DESIGN GENERATIVO DI MEGA-STRUTTURE: DEFINIZIONE DI UNA SHAPE GRAMMAR STRUTTURALE

GENERATIVE DESIGN OF MEGA-STRUCTURES: A STRUCTURAL GRAMMAR APPROACH

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ABSTRACT

The combination of structural optimization and generative design is nowadays an important tool in the design process and one of the most used methods for sustainable and efficient design. Among various generative methods, an interesting approach deals with shape grammars, defined by parameters and intertwined rules through which the algorithm generates a great number of geometric solutions, potentially unexpected in the phase of algorithm writing. Shape grammar and structural optimization approaches allow to obtain structural grammars, which merge geometrical/architectural and structural/constructive aspects. In the present paper, structural grammars are applied for the generative design of triangulated megastructures, such as diagrid tall buildings and gridshells canopies, to investigate different structural patterns that are compared in terms of structural weight and structural performances.

SOMMARIO

La combinazione di approcci di ottimizzazione strutturale e design generativo è oggi uno strumento importante nel processo di ottimizzazione e uno dei metodi più utilizzati per una progettazione sostenibile ed efficiente. Tra i vari metodi generativi, un approccio interessante è relativo alla grammatica della forma, definita da parametri e regole intrecciate attraverso cui l'algoritmo genera un gran numero di soluzioni geometriche, potenzialmente inaspettate in fase di scrittura dell'algoritmo. Combinando la grammatica della forma con approcci di ottimizzazione strutturale, è possibile ottenere una grammatica strutturale, che fonde aspetti di tipo geometrico/architettonico e strutturale/costruttivo. Nel presente lavoro, le grammatiche strutturali vengono applicate per la progettazione generativa di megastrutture triangolarizzate, come edifici alti di tipo diagrid e gridshell, al fine di generare diversi pattern strutturali che vengono poi confrontati in termini di peso strutturale e prestazioni strutturali.

1 INTRODUCTION

The sustainability and efficiency in the architecture, engineering, and construction industry (AEC) have received increasing concern in the past few decades. With the advent and development of computational tools and information technologies, structural optimization has become an important tool in the design process and one of the most commonly used methods for the sustainable and efficient design. The objective of structural optimization is often to minimize the weight, the compliance, or in a more complex way the cost, for a given amount of material ensuring strength and stiffness design requirements. To guarantee an adequate exploration of the various design solutions, structural optimization methods should be combined with a generative design, i.e. a strategy that employs algorithmic or ruled-based processes to generate multiple and complex solutions. Among these, an approach conceived many years ago [1], but re-evaluated in recent years [2] thanks to technological advancement, is the shape grammar. The shape grammar is defined by some parameters and intertwined rules with which the algorithm generates a great number of geometric solutions, potentially unexpected in the phase of algorithm writing. To compare the generated solutions on the basis of the structural performances, for each one, a structural model should be created, and the design of the structural members and analyses should be carried out under design loads. The choice of the optimal solutions is, instead, devoted to optimization algorithms, such as genetic ones. The combination of shape grammar, structural analysis and optimization algorithms gives life to the structural grammars. In the present paper, structural grammars are applied for the generative design of triangulated megastructures, such as diagrid tall buildings and gridshell canopies, to investigate different structural patterns. In these kinds of structures, the choice of the pattern involves both geometrical/architectural aspects and structural/constructive ones, since the pattern is properly defined by the disposition of structural elements that are arranged on sight. In the last two decades the diagrid emerged as the most efficient solution for tall buildings with tube configurations [3], [4]; it is constituted by triangulated pattern of the building façades composed by a uniform grid of diagonal members, that confers to the diagrid an inherent rigidity. The efficiency of the diagrid could be further improved by optimizing the topology of the triangulated pattern; indeed, by considering the analogy with a vertical cantilever beam under lateral load [5], [6], the structural pattern should be not uniform to accommodate the variation of bending and shear stiffness demands along elevation and base, with diagonals gradually steeper going from the top to the base of building, and from the inside out along the base. In this context, the proposed structural grammar aims to find the optimized pattern by changing the number and slope of diagonals both along elevation and base. Gridshells are widely used as canopies for long-span public buildings for their capacity to cover large span with low thickness, thanks to the inherent rigidity of a double-curvature shell. Different optimization approaches are proposed in literature, which consider as variable the topology [7] or the shape [8], and other that try to combine some of these with sizing optimization ones [9]. Nevertheless, the actual trend to design free-form gridshells enhances the importance of optimizing the structural pattern. As already mentioned, although the concept of shape grammar was born many years ago [1], only recently it has been re-evaluated and combined with structural optimization, introducing the structural grammar [10]. It may be therefore of interest to conceive and apply this innovative concept to support the design of structural systems that are spreading over the last 20 years, such as gridshell canopies and diagrid tall buildings. Further, the structural weight and performances of these two kinds of structures are strongly affected by their structural pattern, thus it could be of interest to propose a design strategy based on structural grammar able to generate an optimal structural pattern, also accommodating the different demands in term of stiffness and strength requirements, which change in function of the geometric characteristics of the structures (i.e. the curvature for gridshell and the slenderness for diagrid). Downstream of these considerations, the paper presents a structural grammar for gridshell and diagrid structures aiming to optimize the topology of the pattern by varying number, slope, and position of the structural elements. All the results are provided in terms of structural pattern, structural weight and stiffness/strength requirements, showing that the different structural needs are satisfied in function of the slenderness of the tall building and the rise-to-span ratio of the gridshell.

