Ruan, Gengmu; Filz, Günther H.; Fink, Gerhard

Planar rectangular, slide-in reciprocal frame structures using salvaged timber and wooden nails

Published in:
Proceedings of the IASS 2022 Symposium affiliated with APCS 2022 conference

Published: 01/09/2022

Planar rectangular, slide-in reciprocal frame structures using salvaged timber and wooden nails

Gengmu RUAN*, Günther H. FILZ[a], Gerhard FINK[b]

* Aalto University, Department of Civil Engineering, Rakentajanaukio 4 A, 02150 Espoo, Finland
gengmu.ruan@aalto.fi

[a] Aalto University, ENG | Department of Civil Engineering ° ARTS | Department of Architecture, Finland
[b] Aalto University, Department of Civil Engineering, Finland

Abstract

In this paper, we present a preliminary investigation of planar rectangular reciprocal frame (RF) structures considering structural, architectural, environmental, fabrication and assembly aspects. Following a timber-only concept and a low-tech design philosophy, we specifically propose to use salvaged timber and wooden nails only, as materials for fabricating and connecting RF structures, which is in line with an ongoing research project that has initially investigated the characteristics of salvage timber and the structural behavior of wooden nail connection. The present experimental investigation focuses on the single multi-layered element in a basic layout of a four-element planar rectangular RF unit. The single elements are fabricated out of small timber boards to create an opening that serves as a slide-in connection for the ease of assembly. We experimentally investigated the structural behavior of the single element in the proposed unit under bending loads. We also explored the assembly process and the resulting patterns by using the proposed approach to build RF structures. Moreover, to showcase the structural and architectural features of the proposed RF unit, a design case was physically realized.

Keywords: Reciprocal frame structures, salvaged timber, wooden nails, planar rectangular layout, slide-in connection, timber-only, assembly process, sustainability.

1. Introduction

Timber has recently been increasingly used in the building industry, among others due to its ecological advantages. Structural timber as well as timber for concrete formworks are typically available as standardized elements. For construction, those elements need to be further processed to achieve the desired dimensions, which usually leads to significant cut-offs that are mostly considered as "waste" and are used only for energy recovery. However, timber cut-offs from graded timber have sufficient structural quality, but they come in random and mostly short sizes. It is therefore possible to use cut-offs for new structural applications. Reciprocal frame (RF) structures can be seen as such a possibility.

In RF structures, all elements, usually linear, support each other to form a closed load-bearing system [1]. Structurally and architecturally, RF structures provide an intriguing approach of using short elements to create a span longer than the element itself by interlocking all elements. Traditionally, timber has been the preferred material for RF structures, and planar RF structures can be realized by notched connections. A traditional notched element in a four-element planar rectangular RF unit is shown in Figure 1(a).

In this paper, we present a preliminary investigation of planar rectangular RF structures considering structural, architectural, environmental, fabrication, and assembly aspects. As part of our ongoing research on timber-only structures using salvaged timber [2, 3] and wooden nail connections [4], as well as their design aspects and application spaces [5], we follow a low-tech design philosophy [6] and specifically propose to use salvaged timber and wooden nails only, as materials for fabricating and connecting RF structures. This paper focuses on the basic planar rectangular layout of a four-element RF unit, in which each linear element consists of several short, salvaged timber boards that are joined together with wooden nails. The timber boards are arranged in a way that an opening is left that serves as a slide-in connection (Figure 1(b)). This opening serves in many ways, including ease of assembly, as a joint that allows for overlength of the boards, possible tool-free assembly and disassembly, and modular prefabrication of the elements. An exemplary prototype of a four-element, planar RF unit that applies the slide-in connection is shown in Figure 1(c). To achieve a basic understanding of the structural behaviour of the proposed RF element, a preliminary experimental investigation on the load-bearing capacity of the single RF element was carried out. In addition, we also explored the assembly process and the resulting patterns by using the proposed approach to build RF structures. Based on the findings from the preliminary experimental investigation and the exploration of assembly process and patterns, a prototype was designed and built to showcase the structural and architectural features of the proposed RF unit. To clarify the terminology, we use element for the single member or beam that an RF unit is assembled of. In our case, the RF elements are fabricated of several salvaged timber boards in three or more layers. The boards are jointed in overlapping areas with wooden nails only. The RF unit is the smallest single composed structural cell, which can be expanded into larger systems or be filled with one or several smaller units in a fractal way.

