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Two-way Reciprocal Frame

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Abstract

The paper reports on research aimed at developing a new design method for constructing double-curved structures, integrating two well-established and widely studied systems: the reciprocal system and the two-way joist (waffle) system. This leads to the creation of the Two-Way Reciprocal Frame, which enhances the remarkable structural intelligence of reciprocal frames while incorporating the geometric rigor of waffle structures. Within the relative freedom of form, the small structural elements remain orthogonal to each other, resulting in a highly regular grid when projected onto the horizontal plane. The elements consist of vertical lamellae joined together using custom-shaped half-lap joints, allowing for reciprocal arrangement. This apparent complexity is managed through a computational design algorithm that directly generates file-to-factory outputs for numerical control cutting (CNC) and digital fabrication. In particular, the orthogonality of the elements and the shaped half-lap joint enable the use of simple and cost-effective machines, such as laser cutters and three-axis CNC routers, as the shaping process requires only orthogonal cuts to the plane of the base panels. The study emerges from the integration of technological, structural, and geometrical disciplines.

Keywords: reciprocal frame, two-way structures, computational design, digital fabrication, structural systems

1. Introduction

This research proposes an innovative construction system that integrates the structural logic of reciprocal frame structures with the geometric regularity of the two-way joist system. By employing computational design tools and digital fabrication techniques, the study explores a new architectural grammar capable of combining formal freedom, structural efficiency, and constructional precision. The project has a dual objective: on the one hand, to identify an effective synthesis between two well-established structural systems—seemingly distant yet inherently complementary; on the other, to leverage the potential of parametric design in managing geometric complexity in a simple and repeatable manner. The proposed system is based on the generation of an orthogonal grid composed of small-scale reciprocal elements, whose mechanical performance is enhanced by interlocking joints and the inherently collaborative nature of the structural configuration. These elements, arranged to form an orthogonal pattern with reciprocal interconnections, are shaped using half-lap joints. This configuration enables a dry-assembly process that is reversible and potentially expandable, fully exploiting the capabilities of digital fabrication. The combination of the two systems gives rise to a novel construction language, adaptable to different scales and morphological conditions, while maintaining geometric and structural coherence.

2. Background

The development of this research is based on the synergistic integration of four main themes, each of which significantly contributes to defining an innovative and cutting-edge design and construction approach. These areas include reciprocal structures, the Two-Way Joist system, digital fabrication, and finally computational design. The interaction between these fields enables the development of an advanced structural system, capable of combining theory and practice, material optimization, and technological innovation, thus opening new perspectives in contemporary architectural design.

2.1. Reciprocal frame

Reciprocal structures are based on the principle of mutual support: each element is simultaneously supporting and supported. This configuration enables the creation of self-supporting systems without mechanical joints or rigid nodes, where stability is ensured by the interdependence of the individual components. Reciprocal frames allow for high morphological flexibility, are often inspired by natural geometries, and offer significant advantages in terms of lightness, modularity, and material efficiency. From a historical perspective, the principle of reciprocity dates back to antiquity, as evidenced by traditional constructions from Neolithic civilizations that employed overlapping beams to create self-supporting roofs. In more recent times, the concept was rediscovered and formalized by engineers and architects such as Leonardo da Vinci [1], who explored its potential in temporary military structures. The 20th century saw a renewed interest in these configurations, particularly through the studies of researchers like Olga Popovic Larsen [2][3], who contributed to establishing a theoretical and experimental framework for reciprocal structures within contemporary architectural discourse. Among the case studies examined, the research also considered the 2005 Serpentine Pavilion by Siza, Souto de Moura, and Balmond [4], which—although not a perfect reciprocal frame—explores core principles of reciprocity, such as the interdependence of elements and the achievement of static equilibrium through complex geometric articulation. Despite their conceptual simplicity, these systems demand high precision in both design and assembly, as any error can compromise the stability of the entire structure. The adoption of computational design tools [5] makes it possible to control tolerances, optimize construction sequences, and simulate structural behavior.

