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CONSTRUCTIVE SYSTEM OF RECIPROCAL FRAMES IN TERMS OF CONTEMPORARY ARCHITECTURE

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Zlata Tošić, Sonja Krasić, Dragoslav Stojić

University of Niš, Faculty of Civil Engineering and Architecture, Serbia

Abstract. *In this paper, the reciprocal frame constructions are analyzed, starting from their definition, historical survey, to static and geometric characteristics, types and forms. Although very familiar for their shape, their earlier usage in contemporary architecture was not the same as at present. An overview of some of the more recent examples of conceptual solutions and derived pavilions has been established. These structures represent good example for temporary structures in a form of pavilions. Goal in this paper is to design a sample of a closed permanent building combining classical structural systems and RFs. The chosen geometry was predefined as regular in order to use its properties to determine if there is a possibility to form equal units. Finally, based on defined entities, the pavilion's conceptual design was made using a parametric design in plug-in Grasshopper and Rhinoceros software.*

Key words: *reciprocal frame constructions, design complexity, architecture design forms, Grasshopper, Rhinoceros*

1. DEFINITION AND CHARACTERISTICS OF RECIPROCAL FRAME CONSTRUCTIONS

Increasing number of designers and architects are aware of the fact that knowledge of form is a very important aspect of design of structures and perceptual process of observers [1][2]. Light constructions in architecture are a common trend that stems from the need for effective constructive systems and improvement of visual architecture qualities. There are many types of lightweight constructive systems in engineering [3], but this time subject of the work are *reciprocal frame constructions (RF).*

What does the word "reciprocal" mean when it comes to structure and what kind of quality does it stand for, if there is any? The Reciprocal Frame (RF) is a 3D structure composed of three or more pieces of sticks. Generally speaking, the rods are placed together

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Corresponding author: Zlata Tošić
Faculty of Civil Engineering and Architecture, Aleksandra Medvedeva 14, 18000 Niš, Serbia
E-mail: zlata10@live.com

to form a closed circuit called an RF unit, while multiple RF units can be further assembled to form large RF structures [4]. Although the structures are made of simple elements, no central support is required for its static maintenance [5]. Thus, these constructions make a perfect system for big continuous surface area such as ones with non-standard geometry. When it comes to combining elements, RF structures have been used for different types of modules and compound shapes which are made of several interlaced and single units (see Fig. 1) [6][7]. Their definition gives us possibility and freedom in making custom shapes by only assembling basic elements into proper structure.

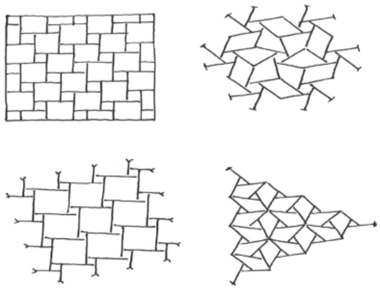


Fig. 1 Examples of the RF module assembling [7]
(Source: O. Popović Larsen 2014)

RF structures need a precise spatial definition when free or irregular forms are used. Understanding the geometry of the structure and parameters (see Fig. 3) that defines it is important to enable the design and construction of a reciprocal frame (RF). Parameters defining RF units with regular polygonal and circular geometry are the following [4]:

- Number of rods (n)
- Radius of the outer circle of rods (ro)
- Radius of the circle through the cross section points of rods (ri)
- Vertical distance from the outer rods to the beam cross-section (H)
- Vertical distance of the beam axis at their cross-section (h2)
- Thickness of the beam (L).

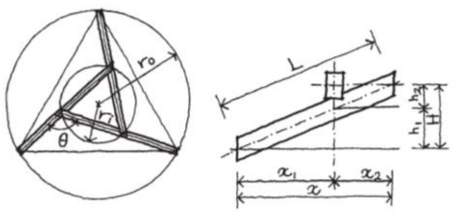


Fig. 3 Geometric parameters for RF constructions [4]
(Source: O. Popović 1996)

In practice, all this means that a set of well-chosen relationships between RF parameters should be determined in order to form a three-dimensional RF structure. These should help to select the initial parameters, and then we get guidelines for defining others.

Depending on the intention of the designers and constraints, the initial parameters will be selected and the others determined. It is important to note, however, that RF is a complex structure and that all factors should be taken into account at the same time. Considering any geometric parameter, separately of others, it would not bring optimal results [4].