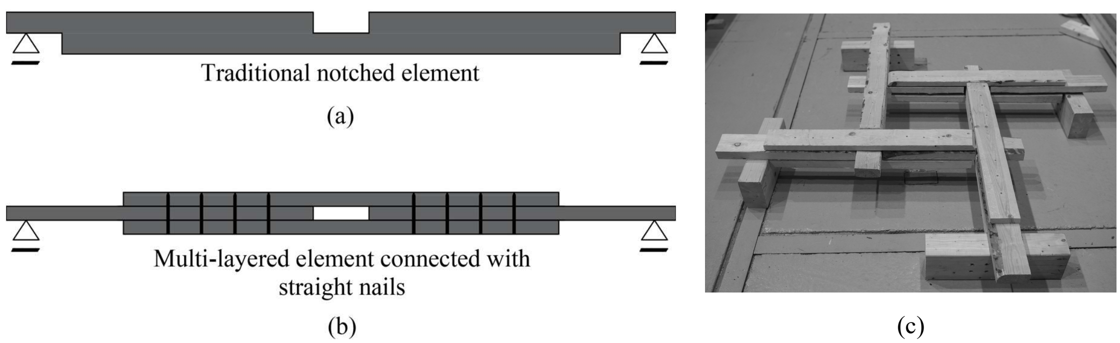

Figure 1: (a) Traditional notched element for an RF structure, (b) multi-layered element connected with wooden nails for an RF structure, and (c) RF unit prototype using four multi-layered elements.

2. Preliminary experimental investigation

For a single element in the proposed RF unit, in most of the loading cases, the lower layer(s) of the multi-layered element is point-loaded by the neighbor element through the slide-in connection. The structural behavior of the multi-layered element was investigated in the preliminary experimental investigation carried out at the laboratory of the Department of Civil Engineering, Aalto University, Finland. The specimens were fabricated from rough sawn timber boards with a cross-section of 100 mm × 25 mm and beech wood nails (Lignoloc©) with a length of 75 mm and a diameter of 4.7 mm.

Inspired by the investigation of wooden nail connection under shear loads [4], nail inclination has been considered in the preliminary tests for fabricating the elements. Two nail arrangements, namely RF00 and RF15, were investigated. The details of the two arrangements are shown in Figure 2. In total, four specimens (two specimens for each arrangement) were fabricated. Noted that due to the limited number of specimens in the preliminary tests, the test results are used to explore the potential of the multi-layered elements with straight and inclined nails. For a quantitative evaluation, more tests will be required.

The multi-layered elements were tested in three-point bending with a span of 1 m (see Figure 3). The load was applied at the bottom layer through a steel plate that was inserted into the slide-in connection in the middle of the element. A hydraulic loading device with a maximum loading capacity of 200 kN was used to apply force. Each specimen was loaded until failure with a constant rate v = 2 kN/min. The load-displacement curves of all the specimens are illustrated in Figure 4. It should be noted that no linear variable differential transformer (LVDT) was assembled on the specimens and the displacement was directly taken from the loading device.

