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The Effect of Slenderness on the Design of Diagrid Structures

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Abstract

Diagrid structures have emerged in recent decades as an innovative solution for tube tall buildings, capable of merging structural efficiency and aesthetic quality. This paper investigates the effect of the building slenderness (grossly quantified by means of the aspect ratio, i.e., the ratio between the height and the plan dimension) on the structural behavior and on the optimal design parameters of diagrid tall buildings. For this purpose, building models with different slenderness values are designed by adopting preliminary design criteria, based on strength or stiffness demands; in addition, a design method based on a sizing optimization process that employs genetic algorithms is also proposed, with the aim to compare and/or refine the results obtained with simplified approaches.

Keywords: Tall buildings, Diagrid, Steel structures, Slenderness, Structural optimization

1. Introduction

The major issue in the structural design of a modern skyscraper is related to the behavior under lateral loads, and in particular to its slenderness, which can be quantified by means of the aspect ratio, i.e., the ratio of the height to the footprint depth of the lateral load resisting system. Building deflections imposed by wind loads, indeed, increases as a function of the building height, and can be contrasted by increasing the structural depth.

Taking the cantilever beam under uniform transversal loads as a simplified model of the building under wind actions, the above considerations can be easily grasped. A slender beam, characterized by an aspect ratio H/B (ratio of beam length to cross section depth) equal to or larger than, say, 8-10, has a predominant flexural behavior. Transversal loads acting on the cantilever can be represented by means of the global external actions, namely the shear force and overturning moment. Increasing the beam length (i.e., the building height), while the resultant shear force linearly increases, the overturning moment increases as a quadratic function of the length; furthermore, the lateral deflections (i.e., the building drifts) increase even more quickly, with the fourth power of the length. For the buildings, as well, the flexural stiffness demand increases more quickly than the bending strength demand as the height increases, therefore the structural design of tall buildings is mainly governed by the stiffness rather than by strength.

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Quite trivially, the way of increasing flexural stiffness for the beam is to increase the moment of inertia of its cross section, which requires the centrifugation of the areas from the neutral axis. For the building, the moment of inertia of the equivalent beam section should be calculated considering all the vertical structural elements, such as walls and columns, continuous along elevation and active in the lateral load resisting system. Therefore, the increase of the building flexural stiffness requires the placement of such vertical elements as far as possible from the plan centroid, i.e., at the building perimeter, giving rise to the concept of tube. However, when the height of the building is coupled to a relatively small plan depth, thus resulting in a large value of the aspect ratio H/B, or slenderness, the available lever arm for counteracting the overturning bending moment and, more importantly, for providing an adequate flexural stiffness, is limited. In such cases, new concepts for developing innovative and efficient structural systems are mandatory.

In this perspective, the diagrid structures, characterized by a narrow diagonal grid, which allows for the complete elimination of vertical columns, can be considered as the latest evolution of the tube (Mele et al., 2014). Thanks to the triangle tessellation of the façades, indeed, internal axial forces are largely prevalent in structural members, and the global deformation demand gives only rise to the member shortening/extension, thus ensuring a high inherent rigidity and a strong reduction of both shear lag effects and racking deformations.

From the geometric point of view a diagrid building is based on the diagrid module, the structural unit of the triangular pattern, which usually extends over multiple floors,

repeats horizontally along the building perimeter and stacks vertically along elevation. The division of the building shaft into diagrid modules is usefully employed for the preliminary design and analysis. Since the module usually extends over multiple floors, loads are transferred to the module at every floor level, and load effects vary along the diagonal length. However, considering that a single cross section is adopted for the diagonal along the global module height, i.e., diagonal section only varies from one module to another, the loads utilized for the member sizing of the diagonals are the ones referring to the base of the relevant module. As demonstrated by Moon (2007, 2008) and Montuori et al. (2013), and also as recalled in the following sections, lateral loads acting on the building give rise to global strength and stiffness demands, which translate in axial strength and stiffness demands in the diagonal members. Both the above demands and, in turn, the strength and the stiffness capacities of the diagrid module, strongly depend on the diagonal angle. Indeed, as observed by Moon et al. (2007), a diagonal angle of 35° maximizes the shear strength and stiffness of the module, and, in turn of the diagrid structure, while an angle of 90° maximizes the global bending strength and stiffness of the diagrid structure. Therefore, the optimal angle, which balances the need of shear and bending capacities, should be an intermediate value between the above values.

