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Democratizing the construction of multiple reciprocal frame structures using adaptive connectors

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Abstract

The heavy dependency on advanced automated machinery to produce the complex member orientations and junctions of Reciprocal Frame (RF) Structures makes it unviable for common applications. This paper seeks to bridge that gap by developing an adaptive mechanism for the junctions and to simplify construction of any given RF structure typology. First goal of this research is to establish the critical parameters to address complete adaptability at system and junction level using non-uniform member types with irregular cross section and centerlines. While the second goal focuses on developing the adaptive tool from the collected data through prototyping on single unit RF structures. The paper concludes with a successful construction of a 1:1 scale anticlastic multiple RF structure as an architectural application using only the adaptive connector, solid bamboo and simple manual fitting as a proof of concept. This research serves as a guide for how to make this complex structure utilizing any available linear members thus making it broadly accessible.

Keywords: Reciprocal Frame Structures, Adaptive Connector, Non-standard Member, Rapid Construction, Buildability, Anticlastic Surface Structures, Fabrication, Swivel-Ring Coupler, Riveting System.

1. Introduction

There are many different tools available with different logical approaches to design Reciprocal Frame (RF) structures, one such software is Grasshopper with its physics engine plug-ins like Kangaroo and Karamba. More sophisticated tools are also developed, which are privately owned and developed by experts, like 'Shift Frame Geometry' by ARUP or 'Reciprocalizer' by Dario Parigi & Poul Kirkegaard. These tools have found a new direction in the past decade with state-of-the-art CNC machines and robotic arms that could bring any complicated design to reality. They provide precision, which is very crucial for RF structures but these are reasonably expensive as well and thus available to only selected individuals. But due to the system's demand of accuracy, this approach is now widely adopted for execution of RF structures in different small scale & large-scale projects like, Kreod Pavilion in UK, Rokko Observatory in Japan, Piazza HIL Pavilion at ETH Zurich and others [11].

"Controlled networks of elements must be assembled, and reciprocal structures require remarkable precision and uncommon expedients for their fabrication because the overall geometry of the assemblage is the result of the complex and simultaneous interaction between all elements' position and size. Therefore, the values of the geometric parameters at each connection are dependent on the values of all the others in the assembly" [12].

These lines are from established researchers; Dario Parigi and Poul Henning Kirkegaard, who have been exploring RF systems for some time now, clearly highlight the lack of alternate low-tech assembly mechanism for construction of RF structures. This research builds on existing research by establishing the critical adaptability parameters and forms the foundation for conceptualizing the adaptive tool. The design evolves into a one of kind swivel-ring coupler with a unique riveting system that provides the required tolerances to incorporate the deviations of non-uniform linear members at local and global system levels. When evolved further, these connectors can be mass produced as components of a kit of parts with manuals for customized applications like emergency shelters, deployable tents or even large-scale community projects.

2. Adaptability & analysis

A pure RF unit would always carry a positive or a negative Gaussian curve and the multiple RF unit systems are surface typologies with combinations of these curves. An essential aspect to generate these surface typologies is the RF structure's local system that governs the member orientations and vis-à-vis the surface geometry. But any surface typology with multiple curves causes each local system to become exclusive, making the execution much more elaborate and machine dependent. The local design for an RF structure comprises mainly of junction detail, member preparation and kinetic determinacy. These attributes would, of course, further define the sequence of construction and assembly.

2.1. A case of Rokko observatory

This is better understood through the case of Rokko Observatory and its interpretation by the team at Aalborg University to achieve the same complex form by redesigning at junction level. While ARUP had an extensive team of experts that developed a master slice with standard scaffolding jig [10], the team of students at Aalborg University adopted a two-fold assembly system, i.e., tying each member loosely with sheer lock spheres in between, allowing correction of errors and then drilling through two the members to put a final tie, as described by Dario Parigi and Poul Henning Kirkegaard [12]. This case study helps establish the three major aspects for complete adaptability at junction & system levels:

2.1.1. Material

Timber has been a go-to material for RF structures for a long time as it is more suitable for CNC router machines or working hands-on. But members in their raw natural form with varying cross sections & deviating centrelines are more readily available. If a mechanism could cater to such member types without the use of high-end machinery, then it would make the mechanism adaptable at all levels.