When it comes to structural advantages of RF it is important to mention that because of their ability to find alternative load transfer paths, they have an excellent level of static uncertainty, which we know is important for local breaks. This property varies most from the type of RF structure. On the other hand the type of connections of structure make them partially work in bending which is perhaps one of the few faults that the RF structure has [4].

2. History of RF Structures

Systems consisting of beams that support one another are known for centuries and there are numerous illustrations of such structural systems. For example, during the Middle Ages, French architect Villard de Honnecourt [4] gave a solution based on a mutually supportive framework for the problem of covering shrubs with shorter shrubs.

Leonardo da Vinci was also interested in this concept, made sketches for arrangements with a bundle similar to Villard de Honnecourt [8]. Another architect of the Renaissance period, Sebastiano Serlio, proposed similar drawings for short-beam spaces [9]. The historical record of the reciprocal frames and the overview of the constructed examples can be found in the work of Popović Larsen [10]. The RF is also used as term "nexorade" [11, 12, 13], which describes the spatial generalization of straight beams. This generalization relies on the fact that the eccentricity between the elements at the points of connection is dictated by the final form. This characteristic represents a special geometrical problem which is conducted out of spatial placement of the elements in order to match certain shape. The RF lamellas were, also, later used by Pier Luigi Nervi for hangar planes in Orvieto, destroyed in the Second World War (see Fig. 2).

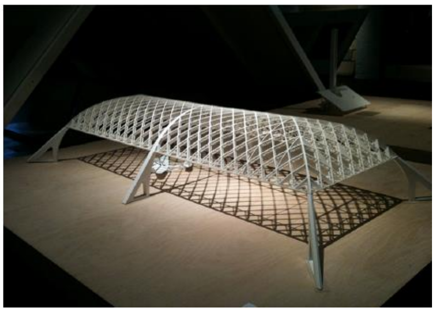


Fig. 2 Model of structure Orvieto hangar from Pier Luigi Nervia [7]
(Source: O. Popović Larsen 2014)

3. Contemporary Constructions of the RF System

In the past few years, RF structures have become a popular constructive medium. The Mount Rokko-Shidare Observatory, designed by architect Hiroshi Sambuichi and Ove Arupa and Partner in Japan, was completed in 2010 (Figure 4) [14].

Fig. 4 Observatory Mount Rokko-Šidare [7]
(Source: O. Popović Larsen 2014)

Although it is irregular, the shape is constructed of the straight rods. The main construction is made of 50 mm welded steel pipes 1-2 m long, arranged according to a specific RF scheme. The problem becomes complex geometrically with the introduction of a cross-section of elements because this parameter affects the overall geometry. According to Olga P.L., this was extremely important because precision was not of sufficient quality - it would be impossible to construct RF and connect RF members [7] [15].

Another interesting RF structure shown in Figure 5 is the Pavilion Kreod, which was developed by the Pavilion architecture, and was designed by the research and development team Rambøll London. The idea was to develop a cheap, easily feasible, assembly and disassembly structure, easily dismantled and then set up at new locations.

Fig. 5 Pavilion "Kreod" [7]
(Source: O. Popović Larsen 2014)

The Italians Francesco Gherardini and Francesco Leali suggested the exploration of some temporary architectural pavilions from the aesthetic and parametric point of view. The basic modules consist of four bamboo planks that rely on the circle (clockwise). Each basic module shares a board with each of the adjacent four units (the unit represents four elements bound in a circle) [6].

a) b)

Fig. 6 Pavilion of the Forest Park: the whole structure [6]
(Source: Gherardini et al. 2017)

There is a connection of 44 tiles (see the shadow in Figure 6 b). The shell structure is a double curved geometry with a transition from the concave and convex surface. These curve changes arise from the various final disposition of the elements in each unit and, furthermore, by using uneven distances when connecting with the elements themselves, as in [16]. The five bundled steel pillars support the structure (Figure 6a) [6].

4. Non-standard geometry RF design with hexagonal modules

After analysis of RF constructions, examples of built structures as well as suggestions for future works, final goal was to demonstrate an example of a designed RF construction in non-standard geometry shape. Recognizing the mentioned problems in assembling elements, this solution was designed to apply the system on a permanent closed building. Moreover, the aim was to start from the chosen geometry and try to create modules with identical elements, if possible.

This object is designed using RF structures with hexagonal units (Fig. 7). The tessellation is made by shearing wooden modules for half side of the unit. The main geometry used for shell is a hyperbolic paraboloid intersected with an elliptical cylinder [17] (Fig. 8).