2 STRUCTURAL GRAMMARS FOR THE GENERATION OF OPTIMIZED PATTERNS

A structural grammar is here proposed for the design of both gridshell structures and diagrid tall buildings, by means of a topology optimization process. It is well known that an optimization process is defined by a fitness function, variables, and constraint conditions. In this study, the fitness function is the weight, since it gives a measure of the material consumption to satisfy a required performance level; the variables are the position of the nodes of the grishell/diagrid; the constraint conditions are imposed on the range of variation of the variables. The whole structural grammar is schematized in the flowchart of Fig. 1 that is divided into four groups: generation of geometry with rule-based shape grammar (group a); creation of the structural model (group b); structural analysis, cross-section sizing and output processing (group c); optimization with genetic algorithms, i.e. generation of Topology Optimization (TO) patterns (group d).

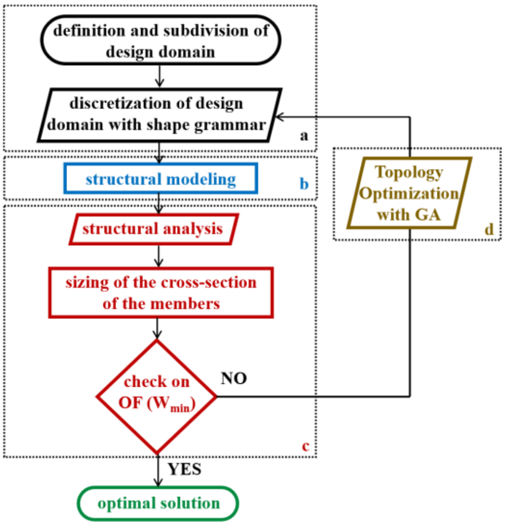

Fig. 1. Flowchart of the structural grammar

The shape grammar (group a of Fig. 1) consists of two types of rules: rules for the definition of the design domain (rules 1), and rules for the discretization of the design domain (from rules 2 onwards). Both types of rules differ for gridshells and diagrids, and they will be described in detail in section 3 and 4, respectively, together with the discussion of the obtained structural solutions. The sizing of the cross-sections is carried out, within the structural grammar, through an iterative optimization process that selects, for previously defined groups of structural elements, the smallest cross-section that guarantees to obtain a maximum Demand to Capacity Ratio DCR_{max} lower than 1 (i.e. the limit value), and a maximum displacement D_{max} lower that limit one D_{lim}, which value is different for gridshell and diagrid. More precisely, D_{max} rifers to the maximum vertical displacement for gridshell, while it refers to the top horizontal displacement for diagrid.

3 GRIDSHELLS

3.1 Design rules of the shape grammar and generation of optimized patterns

The rules for the generation of the optimized patterns for gridshell structures are graphically reported in Fig. 2.

In general, these rules allow the generation of different patterns by varying the positions of the nodes of the gridshell, which are therefore the variables of the optimization process. Rules 1 define the design domain, i.e. the shape of the gridshell, which is obtained by defining control points that pass through a NURBS (Non Uniform Rational Basis Splines) surface. In particular, rules 1.1 define the footprint in plan of the gridshell, i.e. a quadrangular shape with dimensions BxB; rules 1.2 define the whole design domain, by imposing the maximum height (H) of the gridshell from its base. Rules 2, 3, and 4 are devoted to the discretization of the design domain, i.e. to the generation of the gridshell patterns with distribution of the members. In particular, rules 2.1 select one eighth of the NURBS surface, i.e. the triangular zone in the normalized domain of local coordinates (x, y) provided in Fig. 2; rules 2.2 identify the discretization points $P_i(x_i, y_i)$ of the triangular zone, initially placed at a distance of 0.1 in both directions, with i = 1, …, n, and n the number of

