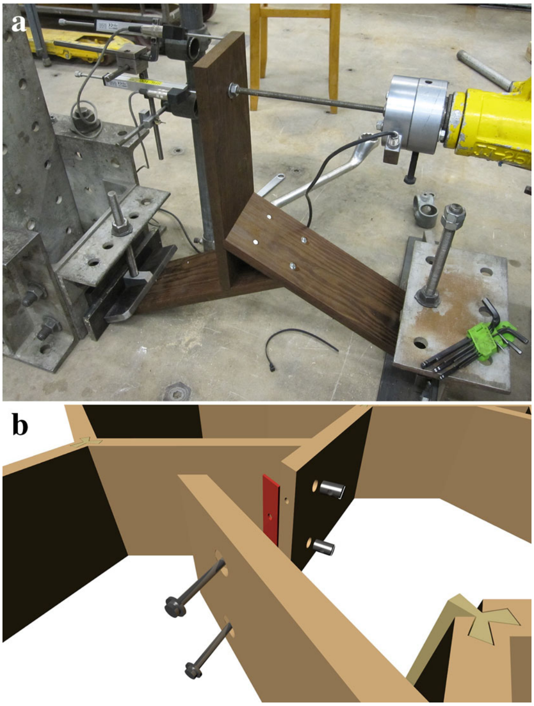


Fig. 12 Kreod Pavilion, joint testing and detail of connection. Photo: courtesy Rambøll

Kreod Pavilion

Another interesting RF structure is the so-called Kreod Pavilion developed by Pavilion Architecture and engineered by the research and development team of Rambøll London. The idea was to develop an inexpensive, easily constructed, demountable structure. It was designed in connection with the London Olympic games as a pavilion that could be used as a temporary structure, put up easily and afterwards moved to new sites. The research and development team of Rambøll London came up with the idea of RF joints to fulfill the requirement for easy construction. The joints where only two members come together are easier to assemble and to disassemble than nodes where more members need to be joined together. Inspired by the types of connections used in furniture, the joints for the demountable pod structure were developed. The Kreod Pavilion is an example of a clever, lightweight solution of a RF structure with joints that can be assembled and dissembled easily. It shows the great potential of RFs not only to create interesting spatial configurations, but also ones that are efficient structurally and in terms of ease of construction.

Explorations with Student Workshops

Building on previous research and having insight into recently completed innovative RF examples, I have explored possibilities for innovative RF complex configurations in workshops carried out at The Royal Danish Academy of Fine Arts School of Architecture in Copenhagen (KADK). These were planned as intense, one-week long, hands-on explorative teaching sessions. The students were first introduced to the RF principles, followed by small-scale explorations, after which one of the models elaborated was chosen to be scaled up and built in full-scale (Cavanagh 2012). The workshops involved third- and fourth-year students with no previous knowledge of RF systems.

It is worth mentioning that the RF models in full scale were constructed in a single day. It was therefore important to use simple connections which allowed for easy, fast construction as well as easy disassembly. For the large-scale models students used timber rafters 1 m long with a square section, with four equally-spaced predrilled holes. In the several examples presented below the same timber rafters were reused. They remain packed and awaiting for their next application in future workshops.

From Small to Large Scale

Some of the small-scale models are presented in Fig. 13. It is clear that they are of different quality, both from the point of view of craftsmanship as well as of level of

