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Metamorphosis: static and kinematic free form reciprocal structure

Dario PARIGI

Associate Professor, Department of Civil Engineering, Aalborg University
Sofiendalsvej 11, Room 11.139, 9200 Aalborg SV, Denmark
dp@civil.aau.dk

Abstract

The paper presents the static and kinematic free form reciprocal structure "Metamorphosis" submitted for the Expo contest at IASS 2015, Amsterdam. The design of the pavilion relied on the use of the geometric form finding tools Reciprocalizer, a form-finding digital design tool that embeds the constructional logic of reciprocal structures within the Grasshopper parametric design environment, and the KRS algorithm, a software for the design of free form kinetic reciprocal structure, both developed by the author, and coupled with structural form finding processes.

The pavilion incorporates novel digital processes from design to fabrication for geometric and structural form finding. The newest releases of the Reciprocalizer software enable to handle new levels of complexity and precision which affect the design process itself, as the final shape is, rather than imposed, the result of continuous negotiations between a variety of geometric parameters, structural optimization and intended spatial effects.
The fabrication of the pavilion required the development of a custom developed digital fabrication machine, the Reciprocalizer robot, which marks and drills the bars at the joints position at precise angle and distances. Furthermore it required the development of a joint that enables handling the complexity of the free form shape and the varying bars shape with a limited set of adaptable custom developed laser-cut pieces.

1. Introduction

Reciprocal structures have been studied and used since the antiquity on the basis of different needs and purposes. The work of Leonardo Da Vinci on reciprocal structures witnesses the potential of application to a wide range of loadbearing structures as slabs, domes and bridges.

Despite their apparent simplicity, the geometry of reciprocal structures is extremely difficult to design, because each element position depends on each and every element in the configuration. For this reason their use in practice has been so far somewhat limited, and confined to simple, regular geometry, regardless of the advantages they offer in construction and detailing.

The research project carried by the author at the Department of Civil Engineering at Aalborg University aims at expanding the design scope of reciprocal structures enabling the possibility to design and control complex geometries while maintaining the original philosophy of reciprocal structures based on the use of standardized elements and simple jointing techniques.

The research constitutes an innovative approach to the topic of rationalization and automation of construction with the essential role played by custom developed advanced computational design tools. Such tools allows shifting complexity from manufacturing to design, enabling the possibility to generate potentially infinite variety of complex three-dimensional structures employing standardized wood components.

The pavilion "Metamorphosis" submitted for the Expo contest at IASS 2015, Amsterdam, is inspired by the woodcut print "Metamorphosis II" by the Dutch artist M.C. Escher, which features a continuous morphing of one image after the other through slow, continuous alterations of patterns. The two panels in Figure 1 should be read as a continuous uninterrupted strip of 19.2 by 389.5 centimetres. Besides being an homage to the host country of IASS 2015, Metamorphosis II was an inspiration for the ways Escher manages to smoothly link one pattern to the other, combining in this process intuition, creativity and understanding of underlying geometrical rules.

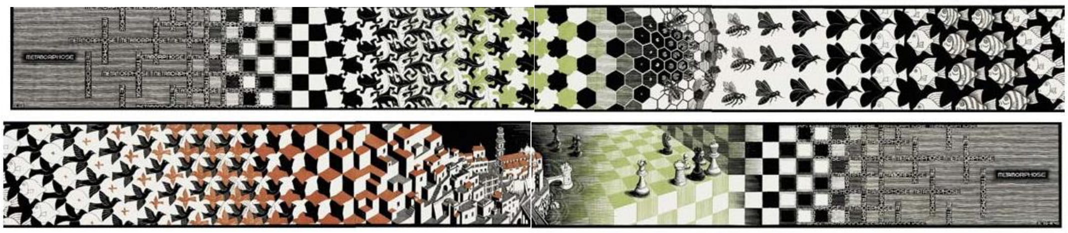

Figure 1 - Metamorphosis II by M.C. Escher [1]

The pavilion Metamorphosis presents the idea of smooth, continuous transitions is applied to several structural patterns, static and kinematic, which all have in common the principle of structural reciprocity.

The pavilion demonstrates the capabilities of the new release of the form finding tool Reciprocalizer, which can now handle and concatenate any reciprocal pattern with no restrictions on the number of bars and geometry. The improved speed of the software allows engaging into real-time iterative processes, which enable an understanding on the effect of the geometric parameters on the three dimensional geometry of each reciprocal pattern. Furthermore, it integrates a structural optimization algorithm to assign the elements thicknesses according to internal structural stresses.