On the basis of this simplified discussion, some interesting questions arise when diagrid structures are adopted for slender buildings. Firstly, considering the large stiffness of the triangulated structural patterns, the shift of the predominant design criterion from strength to stiffness is likely to occur at a higher slenderness value for diagrids than for other structural systems. Furthermore, being the stiffness of the diagrid highly dependent on the diagonal angle, as previously discussed, then optimal angle values should be defined by varying the building slenderness, in order to maximize the potential efficiency of the diagrid system.

In this context, this paper investigates the effect of the slenderness on the predominant design criterion (stiffness vs. strength) and on the optimal angle for diagrid structures, with the final aim of providing practical guidelines for design solutions characterized by high structural efficiencies. For this purpose, building models with different slenderness values and diagonal angles are designed by adopting preliminary design criteria, based on simplified assessment of both strength and stiffness demands (Montuori et al., 2013, Moon et al., 2007). In addition, a design method based on a sizing optimization process that employs genetic algorithms (Goldberg, 1989) is also proposed, with the aim of comparing and/or refining the outcomes obtained with hand-calculation approaches.

2. The Building Parametric Model

The tall building model utilized as a case study in this paper has a square plan dimension of 53×53 m and inter-story height of 3.9 m. The number of stories of the building model is varied in order to obtain values of the aspect ratio H/B from 2 to 8. The floor unit dead load G is 7 kN/m^2, including the weight of the steel structure and deck, the concrete slab and the floor finishes, the interior partitions and the exterior claddings; the live load Q is equal to 4 kN/m^2. The floor plan has a central service core, realized by means of a simple frame structure, which carries tributary gravity loads and provides a negligible contribution to the lateral load resisting system; for this reason, the core structure is not considered in the design process and is omitted in the FE analysis models.

The horizontal load due to wind pressure is evaluated according to Eurocode 1 provisions (EN 1991-1-1, 2002), considering a wind speed of 50 m/s with exposure category B. In Table 1 are reported the lateral loads distributions, and the resulting base shear and overturning moment values, adopted for the building models varying the ratio H/B. A maximum allowable top drift, D_{top}/H, of 1/500 and a maximum member strength demand to capacity ratio (DCR), equal to 1 are adopted as design targets for the stiffness and the strength based design, respectively. The material employed for the diagrid is steel S275 (f_{yk}=275 MPa) for the stiffness-based solutions, while both S275 and S355 (f_{yk}=355 MPa) are adopted for the strength-based design; square hollow sections (SHS) are used for diagonal members in all diagrid patterns.

