ASYMMETRICAL DOUBLE-NOTCH CONNECTION SYSTEM IN PLANAR RECIPROCAL FRAME STRUCTURES

REBEKAH ARAULLO1 and M. HANK HAEUSLER2
1,2 Computational Design, University of New South Wales, Australia
1,2 {r.araullo|m.haeusler}@unsw.edu.au

Abstract. Reciprocal Frame Structures (RF) have broad application potentials. Flexible to using small available materials, they span large areas, including varied curvature and doubly-curved forms. Although not many buildings using RF have been constructed to date, records indicate RF efficiencies where timber was widely used in structures predating modern construction. For reasons of adaptability and economy, advances in computation and fabrication precipitated increase in research into RF structures as a contemporary architectural typology. One can observe that linear timber such as rods and bars feature in extensive RF research. However, interest in planar RF has only recently emerged in research. Hence one can argue that planar RF provides depth to explore new design possibilities. This paper contributes to the growing knowledge of planar RF by presenting a design project that demonstrates an approach in notching systems to explore design and structural performance. The design project, the developed design workflow, fabrication, assembly and evaluation are discussed in this paper.

Keywords. Reciprocal Frame Structures; Space Frames; Computational Design; Digital Fabrication; Deployable Architecture.

1. Introduction

Reciprocal Frame Structures (RF) continue to be popular as a research topic due to their diverse tectonic capabilities, works of Baverel, Larsen, and Pugnale, to name a few (Baverel 2000; Larsen 2008; Pugnale et al. 2011). RF comprise a family of structural systems characterised by the interdependent relations of their constituent parts (Danz 2014), where each beam supports and in turn is supported by all of the others (Larsen 2008). The concept of the reciprocal frame can be traced to prehistoric building types (Danz 2014). However, in recent years, developments in computation and fabrication motivate designers, architects and engineers to use RF when exploring form and elaborate structures. As well, studies by Nelson & Kotulka (2007) suggest that RF systems can potentially achieve infinite load paths.
that can lead to structural efficiency. As mobile and rapidly assembled structures play a major role in contemporary society where speed of response is of primary importance (De Temmerman & Brebbia 2014), hence the paper argues, planar RF structures can offer solutions and be beneficial in such situations. As well, as our global resources are subjected to greater pressure, mobility and availability renew the role of human agents predating the introduction of modern building. This is evidenced by small-scale fablabs to a new shift in DIY full scale RF assemblage of rods and bars featured in most research projects. In this paper we also show that like linear RF, planar RF’s prolific network results in elaborate jointing producing design opportunities.

1.1. OBSERVATIONS

RF’s significance in design and construction predating modern techniques is explored in new ways with advances in computation and fabrication tools. As computation and digital fabrication require specialisation, the development, design and production of these structures usually remain exclusive. Although, as these structures are mainly assembled through physical labour, the role of human agents has never been more evident in such pursuit. How can this gap be lessened to create a more inclusive culture in the practice of RF? Potentially traditional means that enable the production of RF can be adapted and integrated in the process. Especially with more complicated RF designs, jointing for their prolific network usually mean they are too complex and expensive to produce, or, are not always structurally effective as a building for end use.

1.2. RESEARCH QUESTION

In considering these observations, the paper aims to address the research question: Can traditional means of building be adapted and integrated to avoid custom and mechanical devices that may not be readily and easily available, when exploring and investigating planar RF as a potential contemporary architectural typology? Based on the research question, the objective of this paper is to present the method of asymmetrical double-notching at the intersection events as contribution to the growing knowledge base for planar reciprocal frame systems.

1.3. METHODOLOGY

Drawing on findings in research by Puyol (2015) and Baverel & Pugnale (2013), the research used a design research method to develop a 1:1 scale prototype of a multi-unit quadrilateral reciprocal frame system with three dimensional capabilities (Tong & Zhou 2016) designed and developed for the Vivid Sydney Festival in Australia.

