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Secondary bracing systems for diagrid structures in tall buildings

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ABSTRACT

In this paper the authors define a framework for assessing the "local" structural issues in the design of diagrid tall buildings, and present a methodology for establishing the need for a specific secondary bracing system (SBS) as a function of the diagrid geometry. Further, design criteria for secondary bracing systems are worked out and applied to some 90 story building models, characterized by perimeter diagrid structures with different module height and diagonal cross sections. The outcomes of the proposed simplified procedures, both for assessing SBS necessity and for the consequent SBS member design, have been compared to the structural response of the diagrid building models, obtained without and with SBS, demonstrating both the accuracy of the proposed formulations and the primary importance of the discussed local questions. In fact, all analyzed diagrid models exhibited problems concerning stability of interior columns (i.e. multi-storey buckling modes) and/or local flexibility (excessive interstory drift); the above local problems are completely solved after the introduction of a SBS at the central core location, and, against a modest increase of structural weight (about 3%), any flexural engagements in the diagrid member is eliminated.

1. Introduction

Diagrid structures represent the most popular and featuring solutions for tall buildings of the new millennium, a sort of signature element of the latest design practice. Both in the case of prismatic, regular buildings, and in the case of complex, non conventional forms, the diagrid concept offers the structural possibility of combining high efficiency and aesthetic connotation. Several renowned examples testify this statement: the 30 St. Mary Axe, the Hearst Tower, and more recently the Bow, all designed by Norman Foster but each characterised in a unique manner by triangulation in façade; the CCTV Headquarters (named Best Tall Building Worldwide by the CTBUH on November 2013), designed by Rem Koolhaas with the inspiring structural involvement of Cecil Balmond, where the variable density diagrid wrapping the loop shape contributes to create an affect of complexity and gradation; the Doha Tower, designed by Jean Nouvel, an elegant cylindrical form that stands out for the overlapping and merging of the concrete diagrid structure with the complex "mashrabiya" pattern, conceived for sun shading purposes; the Capital Gate, "world's furthest leaning manmade tower", characterised by a steel diagrid that finely tessellates the external façade of the tower describing a striking organic form. The above recalled buildings all together exemplify the multiple and variegated use of triangulation in diagrid solutions, with the unit triangle module that, extending over several floors, completely tessellates the façade surface.

From the structural point of view, a major reason for the diagrid appeal (attractiveness) is that it can be considered the latest mutation of tube structures, the one which best exploits the potential advantage of tube configuration, thanks to the triangulated arrangement of structural members and the complete elimination of the right-angle framework, which dramatically reduce racking deformation and shear lag effects. A comparative analysis of the structural performance of some recent tall buildings carried out by the authors [10] has proved that diagrid structures couple significant lateral stiffness and strength capacity to remarkable material economy, thus allowing for tremendous structural efficiency.

As frequently happens in the field of tall building design, it can be observed that the research lags behind the advanced state of the practice: despite the wide use of this structural solution, remarkably little formal research is conducting by academic institutions on diagrid structures and relevant behaviour, design and analysis issues. Some exceptions are the important contributions provided by Moon starting from 2007 [13,14] and more recently by [20], mainly devoted to develop design criteria both for regular and varying angle diagrids; always on design criteria is a previous paper by the authors [11], where both global stiffness and member strength demands are examined in a parametric study and simplified formulae are suggested for quick member sizing. Similarly, in

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[12], different diagrid patterns (regular, variable angle, variable density) are generated, designed, analyzed in terms of structural weights and performances, in order to assess comparatively the relevant efficiency potentials. Some worthwhile contributions concerning the seismic performance of diagrid structures come from both the academia [9] and the professional world [5].

However to the authors' knowledge, an important question related to the design of diagrid buildings has not received adequate attention so far, namely the need for bracing of the multiple-story diagrid module. In [11,12] it has been observed that, though the diagrid structure provides the required lateral stiffness to the building under wind loads, large interstory drifts arise at floor levels located within the diagrid module, particularly the ones characterized by the steepest angles (i.e. the tallest diagrid modules) and/or the most flexible diagonal members.

From an overview of recent realizations and projects of diagrid structures, partially reported in [10], it seems that only the 30 St. Mary Axe, characterised by a module 2-storey tall, has an interior core structure designed as a simple frame, merely resisting gravity loads. All other buildings, with diagrid module extending over 4–6 storeys and more, have a core structure that, while sharing the global stiffness and strength demand in a tube-in-tube configuration, also provide local floor-to-floor restraints to the diagonal members, thus avoiding flexural engagement along the member length, and preserving the purely axial behaviour in the diagrid structure.