The pavilion applies a novel technology for fabrication, with the use of a digital fabrication machine, the Reciprocalizer Robot, and a custom developed joint which allows to handle the geometric complexity with a limited set of adaptable, laser-cut components.

At a more general level, the pavilion aim is to demonstrate the role of computational tools in expanding the possibilities for creative work in architectural design.

Performance Aided/Assisted Design (PAD) indicates an evolving paradigm in architectural and structural design that aims at including rather than excluding the complexity implicit in the design process, and that uses complexity as source of inspiration for expanding the design space and triggering the development of adapted, unique, design solutions.

2. The Reciprocalizer software

Because of their non-hierarchical nature, the geometry of reciprocal assemblies cannot be described conveniently with the available CAD or associative parametric modelling tools. The geometry of a network of reciprocally connected elements is a characteristic that emerges, bottom-up, from the complex interaction between all the elements' shape, topology and position, and requires numerical solution of the elements' geometric compatibility [2]. The Reciprocalizer developed by the author is a Grasshopper plugin developed to solve in real-time the geometry of reciprocal structures on the basis of the parameters necessary to describe the geometry of reciprocally connected elements.

The plugin has received for the development of the pavilion two major updates:

1) the direct control of the clockwise/anticlockwise direction of the reciprocal joint, while in the previous releases this was enabled only indirectly through the manipulation of the fundamental geometric parameters (eccentricity, engagement length and top/bottom position)

2) Each joint can have an unlimited number of converging bars, while in the previous releases the maximum number of bars was 3, limiting the design to hexagonal / voronoi patterns.

3. The KRS software for Grasshopper

Kinetic Reciprocal System (KRS) are a new kinetic system based on the principle of reciprocity with internal pin-slot constraints developed by the author. The KRS algorithms was developed for the generation of pin-slot paths starting from the local displacements of element, so that it could handle large sets of rigid bodies interconnected reciprocally with multiple pin-slot constraint.

As in the design of kinetic structures, in particular when complex three dimensional and non-regular configurations are involved, the functionality is frequently related to a global displacement capability of the assembly rather than the local displacements of elements, the KRS algorithm was included into a larger optimization procedure to translate global displacement capability into local displacements of elements. The KRS algorithm can be described as a generalized procedure for the generation of free-form kinetic structures [3].
For the design of the pavilion the algorithm has been ported from Matlab to Grasshopper. While the algorithm retains the same features, the benefits of embedding it into Grasshopper are

- The increased usability thanks to the user-friendly interface

- The integration in the same environment of the Reciprocalizer

In particular the KRS algorithm now allows an integrated design process with the free form reciprocal structures, enabling the coupling of the static and kinematic pattern.

4. The digital design process

The features of the newest release of the Reciprocalizer and KRS enable new levels of complexity, which affects the design process itself. The capabilities of the two software allow to generate and to concatenate patterns while solving the overall geometric compatibility, in new and surprising ways. The resulting geometry is the, often unpredictable, result of the multiple, complex interactions of the elements at the joint level. The final shape is, rather than imposed, the result of continuous negotiations between a variety of geometric parameters, structural performance and intended spatial effects. The designer becomes part of an active process where form is gradually discovered, as a result of the interplay between starting mesh, boundary conditions, geometric parameters and structural analysis, which can lead to the discovery of beautiful, unexpected shapes.

5. The geometric form finding

At first a sketch has been drawn to detect intuitively possible ways of concatenating patterns. In particular a specific attention was placed in the way a quadrangular pattern can morph into a hexagonal pattern, and in the way a static pattern can turn into a bending active pattern and into a kinetic pattern (Figure 1).

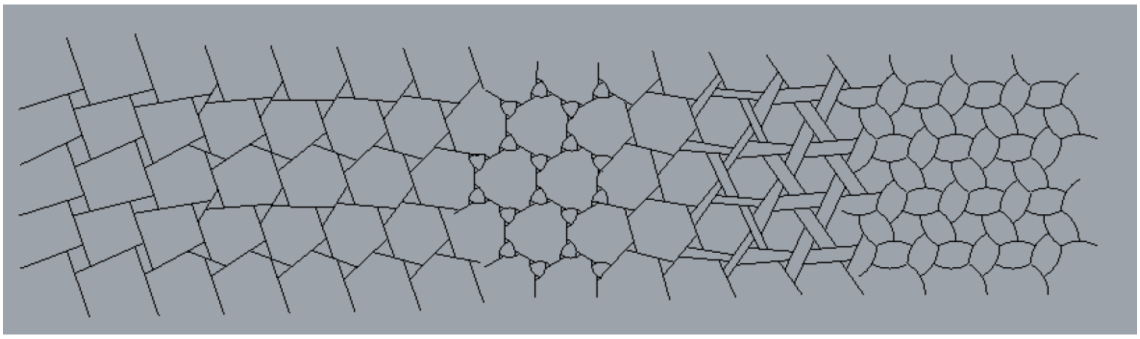

Figure 2. sketch of the morphing between: quadrangular patter, hexagonal patterm bending active pattern, hexagonal pattern II, kinetic pattern