2.1.2. Junction detail

In the research paper from Aalborg University, they had chosen pin joint and friction of ropes to hold the members together. A two-part assembly helped give enough scope for correction of member position. Another vital aspect was that the junction point is the sole defining factor in the geometry and needs to be at a regular distance from the centreline. The rest of the member cross-section is insignificant and primarily a medium to conduct load transfer.

2.1.3. Kinetic determinacy

A three-member unit is the only unit type where with a simple pin joint at the respective junction points, one can lock the overall geometry. Thus, it helps significantly to have a no-scaffolding assembly and still efficiently cater to the system's geometry.

2.2. Construction and performance analysis of prevailing junction typologies

The above example helps address the required criteria to conduct experiments and understand how adaptable are the known prevailing junction typologies for RF structures. The next step is to test these criteria on known existing junction typologies for a basic three member RF structure constructed out of non-uniform members with irregular cross section & centerline i.e., solid bamboo in this case. This is done in order to establish a junction type with maximum potential in terms of execution but also the adaptability of varying cross section and deviated centerline.

Table 1: Comparing different construction and performance parameters for prevailing junction typologies in RF systems made from non-uniform members (irregular cross-section & centerline). [Source: Author, 2021]

	Elastic Tie (Without Notch) 	**Zip Tie (With Notch)** 	**Pin Joint (Threaded Rod)** 	**Hinge Joint (With Notch)** 	**Swivel Coupler Joint** 
Member Preparation	None	Elaborate	Complex	Complex	None
Assembly Jig	Elaborate	None	Complex	Complex	None
Type of Labor	Unskilled	Basic	Skilled	Skilled	Unskilled
Degrees of Freedom	Translational and Rotational	Rotational	None	None	Translational and Rotational
Precision & Tolerance	High Tolerance Very low Precision	Balanced	Low tolerance Precision (extensive process)	Low Tolerance Precision (extensive process)	Balanced
Cross-Section & Centerline	None	Only Cross-section No Centerline	None	None	Only Cross Section No Centerline

The comparative analysis shows that even though Swivel coupler fails to efficiently accommodate the irregular cross section & centerline, it is still the most adaptive amongst all the known prevailing junction types. The principles governing its mechanisms can be used as a starting point for design development of the adaptive connector. Following are the key aspects that need to be addressed from this experiment:

- The junction needs to cater all 360 degrees of movement for members in all three planes. It means rotation about the member's axis and in the respective tangential planes with respect to its complimenting member's position, is required.
- Member Preparation needs to be cut down to a minimum, removing the stage of using state-of-the-art automated machinery to create the complex grooves or notches onto the members.
- Create easy-to-use mechanisms to install the junction, along with a no-scaffolding assembly. No complex jigs should be required to put the structure together.
- It should be possible for any able personnel to construct an RF structure manually on their own, using the members and junctions with simple instructions.
- The junction should provide precision in the positioning of contact points and enough tolerance to carry out the assembly manually.
- The most important characteristic would be for the junction to accommodate irregular members, i.e., varying cross-sections and with non-linear centerlines.

2.3. Digital fabrication & non-standard members

Major setback in the earlier prototyping of five existing junction typologies is the lack of accommodation of centerline deviations. Incorporating these deviations without computational aid is complicated as they offer a very tight range of tolerances. Usually, we find that the workflows for such construction are typically unidirectional in practice. Currently the most reasonable method to link the process of design and fabrication for such non-uniform member types is that of 'in process-survey' [7]. This process involves a sensory system and an open design system. The first part is where the members are scanned and that is taken as input data. The open design system then responds and recalibrates the junction accordingly to adopt an adaptive fabrication process. Each junction is then produced to cater to those corrections. Thus, it is impossible to construct complex RF systems using irregular members if one does not address the incorporation of varying cross section & deviating centerline. This aspect has to become the anchor point, and enough tolerance will have to be offered at the junction level to achieve that.