Diagrid patterns, characterized by angle θ from 50° to

Table 1. Lateral loads

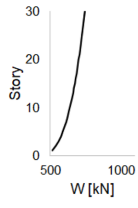
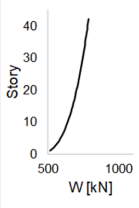
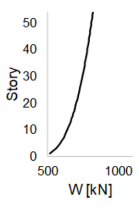
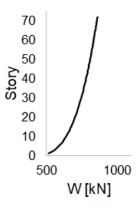
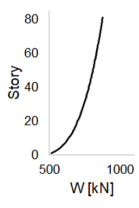
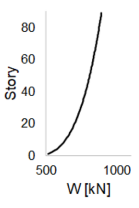
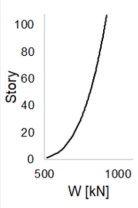
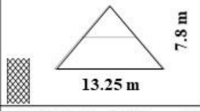
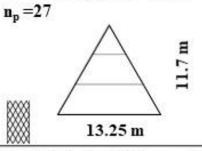
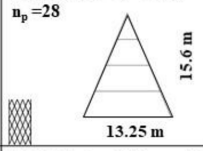
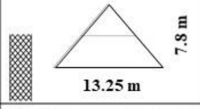
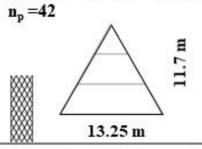
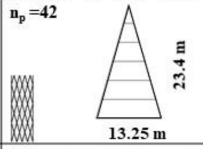
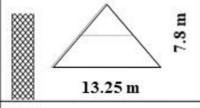
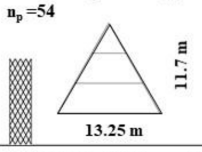
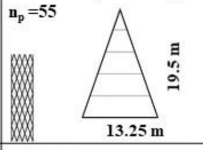
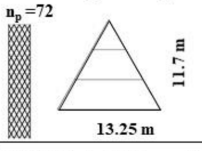
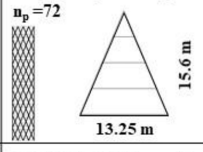
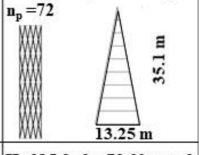
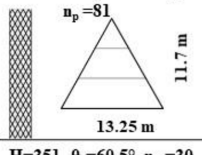
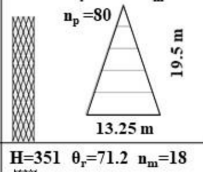
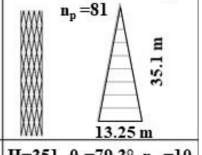
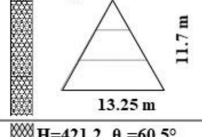
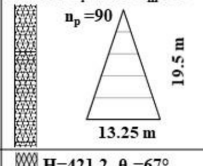
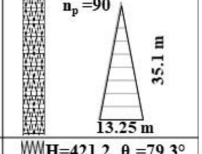
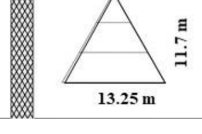
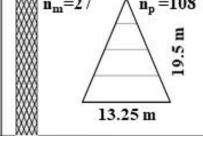
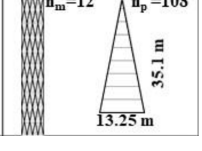
H/B	2	3	4	5	6	6.6	8
G [kN/m^2]	7	7	7	7	7	7	7
Q [kN/m^2]	4	4	4	4	4	4	4
W [kN]							
V_{base} [kN]	18471	29194	38858	54010	60963	69375	85737
M_{base} [kN*m]	1096947	2584657	4413936	8170595	10245356	13043199	19363431

Table 2. Diagrid structures: parametric range

Θ [°] H/B	50	60	70	80
2	H=109.2 θ_r=49.7° n_m=14 n_p=28 	H=105.3 θ_r=60.5° n_m=9 n_p=27 	H=109.2 θ_r=67° n_m=7 n_p=28 	
3	H=163.8 θ_r=49.7° n_m=21 n_p=42 	H=163.8 θ_r=60.5° n_m=14 n_p=42 	H=163.8 θ_r=74.2° n_m=7 n_p=42 	
4	H=210.6 θ_r=49.7° n_m=27 n_p=54 	H=210.6 θ_r=60.5° n_m=18 n_p=54 	H=214.5 θ_r=71.2° n_m=11 n_p=55 	
5		H=280.8 θ_r=60.5° n_m=24 n_p=72 	H=280.8 θ_r=67° n_m=18 n_p=72 	H=280.8 θ_r=79.3° n_m=8 n_p=72 
6		H=315.9 θ_r=60.5° n_m=27 n_p=81 	H=312 θ_r=71.2° n_m=16 n_p=80 	H=315.9 θ_r=79.3° n_m=9 n_p=81 
6.6		H=351 θ_r=60.5° n_m=30 n_p=90 	H=351 θ_r=71.2 n_m=18 n_p=90 	H=351 θ_r=79.3° n_m=10 n_p=90 
8		H=421.2 θ_r=60.5° n_m=36 n_p=108 	H=421.2 θ_r=67° n_m=27 n_p=108 	H=421.2 θ_r=79.3° n_m=12 n_p=108 