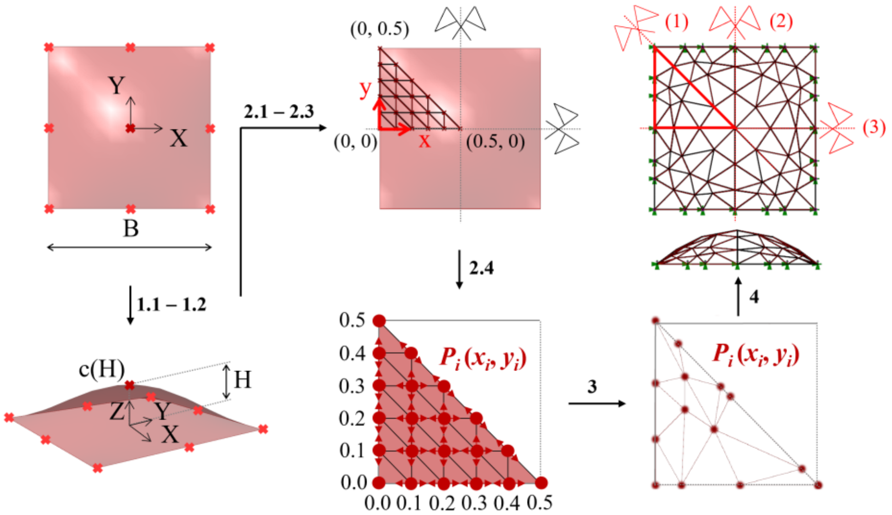

Fig. 2. Grid-shells: rules for the definition and discretization of the design domain

points; rules 2.3 create lines between points, thus defining the connectivity of the pattern; rules 2.4 define the range of movement of each point (± 0.1). The vertices of the triangle zone are fixed, while the other points can move, since their coordinates are defined by sliders that can assume different values within a certain range. The points of abscissa x = 0 can move only along the y direction, the points of ordinate y = 0 can move only along the x direction, the points placed on the hypotenuse of the triangle zone can move only along it, while the internal points can move in all directions. Hence, the coordinates (x_i, y_i) of the points P_i are the variables of the optimization problem. Rules 3 delete coincident or very close points to avoid nearby elements with very similar inclination, which affects the pattern constructability. Thanks to these rules, also the number of nodes and grid elements change during the geometry generation process. At the end, rules 4 mirror seven time the triangular unit to obtain the whole gridshell.

3.2 Structural solutions and performance assessment

The proposed structural grammar has been applied to gridhells characterized by a dimension of the base quadrangular plan B of 24 m, and three values of rise to span ratio H/B equal to 0, 0.21, 0.42, respectively; about structural performances, constraint conditions are imposed on strength requirements (DCR ≤ 1) and stiffness requirements ($D_{max} \leq D_{lim}$) for which two different limits are considered: D_{lim} = B/250 and D_{lim} = B/500. Further, two levels of superimposed loads *q* are considered, in addition to the structural weight: 3.5 kN/m^2 and 10 kN/m^2. The results are reported in Fig. 3 in terms of unit steel weight W/A (i.e. the total weight of the structural steel utilized for the pattern solution divided by the total area of the canopy), DCR_{max}, D_{max}/D_{lim} for each obtained structural pattern. The structural material used for the gridshell is steel S275 (f_{yk}=275 MPa).
The results obtained for H/B = 0 show that the design is dominated by stiffness: for each structural solution, the values of D_{max}/D_{lim} reach the unity, while the values of DCR_{max} are lower than 0.7. The structural weight increases by decreasing D_{lim} and increasing *q*. The two different structural patterns obtained for *q*=3.5 kN/m^2 and *q*=10 kN/m^2 are both characterized by grid density increasing near the edges. For a given value of *q*, the increase of stiffness demand due to the reduction of D_{lim}, is satisfied by increasing the members' cross-section in the patterns; instead, for a given value of D_{lim}, the increase of stiffness demand due to the increase of the external load *q*, is satisfied by increasing the number of structural elements in the pattern.