3. Developing the adaptive connector

The basic concept is to have a precise ecosystem to make the junction points regular and then incorporating the irregular members in that setup. It can be explained using a basic Reciprocal unit made out of perfectly regular cylinders. Their contact points are defined and precisely located as well. Imagine this cylinder being transparent and being inhabited by multiple non-linear lines. That is precisely how this junction will work, a sleeve typology that helps maintain junction points' regularity. At the same time, the irregular members are incorporated within the imaginary cylinders formed by the sleeves.

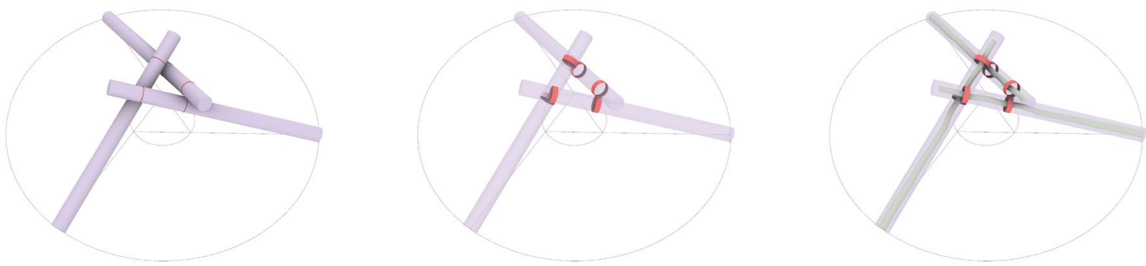

Fig 1. Conceptual development for the adaptive connector [Source: Author, 2021]

The inner radius of the sleeves determines the tolerance for any of the irregular members. Theoretically, this is an ideal mechanism to incorporate both deviated centerlines and the respective cross-sections, given that the tolerance of the sleeve is enough. Merged with the concept of swivel couplers, these have the potential to address the aspects of developing an adaptive joint for easy construction of complex RF structures. Thus, the developed sleeve comprises of two major components:

3.1. Swivel mechanism

A rivet in the form of a pin joint is ideal for achieving the desired swivel-type motion between them as well as for ease of mass production. A crucial design component is the introduction of a washer between the rings, at the contact point which helps induce a certain degree of movement. This allows correction of the respective junction orientations when mounted on supports, under the gravitational force.

3.2. Clamping mechanism

This mechanism needs to adapt to the varying cross-sections of the members. It would also need to allow them to be off-center and anywhere within the sleeve's inner radius. Adjustable screw-like arms with compressible tips made of teeth profile rubber allow equal distribution of force along the circumference of the member (which is three in this case) and accommodate any irregular cross-sections (circular and orthogonal). The head of these arms are made as knobs to manually tighten them.