2. Reciprocal Frame Structures

Mandala roofs, weaving structures, tensegrity, nexorades, 3D and planar grillages are commonly associated with RF structures and share many design principles. Typically, the use of linear materials such as rods, bars and beams features in many of the well-known RF projects to date (figure 1). The basic assembly of these are clearly described by Popovic Larsen (2008).
A reciprocal frame structure can also be constructed from identical or non-
identical basic elements as long as a tessellation pattern exists (Kohlhammer &
Kotnik 2011). One can argue that where linear materials in these assemblies are
replaced by 2D shapes, design opportunities arise with the introduction of the size
and nature of the shapes

2.1. PLANAR RECIPROCAL FRAME STRUCTURES

Planar RF in this paper is understood as having the kind of structure that uses planar
shapes in an RF assembly in place of linear elements such as rods, beams and bars.
To avoid confusion, it is important to point out that the term ‘planar RF’ had also
been used by Popovic Larsen (2008) as referring to those that are used as planar
grillage on a 2D plan, such as the flooring of Mill Creek Public Housing Project
by Louis Kahn. This paper means the use of planar materials when referring to
‘Planar RF’.

In planar RF, the sizing of the members - their depth - is an external parameter
(Puyol 2015). The few examples of planar RF structures include the Coca Cola
Beatbox Pavilion by Khan and Ohrstedt in 2012 for the London Olympics and the
Serpentine Gallery Pavilion 2005 by Siza and de Moura with Balmond (figure 2).
The boards informed on the overall pavilion aesthetics.

2.2. CUSTOM SHAPE RECIPROCAL FRAME STRUCTURES

Another design opportunity arises when an irregular 2D shape is used in an RF
assembly. In 2013, we developed a structure called Euphonious Mobius where the
basic principle of RF is adopted using an irregular 2D shape that would result in an
abstraction of the Mobius strip or form (figure 3). In effect the 2D custom shapes
were assembled as a spaceframe. The outcome was a self-supporting complex
form where the connection events allow the components to transmit traction and
compression forces. It would generally classify as ‘Planar Elements as Part of a
Truss’ if one would categorise it according to Bavarel and Pugnale’s planar RF
classification (2013).
2.3. CONNECTION JOINTS
Like linear RF, due to irregularities of local conditions at intersection events in these planar RF examples, connection of all members often presents a whole new design undertaking for which off-the-shelf fasteners prove insufficient. To analyse the two examples given above: in the Coca-Cola Beatbox project lightweight panels were braced against each other to stabilize the system. The bracing itself required customisation. The Serpentine Gallery 2005 used the mortise and tenon jointing but ensured that all members are of the same size so the mortise and tenon could be typical throughout. In the case of Euphonious Mobius, the use of industrial strength cable ties was a quick solution to ensure slight movement was maintained between the 10mm acrylic panels which enabled the structure to be non-static however free-standing. A connection joint using cable ties is naturally not ideal but it demonstrates the importance of the connection joint in RF structures. To conclude: in order to achieve irregularity and structural efficiencies in RF assemblies, connection technique is the key to ensuring they perform as a viable architectural typology, potentially for end use and beyond exhibition purposes.

Following the background on RF structures and the overview of Planar RF, the paper will present and discuss a project that took findings from the custom shape RF structures and connection techniques into consideration.

3. Ptolemi
Commissioned by Destination NSW, Ptolemi is a site-specific installation for exhibition at Vivid Sydney 2016, located in Campbell’s Cove, The Rocks. Ptolemi was developed as a semi-permanent deployable exhibition piece and subsequently, the multi-unit planar timber RF were redeployed for exhibition at the University of New South Wales, exposed to the elements for a six-month period. Here it withstood extreme weather conditions bearing over 100km high winds and severe rain falls.
3.1. PTOLEMI DESIGN PRINCIPLES

Based on a multi-unit quadrilateral RF system, the design is a set of curved wall structures with sloping grid producing irregular and unique components. The highest point of the slope measures four meters, the lowest is one meter, curved to form a half circle with a diameter of nearly 6 meters (figure 4).

