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Flexible Shaping Architectural Forms Using Reciprocal Structures

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Abstract

Systems based on reciprocity of structural components allows to combine them into various configurations, with the use of the same principle of combining. The paper concerns applications of reciprocal structures in twisted multistory buildings and modular shell roofs. The essence of first application focuses in support of floor slabs on systems of reciprocal beams, rotated in the whole to one another, due to various rotations of individual beams relative to vertical columns. The second application refers to shell roofs, constructed with the use of structural components of two types: beams and arches. The paper presents rules of shaping architectural forms belonging to both mentioned categories, as well as computer programs developed in the Grasshopper language, which gives architects the useful tool for flexible design and for finding the relations between dimensions of particular components and architectural form of the whole object.

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*Keywords:*reciprocal structures; twisted buildings; shell roofs, Rhinoceros; Grasshopper

1. Introduction

Flexibility, understood as the ability to use the same components and manners of construction in various objects, is an important issue in architectural design. The most conventional approach to this problem is the use of modular coordination. It is a useful tool in the design of typical objects, but difficult to apply in design of free architectural forms. Free-form design, which a natural feature is flexibility, has been developed in recent years with advances in computer software development. Computer technology allows to build 3D model of an architectural object; which

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dimensions may be easy changed even in the real time. The availability of model enables the designer to follow all detailed dimensions, which are changeable in the result of correction of main design parameters, as well as to analyze distribution of internal forces in the structural system. Optimal determination of the relationship between all components forming the architectural object is the key to efficient flexible design.

2. Architectural and structural forms

According to the widely accepted view, an architectural work is characterized by a function, a structure and a form. The form, called usually an architectural form, is defined as the place of contact between mass and space or an external appearance limited to the outline [1]. It references to an exterior of the architectural work and may be the subject of aesthetic evaluation. The function and the structure are relative to the interior. The function means an organization of internal space in a manner proper for specific needs of a man. Due to the fact that those needs may change over time, objects whose interiors are adaptable, are especially functional. The structure is a set of those elements of architectural object, which transfer loads to the ground. Rational structure is characterized by as much as possible rigidity, at as low as possible weight.

Architectural work should be designed in such a way that neither of three qualities: a form, a function and a structure get an advantage over others [8]. A symbiosis between form and a structure into so-called a structural form, which is characterized by simplicity acceptable both from an aesthetic and static points of view, is a proper step to achieve this goal. The metric deformation of the structure, at strong relationship between it and the architectural form, should result only to metric deformation of the architectural form or inversely, and never cannot change the affine properties. This feature is called structural stability [6].

3. The essence of reciprocity in structural context

The topic of reciprocal structures is known from the Middle Ages and it is experiencing a renaissance in recent years. The authors understand the reciprocal structure as the structure composed of elements joined together in such a way that each element is supported and supports all other elements of the structure [5]. The important features are that elements should be connected in one point with only one other element or the external support and that these points can be arranged freely along the spans of the elements.

The qualification of structural system as reciprocal or not, depends on mentioned features, not on the way of making connections between components. Contemporary studies focus on structures realized without connectors, what limits the range of considerations to only spatial layouts. The authors refer their work to such arrangements of components, which evidently require additional fasteners, what bring them closer to original ideas related to applications in flat ceilings.

4. Flexible design of stable structural forms with the use of reciprocal structures

4.1. Assumptions

The independent dimensions of a simple rotationally-symmetric reciprocal system, regardless of the type, are relative to lengths of elements, the arrangement of points of connection of elements and the arrangement of outer supports (Fig.1). On the base of them, the multi-reciprocal systems may be constructed, with that proviso that not all items must be supported on the outer supports.

4.2. Twisted forms of multistory buildings

Twisted buildings are the buildings, whose next floors are built up by repeating a ground floor plan with rotation around a vertical axis [7]. From the point of view of ensuring maximum functionality of the building, the ideal solution is to transfer the loads from the ceiling to the ground only through the vertical columns. In such a case, the arrangement of the columns with respect to the individual floors is not identical. The use of systems of reciprocal beams as structures that mediate in the transfer of loads from the slab floors to the columns is reasonable solution found for described situation [4].