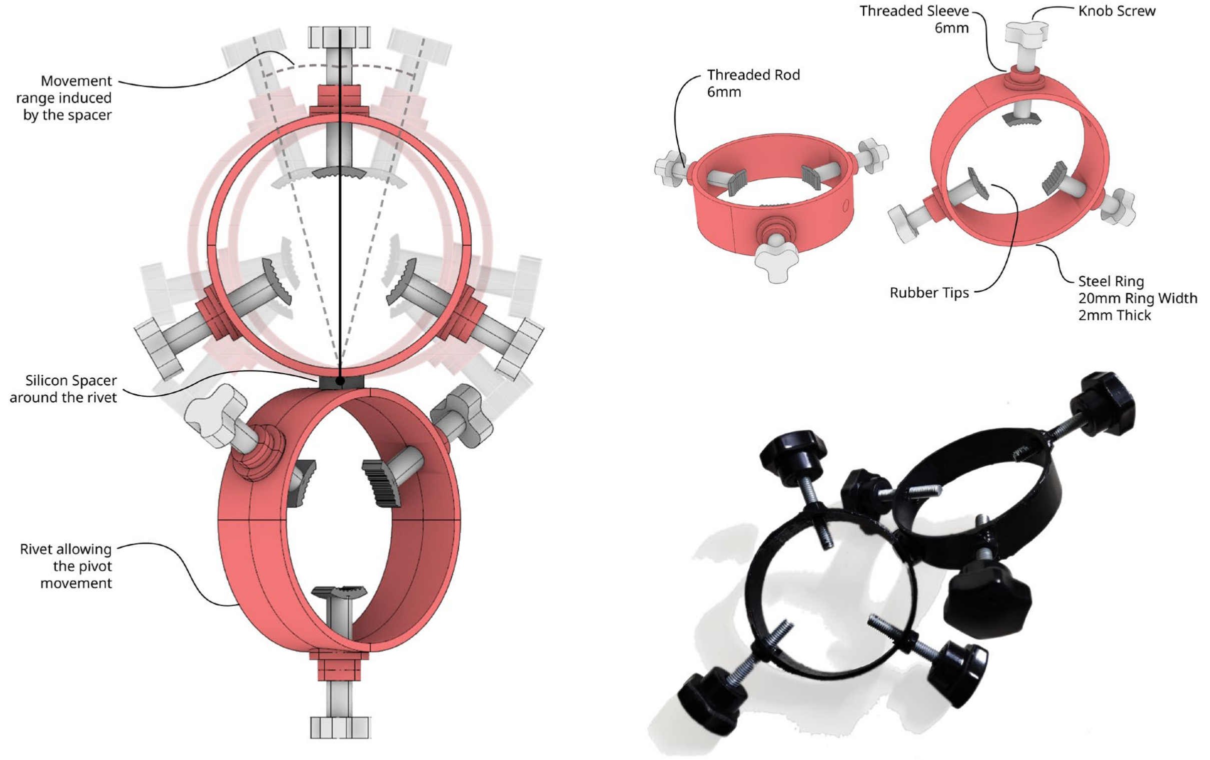

Fig 2. Developed adaptive connector and its components. [Source: Author, 2021]

4. 1:1 Scale application

Zeroclastic, Monoclastic, and Synclastic surface RF structures have a regular propagation, i.e., there is regularity in distances between junction points and member orientations. They have zero or one-way curvature, which results in a monotonous repetition, and thus it would not help explore the adaptive connector's potential. On the other hand, an Anticlastic surface (two-way curved surface) RF structure would pose a wholesome challenge in its execution with irregular junction points and varying member orientations. So, the preliminary stage was to digitally generate a two-way curved surface RF structure under gravitational force with necessary tolerances for irregularities of the selected members. Information from this simulation will guide the parameters for the for fabrication, member markings and assembly of the structure.

4.1. Fabrication

For this project, steel hollow pipe is carefully marked with the spacing of 18mm wide sleeves after dividing the pipe longitudinally with four lines to punch the holes. Markings are done of three 5.5mm holes for the screw arms and one 4mm hole for the solid rivet. Then 5mm nuts are welded onto the screw arm holes followed by two rings then coupled using solid rivet with inclusion of a washer in between (see Fig 2).

4.2. Member preparation

The preparation involves marking the junction points onto the members based on the acquired data from the optimized geometry. This is done by making a measuring jig, and the measurements from the extreme ends are written on the respective extreme markers, which would help with the member orientation. At the same time, markers in the middle carry the member numbers. These markers are of the smallest width of about 4-5mm, helping maintain a certain level of precision.

4.3. Assembly

The requirements for erection of the structure are limited to only the marked Bamboo pieces, adaptive connectors, and vertical supports (anchor points). These three components combined with the two assembly sheets (one for orientation and one for the line-out) are enough to execute the assembly. This process is a no scaffolding assembly, which is done in isolation from the line-out and member marking process.