Afterwards an in depth analysis has been carried to understand the rules and the geometric parameters values for a large set of different reciprocal patterns: Such an analysis allowed to identify analogies and similarities between patterns beyond visual appearance. This enabled to develop the rules to couple patterns one to another and establish smooth transition between them by controlling seamless variations of the design parameters. The next step consists in the control of the third dimension of the pavilion. Because of the intrinsic three-dimensionality of reciprocal structures, the third dimension is determined by the values of the geometric parameters eccentricity, engagement length, top/bottom position and clockwise/anti-clockwise direction of each unit.

5. The final design

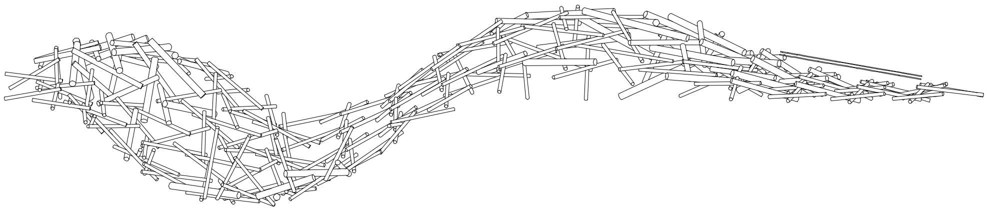

Figure 3. view front

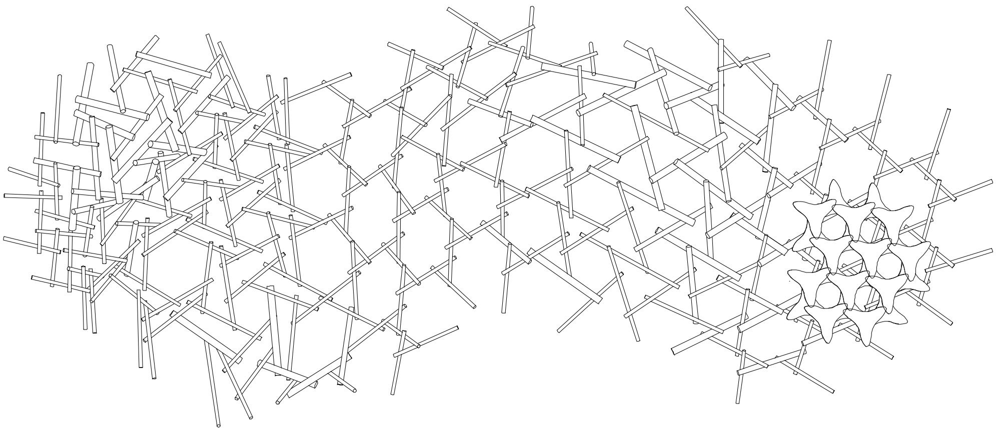

Figure 4. view top

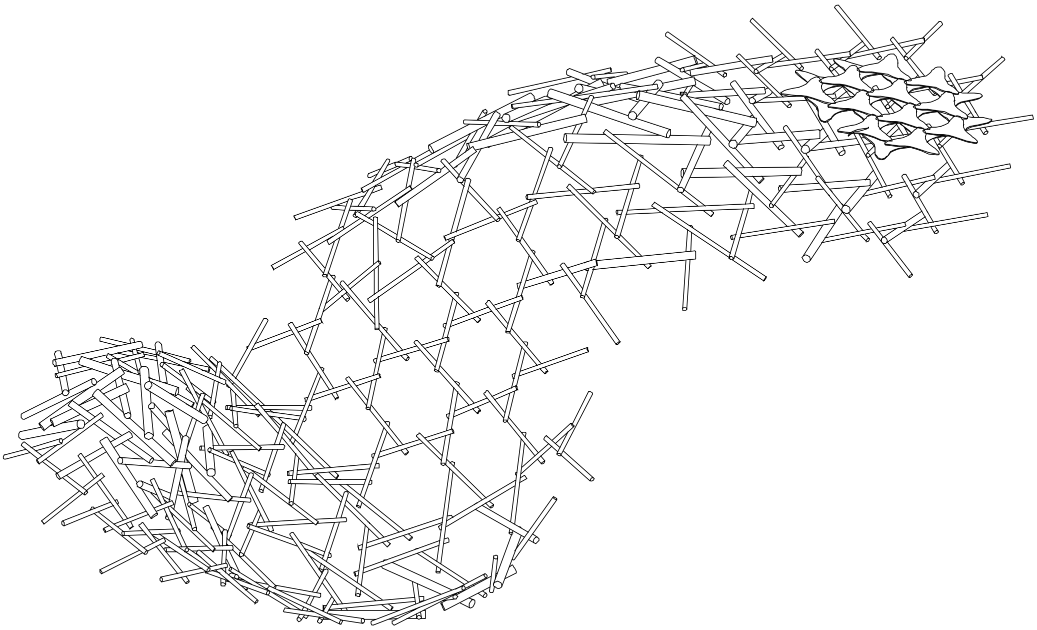

Figure 5. isometric view

The final design consists of a seamless integration of a free-form reciprocal structure and a kinetic reciprocal structure (Figure 3,4,5).

6. Structural optimization of patterns

The 3d model of the pavilion has been loaded with self weight increased with a factor of 1.5 and a series of 9 points loads of 0.02 kN where the kinetic panels are supported. Karamba plugin for Rhinoceros was used for a preliminary FEM analysis to detect the weakest area and, with quick feedback loops, increase the density of the patterns where the maximum dispacement took place. The end result of this first optimization phase for the maximum displacement is 270 mm.

7. Structural optimization of bars size

The next phase consisted in optimizing the distribution of the timber member size - 22mmØ, 33mmØ and 43mmØ according to the utilization ratio and the availability of material for each dimension. New dimensions are updated and the elements with the highest utilization ratio are assigned with the member size of 33 mm Ø and 43mm Ø, respectively 27 elements for a total of 6.7 meters, and 17 elements for a total of 4.2 meters. After the dimension update the Reciprocalizer is run again to restore the geometric compatibility of the elements whose dimension, and therefore eccentricity has changed, and the FEM analysis is also run again.
The end result after this second optimization phase for the maximum displacement is 137 mm.

8. Detailed structural analysis in Robot

The following step was to calculate the structure in Autodesk Robot, for a detailed FEM structural analysis. The timber members were verified according to Eurocode 5; the utilization ratio for all members ranges from 0.1 to 0.7.