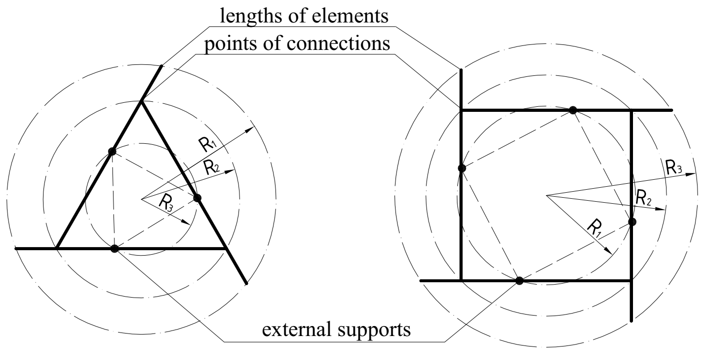

Fig. 1. Independent dimensions defining the simple reciprocal system.

The idea is based on abilities to move the external support and the joint point along the length of component of reciprocal system. Reversal of this concept consists in keeping a fixed position of the columns and in a change of the lengths of the beams on both sides of the support points. The initial result of the concept is shown in Fig.2. Fig.3 presents the extension of the concept into systems consisting of beams one- and double-cantilevered. The proposed structural system can be adapted to building with floors in a shape of any regular polygon and allows to accept arbitrary dimensions and rotation angles for each floor. Due to the fusion of a structure and a form defined by edges of the floor slabs into the stable structural form, the formation of twisted buildings, flexible in the meaning mentioned earlier, is easy available. There is possible to shape in similar way twisted buildings based on multi-reciprocal systems, supported on the greater number of columns.

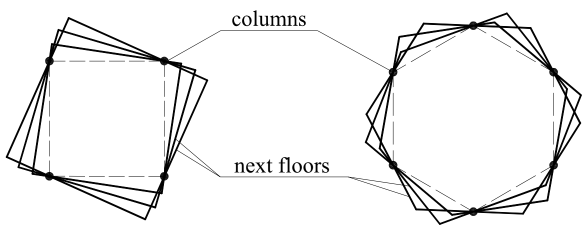

Fig. 2. Supporting next floors of twisted buildings on columns.

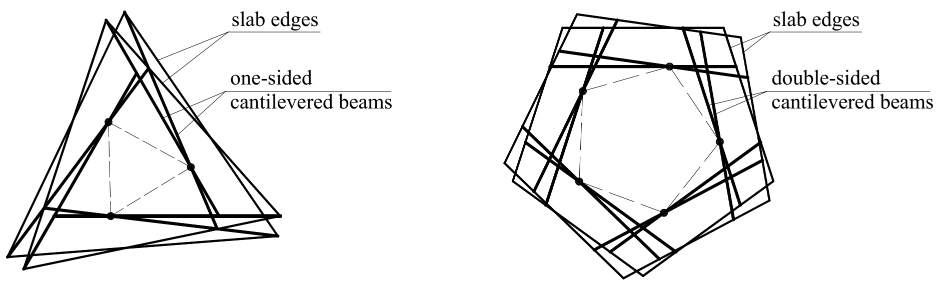

Fig. 3. Supporting floor slabs with the use of systems of cantilevered beams.

4.3. Modular shell roofs

The shell roofs considered in the paper are designed on the base of multi-reciprocal structural systems thanks to applying, apart from straight, also arched structural elements, which are responsible for curvature of shell segments [3]. Exemplary arrangements of components are shown in Fig.4. The idea is especially suitable for roofs of lengths considerably greater than widths and side edge lines out-of-parallel to directions of structural elements, because in such a case shapes of individual segments are especially interesting and their diversity is significant in comparison with the size of the roof (Fig.5). The roofs are characterized by the stable structural forms naturally, because exactly the same components are shaping the structural systems and the architectural forms.

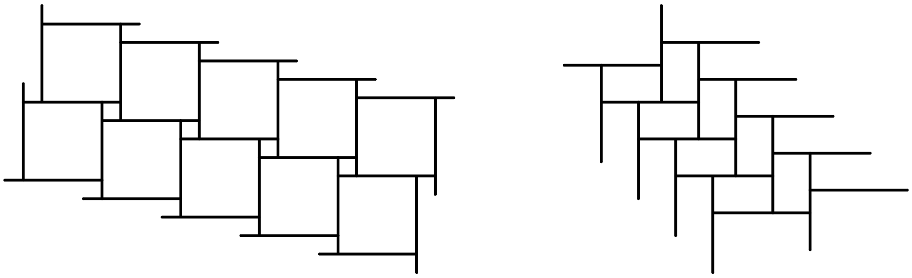

Fig. 4. Schemes of multi-reciprocal systems being bases of modular shell roofs.