Fig 3: A) No scaffolding assembly B) Anticlastic Surface - Hyperbolic Paraboloid form
C) Comparison with its digital precursor. [Source: Author, 2021]

5. Results

- It took about 10 hours for one person to assemble and erect the entire 3.5x3m using these adaptive connectors. This observation helps us gauge how more hands can make this process even faster, highlighting the connector's potential to help create an easy, economical and faster method of constructing RF structures.

- The inclusion of the washer in the rivet detail offers lot of tolerance. It allows the junctions to adjust and flatten out while assembling. Then take form when placed onto the vertical supports under the gravitational force.

- The final structure was very light and possible to be lifted by two people easily. This aspect shows how these structures can be assembled off-site and then placed simply on the vertical supports on-site.

- The tips of the screws could use some better detail. Currently, the tips were slightly digging into the bamboo, keeping them in position, but there was still some rotational movement between the tip and bamboo, resulting in minor errors.

- Vertical supports anchored onto the ground and made with rigid material will help resist the outward thrust by the structure. Such additions will help get a more precise form.

6. Discussion, conclusions & further work

This research project presented an alternate method of designing and constructing RF structures by focusing at the junction level of the system. The existing application of RF systems along with thorough analysis of the RF junction typologies helped identify the critical gap for execution of these structures. It resulted in developing a coherent approach, an adaptive connector at junction level, that subsequently affects the overall system. This has enabled the development of an adaptive tool making it possible to design and construct all possible geometries of Reciprocal Frame Structures. Current RF junction typologies have managed to achieve the 'degrees of freedom' parameter, but are limited to members with uniform cross section and centerline for precision. While the presented adaptive mechanism with its unique riveting system manages to accommodate non-uniform members with varying cross-sections and non-linear centerlines, without any member preparation or CNC tools. It is essential to realize that this is more of a mechanism; that can have numerous variations in providing different tolerance ranges for other non-uniform linear members as well.

The adaptive connector has efficiently simplified the construction process for RF structures, making it standard for all geometries by altering the current method of designing an RF structure and offering a new framework. Now a user can digitally generate any complex three-member RF geometry (with proper tolerances for the decided linear member), gather the respective junction locations on each member and use the designed connectors to manually assemble them. Three-member type RF units and calculated vertical anchor points help lock the structure into its final form, which otherwise would flatten due to the unrestricted motion between two members. This highlights the potential for devising an off-site assembly process and later installing onto the vertical supports on site. The knob screws make the construction simpler as well, by eradicating the requirement of high-end machinery or tools at member preparation and assembly stage. All these factors allow faster construction of RF structures with minimum number of resources.