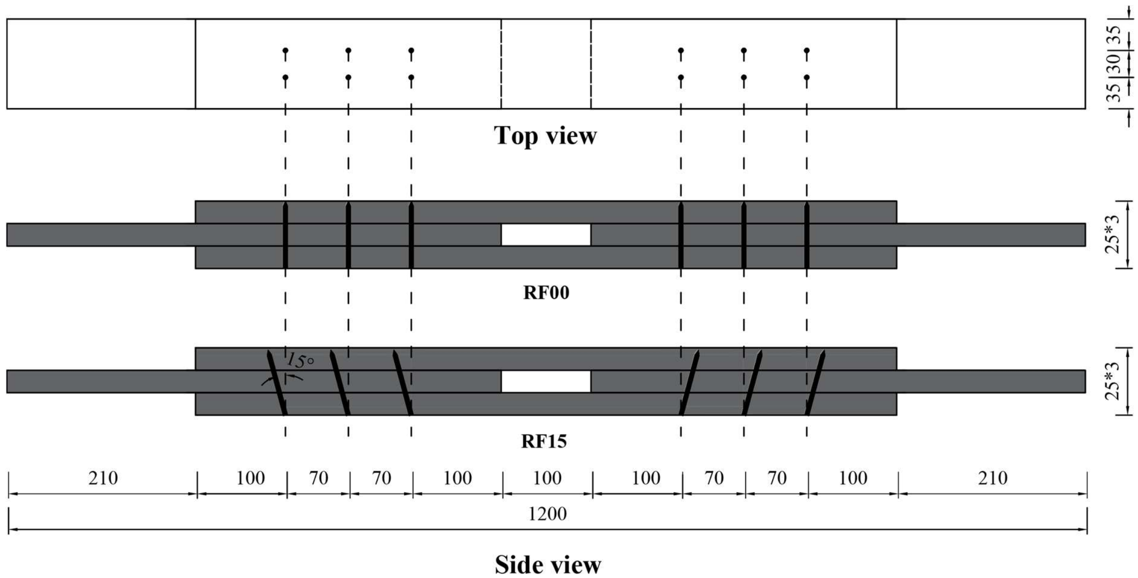

Figure 2: Design of specimens for preliminary experimental tests (dimensions are in [mm]).

Figure 3: Setup for preliminary experimental tests.

Different failure modes have been observed in the specimens with different nail arrangements. For RF00 specimens, the failure happened in the wooden nails between the bottom and the middle layers, which resulted in the bottom timber board falling apart from the specimen (see Figure 5(left)). The wooden nails were either pulled out or failed in tension. This indicates that with the straight arrangement wooden nails are loaded in tension and the interface between nail and timber can be activated. For RF15 specimens, a combined failure mode was observed: the wooden nails were pulled out or failed in tension in between the top and middle layers, while the bottom timber board failed in bending (see Figure 5(right)). In both RF15 specimens, a knot was located in the central area of the bottom timber board, and therefore, the observed failure mode and the achieved load-bearing capacity might not be representative for the cases without knots. Based on the preliminary tests and due to the practical issues, we selected the straight nail arrangement for the fabrication of the proposed RF elements.

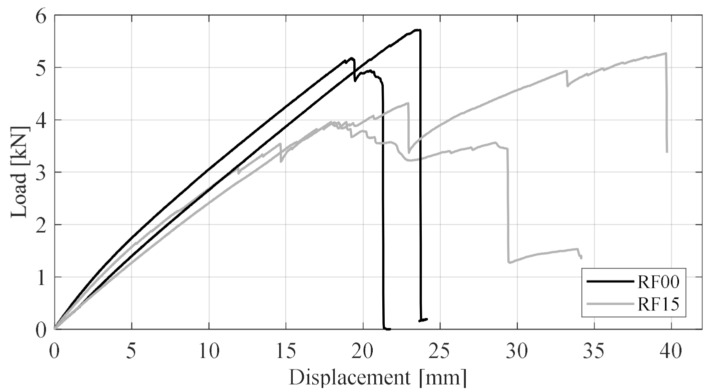

Figure 4: Load-displacement curves of the specimens from preliminary experimental tests.