2.2. Two-way joist

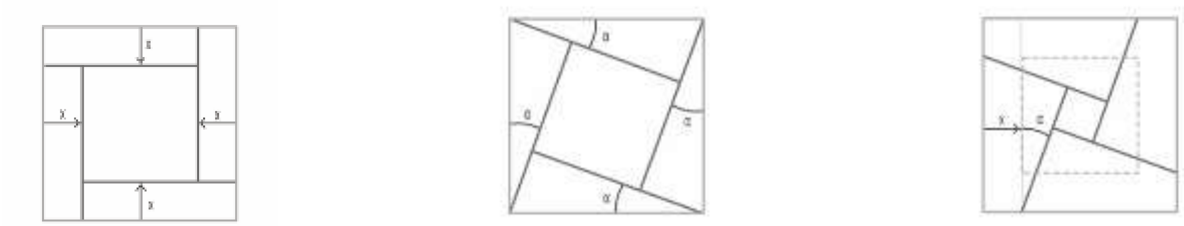
The two-way joist system refers to a bidirectional structural configuration composed of an orthogonal grid of linear elements that work together to distribute bending loads in both directions. This morphology derives its name from its resemblance to coffered slabs, a technique already employed in Roman times to lighten masonry roofs while preserving their structural integrity. With the advent of computational design and prefabrication technologies, this typology has undergone significant evolution. It now manifests as modular, lightweight, and efficient systems that optimize material usage and simplify construction and assembly processes. The research analyzed several representative case studies, including the airplane hangars designed by Pier Luigi Nervi [6], where the structural logic of intersecting rib systems is emphasized through the use of precast reinforced concrete, and the Taoist Temple by Kengo Kuma [7], which offers a contemporary reinterpretation of the two-way system. Kuma's design employs modular timber structures that combine technical performance, sustainability, and symbolic meaning.

2.3. Computational design and Digital fabrication

At the core of the system lies the integration of computational design and digital fabrication—two fields that, in recent years, have shown the potential to revolutionize the way contemporary architecture is conceived and constructed. Computational design [8] enables the generation of complex geometries through algorithms and parametric logics, allowing for the exploration of a wide range of formal configurations. By using software such as Grasshopper for Rhinoceros, designers can manipulate geometric data in real time, translating it into precise and adaptable digital models ready to be transformed into physical components. Digital fabrication, on the other hand, converts these models into tangible elements using computer-controlled manufacturing technologies such as laser cutters and CNC machines. This process, known as file-to-factory, allows for the production of customized components with high precision, minimizing material waste and reducing production time. It is precisely through this synergy that the project succeeds in combining geometric rigor, design adaptability, and technological accessibility—enabling the construction of complex structures even with limited resources. This technological integration is not merely a tool to streamline production, but becomes an integral part of the creative process itself.

3. Pattern and moduls

The design phase began with the development of regular geometric patterns capable of accommodating both the structural logic of reciprocity and the simplicity of execution. Unlike a simple grid or conventional lattice, where elements meet at fixed nodes or connection points, in reciprocal structures, these intersections are generated through the rotation or translation of individual components. The final configuration of such a structure depends on several factors, including the number of elements composing each module, as well as the angle and direction of rotation.



a. b. c.

Figure 1: a) Traslation; b) Rotation; c) Roto- traslation.

The base pattern is articulated through regular modules, each consisting of four linear elements arranged according to specific geometric rules of interlocking and overlapping. These modules are not conceived as isolated entities, but rather as autonomous yet interdependent building units, capable of generating a continuous and coherent structure. The process begins with the definition of an initial cell, which serves as the generative core of the entire \

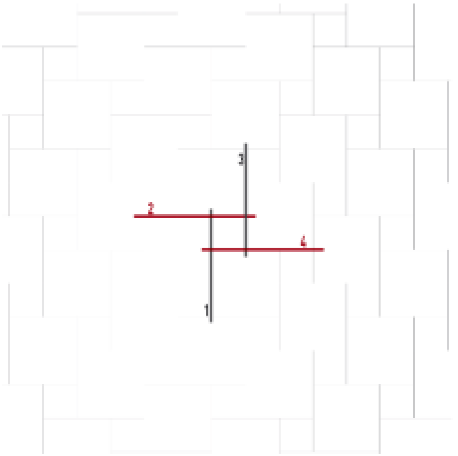


Figure 2: Basic module composed of 4 elements.

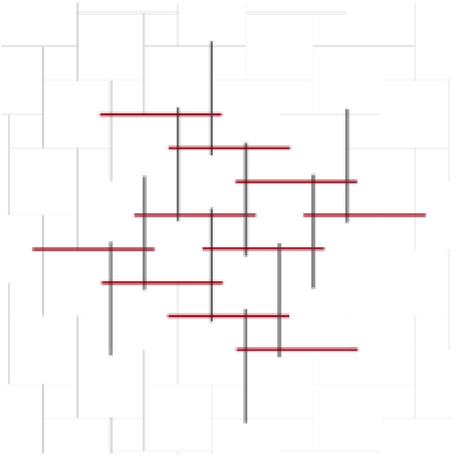


Figure 3: Pattern defined by the union of multiple modules.