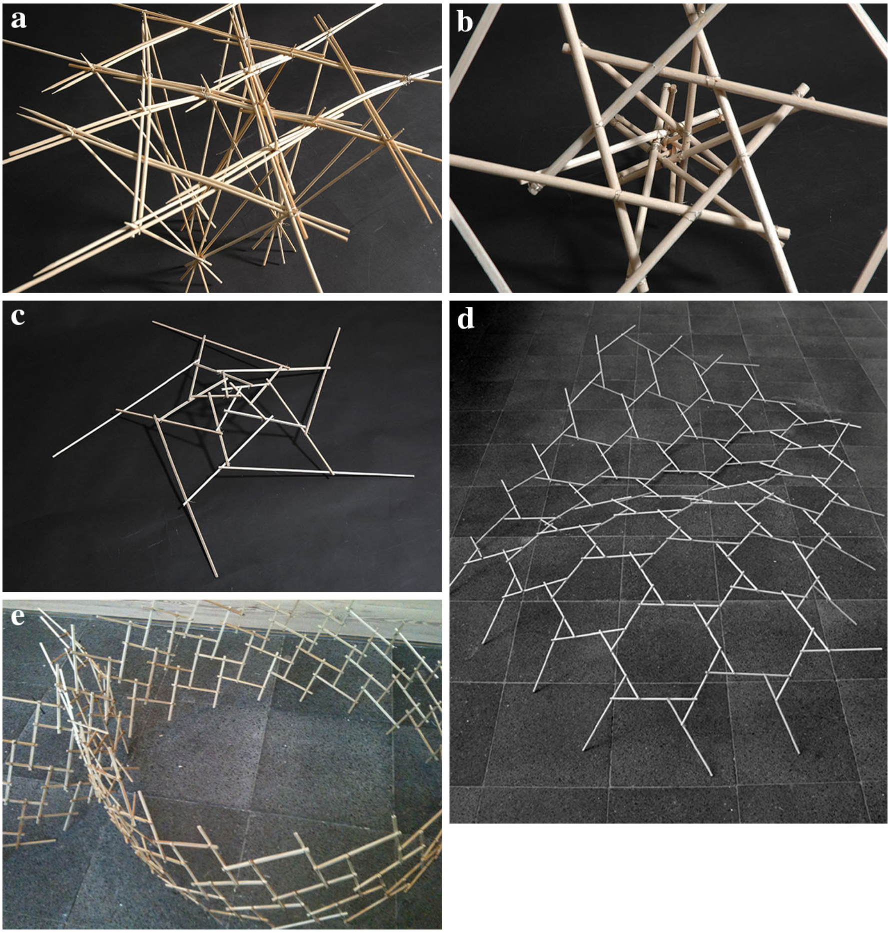


Fig. 13 **a–e** Some examples of small scale RFs developed at KADK in the period 2008–2012

practicality and the possibility of development into a large-scale RF structure. However, it is important to state that the small-scale explorations were aimed firstly at giving the students an opportunity to learn about RFs at a basic level and get a feel for how they can be formed and, secondly, at giving them an opportunity to develop new RF forms and configurations.

The small-scale models showed some of the challenges of using the structure: they clearly showed what was possible and what was not. The workshops were structured so that typically, after 2 or 3 days working with small-scale RF structures, the students would present their work and one of the small-scale models would be chosen to be scaled up in full size.

Production in Large-Scale

The RF models that were chosen for scaling up were constructed outside on the grounds of KADK. They were exhibited for several months after which they were disassembled and the timber rafters were packed and stored for future use. The first large scale RF in the series built at KADK is a model shaped as doubly-curved wings RF structure. It was scaled up and constructed in a single day.

As only part of the small-scale model was scaled up (Fig. 14), and to avoid vertical supports, cables were used to put the two wings in tension and stabilize the structure. The wing-like structure consisted of a grid formed by four-member single RF units. It was about 7 m long (Figs. 15, 16).

Because the RF rafters were predefined and used as given, the structure could achieve only a certain curvature. Different curvatures could be achieved by changing the rafter sizes and the sizes of the RF single units and their relative proportions. This is very interesting, because not only does the structure have an imaginative form, but also because a curved form can be achieved by using straight timber elements. This is a clear advantage of RFs, because there is no need to use curved members: one can achieve curved forms by using straight members.

One can easily imagine a the wing RF being used as a small shelter or a garden play structure.

In one of the other RF workshops, again using the same timber rafters a roof-like RF structure was designed and constructed at full scale (Fig. 17). When constructed, the RF structure was very stiff, even though only simple ties were used to form the temporary connections. The small-scale model where the first idea was developed, was a grid-like structure consisting of several of these “roofs” put together. If further developed one can easily imagine the structure both as a single structure as a roof over a glass house or a garden retreat. Further, a canopy of several of these “roofs” could be built to form a grid and create a roof over a restaurant or house that required a clear span function.

