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Optimization of structural patterns for tall buildings: The case of diagrid

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1. Introduction

The imperative design requirement for large scale structures is efficiency, that is the accomplishment of performance targets by means of minimum employment of structural material. The importance of efficiency is even more stressed by looking at the contemporary architectural trends, which embrace complexity of form as a signature for important projects. This is particularly the case of tall buildings that, being from the birth expressions of human achievement and corporate power, today are growing to greater height and strive to incorporate more unique forms.

Structural efficiency is the outcome of an optimization process that can be carried out, more or less explicitly and more or less rigorously, at different levels.

At the highest level there is the optimization of the tall building form: the geometrical shape of the building mass and volume has in fact a great impact on the wind structure interaction. Wind tunnel tests and computational fluid dynamics (CFD) simulations are the typical approaches for sculpting the optimal profile of tall buildings, as well as for suggesting local shape modifications (e.g. building corners or top), which ensure better aerodynamic performance.

At the intermediate level there is the optimization of building structural system, that encompasses both the mechanical concept behind the global configuration and the arrangement of the structural elements, i.e. the geometry and connectivity of the structural pattern. The global mechanical concept has a paramount role on the efficiency, and defines the global stiffness (and strength) capacity of the building. The structural pattern, which translates the concept into a specific arrangement of members, defines the local deformation modes and resisting mechanisms, as well as the strength demand distribution.

Finally, at the lowest level there is the member sizing optimization: given a certain pattern, the geometrical properties of the member cross sections, i.e. shape, area, inertia, strength modulus, defines the local strength and stiffness capacity. At this level, the choice of different material strengths (e.g. different steel grades or concrete strength) can further enlarge the designer options, driving to the possibility of differentiating the allocation of strength and stiffness in a single member.

According to [1], the development and application of formal optimization methods to the design of tall building structures is quite recent, covering the last two decades. Few papers ([2–6]) integrate CFD analyses with optimization algorithms for exploring geometric alternatives (building twisting, tapering, etc.; corner rounding, chamfering, slotting) and finding optimal aerodynamic shapes. Several studies, instead, deal with topology optimization, utilized to understand and replicate the load path in the structural system of tall buildings ([7–11]); starting from continua or discrete ground structures, optimal solutions and innovative bracing arrangements are obtained, coupling structural efficiency and esthetics. Finally, optimization methods have been used since the late 90s ([12–14]) for sizing member cross sections of complex super-high-rise buildings, whose structural layout is already predetermined.

However, it is worth recalling that the conscious search for the structural efficiency in tall building structures dates back to the 60s and can be traced as an informal process of optimization triggered by the deep insight into the inherent mechanical aspect of the problem. In this process, the major milestone was the concept of tube, then translated into new structural systems and solutions (framed, braced and bundled tube). While the idea of tube was actually a revolution in the structural conception of tall buildings, the adoption of the traditional rectangular pattern in the framed tube, made of the orthogonal arrangement of beams and columns, strongly undermined the closeness of the idea to its concrete realization, due to racking deformation and shear lag effect. The search towards solutions characterized by reduced shear deformation has then resulted in the braced tube system, where the exterior mega-diagonals spanning the façade virtually cancel out the bending deformation in beams and columns, thus almost eliminating shear racking contribution to the global building behavior. Similarly, the idea of reducing the shear lag effect and obtaining the perfect tube, led to the insertion of additional interior structural alignments in the building plan, resulting in the bundled tube.

A new solution for reducing both shear flexibility and shear lag has emerged in the last two decades [15]: the diagrid, which can be seen as the latest mutation of tube structures. The underlying idea is quite trivial: preserving the bending efficiency of the tube configuration, while increasing the shear stiffness of the structural pattern in façade, by going from a bending dominated pattern to a stretching dominated

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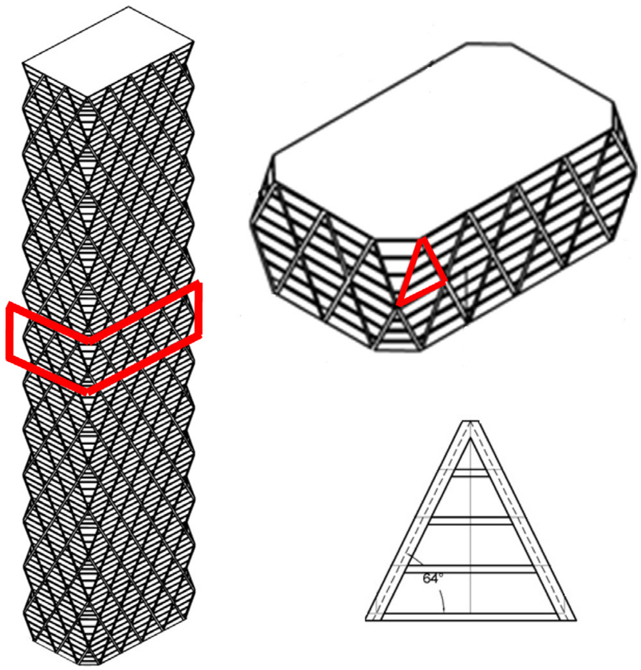

Fig. 1. Diagrid pattern, 3D module and triangle base unit.

pattern. The diagrid is a narrow grid of diagonal members arranged according to a triangulated tessellation of the building façades (Fig. 1), where the diagonals act both as inclined columns and as bracing elements, carry only axial forces, and experience only axial deformations, thus minimizing racking and shear lag effects.