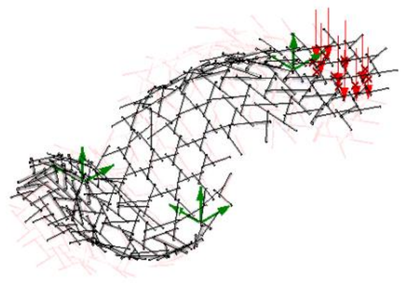

Figure 6 : Deformation diagram in Karamba 3d

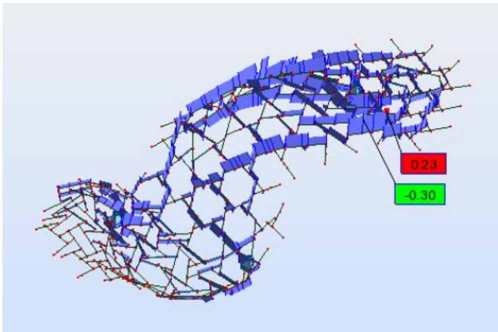

Figure 7: *N diagram in Robot*

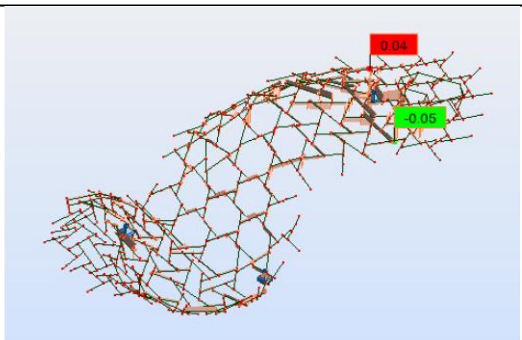

Figure 8: *Mx diagram*

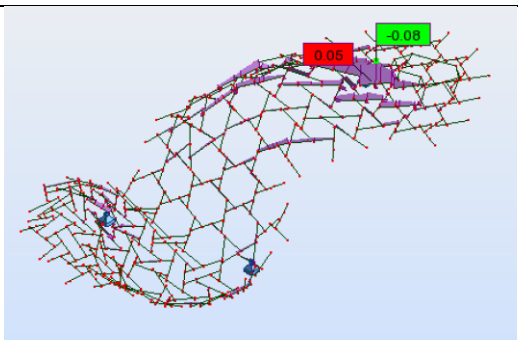

Figure 9: *My diagram*

9. The fabrication data

The rules for participating to the IASS Expo 2015 states that the pavilion must weight no more than 120 Kg and it should fit in standard boxes with the maximum dimension not exceeding 1 m. Metamorphosis is realized with 248 timber bars ranging from 17cm to 77cm, in 3 different sizes (Ø22mm, Ø33mm, Ø43mm), assembled with 647 joints each made of 3 laser cut connecting caps fitted to the changing dimension of the connecting bars.

timber bars (max lenght 77 cm)				
volume [m^3]	radius [m]	length [m]	spec weight	weight
0.029650351	0.011	78	510	15.12167925
0.012256429	0.0165	14.33	510	6.250778758
0.021768496	0.0215	14.99	510	11.10193299
Acrylic joints				
volume [m^3]	radius [m]	length [m]	spec weight	weight
0.007068583	0.015	10	1400	9.896016859
bolts, nuts and washers				
number	weight [Kg]			weight
647	0.01			6.47
PC panels				
area [m^2]	thickness [m]	volume [m^3]	spec weight	weight
0.67	0.002	0.00134	1400	1.876
			total weight	50.71640785

Table 1. The estimated weight of the pavilion,

10. The Reciprocalizer Robot and digital fabrication process

When dealing with non-regular reciprocal geometries, each bar meets the adjacent one in a different position and in a different angle. Because the global geometry is the result of the local interaction between bars, precision at the joint level is crucial in order to obtain the goal geometry and to maintain the geometric compatibility during the construction process. A fabrication machine has been designed by the author in order to transfer the necessary information from the digital model to the wooden bars. The fabrication machine retrieve the data needed for the fabrication from a table of values outputted from the Reciprocalizer software. The table contain, for the element b_i, the position of the contact point P_{ij} with each of the b_j connecting elements. Point P_{ij} is located along element bi surface and its position can be described with two values: its distance from one reference end D_{ij}, and the angle α_{ij} that it creates with a reference line arbitrarily set on the side element, measured from the element axes and in a perpendicular plane. [4]

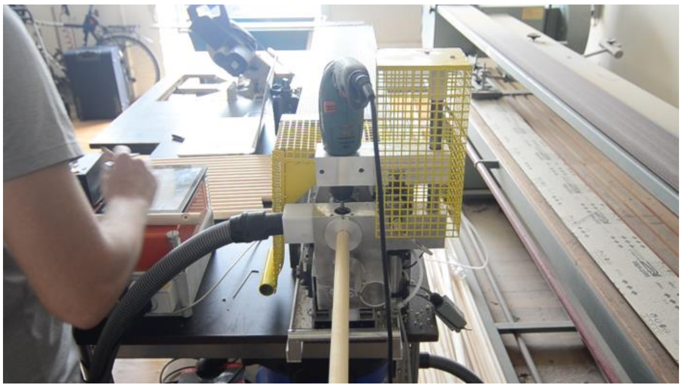

Figure 10: the Reciprocalizer Robot in action

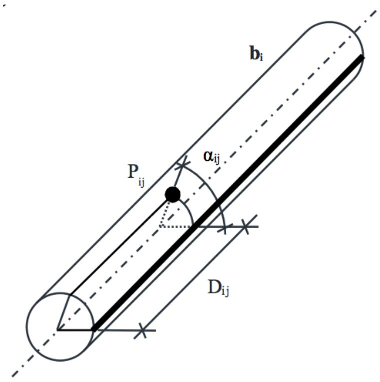

Figure 11: the measure of distance and angle for each bar

Conclusions

The design of the pavilion relied on the use of the geometric form finding tools Reciprocalizer, and the use of a custom developed digital fabrication machine, the Reciprocalizer robot. The pavilion demonstrates the expansion of the design space in reciprocal structures, both static and kinematic, brought by the custom developed software and hardware instruments. The newest releases of the two software enable new levels of complexity which affect the design process itself, as the final shape is, rather than imposed, the result of continuous negotiations between a variety of geometric parameters, structural performance and intended spatial effects.

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