80° have been used for the structural system; in fact, as the building slenderness H/B increases, the bending behavior becomes more dominant than the shear behavior, thus steeper diagonals should be assigned to the most slender buildings (Moon, 2008). Therefore, while diagonal slope of 50°, 60°, 70° are used for H/B from 2 to 4, slope of 60°, 70°, 80° are used for H/B from 5 to 8. Starting from the building width, the selected value of the aspect ratio H/B, and the assigned diagonal angle θ, the geometry of the diagrid model is defined. In particular, the width of the module is set equal to 13.25 m, resulting in 4 modules along each building façade for all diagrid patterns. Then, the value of θ is slightly varied in order to obtain an integer number of stories in a single module ($n_{st,m}$), an integer number of stories along the height (n_{st}), and, in turn, an integer number of modules along the height (n_m). In Table 2 the different diagrid patterns and the unit triangle modules are depicted as a function of the building slenderness H/B and the diagonal angle θ; the module height and the exact values of H and θ are also provided, together with, the number of stories and the modules along elevation.

The parametric models are built within the software Grasshopper (Rutten, 2007), plug-in of the 3D modelling software Rhinoceros (McNeel, 1998), while numerical analyses are developed by means of Karamba (Preisinger, 2008), a FEA code developed for Grasshopper.

For each H/B and θ, the building model is designed according to the following three different strategy: stiffness-based design, strength-based design, sizing optimization. They will be briefly described in the following section.

3. Hand Calculation and Sizing Optimization Procedure

Preliminary design procedures provided in literature for diagrid structures (Moon et al., 2007, Montuori et al., 2013, 2014a) are usually based on the subdivision of the diagrid into a number of triangular modules, each spanning a certain number of floors (Fig. 1). Adopting the conceptual simplification of considering the building as a vertical cantilever beam, the global horizontal deformation, given by a combination of bending and shear modes, can be easily calculated, as well as the values of the global shear force and the overturning moment at each beam section (i.e., at each module). Moreover, it is assumed that the building façades (and the relevant diagrid modules) parallel to the wind direction act as the webs of the equivalent beam cross section, and the diagrid modules on the orthogonal façades act as the flanges. On the basis of the above assumptions, the stiffness-based and the strength-based design procedures consider the contribution of the diagrid modules on the flange façades for providing flexural stiffness and resistance while the contribution of the diagrid modules on the web façades for providing shear stiffness and resistance (Fig. 1). In the following, the two procedures are briefly described.

3.1. The stiffness-based criterion

The stiffness-based criterion, proposed by Moon et al. (2007) and Moon (2008) is based on the consideration that diagrid structures are much more effective in minimizing shear and flexural deformations than conventional framed tubular structures because the first ones carry shear by axial action while the others carry shear by bending. Then, being the single elements subjected to axial loading, strength requirements can be satisfied by relatively small cross-sectional areas and, as consequence, the global stiffness requirement (i.e., the top displacement) could become predominant, above all if the slenderness increases. Indeed, one of the authors' conclusions is that, compared with a conventional strength-based iterative methodology, a stiffness-based methodology is a more efficient tool for light and flexible structures such as tall buildings, the design of which is, in many cases, governed by motion rather than strength.