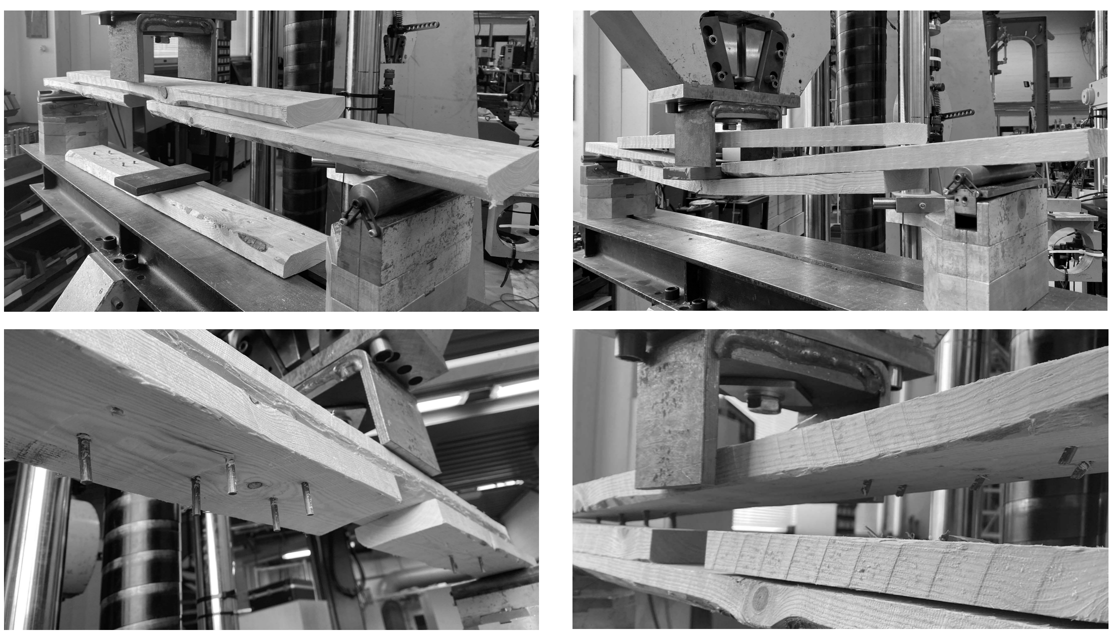

Figure 5: Failure modes of the specimens from preliminary experimental tests: RF00 (left), and RF15(right).

3. Assembly and patterns

The proposed RF unit, which follows a modular design thinking combined with the intent of low to no material processing and a design for disassembly strategy, aims to be fully prefabricated and easily assembled and disassembled. A premise for the assembly of the proposed RF unit is that the above-mentioned and -described openings for the slide-in connection need to be slightly wider than the width of the timber board. This is based on a consideration of two interconnected parameters in the specific layout of our proposed RF element – the width of the opening w_o and the overlapping length between timber layers $l_{o,i}$ (i = 1, 2), as shown in Figure 6, where w is the width of the inserted timber board from a neighbor element and l is the length of the timber board in top/bottom layer. Due to the geometrical relationship between the two parameters: $l = w_o + \sum_{i=1} l_{o,\, i}$, one of the parameters' increase results in another's decrease. Consequently, an opening that is slightly wider than the timber board can offer: (i) tolerance for assembly in case some manufacturing errors occur, and (ii) maximized overlapping areas for wooden nail connections, which can increase the load-bearing capacity of the element. Due to this premise, the structure can be only assembled in one plane and each sliding-in must have a specific direction. With this regard, it is important to understand the assembly sequence of the proposed RF unit into a larger RF system.

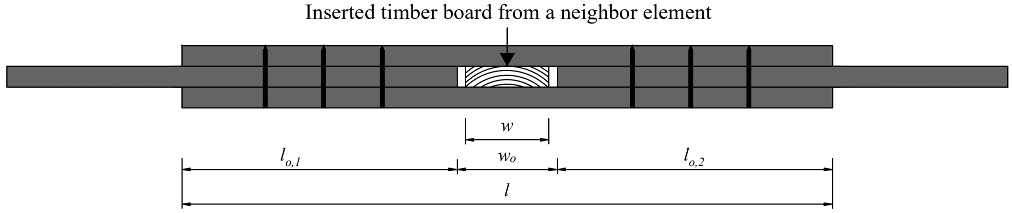

Figure 6: Geometrical parameters of the RF element.

A planar RF system can consist of multiple RF units with various geometries and patterns. As described by Pugnale and Sassone [7], in an RF system, each element has to be mutually supported by and supporting other elements. This reciprocity shows the main difference with a hierarchical system of a traditional frame structure.

In our proposal, the RF unit can be arranged in two ways: (i) the RF unit is mutually supported by and supporting elements from other units, namely base unit, which can be seen as the main load-bearing structure of the whole system (Figure 7(b)), or (ii) the RF unit is fully supported by another unit with a clear hierarchical difference, namely fill-in unit (the inner RF unit in Figure 7(c)). This combination offers some advantages, especially in terms of using salvaged timber with random and variable dimensions. Using fill-in units architecturally enriches the possibility of planar and spatial pattern generation, while structurally it can reduce the local stress concentration in the base units, and material-wise it allows short timber boards to be used.