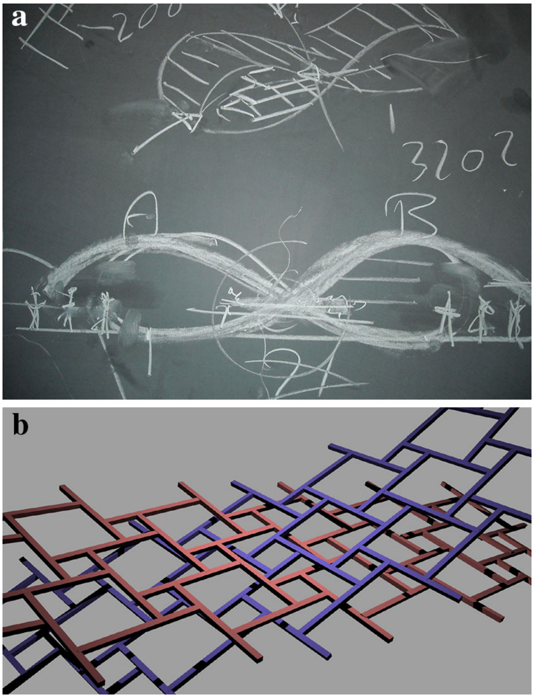


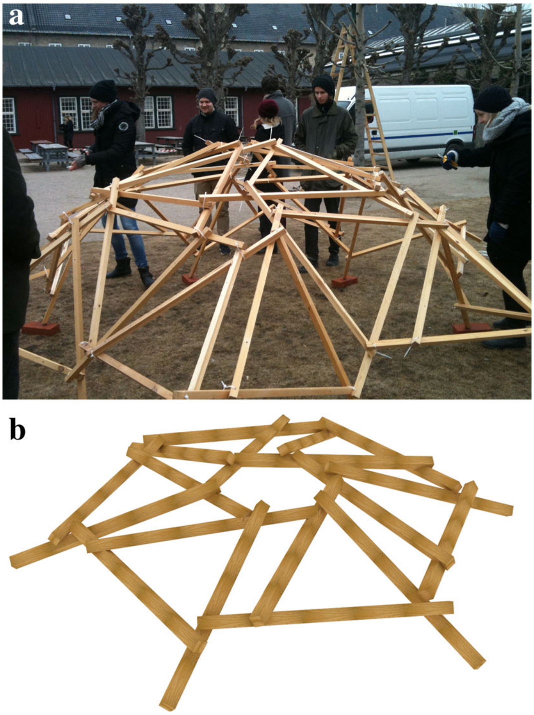
Fig. 14 The wing structure shown in Fig. 15 is a scaled up part of the small-scale model shown in the photo of Fig. 13e

Fig. 15 The wing structure

After the student workshop structural analysis was carried out to determine the shear forces, moments and deflections. Further studies are being carried out at

Fig. 16 The wing-like RF during the construction process

Fig. 17 The nearly completed RF roof: **a** *up* full-scale model 4.5 m in diameter; **b** *down* the CAD model



present for a grid structure consisting of several “RF roofs” so that the overall behavior of the grid can be determined (Figs 18, 19).

A third workshop using the same timber rafters featured the development of a full-scale RF tower (Fig. 20). The tower behaved as a spring: it was extremely flexible. This was very interesting because the same members with the same type of connections created a very different structure. It would of course be possible, by adding additional ties, to stiffen the structure. By stiffening it and developing it further one can easily imagine it as a play structure in a school playground.

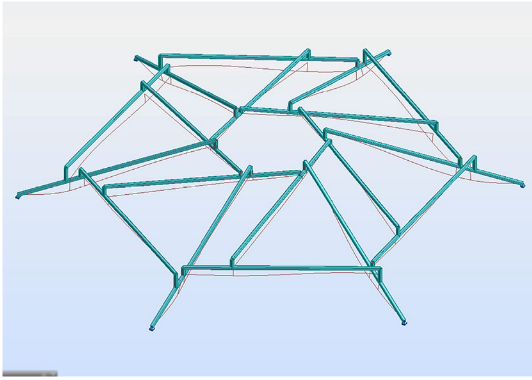


Fig. 18 Study of the RF roof deflections

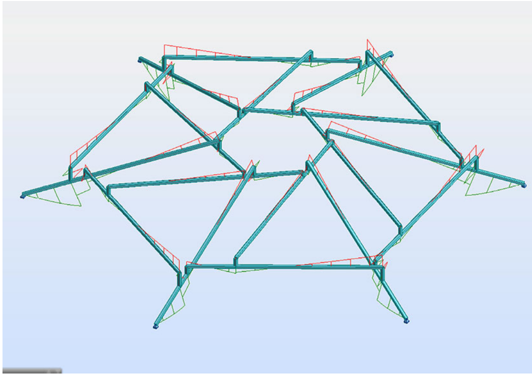


Fig. 19 The RF roof: shear force and moment diagrams

Fig. 20 The RF tower

A variation of the tower was developed using wooden poles with a circular section and a bolted connection to construct a RF structure for an art exhibition. The structure, approximately 6 m tall, was constructed and exhibited at the Kivik Art Centre in southern Sweden in 2011.[2] In addition to the sculptural function of the structure, it aimed to inspire and to evoke ideas for new uses of reciprocal frames (Popovic Larsen Olga 2012) (Fig. 21).