However, the application of this construction logic introduces a significant challenge during the module closure phase. Specifically, the insertion of the final element proves problematic due to the geometric configuration of the system: it is constrained by the presence of the three previously placed elements, which limit its ability to rotate and prevent it from being positioned without interference. This obstacle arises from the very nature of the reciprocal system, in which each element is simultaneously supporting and supported, creating a structural equilibrium that can complicate the final stage of assembly.

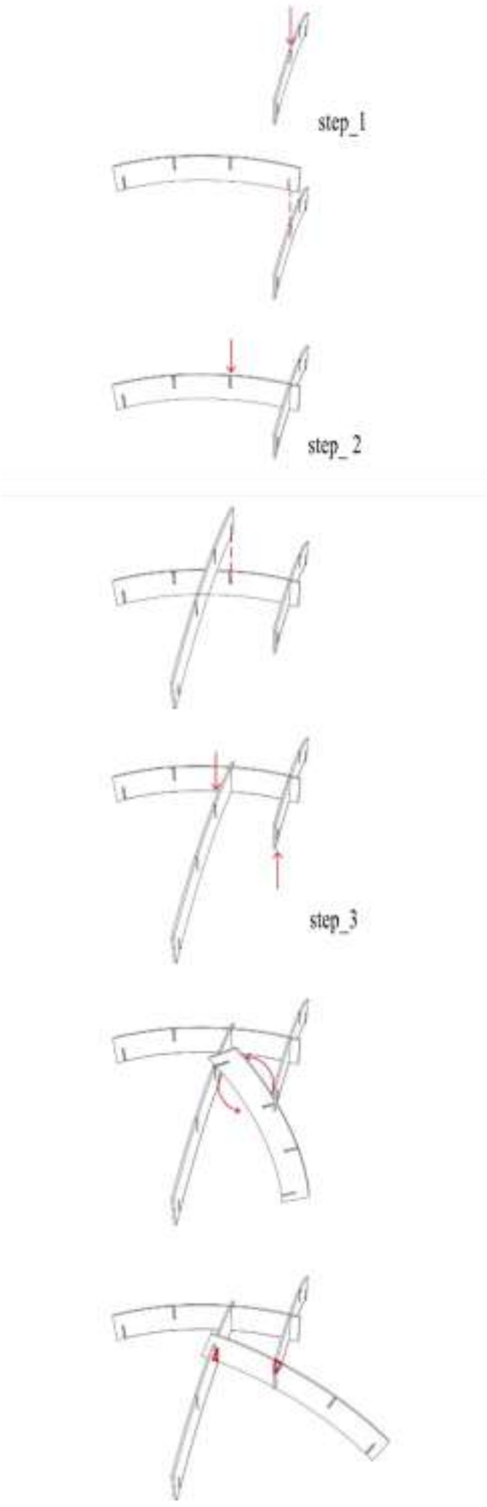
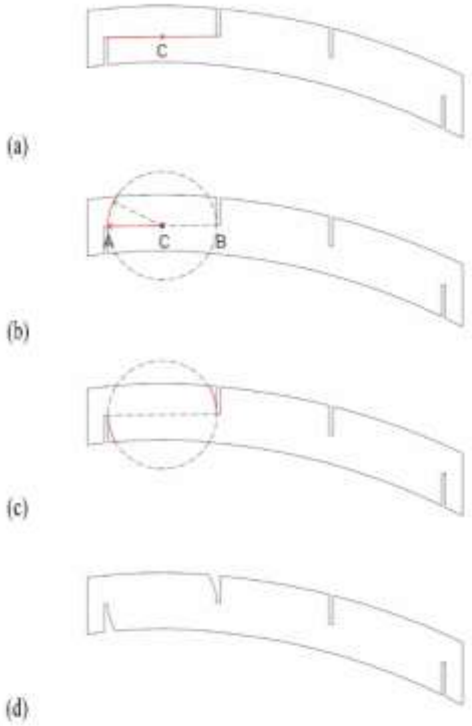


Figura 4: Assembly process of a module.

This challenge was addressed through a shaping process of the elements, developed using parametric design tools. The algorithm created in Grasshopper analyzes the position and function of each component and calculates the portions to be removed to enable proper interlocking and complete the reciprocal configuration.



Starting from the distance created between two consecutive joints (points A and B), an axis is defined, and a midpoint is identified on it (point C). This point will serve as the center of rotation for the element. (Figure a).

Next, a circle is drawn with point C as the center and the radius equal to the distance between point C and point A. (Figure b).

The intersection between the circle and the initial element defines two circular arcs that outline the portion to be removed in order to facilitate rotation. (Figure c).

Shaped element. (Figure d).

Figure 5: Shaping process of the element.