Following the two ways of arranging RF units, we explored the possible assembly sequence and its resulting patterns. A general definition for the directional arrangement of an RF unit is given according to the geometric shape of unit. As shown in Figure 7(a), an RF unit, namely unit-0, in which the extension of the boards indicates a clockwise orientation, is further referred to as a clockwise unit. Likewise, a counterclockwise unit is defined.

For base unit, it is possible to connect a counterclockwise unit either with another counterclockwise unit (unit-0 with unit-2 in Figure 7(b)) or with a clockwise unit (unit-0 with unit-1, or unit-0 with unit-3 in Figure 7(b)). The assembly process can be easily realized by first connecting the two elements in each corner (an "L") and then sliding the pair into another one by one.

For fill-in unit, with two counterclockwise or two clockwise units, the assembly would require a slide-in from two directions at the same time, which cannot be realized in the proposed RF system. It is only possible to connect a counterclockwise unit with a clockwise unit (see Figure 7(c)). The assembly sequence of the fill-in unit is shown in Figure 8.

According to the findings from the exploration of assembly process, various patterns can be created by applying the principles regarding the directional arrangement of RF units. As a simple example, we select a square RF unit as the base unit of the system (the outer unit) and explore the possibility of inner patterns with fill-in units. Some examples with their assembly logic are illustrated in Figure 9.

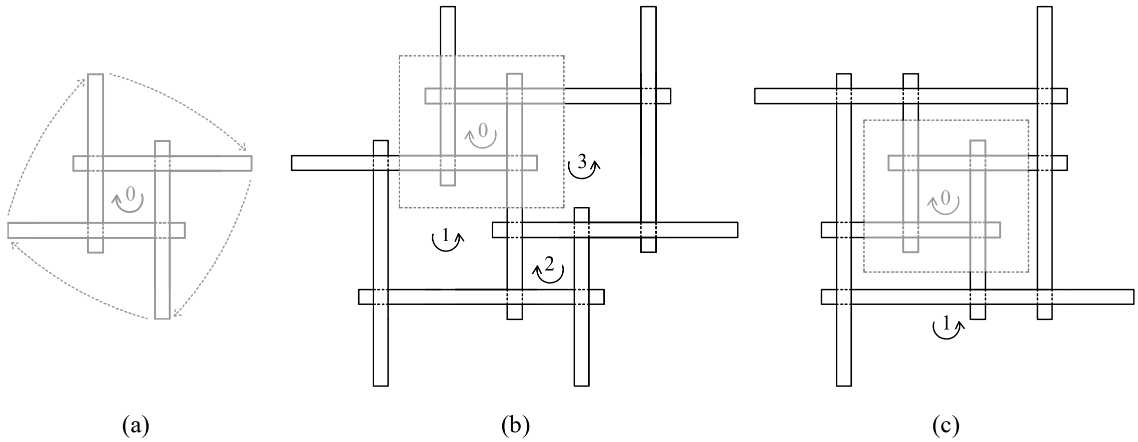

Figure 7: The RF unit: (a) definition of a counterclockwise RF unit, (b) applied as a base unit, and (c) applied as a fill-in unit for an outer base unit (unit-1).