The aforementioned stiffness-based design criterion assumes that the structural member sizing is governed by the global lateral stiffness to be assigned to the diagrid; for this purpose, the building top drift (D_{top}) is adopted as the design parameter, and the limit to be satisfied is expressed as a percentage of the building height (usually *H/500*), i.e.,:

$$D_{top} = \delta_s + \delta_b = \gamma H + \frac{\chi \cdot H^2}{2} = \frac{H}{500} \tag{1}$$

The design problem is to establish the design values of bending and shear deformations at each module level, namely respectively γ^* and χ^*, such that:

$$\gamma^* H + \frac{\chi^* \cdot H^2}{2} = \frac{H}{500} \tag{2}$$

Known the shear force V_m and the overturning moment M_m at basis of each module due to wind action, the design values of the shear and bending stiffness, namely respectively K_T^* and K_β^*, which constitute the module stiffness demand, are provided by:

$$K_T^* = \frac{V_m}{\gamma^* \cdot h}, \quad K_\beta^* = \frac{M_m}{\chi^* \cdot h} \tag{3}$$

where h is the module height The shear and bending

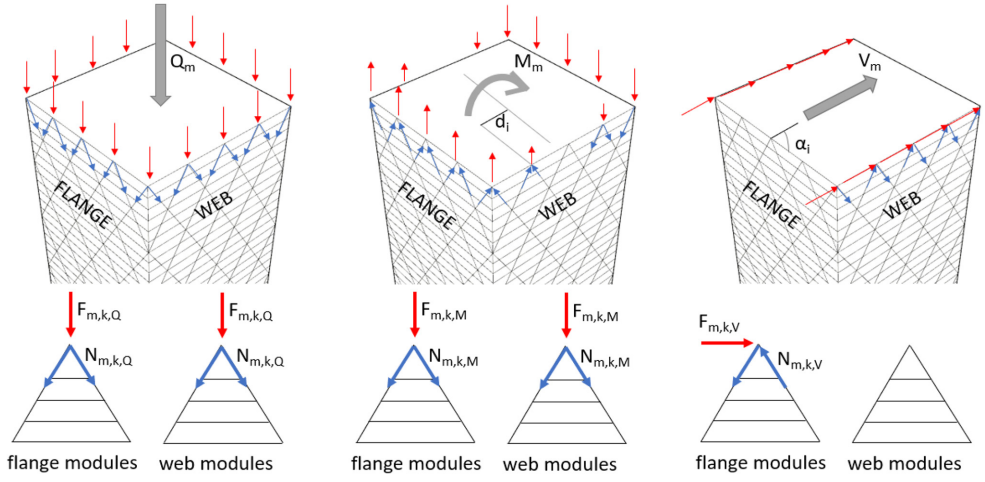


Figure 1. Diagrid module: geometry, loads, internal forces.

stiffness provided by the diagrid on façades, namely respectively K_T and K_β, and providing the module stiffness capacity, can be expressed as a function of the grid geometry, the diagonal cross section properties and the structural material, by the following expres- sion:

$$K_T = 2 \cdot n_w \frac{(A_{d,w} \cdot E \cdot cos^2\theta)}{L_d}$$
$$K_\beta = n_f \frac{(B^2 \cdot A_{d,f} \cdot E)}{2 \cdot L_d} \cdot sin^2\theta \quad (4)$$

where n_w and n_f are the number of diagonals extending over the full height in one web plane and in one flange plane, respectively. Equating the expressions of the stiffness demand Eq. (3) and the stiffness capacity Eq. (4), the diagonal cross sections on the façades parallel and orthogonal to the wind direction, $A_{d,w}$ and $A_{d,f}$, respectively, can be obtained as:

$$A_{d,w} = \frac{V_m \cdot L_d}{2 \cdot n_w \cdot E \cdot h \cdot \gamma^* \cdot cos^2\theta}$$
$$A_{d,w} = \frac{2 \cdot M_m \cdot L_d}{n_f \cdot B^2 \cdot E \cdot \chi^* \cdot h \cdot sin^2\theta} \quad (5)$$