In this perspective, the diagrid seems an "already optimized pattern" for tube configurations, since it eliminates "a priori" the major source of the tube inefficiency, i.e. the beam-column grid. However, the diagrid-like structures can be further improved by means of optimization processes, that can be carried out at the member level (sizing optimization), at the pattern level (topology optimization), or both. Further, in more general terms, a diagrid-like optimized pattern can be rationally derived on the basis of the mechanical behavior of the hollow cantilever beam describing the tube configuration ([9,10]).

In this paper, after a brief overview of research contributions on preliminary design methods and optimization procedures for diagrid patterns, a building model is defined as a case study for generating different diagrid patterns with regular geometry (uniform angle and density), as well as with non regular geometry, namely with variable angle and variable density; a further solution is also considered, obtained by mapping on the façade the principal stress lines of the cantilever beam equivalent to the building. The pattern generation processes are presented and the optimization procedures are described and applied to the different pattern solutions. Comparisons in terms of optimization outcomes, performance parameters and structural efficiency of the patterns are discussed. Finally, the constructability of the patterns is examined by means of simplified metrics, and implications in terms of both efficiency and economics of the structural solutions are discussed.

2. Overview on preliminary design methods and optimization procedures for diagrid patterns

The mechanical concept at the basis of diagrid patterns is triangulation, the oldest and most natural solution in structural steelwork. The simplicity and straightforwardness of the structural system, made of triangulated frame units with members mainly working in axial force condition, allows for preliminary design and simplified "hand analysis" only based on geometry.

Starting from this idea, some studies proposing design criteria and structural assessment of diagrids have been developed, considering both regular and variable angle diagrids.

Moon, in the first of a long series of papers published starting from 2007 [16], proposes a stiffness-based methodology for the preliminary design of regular diagrids. The parametric application of the method to several building models, with different number of stories, different angle of diagonals, different share of bending and shear stiffness, allows for deriving the optimal (minimum weight) design solutions. It is also highlighted the importance of the diagonal angle on the structural performance and efficiency of the diagrids. In [17] a comparative analysis of the structural performance of diagrid buildings, characterized by different heights and geometries (the Swiss Re, Hearst and Guangzhou West towers), is carried out. The results show that the adoption of optimal module geometries, as suggested by Moon [16], allows for obtaining very efficient structural schemes; furthermore, it emerges that the local strength requirements can be of paramount importance in the sizing process of the steel diagonal members. Starting from these observations in [18] the authors analyze to what extent stiffness and strength criteria affect the design of diagrid structures, stating that, in general, it is not possible to predict in advance if either global stiffness demand or member strength demand govern the sizing process of the pattern; therefore both criteria are necessary and unavoidable. In addition, the need for addressing interstory drift as design parameter is observed, particularly in the case of diagonals spanning several multiple floors; in [19] this specific problem is thoroughly examined, and design criteria for secondary bracing systems are proposed.

In [20] a design strategy based on multi-objective optimization algorithms is developed and presented; the authors minimize both the structural cost and the lateral displacements in the optimization process, varying parametrically the geometry of the diagrid. In [21] another design strategy based on multi-objective optimization is proposed, where, varying the density and the inclination of a regular diagrid, the interior daylight is maximized and the cost of the façade is minimized.

A stiffness-based optimization procedure for the preliminary design of diagrid structures is proposed in [22] by applying the principle of the virtual works. The structure is divided into modules and, at each step of the iterative process, the diagonal cross section in each module is varied as a function of a parameter that represents the "deflection influence efficiency factor" of the member, with the objective of minimizing the volume of the structure subjected to the constraint of H/500 for the top displacement.

All the above research contributions deal with regular-geometry diagrids (Fig. 2a), namely patterns with triangle base units (modules) characterized by constant angle and size, as well as by the same number of modules adopted along the façade elevation (i.e. uniform diagrid density). Regular diagrids, in fact, reflect the traditional approach for accommodating the stiffness and strength demands along the building elevation, which is based on the assumption: fixed grid, variable member capacity; this design approach preserves the structure geometry (i.e. column spacing in frame tubes, mega-diagonals length in braced tubes, module scale/size and density in diagrids), and adjusts the cross section properties and/or the steel strength of the structural members. However, in the case of diagrids, design strategies based on the variation of the grid geometry can also be adopted (Fig. 2b, c), resulting in diverse geometrical patterns characterized by density, size, scale, angle and/or depth of the base unit varying along the building façades. Relevant examples of diagrids with variable-geometry come from the world of tall buildings construction: the Lotte Super Tower structure (Fig. 2b), proposed by SOM [23], has a diagrid with variable angle along elevation in order to optimize the involvement of the diagonal members in counteracting lateral loads; diagrids with base units differently scaled throughout the building façades can also be observed in some designs by SOM (e.g. Longgang Tian'an Cyber Park, Fig. 2c).