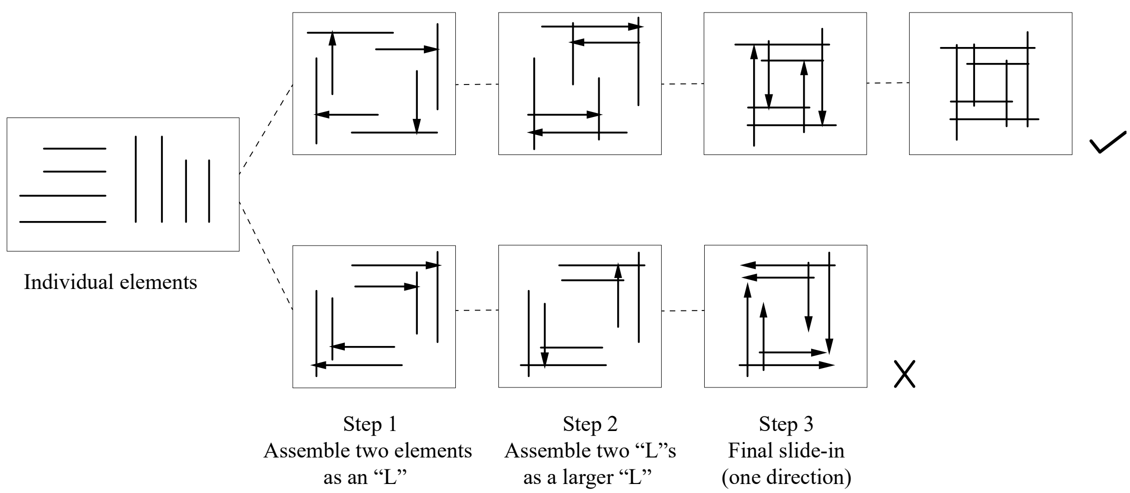

Figure 8: Assembly sequence of fill-in unit.

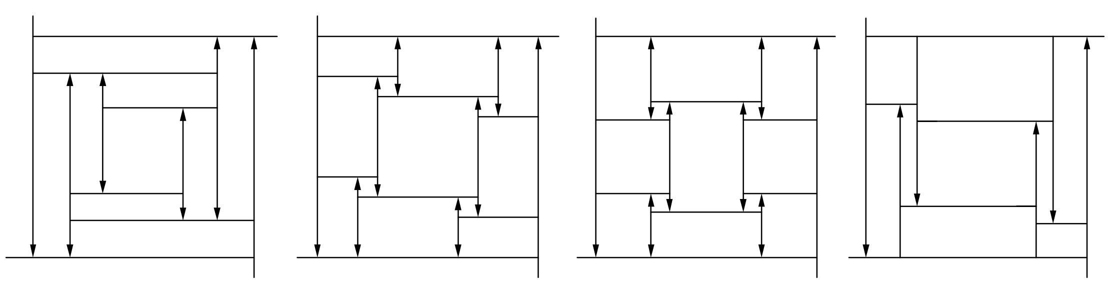

Figure 9: Examples of patterns with feasible assembly.

4. Design case

A design case was realized based on the results from the preliminary experimental tests and the exploration of assembly process. We salvaged timber boards, which have been originally used for concrete formworks, from a local construction site in Otaniemi, Espoo, Finland, as the raw materials for our prototype. These timber boards are spruce or pine and have a cross-section of 98 mm × 22 mm. The lengths of the timber boards are mainly between 1500 – 3000 mm. They have been stored for three months before building the prototype. To connect the timber boards, like in the preliminary tests, wooden nails with a length of 75 mm and a diameter of 4.7 mm have been used. To match the length of the wooden nail with the thickness of the timber board and to consider the test results of the preliminary experimental tests, a four-layered board layout and a straight nail arrangement were adopted for our prototype.

As a starting point of the prototype design, a simple pattern, which consists of a square outer base unit and a square inner fill-in unit (similar layout as in Figure 7(c)) was selected. The whole structure has a width of 2.6 m and four supports, which are located at the outer corners.

The design was driven mainly by two aspects: the minimal required overlapping length of timber boards for wooden nail connections, and the original lengths of the salvaged timber boards. The purpose of defining a minimal overlapping length is to make sure that there is enough space for arranging at least six nails, which can provide sufficient load-bearing capacity for carrying loads, in this case for people to sit on. This value was defined as 350 mm based on the results from the preliminary experimental tests. The original lengths of the salvaged timber boards were considered here mainly due to the intent of low to no material processing. As a benefit from the proposed slide-in connection that allows the use of timber boards with an overlength, the prototype was fabricated by 32 pieces of timber boards with only 16 cuts.

The prototype was designed as "street furniture" that people can sit and use as a table, therefore, a cover (a plywood panel) for the inner unit was built in. To support the cover, we intentionally designed the opening of the slide-in connection 2 cm wider than the width of the salvaged timber board, which allows a use of wedges (see Figure 10(b)). As a friction-based connection, the wedges were used for tightening the slide-in connection, and at the same time, for supporting the table. For the wedge-making, we used salvaged plywood.