A full-scale 1:1 prototype [Figure 6] was built with the aim of testing and validating the shaping system, allowing a thorough analysis of both the structural behavior and the assembly methods of a single module. This approach enabled a concrete evaluation of the system's performance.

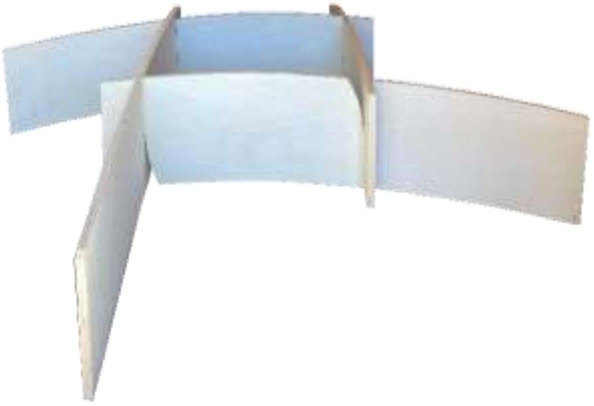


Figure 6: 1:10 scale prototype.

Two main assembly strategies were experimented with:

- **Spiral arrangement**, which involves extending the grid from a central core following a spiral development. This approach is adaptable but results in a random pattern in the positioning of the elements to be shaped; [Figure 7]

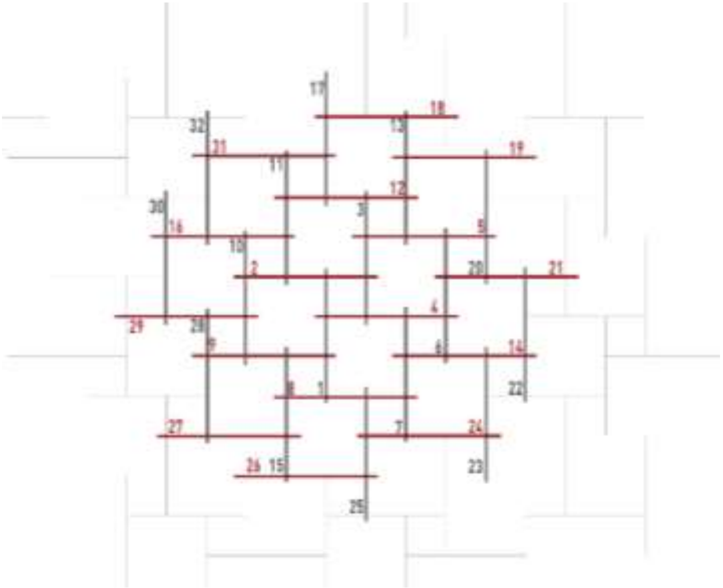


Figure 7: Spiral arrangement.

- **Linear arrangement**, which allows for the sequential implementation of modules along one or both primary directions of the grid, enabling the definition of a repeatable logic to identify in advance the elements to be shaped. Starting from a module composed of four elements, the pattern develops sequentially. [Figure 8]

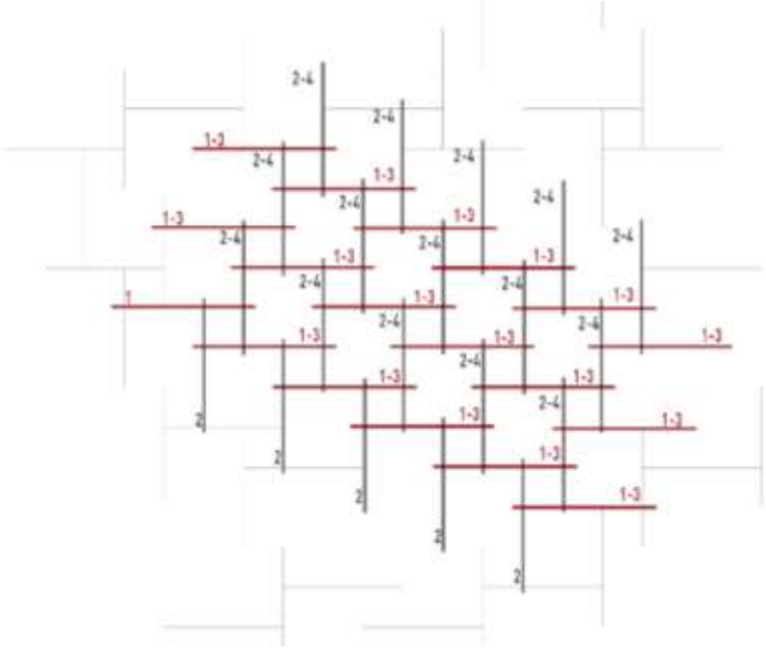


Figure 8: Linear arrangement.

