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Geometrical patterns for diagrid buildings: Exploring alternative design strategies from the structural point of view

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ABSTRACT

Diagrid structures for tall buildings are very popular among engineers and architects, thanks to the inherent qualities of structural efficiency, decorative attributes and morphological versatility. However limited academic research have been developed with focus on the structural behavior, design criteria and performance assessment of this structural system; further, the scientific contributions in literature mainly concern regular diagrids, i.e. patterns characterized by constant geometrical attributes of the base module (width and height, angle, scale). In this paper, a first step toward a systematic and comprehensive study of geometrical patterns for diagrids is provided. For this purpose, diagrid structures characterized by regular patterns are compared to alternative geometrical configurations, obtained by changing the angle of diagonals (variable-angle, VA) as well as by changing the number of diagonal (variable-density, VD) along the building height. Eight different diagrid patterns are generated and designed for a 90-story model building, according to procedures either provided in the literature or suggested by the authors. The resulting diagrid structures are assessed under gravity and wind loads and various performance parameters are evaluated on the basis of the analyses results. The comparison in terms of structural weights and performances finally allows for discussing efficiency potentials of the different patterns.

1. Introduction

"*This is the moment of diagrid*". With these words Ian Volner, on The Magazine of the American Institute of Architects, states that "the diagonally based structural system of the diagrid is becoming a hallmark of 21st century Modernism" [20].

The concept of diagrid is not new at all: people have always been intuitively familiar with the inherent stability of triangular structures. Placement of diagonals is the oldest and most natural solution in steel structures, and has had widespread applications, receiving great popularity among engineers and architects; however the past architects considered diagonals highly obstructive and usually embedded them within the building interior cores. A rare example of building with a trussed façade was the Chocolate Factory Menier at Noisel, France (Fig. 1), designed in 1873 by the architect Jules Saulnier [19].

The first modern application of diagrid dates back to the early 1960s, with the dramatic diamond – lattice exoskeleton of the IBM building in Pittsburgh (now known as the United Steel Workers Building), "*an architectural and engineering breakthrough, with diamond-patterned walls that act as both skin and skeleton*" [7]. Previous conceptual studies can be found in the seminal work of Goldsmith [9], within the Master Thesis that he developed in 1953 at the Illinois Institute of Technology, Chicago, under the supervision of Mies Van Der Rohe. Goldsmith proposed three diagonalized structures for tall buildings, namely a variable-density diagrid, a regular narrow diagrid, and a mega-diagonal solution (Fig. 2). The latter was nothing less than the embryonal idea of braced tube, that shortly thereafter Fazlur Khan would have worked out and applied in the smart and impressive John Hancock Center, paradigmatic example of the structural honesty of the second Chicago school. The two Goldsmith diagrid solutions, instead, did not receive comparable attention, probably due to difficulties in detailing and fabrication of curtain walls.

If diagrid is based on a quite old concept, why "*this is the moment of diagrid*"? What is strikingly new in the latest years is a multiple and variegated use of triangulation which brashly characterizes the aesthetics of important tall buildings (Fig. 3). In the Swiss-Re Tower the diagrid solution addresses the distinctive shape and the unusual geometry; in the Hearst Tower, the crystalline pattern shapes an elegant building "*that clearly emerges from rational thought*" [8]; in the China Central Television (CCTV)

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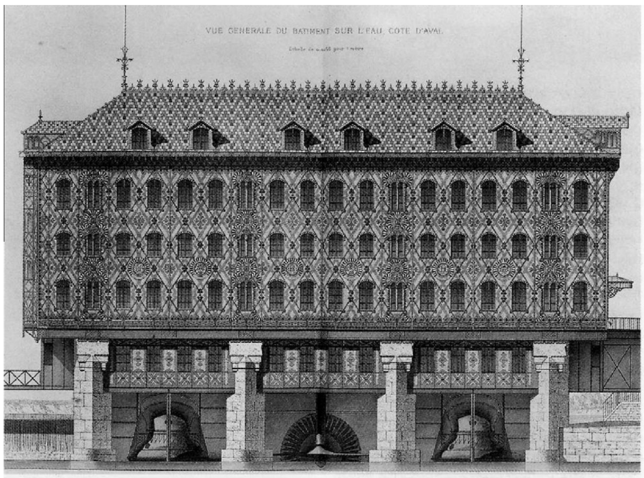

Fig. 1. The trussed façade of the Chocolate Factory Menier at Noisel (from: [19]).

headquarters, the diagrid structure wraps a challenging building form, resembling a Moebius strip; in the Guangzhou West Tower the diagrid gives a subtle depth, strength and character to the building, as reported in the jury statement that recognized the tower as "Best Tall Building Asia & Australasia" in the 2011 CTBUH Awards Program.