The design problem is, then, to establish the design values of bending and shear deformations (γ^* and χ^*), to satisfy Eq. (2). However, the described design process is not univocal since the same target displacement (H/500) can be obtained with different couples of γ^* and χ^*, i.e., with structural systems characterized by different shares of bending and shear stiffness. The optimum solution satisfies the restraint on D_{top} (Eq. (2)) with the minimum material consumption, i.e., with the smallest diagonal cross sections. For this purpose, a s factor has been defined (Moon, 2007) as the ratio of the bending to shear design deformation at the building top:

$$s = \frac{\chi^* \cdot H^2/2}{\gamma^* \cdot H} = \frac{H \cdot \chi^*}{2\gamma^*} \quad (6)$$

with γ^* and χ^* expressed as:

$$\gamma^* = \frac{1}{(1+s) \cdot 500} \quad \chi^* = \frac{2 \cdot s}{H(1+s) \cdot 500} \quad (7)$$

Substituting Eqs. (6) and (7) into Eq. (5) provides the following expressions for $A_{d,w}$ and $A_{d,f}$, which contain only the unknown parameter s:

$$A_{d,w} = \frac{V_m \cdot L_d \cdot (1+s) \cdot 500}{2 \cdot n_w \cdot E \cdot h \cdot cos^2\theta}$$
$$A_{d,f} = \frac{2 \cdot M_m \cdot L_d \cdot H \cdot (1+s) \cdot 500}{n_f \cdot B^2 \cdot E \cdot h \cdot sin^2\theta \cdot 2s} \quad (8)$$

The design problem is, then, to establish the optimal value for s, i.e., the value of s that provides the minimum values for $A_{d,w}$ and $A_{d,f}$: The choice of s for the minimum amount of structural material usage depends on H/B and on the diagonal angle, as proposed by Montuori et al. (2013) in the following equation, according to the analogy between the diagrid building and a Timoshenko cantilever beam:

$$s_{opt} = \frac{u_\chi}{u_\gamma} = \frac{0.19}{tan(\theta)} \frac{H^2}{B^2} \quad (9)$$

3.2. The strength-based design criterion

The strength-based design criterion (STR_1 for steel S275, STR_2 for steel S355) proposed by (Montuori et al., 2013) is also adopted to design the diagrid models. In particular the STR_2 approach has been applied only to slenderness values H/B equal to 2, 5, 8, with the objective to highlight the effect of material strength on the provided solution. The gravity loads give rise to a global downward force on the generic diagrid module (Figure 1, the first on the left) identified by the subscripts m and k along the building elevation and perimeter, respectively. Assuming that the central core occupies the 25% of the floor area, the perimeter diagrid shares the 37.5% of the floor gravity load. The gravity downward load on each module ($F_{m,k,G}$) and the diagonal compressions ($N_{m,k,G}$) are given by:

$$F_{m,k,Q} = \frac{0.375 Q_m}{n_k} \quad N_{m,k,Q} = \frac{0.375 Q_m}{n_k} \cdot \frac{sin(\theta)}{2} \quad (10)$$

where n_k is the number of modules along the perimeter.

The horizontal wind forces cause a global overturning moment and a shear force. In particular, the global overturning moment M_m that acts on the m-th module, provides a vertical force on the module $F_{m,k,M}$, whose direction and value varies with the position of the module itself, as shown in Fig. 1 (the one at the center). The values of $F_{m,k,M}$ and of the relative axial loads $N_{m,k,M}$ on diagonals (that could be in tension or in compression), are given by the following equations:

$$F_{m,k,M} = \frac{M_m \cdot d_k}{\Sigma_{i=1}^{n_k} d_i^2} \quad N_{m,k,M} = \pm F_{m,k,M} \cdot \frac{sin(\theta)}{2} \quad (11)$$

where d is the distance between the module and the centroid of the plan shape.

where d_i is the distance between the *ith* module and the centroid of the plan shape