Exterior plywood panels are layered with 0.8mm stainless steel in mirror finish, similarly locked in place through notches of intersecting plywood panels, therefore required no adhesives or fasteners.

![Figure 4. PTOLEMI - Elevations and prototype.](image)

A reciprocal configuration was made on plan, i.e., the thickness of the walls is determined by the number of quad units arranged along the width (figure 5). In this case, single units were arranged along the curvature.

![Figure 5. PTOLEMI - Plan; horizontal panels.](image)

Using planar materials, boards arranged vertically resulted with a parametric value in height. This allowed for a reciprocal configuration to be observed on elevation as well. To test the efficiency and performance of this system, no added fasteners were used only a simple notched joint.

3.2. PROJECT LIMITATIONS

There were challenges in ensuring the project met exhibition criteria. The project must comply with strict guidelines in occupying and installing on the exhibition space. The Sydney Harbour Foreshore Authority which is the consent authority for site occupation, required the structures be placed onto platforms to avoid damages to the pavement of the licensed area. As well, installation time and the time for bump-out must take no more than one day and must be done within a seven hour period including the installation of embedded LED and sensor technology. We were faced with challenges in planning and coordinating the manner of build as well as securing the structures onto platforms. The platforms as well became a great consideration. Arup, the engineering team collaborating on the project, required the platforms made of 20mm steel base as appropriate to the sheer scale
and weight of the structures. As well, the Sydney Harbour Foreshore Authority imposed minimal construction activity on the licensed area, which made coordinating all the panels for assembly on site not possible. Under all these conditions, the structures required off-site assembly and brought on site in a near complete state. The structures had to be secured onto the 20mm base plate and delivered via a hiab crane truck.

3.3. ENGINEERING AND NOTCHES

The structural design for the notches was critical in resisting vertical and lateral forces throughout crane activity, road travel within a 10km distance as well as placement on site and performance throughout the public exhibition. The site experienced gale force damaging winds as well as heavy rains and flooding during the exhibition on Campbell’s Cove, The Rocks. Again structural performance was tested in these conditions as the structures remained intact but for minor damage to embedded technology. The CNC routed panels consist of 15mm structural ply for the horizontally arranged panels along the elevation (bracing panels), and 25mm structural ply for the vertically arranged panels in between (column panels). They are connected via a simple notched joint.

3.3.1. Asymmetrical Notches

In this assembly the traditional principles of halved joint and notch joint are explored for design and structural purposes. In a digital workflow the line of intersection between two panels which is the contact length (c) is halved to produce the size of the notch (n), also common in traditional carpentry, (d) being total depth of panel (figure 6). In linear RF assembly, the vertical spacing of the centres of rods at the intersection point called eccentricity (e) is an important parameter in constructing RF (Larsen 2008; Rizzuto & Larsen 2010).

Studies by Garcia Puyol with the object of mass customisation use a digital workflow that considers the contact length, the eccentricity, total depth of panel and depth at centreline, where the eccentricity and the depth of the panels define the depth of the notch (Puyol 2015). As well, this workflow results in shape adjustment of the panels in order to meet structural criteria.

However, for this project, the panel shapes must be maintained for aesthetic ambition. The underlying geometry is discretised into an irregular quad grid producing panels positioned horizontally intersecting with vertical panels. In addition
to the approach described above we looked at the manner of defining the size of the notches for each panel. To keep the panels in a specific reciprocal configuration, an approach to notching must be central in the process to ensure structural efficiencies.

3.3.2. Digital Design Workflow

In this top-down approach, the digital design workflow computationally forces the position of each panel into this RF configuration. Joint design and management can become complex due to the heterogeneous nature of this elaborate jointing. To avoid much reduction in the panel depth which can weaken panel performance, a hierarchical approach to notching was introduced in the workflow. As the profiles of horizontal panels must be maintained for aesthetic purposes, notches for horizontal panels were first calculated according to engineering details (figure 7). Horizontal panels become primary.