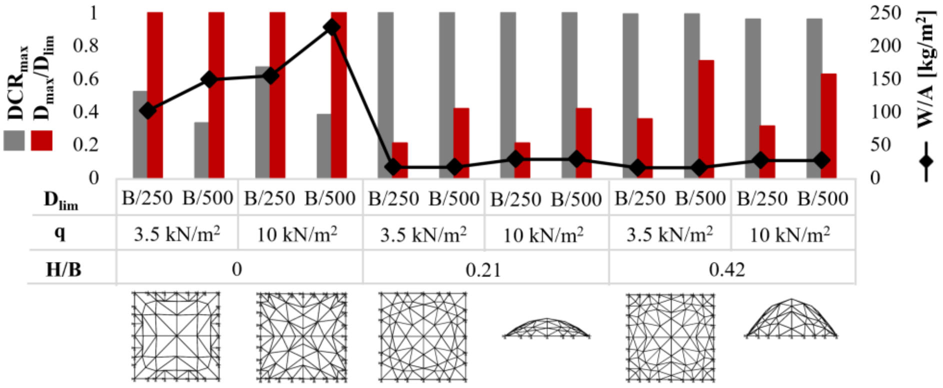

Fig. 3. Gridshells: optimized patterns and performance assessment

By observing the gridshells for H/B = 0.21 and H/B = 0.42, it emerges that the design problem is dominated by strength, as the gridshell tends to work in compression rather than bending (as for H/B = 0). Indeed, the structural patterns do not depend on the value of D_{lim} and q, while the structural weight increases by increasing the load q: the weight is insensitive to the different values of D_{lim}, since the problem is governed by the constraint condition on DCRs.

4 DIAGRID-LIKE STRUCTURES

4.1 Design rules of the shape grammar and generation of optimized patterns

The rules for the generation of the optimized patterns for diagrid tall buildings are graphically reported in Fig. 4. Rules 1 define the design domain, i.e. the building façades and their subdivision along the height of the building into a certain number of macro-modules and modules. Rules 2, 3, and 4 define the discretization of the design domain, by generating the diagrid pattern on the façades, with distribution and cross-sections of the diagonals that vary within a module and from one macro-module to another. In general, these rules allow the generation of different patterns by varying the distances between the end points of the diagonals, which regulate both their slope and number.

More in details, rule 1.1 defines the plan of the building and rule 1.2 the design domain and its subdivision along elevation into a number of macro-modules (here 3), each one containing a number of modules with the same diagrid geometry. The single module represents the horizontal fascia covering the full width of the building façade and spanning multiple floors, and it contains diamond units made by superimposing base-to-base two triangle units. By exploiting the doubly symmetric of each module, the algorithm defines the diagonals starting from one quarter of the lowest module of each macro-module through rule 2.1, by assuming a system of local coordinates (x, y). The geometry of the triangular units is obtained by means of sliders that controls the horizontal distance a_{ij} between the end points $P_{ij}(x_{ij}, y_{ij})$ of diagonals, with $i = 1, \dots, n_{dj}/2$, $j = 1, \dots, n_M$, n_{dj} the number of diagonals in the width of the module of each macro-module, and n_M the number of macro-modules. The point of local coordinates $(0, h_{mj}/2)$ is fixed, while the other

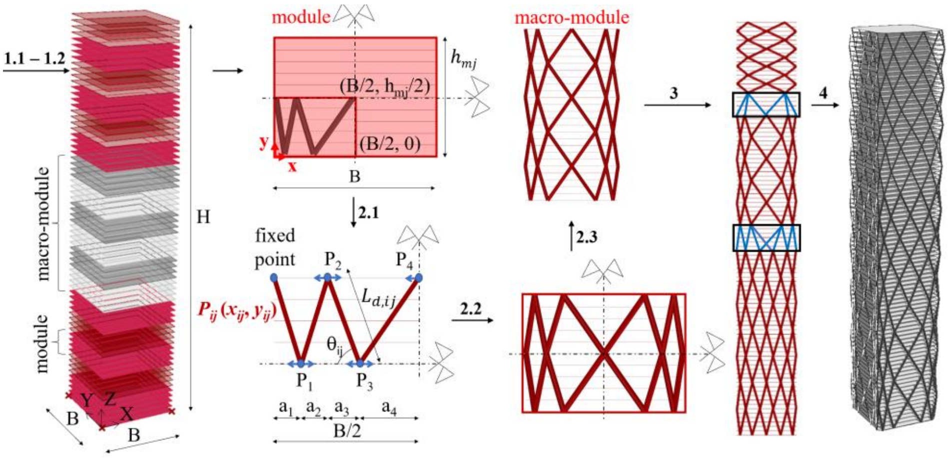

Fig. 4. Diagrid: rules for the definition and discretization of the design domain