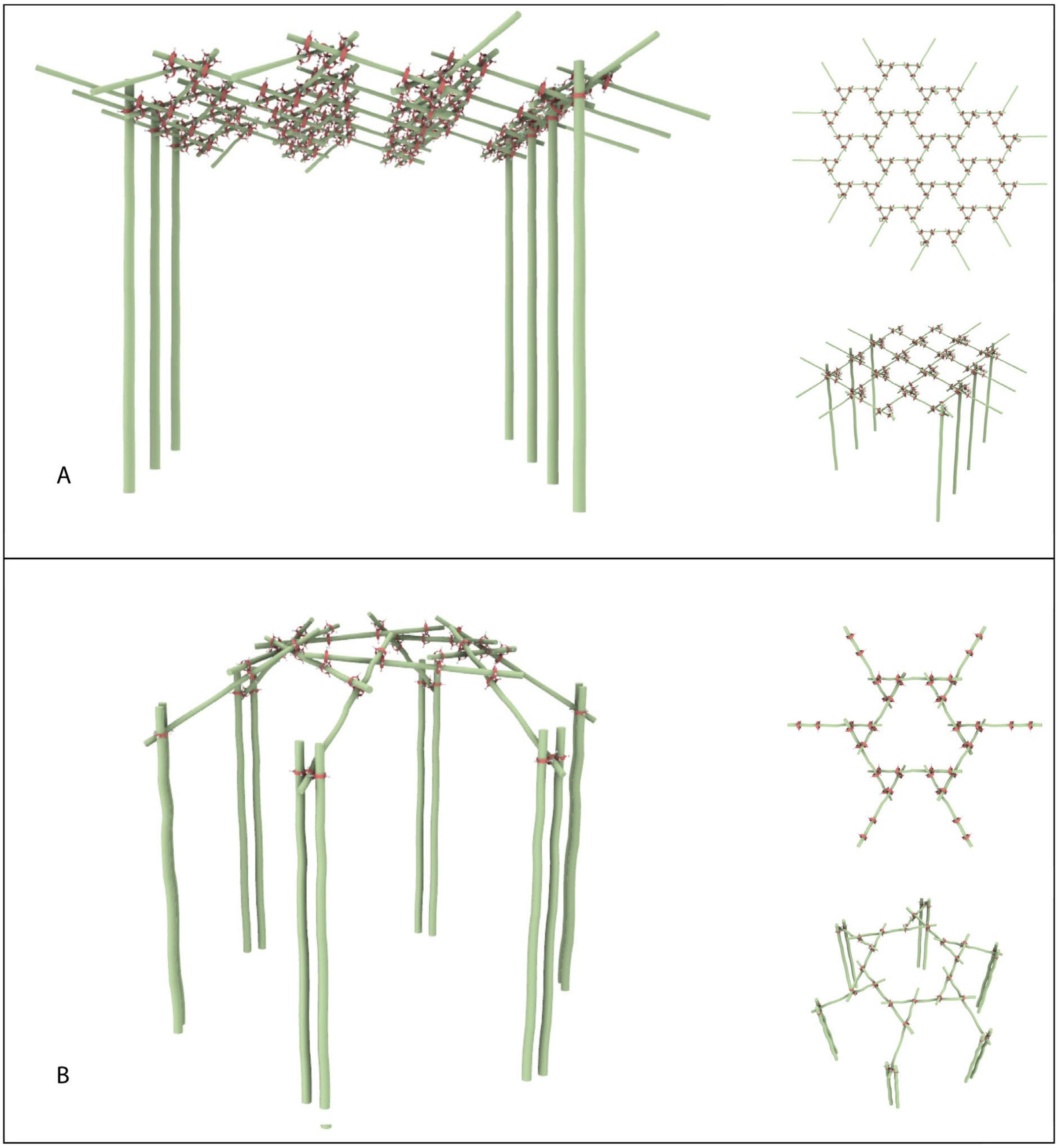

Fig 4: Digital simulations of RF systems using the developed adaptive connector A) Monoclastic spanning system B) Synclastic spanning system [Source: Author, 2021]

Even though the derived connector helps adapt at junction and system level, it does have some critical drawbacks. A big limitation of this system is usage of three member units which helps locking the system through kinetic determinacy. But even after locking the geometry, the connector's riveting system with the silicon spacer induces uncontrolled movement which results in shifting of sleeves during assembly. A further in-depth study would be needed to design the contact point between the member and the connector. Informed design of the knob screw and its ends will help maintain the member's integrity overtime. Furthermore, there is need to explore alternate materials to have a controlled movement of these connectors. Apart from this, minimum contact between the sleeve and the member also affects the load transfer of the overall structure. It would limit the sleeve's possible materials for structural stability.

This research forms the foundation for a much wider scope of work needed to make RF structures more viable for common applications. There is a big scope of research for detailing each component of this connector as well as streamlining the sequence of construction using these connectors. We have established the requirements to provide tolerances for member readjustment but there is still a wide range of mechanisms to be tested for a much efficient solution, like spacers with alternate materials, ball-socket joints and so on. Once resolved it will enable mass production of this connector as a component of a kit for customized applications including emergency shelters, deployable tents, or even large-scale community projects.

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