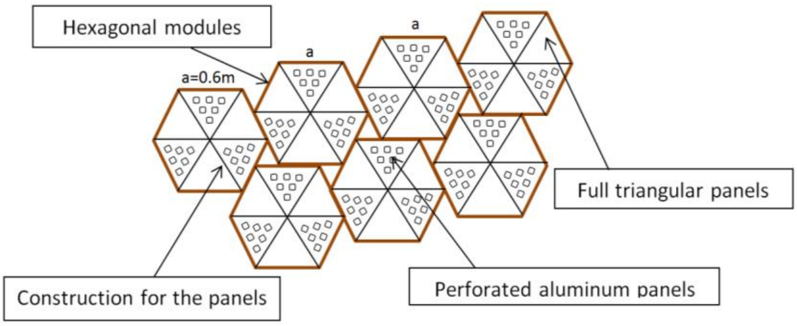


Fig. 7 Scheme of the selected RF structure with its main elements

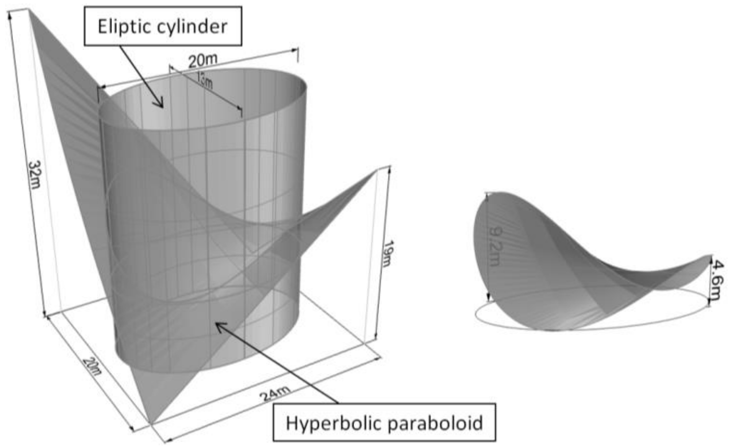
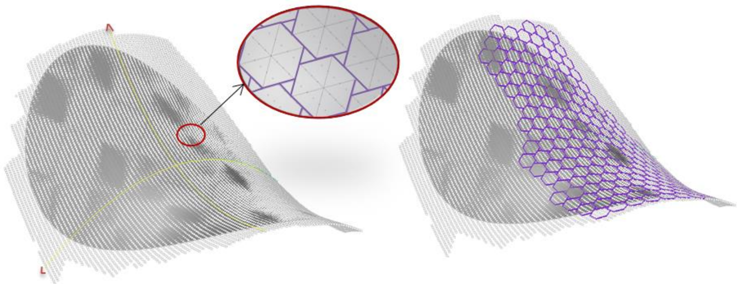


Fig. 8 Schematic breakthroughs done in Rhinoceros of two geometries from which the surface of RF was formed

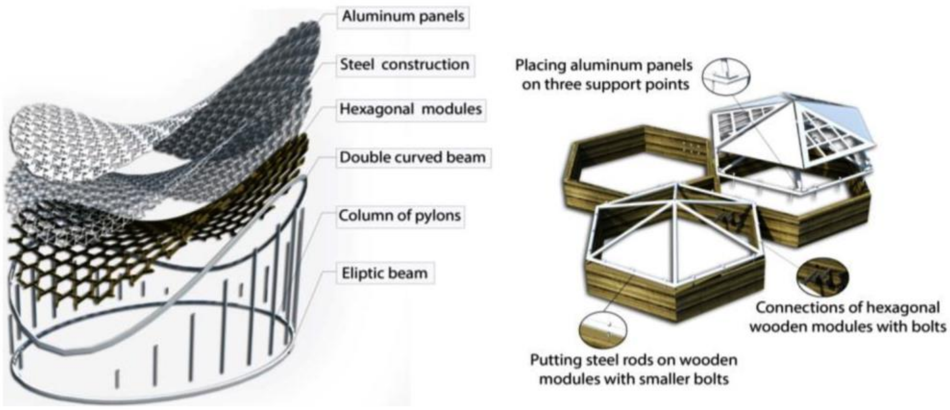
The next phase would be to set up modules on a given surface. In order to try to achieve equal elements we assembled succor points in the form of triangles on the equal x, y distance (Fig. 9 a). The element's length in basic directions x, y are a=0.60m. On the other hand because of a double curved surface and difference in diagonal point's distance the elements there vary a = 0.55m – 0.65m. When it comes to spatial structures, such as this one, we can encounter the problem while giving thickness to modules. In this case the direction of thickness represents the normal vector for the tangent plane in the characteristic points of the module (Fig. 9 b).