Some of the other RF sculptures built at full scale are presented in Fig. 22.

RF Future: Opportunities, Challenges

Examples both real and exploratory show that RFs offer great potential for creating innovative forms, such as those developed in the student workshops as well as the Mount Rokko-Shidare Observatory (Parigi and Pugnale 2012). However, the RF structure is interesting not only because of the potential for achieving novel and expressive forms, but also because it offers a possibility for achieving fast construction by using repetitive elements of equal length. The joints can be simple because they are all the same, as in the example of the Kreod Pavilion by Pavilion Architecture and Rambøll, and the construction becomes easy and fast.

A further quality is the possibility of achieving curved forms by straight elements. Curving wood takes a long time, and if not carried out carefully it can result in cracks and damage to the timber members. It is a clear advantage to build with straight members without having to curve them, and yet still be able to achieve curves.

Another advantage, not mentioned earlier is the built-in redundancy of the structure. By loading to failure, it has been noticed that complex RF structures, because of their ability to find alternative load paths, have a great built-in level of redundancy. This makes them safer structures because of the ability to fail in a ductile manner (Larsen 2008).

RF structures need a precise definition, and when unknown forms are used load testing both of the overall structure and the joints need to be carried out as well. This is the case with any innovative three-dimensional structure, and is neither a great disadvantage nor a challenge thanks to modern CAD modeling tools and techniques.

The fact that the structure works partly in bending is perhaps one of few disadvantages that the RF structure has. That is clearly compensated for by the many advantages it can offer.

It is clear the RF structure offers many opportunities and some challenges. Although a considerable amount of research has been carried out over the past 10 years, there is further room for research (Popovic Larsen 2012). All the student projects presented here explored RF morphologies without investigating connections and buildability, but these aspects are very important and should be studied

[2] Kivik Art Centre, is located in the southern part of Sweden. In a beautifully landscaped open areas it exhibits art, architecture and design. Some of the permanent exhibits are by David Chipperfield & Antony Gormley: Architecture for Subjective Experience; Snøhetta & Tom Sandberg KIivik Start Project and others. In the last couple of years Kivik has started exhibiting work by the Nordic Schools of Architecture.

Fig. 21 The Kivik RF sculpture

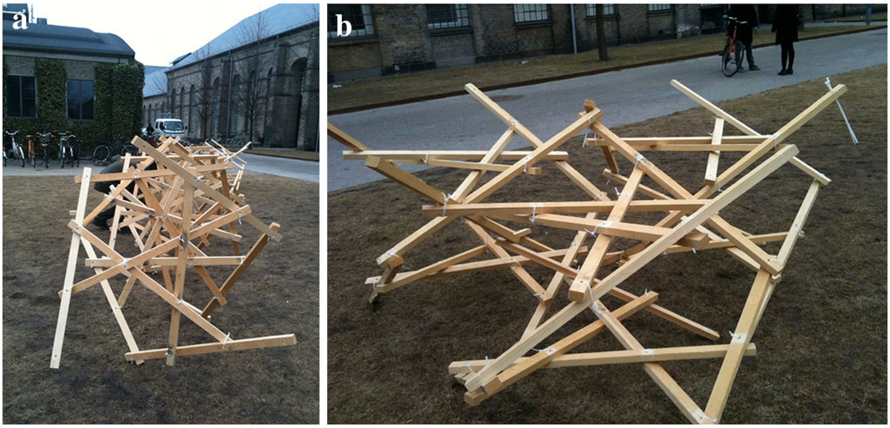


Fig. 22 Two further explorations with RFs in full scale

together with the possible morphologies. A current research project that I am now working on investigates RFs and their application for emergency shelters, with a focus on aspects of quick buildability, simple connections and reusability. At present the international community of researchers and designers are investigating different aspects of RF structures. That is very exciting because the more we know about them, the better we understand RF structures, the more interesting, imaginative, expressive and efficient RF structures we can create.

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