The global shear force acting at the m-th level of the module, provides a horizontal force in each module $F_{m,k,V}$, that depends on the inclination between the module and the direction of wind, as shown in Fig. 1 (the last on the right). The values of $F_{m,k,V}$ and of the relative axial loads $N_{m,k,V}$ on diagonals (that could be in tension or in compres-

sion), are given by the following equations:

$$F_{m,k,V}=\frac{V_m\cdot cos(\alpha_k)}{\Sigma_{i=1}^{n_k} cos(\alpha_i)} \quad N_{m,k,V}=\pm F_{m,k,M}\cdot\frac{cos(\theta)}{2} \tag{12}$$

where α_i is the angle of the *ith* module with the wind direction. In conclusion, under both gravity and wind loads, the axial force in the diagonals is given by the sum of the three contributions $N_{m,k,Q}$, $N_{m,k,M}$, $N_{m,k,V}$, as follows:

$$\begin{aligned} N_{tot}&=N_{m,k,Q}+N_{m,k,M}+N_{m,k,V}\\ &=\frac{0.375Q_m}{n_k}\cdot\frac{sin(\theta)}{2}\pm\frac{M_m\cdot d_k}{\Sigma_{i=1}^{n_k} d_i^2}\cdot\frac{sin(\theta)}{2}\pm\frac{V_m\cdot cos(\alpha_k)}{\Sigma_{i=1}^{n_k} cos(\alpha_i)}\cdot\frac{cos(\theta)}{2} \end{aligned} \tag{13}$$

Then, cross section areas for diagonals are obtained from the design formulae provided by Eurocode 3 (EN 1993-1-1, 2005) for member strength and stability.

3.3. Optimization process

The diagonal cross sections for the diagrid patterns of the building models are also designed by means of sizing optimization processes, which aim to minimize the structural weight, based on either strength or stiffness requirements. Indeed, assessing and comparing the response of the strength and stiffness based structural solutions designed according to the hand calculation procedures, it has been possible to establish whether the strength demand or the stiffness demand governs the design of the diagrid, for each value of slenderness and diagonal angle. Then, in the optimization process: if the predominant criterion is stiffness, the building top drift is constrained to be not greater than H/500 (eq. 14 on the left); on the contrary, if the governing criterion is strength, the member strength demand-to-capacity ratio (DCR) is constrained to be not greater than one (eq. 14 on the right). The optimization problem, treated with mono-objective genetic algorithms implemented in Grasshopper (Rutten 2007), is formulated as follows:

OPT-STF

Minimize	$\gamma_s \cdot \sum_{i=1}^{n} L_i \cdot A_i$
Subject to	$D_{top} \le \frac{H}{500}$
	$10\ cm \le b \le 150\ cm$ $1\ cm \le t \le 20\ cm$
Variables	b, t

OPT-STR

Minimize	$\gamma_s \cdot \sum_{i=1}^{n} L_i \cdot A_i$
Subject to	$DCR_{max} \le 1$
	$10\ cm \le b \le 150\ cm$ $1\ cm \le t \le 20\ cm$
Variables	b, t

(14)

where: γ_s is the unit weight of steel material, L_i and A_i are length and area of the i-th structural member, b and t are width and thickness of the SHS member.

A crucial aspect of the mono-objective algorithms is that, since only one objective function can be optimized, the constraint conditions, to be taken into account, should be included in the expression of the objective function, by means of a penalty factor. The algorithm rejects the solutions that do not meet the constraint; indeed, the penalty factor α is such that, when the quantity, in absolute value, differs from zero, and therefore the constraints are not respected, it affects the value of the objective function and the current solution is rejected.