However, the extraordinary efficiency of diagrid would always allow for a pure tube configuration, with core structure only resisting gravity loads, and diagonalized façade providing the global stiffness and strength to resist lateral loads. But this structural choice requires the need of addressing the "local" behaviour of the structural members within the module height, which can extend several floors apart; the problem is twofold, and, involving both the perimeter diagrid members and the interior core columns, requires: (i) to reduce or avoid the flexural deformations of the diagonal members along their length, and (ii) to stabilize the core gravity columns at intermediate floor levels. Similar structural issues arise in other lateral load resisting systems for tall buildings, whenever mega-bracing elements spanning over several floors are employed: this is the case of tube configurations characterised by mega-diagonals, namely the braced tube, as well as exoskeleton mega-structures [1,16]. However the case of diagrid is unique due to the complete absence of vertical columns in façade.

Therefore the aim of this paper is to provide a contribution towards filling the gap between the advanced state of practice and the research state of art, specifically focusing on the above structural issues that seem nor secondary neither negligible in the design process. This could encourage the applications of diagrid in purely-tube configurations, thus allowing for feasible, efficient and material-saving solutions.

In this paper the authors provide a thorough evaluation of the local behaviour of diagonal members and gravity columns within the diagrid module height, and present a methodology for establishing the need for a specific secondary bracing system as a function of the diagrid geometry. Further, design criteria for secondary bracings are derived both for controlling diagonal flexural deformations and gravity column buckling; the application of the above formulations to some 90 story building models, characterised by perimeter diagrid structures with different module height and diagonal cross sections, allows for comprehensive discussion on design implications of secondary bracings.

2. Statement of the structural issues

The structural behaviour of systems with mega-diagonals could be assimilated to a vertical truss with panel points (diagrid nodes) located multiple floors apart; in Fig. 1a is sketched a typical diagrid system, with a 3-storey-high triangle module. The diagrid structure ensures the global stiffness and strength of the overall building only engaging the diagonal members in a purely axial behaviour (i.e. tension/compression internal forces and extension/shortening deformations), and fully braces the interior gravity columns for stability only at panel points. The intermediate floors, marked with asterisks in Fig. 1a, are not laterally restrained by the global behaviour of the diagrid system; more precisely, if diagonals are continuous throughout the module height, the floors would derive a certain degree of lateral stiffness only from the flexural stiffness of the diagonals (Fig. 1b).

This particular behaviour has important consequences.

First of all, the global lateral system, that guarantees the building stiffness and strength under horizontal loads, is not able to guarantee as well lateral stability of interior gravity columns between the panel points: the lateral restraint is given at regular (multiple floor) intervals, therefore the two requirements of resisting lateral loads and stabilizing columns become somewhat separated. As in the case of other mega-bracing structures, "the problem is one of overall story stability with all columns buckling simultaneously in a multy-story mode between the mega-brace point" [1].

The second important local issue of mega-bracing configurations concerns the flexural deformations of the mega-diagonals along their length, between panel points, that arise while restraining intermediate floors. As a consequence, local deflections within the module augment lateral displacements deriving from the global deformation mode of the diagrid structure. Depending on the number of mega-diagonals on building façade, on the mega-diagonal cross section, and on the module height, the local deformations between the panel points could produce very large interstory drifts, and cause serviceability problems in architectural elements such as claddings, floor finishes and partitions.

These two problems, i.e. gravity column stability and diagonal flexural engagement, are strictly related and concern the local lateral flexibility of the structure; both could be solved according to different approaches [1,15,16].

The first solution consists in leaving the intermediate floors laterally restrained by the flexural stiffness of mega-diagonals only, and accounting for this in the design of gravity columns and other components, i.e. designing the gravity columns as they were braced only at the panel points of the diagrid, and sizing the diagrid members with enough flexural stiffness to control interstory drifts. This approach, however, may lead to quite large cross sections for columns and diagonals, especially for very tall buildings.

The second solution [15] is to add structural members between the panel points of the overall bracing system: examples of local bracing members placed within the diagrid module are provided in Fig. 2a (dashed lines); similar configurations, though designed

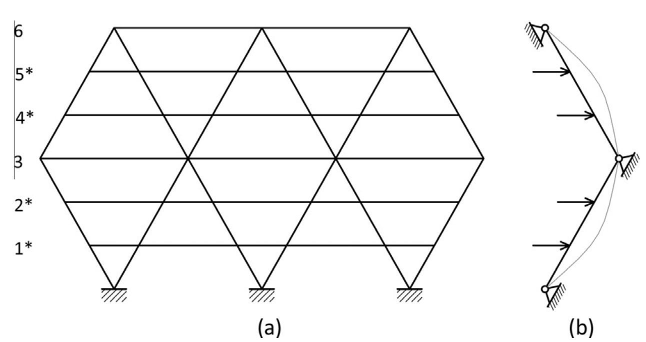

Fig. 1. (a) Sketch of a typical diagrid system; (b) static scheme of mega-diagonal elements between panel points.