In this scheme, element 3 of the current module becomes element 1 of the subsequent module, as does element 4 become element 2, thereby ensuring geometric continuity along the direction of growth.

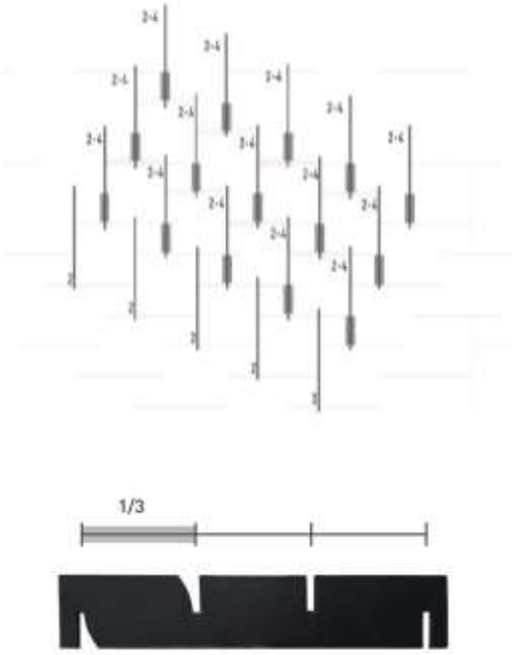


Figure 9: Elements arranged along the y-axis.

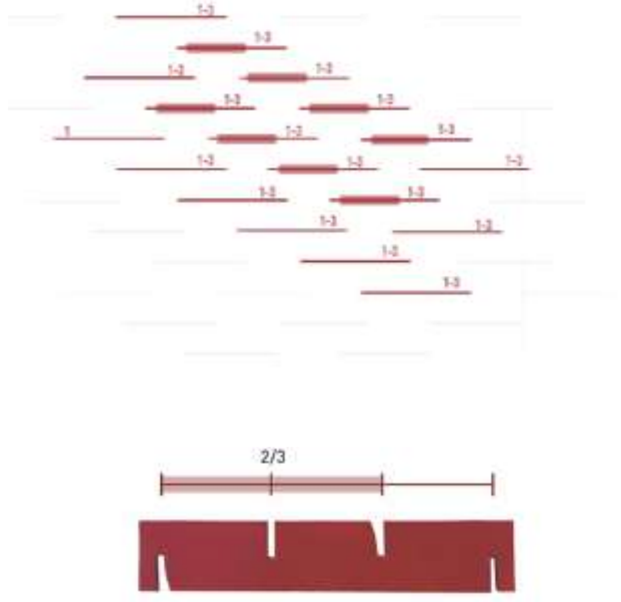


Figure 10: Elements arranged along the x-axis

This latter approach proved to be the most effective for defining a construction system that is orderly and easily manageable during the assembly phase. Elements identified as 2 and 4 are shaped along one-third of their length. Arranged linearly along the y-axis, they close the smaller square of the module while simultaneously serving as elements of the larger square. Conversely, elements 1 and 3 are shaped along two-thirds of their length. Arranged linearly along the x-axis, they close the larger square of the module and, at the same time, constitute the elements of the smaller square.

3.2. Form finding

The application of the system was not limited to planar configurations but also included the study of surfaces with varying curvature to assess their geometric and structural adaptability. Four categories were considered: planar surfaces, developable surfaces, synclastic, and anticlastic surfaces.

In the case of planar surfaces, the system's behavior is predictable and regular. [Figure 11]

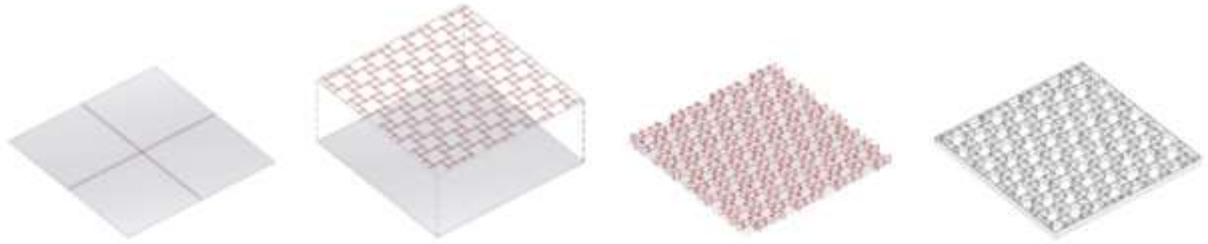


Figure 11: Development of the system on a flat surface.