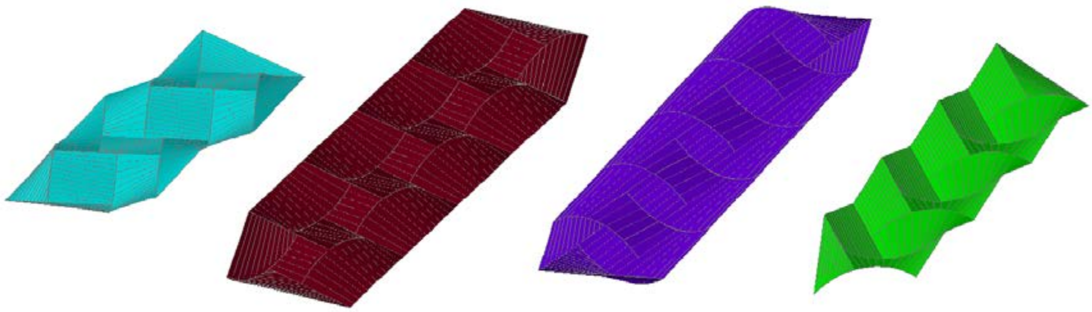

Fig. 5. Models of modular shell roofs based on reciprocal structures.

5. Parametric design aided with application of Grasshopper language

The effective tool for flexible shaping of architectural forms with the use of reciprocal structures, may be developed on the base of present-day software for parametric design of 3D objects. The authors have used the Grasshopper program, which is visual algorithmic programming language running in Rhinoceros environment. All spatial forms, which have been generated, are based on definitions and settings developed in the Grasshopper language, independently by the authors. Due to the lack of possibility to use of constraints implemented in the software, the important issue was determination of proper limits for individual parameters, in order to ensure compliance of the geometric model with structural sense of the designed forms.

The Grasshopper definition of twisted building (Fig. 6) consists of three main parts. The first one is a block of parameters, which can be fully steered by sliders, without input of any random or external data. The parameters are divided into groups, the first of which define the shape of the basic floor, and so the number of floor sides, the length and angle of rotation of the beam, as well as the radius of the quasi-core, appointed by columns. Next groups apply to transformation of data responsible for rotation of beams and high of floors represented by polygons. Those individual settings are merged into two stacks of data. The user chooses absolute height of each floor, but angles of rotations and lengths of beams through selecting values from the interval <0, 1>, which determine them relative to reference dimensions. Because the choose of extreme values causes in generation the solution, which is irrational in structural aspect and conflicting with reciprocity idea, practically the intervals of variability have been limited to <0,1; 0,9>.

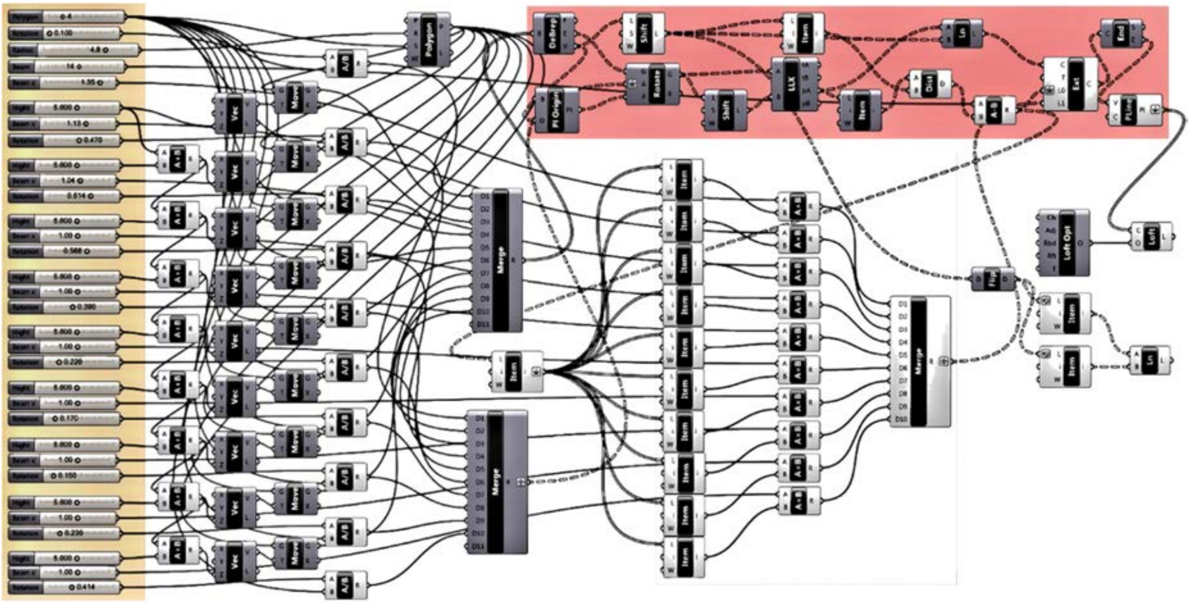

Fig. 6. The Grasshopper definition of twisted building.