a) b)

Fig. 9 Rhinoceros drawing of the distribution of points for the setup of equal modules

These structures usually lack a cover layer. The solution was to cover modules with triangular panels. Half of them are perforated for the daylight illumination and all are connected to the inside part of the units, so modules could be visible outside (Fig. 10 a). Connections for modules are made with bolts, but steel sheets and welding are used for panels and the steel sub-construction (Fig. 10 b). The structural system is transferring loads from modules to the large double curved elliptic beam trough columns to the foundation.



a) b)

Fig. 10 Scheme of elements of the RF structure and the "T" connection between the rods

In these pictures we can see a finished model of the permanent closed building which is represents combination of a classical system of beams and pylons and RF structure. In the case of predefined geometry we were able to optimize elements, but in order for all of them to be equal, a change in geometry could be more visible. The purpose of the building can be various: exhibition hall, closed amphitheater, greenhouse (Fig. 11).

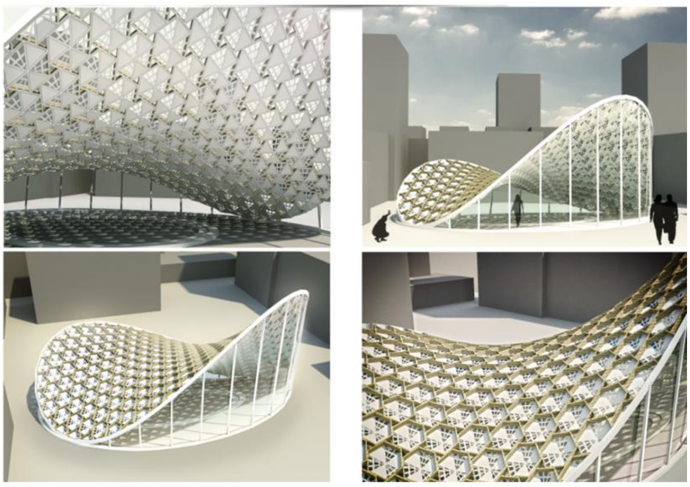


Fig. 11 3D reprezentation of final model of the object

5. Conclusion and Closing Remarks

Examples and built-in and conceptual solutions show that RFs offer great potential for creating innovative shapes. However, the RF structure is interesting not only because of the potential to achieve curved complex geometric shapes, but also because it offers the possibility of quick construction using elements of equal straight length.

Future RF research should focus on their application in constructions of temporary character which are necessary for quick construction, simple connections and their reuse [7]. It is also necessary to explore ways to use them as permanent buildings, where a combination of classical systems with RF would be used (as in this paper). There is a lot of research about geometrical aspect of assembling elements of RF but there are, also, challenges mentioned here that are worth exploring when we use predefined geometry. In this research we were able to design permanent structure of a closed building with optimized elements and solve problem of coverage of these constructions without an extensive modification of the building's shape.

Considering their contribution to connect simple constructions with complex geometry, it is very important that we study various aspects of RF structures. As a result, more interesting, imaginative and efficient RF structures can be designed.

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KONSTRUKTIVNI SISTEMI RECIPROČNIH RAMOVA U KONTEKSTU SAVREMENE ARHITEKTURE

U ovom radu analizirane su konstrukcije recipročnih ramova, počevši od njihove definicije, istorije, do statičkih i geometrijskih karakteristika, tipova i forme. Iako su vrlo dobro poznati njihovi oblici, njihova upotreba ranije nije bila ista kao u savremenoj arhitekturi. Analizirani su neki od savremenih primera konceptualnih rešenja i izvedenih paviljona. Ove strukture predstavljaju dobar primer za privremene objekte. Međutim, cilj ovog rada je definisanje zatvorenog stalnog objekta ovih struktura kombinacijom standardnih konstruktivnih sistema sa RF sistemom. Izabrana geometrija je definisana kao regularna, da bi se mogla koristiti njena svojstva i utvrdilo da li je moguće formirati jednake elemente modula. Na osnovu definisanih parametara, koncept dizajna paviljona određen je parametrijski korišćenjem plug-in Grasshopper i Rhinoceros programa.

Ključne reči: *recipročne konstrukcije ramova, kompleksan dizajn, dizajn u arhitekturi, Grasshopper, Rhinoceros*