A major reason for this "*diagrid craze*" is undoubtedly the structural efficiency of the triangulated patterns: in fact "... *diagrid speaks a reassuring language of stability, a message qualified by its real physical economy and resilience* .... *diagrid looks like it should work, and it does*" [20]. A comparative analysis of the structural performance of some recent tall buildings carried out by the authors [10] has proved that diagrid structures couples significant lateral stiffness and strength capacity to remarkable material economy, thus allowing for tremendous structural efficiency.

Moreover, the almost endless morphological potentials of diagrid allow for adapting to nearly every building shape, obtaining elegant façade appearances through an integrated architectural–structural design. The ultimate example of the extreme diagrid versatility is the Orbit, a "*twisted knot of steel masts*" [20]: both a sculpture and a tower, "*a piece of engineering and architecture and total art work all combined as one*" [3] designed by Anish Kapoor and Cecil Balmond for the London 2012 Olympic Games (Fig. 4).

A review and a sort of classification of diagrid patterns, from geometric, formal and "affective" point of view is given in [17], where, starting from the diagrid base unit, the potential to produce novel and different forms, *"each with unique expressions, sensations and affects"*, is explored.

A similar survey of diagrid patterns from the structural point of view, with the consequent assessment of the relevant structural efficiencies, has never been carried out.

In this paper, a first step toward a systematic and comprehensive study of geometrical patterns for structural façades of tall buildings is provided, with particular reference to diagrids. For this purpose, diagrid structures characterized by both regular and variable patterns are examined in terms of geometrical properties and generation process; design procedures are defined for the preliminary sizing of the diagonal members and the resulting structures are analyzed and compared, both in terms of structural weights and performance parameters, with the final aim of discussing drawbacks and advantages of the different diagrid patterns.

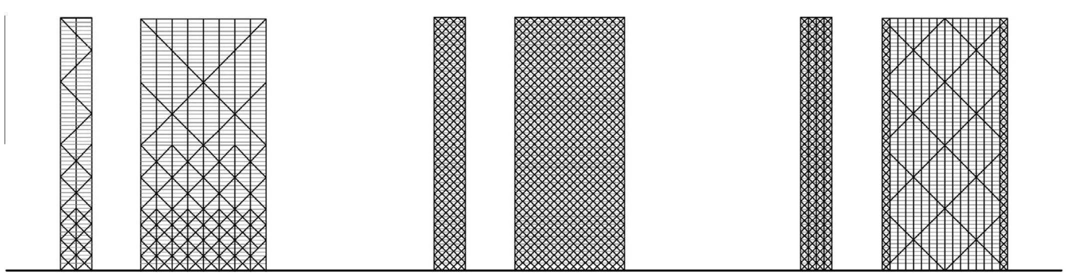

Fig. 2. Diagonalized structure solutions for tall buildings proposed by Goldsmith (redrawn from [9]).

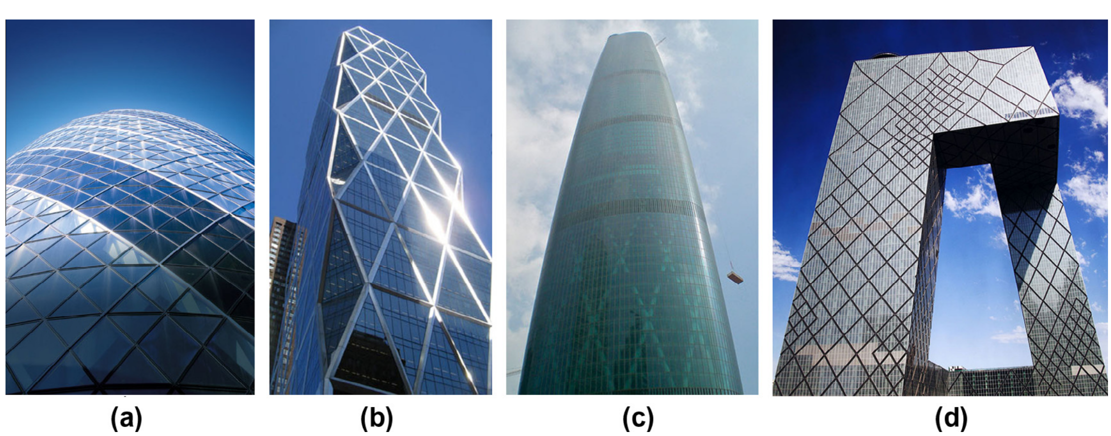

Fig. 3. (a) Swiss-Re Tower (from www.swisspacer.com), (b) Hearst Tower (from en.wikipedia.org), (c) China Central Television (CCTV) headquarters (from www.panoramio.com), and (d) Guangzhou West Tower (from www.worldarchitecturemap.org).