After prefabricating all the elements in the laboratory, we assembled the prototype in an outdoor area at Aalto University, Finland. The assembly process has mainly four steps, as shown in Figure 11. The whole assembly was realized by three people without any electric devices within 10 minutes. The use of the prototype is exemplified in Figure 12.

(a) (b)

Figure 10: Joining details: (a) slide-in joints, and (b) inserted wedge made from salvaged plywood.

(a)

(b)

(c)

(d)

Figure 11: Assembly process of the prototype: (a) connecting the corner elements, (b) inserting the assembled half to another, (c) tightening the connections, and (d) installing supports.

Figure 12: The in-use prototype.

5. Conclusion

This paper proposes an innovative design concept for planar rectangular RF structures using a multi-layered layout for single elements and assembling with a so-called slide-in connection. In line with an ongoing research project, which focuses on timber-only structures, we specifically use salvaged timber and wooden nails as the only materials for fabricating RF structures. From the perspectives of structures, architecture, assembly, and patterns, a comprehensive preliminary investigation of the proposed RF unit is presented. Based on the results of the preliminary investigation, a design case was realized to showcase the structural and architectural features of the proposed RF unit.

We started with an experimental investigation on the structural behaviour of the single RF element with different nail arrangements under bending loads. From the test results, the straight nail arrangement was selected as the nailing strategy for the prototype fabrication. Following, we explored the assembly sequence of the proposed RF unit, in which feasible assembly and its resulting patterns have been identified. As a final step, a design case, which considered the results from the preliminary investigation, was realized to showcase the concept of our proposed RF unit. From the realization of the design case, the flexibility of using salvaged timber with various lengths, the constructability with low material processing, the ease to transport, and the rapid assembly process have been highlighted.

Inspired by the preliminary investigation, some possible future works on the proposed RF unit are also informed. For example, the entire RF unit or system needs to be experimentally tested, in order to understand its systematic structural behaviour. In addition, a more layered layout with a more spatially arranged slide-in connection may bring structural and architectural benefits.

Acknowledgements

Special thanks to Kertu Jõeste and Lassi Liimatainen who contributed to the research on the assembly process of the proposed RF unit and the design/fabrication of the prototype. Thanks to Beck Group for kindly providing the nailing devices.

References

[1] O.P. Larsen, *Reciprocal Frame Architecture*. Oxfordshire: Routledge, 2007.

[2] G. Fink, G. Ruan and G. H. Filz, "Sustainable design concepts for short span, timber-only structures," in *Proceedings of the IASS Annual Symposium 2019 & Structural Membrane 2019: Form and Force, Barcelona, Spain, October 7-10, 2019,* C. Lázaro, K.-U. Bletzinger and E. Oñate (Eds.), 2019. pp. 634-641.

[3] G. Ruan, G. H. Filz and G. Fink, "An integrated architectural and structural design concept by using local, salvaged timber," in *Proceedings of the IASS Annual Symposium 2020/21 & the 7th International Conference on Spatial Structure: Inspiring the Next Generation, Guildford, UK, August 23-27, 2021,* A. Behnejad, G. Parke and O. Samavati (Eds.), 2021. pp. 534-545.

[4] G. Ruan, G. H. Filz and G. Fink, "Shear capacity of timber-to-timber connections using wooden nails," *Wood Material Science & Engineering*, vol. 17, no.1, pp. 20-29, 2022.

[5] G. Ruan, G. H. Filz and G. Fink, "Master Builders revisited – The importance of feedback loops: a case study using salvaged timber and wooden nails only," *Architectural Research in Finland*, vol. 6, no.1, 2022. (Accepted for publication)

[6] G. H. Filz, "Low-tech or high-tech? "cut.enoid.tower" - three times two facets of irregularity," in *Proceedings of the VI International Conference on Textile Composites and Inflatable Structures & Structural Membranes 2013, Munich, Germany, October 9-11, 2013,* K.-U. Bletzinger, B. Kröplin and E. Oñate (Eds.), 2013. pp. 250-257.

[7] A. Pugnale and M. Sassone, "Structural reciprocity: critical overview and promising research/design issues," *Nexus Network Journal*, vol. 16, no.1, pp. 9-35, 2014.