points are sliders able to move on one of the horizontal lines at y=0 and $y=h_{mj}/2$. The distances a_{ij} represent the variables of the optimization problem and define both slope and number of diagonals in each quarter of module; indeed, the algorithm generates different values of a_{ij}, which sum is equal to B/2. Then, rule 2.2 mirrors the diagonals with respect to the two axes of symmetry, and rule 2.3 replicates the modules along elevation, to obtain the single macro-module. The same process is developed for each macro-module. Rules 3 are devoted to the development of a transition belt between successive macro-modules, which ensures the continuity of the pattern when the diagonals' ends do not match at the interface between two macro-modules. Despite the shape grammar only regulates the geometry of structure, rules 3 are conceived to obtain only structural meaningful patterns. Then, rule 4 refines the volume of the building by the construction of the tapered chamfering of the building corners, due to the triangulated pattern and lack of corner columns.

4.2 Structural solutions and performance assessment

The proposed structural grammar has been applied to diagrid models characterized by a dimension of the base quadrangular plan B equal to 54 m, and three values of aspect ratio H/B equal to 3, 5, 6.6, respectively; concerning structural performances, constraint conditions are imposed on strength ($DCR \leq 1$) and stiffness ($D_{max} \leq D_{lim}$, D_{lim} = H/500) requirements. The design gravity loads are: dead load 7 kN/m^2, live load 4 kN/m^2. The horizontal loads due to the wind pressure are computed according to Eurocode 1 (EN 1991-1-1:2002/AC:2009) considering a wind speed of 50 m/s. The resulting global overturning moment and base shear are equal to: 2585 MNm and 29 MN for H/B = 3; 8171 MNm and 54 MN for H/B = 5; 13043 MNm and 69 MN for H/B = 6.6. The structural material used for the diagrid is steel S275 (f_{yk}=275 MPa).

The Fig. 5 shows the outputs of the structural grammar in terms of structural pattern, unit structural weight W/A (i.e. the total weight of the structural steel utilized for the pattern solution divided by the total floor area of the building), maximum value of DCR, DCR_{max}, and D_{max}/D_{lim}. About DCR_{max}, its value is near the limit of unity for H/B = 3 and H/B = 5, while it assumes a lower value for H/B=6.6; on the other hand, the value of D_{max}/D_{lim} increases by increasing the aspect ratio H/B; it suggests that the dominant design criterion is strongly related to the slenderness of the building, as it affects the deformability of the structure. While for high slenderness values, the design problem is mainly governed by stiffness requirements, for low slenderness values, the inherent rigidity of the triangulated pattern is sufficient to satisfy the stiffness requirements, therefore the design problem becomes dominated by strength. Also the patterns recall this behaviour, as increasing the slenderness they become ever more similar to the trend of the isostatic lines, thus further improving the inherent efficiency of the diagrid [6]. The unit weight W/A increases with the slenderness as expected according to the so-called premium for height concept [3].

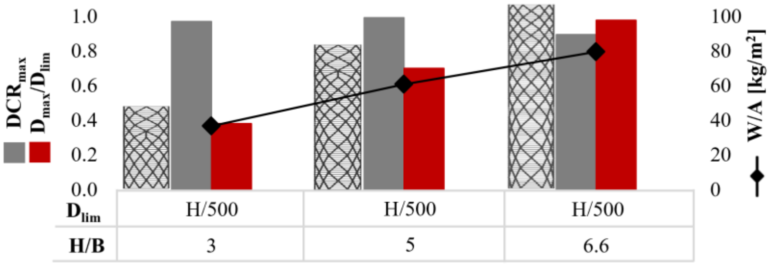

Fig. 5. Diagrid: optimized patterns and performance assessment

CONCLUSIONS

This paper deals with a structural grammar approach for the topology optimization of diagrid tall buildings and gridshell canopies. The structural grammar is developed for generating the geometry of the pattern and sizing the relevant structural members; thus, it merges architectural/aesthetic and structural/constructional aspects. The proposed process allows to generate different patterns by varying the position of the structural nodes, through designed rules that regulates number, density, and slope of structural elements. All the generated patterns are evaluated in terms of structural weight, and the most efficient one is finally selected as a result of a topology optimization process based on genetic algorithms. The procedure has been applied to gridshell and diagrid models with different aspect ratios. The results show that the proposed structural grammar is able to generate solutions according to the different behavior and the predominant design requirement for both gridshell and diagrid structures. It is also possible to create structural patterns characterized by significant geometrical diversity, utilized as a tool to derive different design alternatives, ranked according to the objective function, among which to choose alternative solutions based on aspects that were not explicitly taken into account during the optimization phase.

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KEYWORDS

shape grammar, structural grammar, topology optimization, grid shell, diagrid