Conversely, the implementation on curved surfaces introduces complexities in defining the joints, as curvature affects the rotational and interlocking capabilities of the elements. To address this, it was essential to integrate a portion of the Grasshopper algorithm that calculates the correct geometry of each element based on the angle between the axes of the structural components and the support plane.

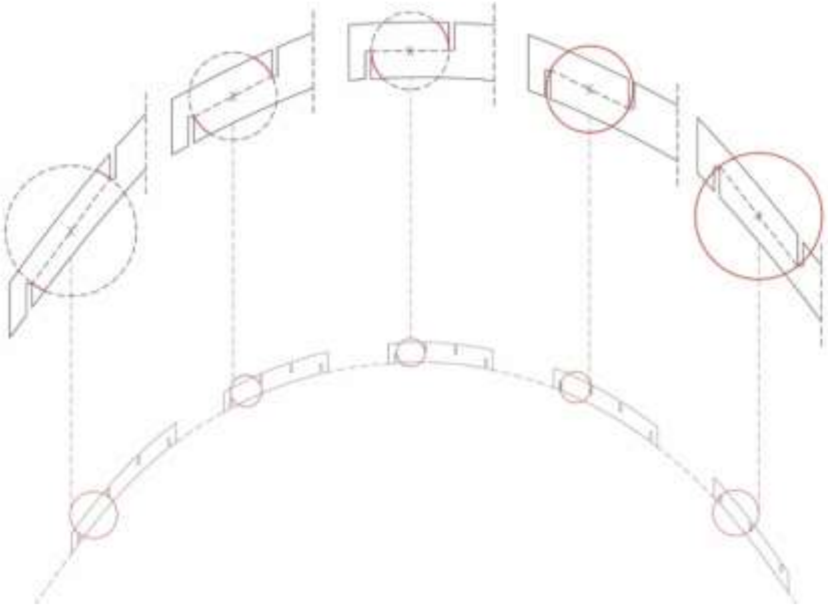


Figure 12: Typical section of a double-curved surface.

The circumference used to shape the element is, in some cases, tangent to the two joints, while in other cases it is secant to them. [Figure 12]. The angle formed between the radius of the circumference and the axis perpendicular to the support plane is a key parameter in defining the algorithm, as the geometric construction of the circumference depends on it. It can be observed that the validity of the method tested so far is efficient for angles ranging from 0° to 90°. As the angle increases beyond this range, the circumference begins to become secant. [Figure 13]

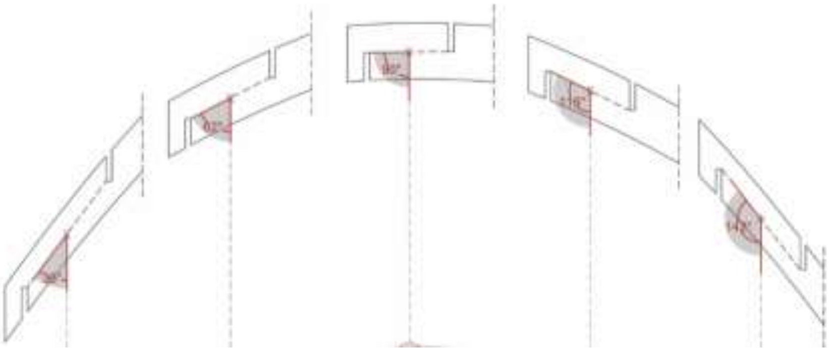


Figure 13: The angles between the radius of the circumference and the axis perpendicular to the support plane.

By considering the angle as a parameter, we can control and adjust the cuts through the Grasshopper algorithm, which is capable of automatically managing various cutting conditions depending on the input parameter (the list of angles). The condition where the angles vary within the range of 90° to 110°

corresponds to the following shaping configuration, achieved through the geometric construction of two circumferences.

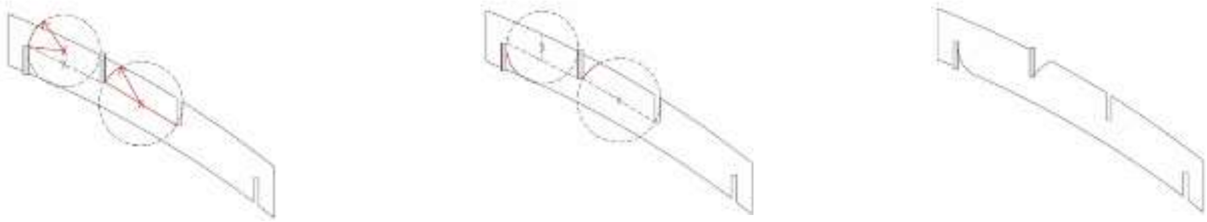


Figure 14: Shaping process for the condition where angles range between 90° and 110°.