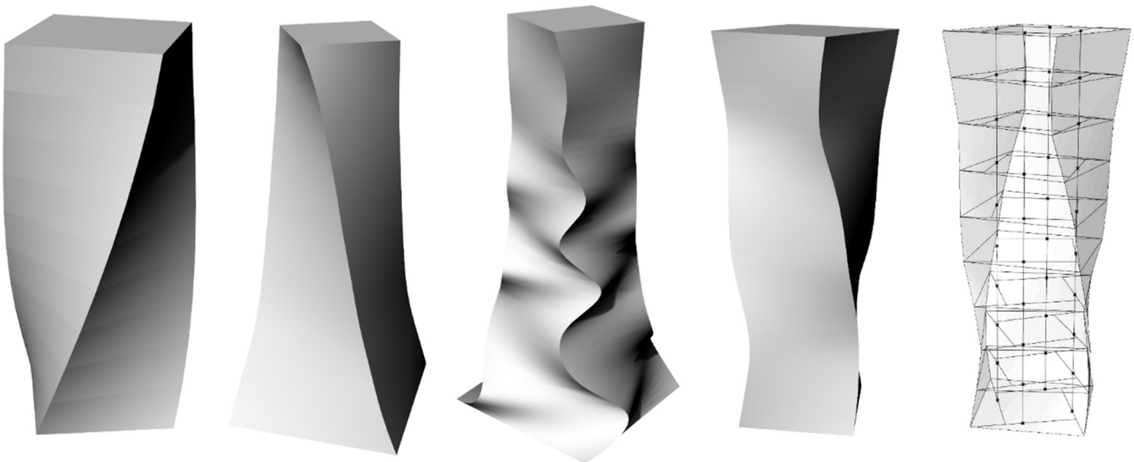

Fig. 7. Exemplary models of twisted buildings generated with the use of Grasshopper application.

The second - top part of definition contains a main algorithm, which uses two lists, one of them contains transformed geometry of polygons for each floor, another is a list of scalars steering a rotation. Data responsible for object is converted to a list of separated parts like segments and vertexes which takes part in a function of main module with a list of rotation factors which creates a stack of flat geometry of a structure. Near the end of restructuring the data is transferred outside the module, into third part of separated items individually changed by sliders responsible for a length factors of beams on every floor. The merged list comes back into main module and is being recalculated giving a results as a set of beams which ends defines the envelope surfaces.

The Fig. 7 presents exemplary models of twisted buildings, generated with the use of developed program, all based on square floors. The less complicated program for similar application, presented in literature [2] doesn't include the aspect of integration between the form and the structure.

The second program, which has been prepared, refers to modular shell roofs formed from segments of ruled surfaces, whose reciprocal structures are created from horizontal beams and vertical oriented arches. The Grasshopper definition has been written on the similar way, except that values of parameters are determined once time, while repetitive duplications of structural modules are taking into account in the definition, by creating network of connections (Fig. 8).

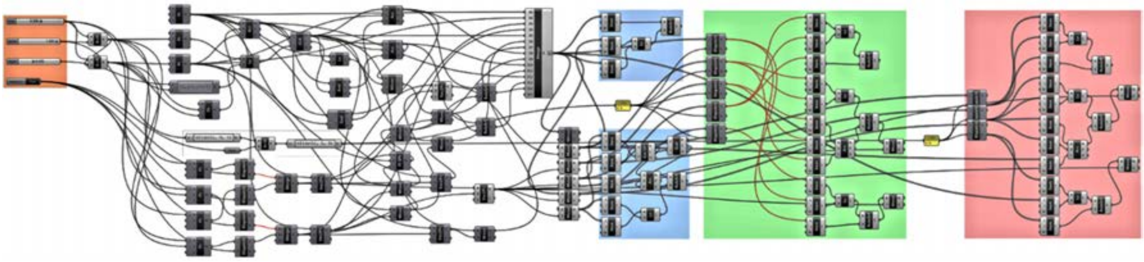

Fig. 8. The Grasshopper definition of modular shell roof.

6. Conclusion

The article presents the concept and functional tool of free design of architectural form integrated with the structural system, for selected categories of buildings: multistory buildings and shell roofs. The proposals offer the architect a large freedom in designing the shape of the object, by releasing at the same time with the necessity of current reflect on the structural rationality. The development of the presented software in direction to implementation of static-strength analysis module, planned for the future, should give a comprehensive tool for integrated shaping of forms, which would be both visually impressive and structurally efficient.

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