In the digital workflow, 1) intersection events were identified; 2) notching uses a sifting process that calculates the total depth of panel along the contact axis. Based on using 15mm ply, panels with a depth of 210-270mm along the contact axis, the minimum 200mm under or over a notch to the edge of the panel must apply (figure 7). Greater depth along the contact axis, will have a maximum 70mm notch at that intersection. Panel depth with less than 210mm along the contact axis, will remove one quarter of its depth to form the notch.

Secondly vertical panels (figure 8) using specified 25mm structural plywood were analysed. The load paths through the structure mean that the loads in each panel vary. Those closest to the base will tend to have the largest axial forces.

In the digital workflow, adjustments to the vertical panels to meet engineering criteria were made, 1) Intersection events were identified; 2) Notching calculated the depth of the panel along the contact axis, the depth of the panel from the top of the notch of the intersecting panel along the contact axis which becomes the size of the notch; 3) The positions and heights of the horizontal panels were adjusted within the reciprocal configuration to ensure the minimum 200mm panel depth ap-
plied over and under any notch. In this process, asymmetrical conditions resulted in corresponding double notches (figure 9).

To ensure the structure is secured onto the base to withstand loads identified previously, the topmost vertical panel at every column is anchored to the 20mm steel plate with a 16mm threaded steel bar lightly tensioned (figure 8). The bottommost vertical panels were secured onto the 20mm steel base plate.

3.4. DESIGN OPPORTUNITIES

Due to its parametric nature we are able to control porosity, position and angles of panels. We also adjusted panel sizes to economise on material usage. As well, we introduced a steel layer for facade aesthetics. In the same way, the 0.8 mm steel sheeting in mirror finish was layered on to the timber panels without any bonding agents and placed with the corresponding timber panel to be locked in place (figure 9).
3.5. EVALUATION

Like a large puzzle, the assembly of this planar RF was achieved in a four hour period. Self-registration, digital fabrication processes and equipment bring a level of simplicity to the production of a complex structure. The condition of whether panel 1 lies under or above panel 2 (Parigi & Kirkegaard 2012) is such a great consideration in an RF assembly. Auspiciously, in planar RF this condition results in design possibilities as evidenced herein. Although the intention was in-situ DIY assembly, building off-site gave us new challenges in transporting sections of a reciprocal framework. In the six month exhibition, timber warping was not evident and the structure appeared stable (climbed onto by university students). The steel layer remained intact but for the lower steel panels that suffered as corners were easily bent whilst not bonded to the timber panels. The digital workflow included an iterative process in the design and production of the notches to meet engineering requirements. Adjusting notches meant we maintained the profiles of the panels to meet efficiencies. Depending on the torsional stiffness of the joints/panels, they could be designed separately and without considering the eccentricity between their centrelines. If there is very little resistance to torsion or if the axial force in the panels is very small then the eccentricity can be ignored. However, as there was hardly any "give" in the joint to twisting and as significant axial force in the panels was expected then eccentricity had to be taken into account. As the panels
interact, the load path through the structure to the base meant that the loads in each panel varied which required computational management of the notching. In the digital workflow, the asymmetrical condition of the double notches meant we were able to nominate primary members in a commonly non-hierarchical system regardless whether they lie under or above secondary members.

4. Conclusion

Design possibilities present itself in the nature and size of the planar panels. Where the issue of economy and availability are central, planar RF’s efficient use of small pieces of material to produce large structures can be most beneficial for deployable modular and rapidly assembled structures. As a sustainable solution, RF is reliant on issues and limits of serviceability. Therefore, further research should be encouraged to bring planar RF from research labs to end use as an inclusive DIY contemporary architectural typology. Planar reciprocal frame assembly as a potential efficient structure or facade system is an exciting area of research that can lead to economic benefits and can provide a viable solution in today’s society.

References