The condition where the angles vary from 110° onwards considers the following shaping configuration, based on the geometric construction of a single circumference. In this case, the diameter is no longer defined by the axis between the two internal vertices of the joint but rather by the external vertices. [Figure 15]

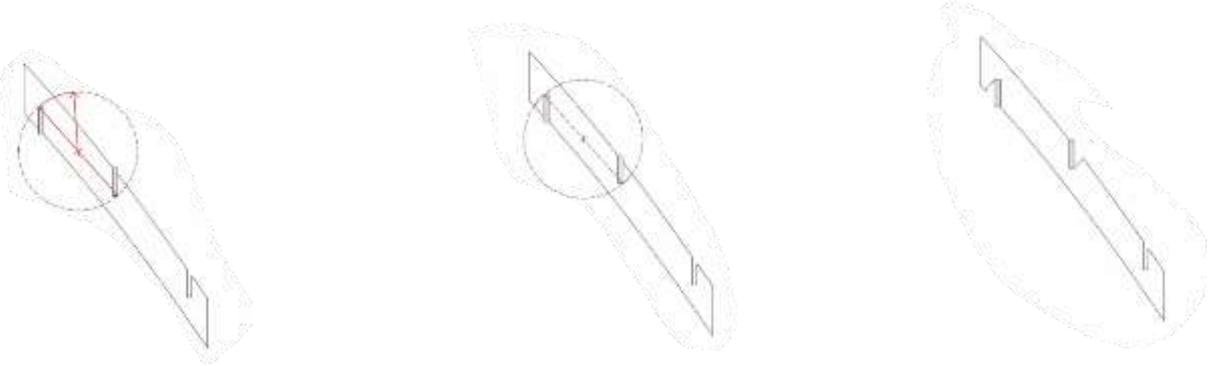


Figure 15: Shaping process for the condition where angles range between 110° and onwards.

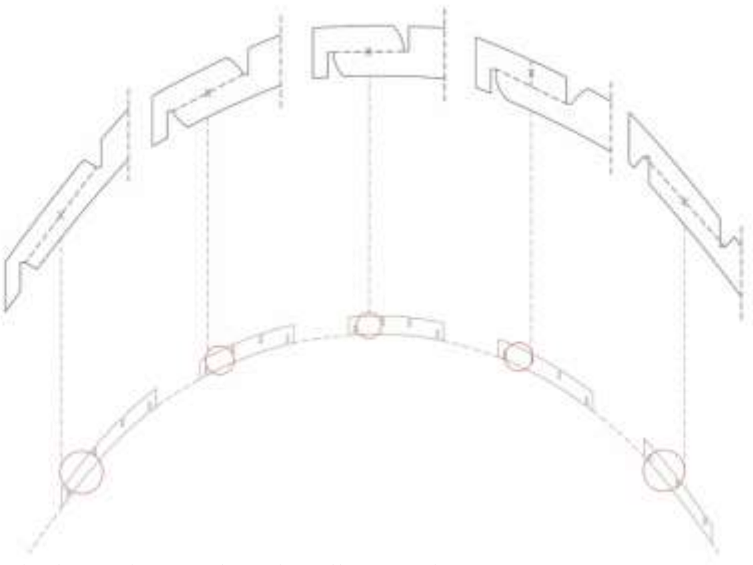


Figure 16 : All elements in the section are shaped to allow rotation.

3.3. Production, Labeling_e_Nesting

The system's realization phase was approached with particular attention to production efficiency and sustainability. Marine-grade Okumé plywood was employed, selected for its technical properties: lightness, moisture resistance, and ease of fabrication. The modularity of the elements allowed for effective panel optimization through automatic nesting techniques. Using a labeling system, each element was uniquely identified based on its position and assembly sequence. This coding [Figura 17] facilitated site organization and significantly reduced the margin of error during assembly. The transition from digital models to machine files followed the file-to-factory workflow, enabling the direct production of components via CNC and three-axis laser cutters. Assembly was carried out entirely dry, without the use of adhesives or permanent mechanical fasteners, thanks to the precision of the interlocking joints. A 1:10 scale model was fabricated to test the entire process, from design to production. The outcome confirmed the technical feasibility of the system, highlighting its structural robustness, ease of assembly, and the regularity of the generated geometry. This approach demonstrates how computational design can serve not only as a formal tool but also as a means to innovate construction processes in a practical and sustainable manner.

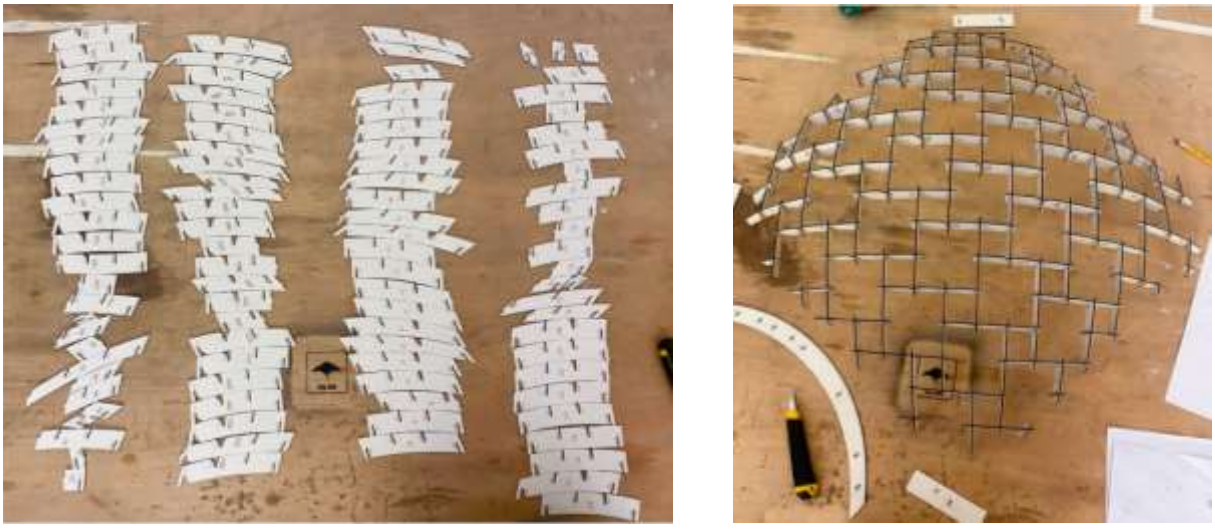


Figure 17: Labeling and assembly.

Figure 18: Assembly of the model completed with the addition of edge beams.

4. Conclusions

The research demonstrated the potential of the Two-Way Reciprocal system, an innovative proposal that integrates two distinct construction systems—the reciprocal frame and the waffle system—to generate highly performant three-dimensional configurations. The analysis of geometric patterns, combined with the use of computational tools and advanced manufacturing technologies, allowed for the exploration of new possibilities in the design and construction of architectural structures. However, certain aspects warrant further investigation. In particular, a deeper study of the system's limitations concerning curvature radius and material capabilities could provide valuable insights to further enhance the system's performance and adaptability. Additionally, full-scale (1:1) prototyping accompanied by a comprehensive structural testing campaign is necessary to verify the actual behavior of the half-lap joints and to explore panelization systems within the plane capable of adding stiffness to the overall structure. In conclusion, the reciprocal arrangement of the construction elements offers a potential solution to overcome the fundamental challenge of two-way joist structures realized with half-lap joints. These are typically composed of two orthogonal grids: one acting as the load-bearing system and the other as the supported system, depending on the orientation of the joint. The use of reciprocity, enabled by the novel shaping techniques proposed in this study, imparts load-bearing capacity to all the elements involved, thereby potentially optimizing the structural performance of the system.

References

[1] Pugnale, A., Sassone, M., *"Structural Reciprocity: Critical Overview and Promising Rese arch/Design Issues"*. Nexus Network Journal, vol.16, pp.9-35. 2014.

[2] Popovic Larsen, O., "*Reciprocal Frame Architecture"*. Elsevier. 2008.

[3] Popovic Larsen, O., "*Reciprocal frame (RF) structures: Real and ex-ploratory".* Nexus Network Journal, vol.16, pp.119–134. 2014.

[4] De Rio-Calleja, B., Grau Enguix, J., Gracia-Santos, A., "*Architectural Systemic Approach: The Serpentine Gallery 2005, a Reciprocal Frame Case Study"*. Buildings, vol.12, pp.1-34. 2022.

[5] Arianna Palumbo; Daniele Lancia; Sergio Pone, "*Digital Tool for Reciprocal Frame"* in Carlos Lázaro, Kai-Uwe Bletzinger and Eugenio Oñate, "*Form and force"*, International Centre for Numerical Methods in Engineering (CIMNE), Barcellona (Es). 2019.

[6] T. Leslie, *"Laborious and Difficult:" The Evolution of Pier Luigi Nervi's Hangar Roofs, 1935-1941.* 2018.

[7] Kuma, K., "*Tao"*. Kengo Kuma & Associates. https://kkaa.co.jp/en/project/tao/. 2018.

[8] Lancia, D., "*Sul Computational Design"*. Op.cit, vol.179, pp.11-23. 2024.