Therefore, the Objective Functions (OF) for the stiffness-constrained (OPT-STF) and strength-constrained (OPT-STR) problem are given by the following Eq. (15):

OPT-STF

$$OF=\gamma_s\cdot\sum_{i=1}^{n} L_i\cdot A_i+\alpha\cdot\left|D_{top}-\frac{H}{500}\right|$$

OPT-STR (15)

$$OF=\gamma_s\cdot\sum_{i=1}^{n} L_i\cdot A_i+\alpha\cdot\left|DCR_{max}-1\right|$$

4. Design Outcomes: Hand Calculations and Optimization

A first assessment of the efficacy of the hand-calculation STF and STR design procedures is provided in Table 3, as a function of both building aspect ratio H/B and diagonal angle θ. In particular, three different marks are used for qualifying the outcomes of the design procedures, as: admissible solution, none admissible solution, best solution. The "admissible solutions" satisfy both strength checks (members $DCR \le 1$) and stiffness requirement ($D_{top} \le H/500$), while the wording "none admissible solutions" means that both the strength and stiffness criteria do not provide satisfactory solutions, i.e., the strength-based design solution does not satisfy the stiffness requirements, and the stiffness-based design solution does not satisfy the strength requirements. The empty symbol indicates that the solution is acceptable, but it is not the best one in terms of structural weight (the lightest one), while solid symbols indicate solutions characterized by the lowest weight.

From the table, it is evident that for low slenderness value (2, 3, 4), admissible solutions are only given by applying the strength-based design procedure, i.e., by selecting the member cross sections on the basis of the member strength (or stability) demand. On the contrary, for high slenderness values (6, 7, 8), the only acceptable diagrid solutions are the ones obtained by applying the stiffness-based design method, i.e., by selecting the diagonal cross sections on the basis of the global stiffness demand. The slenderness value of 5 represents a transition between the

Table 3. Efficacy of STF and STR design procedures

H/B θ	2	3	4	5	6	6.6	8
50°	●	●	●				
60°	●	●	●	■ ○	■	■	■
70°	●	●	×	■ ●	■	■	■
80°				■	■	■	■

■ STF best weight
□ STF admissible
● STR_1 best weight
○ STR_1 admissible
× none admissible

two classes of diagrid behavior: in fact, for θ=60° both solutions are acceptable, with the stiffness-based one lighter than the strength-based counterpart; further, for θ=70°, the two design solutions have the same weight. This observation has been utilized for establishing the constraint to assign in the optimization process, as anticipated in the previous section.

It is worth observing that two cross section areas result from the STF design approach for each module, namely the diagonal member area required for bending stiffness and the one required for shear stiffness (Eq. 8). Since each façade should behave both as flange (in bending) and as web (in shear), the largest area value is finally assigned to the diagonal members for each module. Therefore, within the STF design approach, it is interesting to assess the effect of the building slenderness and diagrid angle on the prevailing stiffness demand, i.e., bending or shear. For this purpose, the non-dimensional height z*/H is provided in Fig. 2, where z* is the height which separates the diagrid modules with cross section area of diagonals deriving from bending stiffness demand (below z*), from the ones with area deriving from shear stiffness demand (above z*).

It is possible to observe that z*/H is between 0.7 and 0.75 for diagrids with θ=50°, whichever is the building slenderness (H/B=2, 3, 4), indicating that ¾ of the diagrid design is governed by the flange behavior. Increasing θ, the height z* is much lower and strongly depends on H/B, being between 0.4 and 0.7 for θ=60° and between 0 and 0.4 for θ=70°. Finally, for θ=80°, z* is always 0. These results show that, increasing the diagrid slope, the bending rigidity of the structure inherently grows, therefore a smaller diagonal area is required to provide bending stiffness, and the shear stiffness demand is the one that governs the cross section sizing.

In Fig. 3 all acceptable solutions are provided in terms of structural weight as a function of the building slenderness. The solid part of the stacked bars allows for identifying the diagrid angle corresponding to the minimum steel weight for each H/B and according to each design approach. As already observed from Table 3, strength (red bars) dominates the design for H/B<4, while stiffness (green bars) dominates for H/B>5, and both stiffness-based and strength-base solutions are acceptable for H/B=5. The sizing optimization procedure (blue bars) provides the lightest solutions, for all values of H/B.

In Fig. 4 the best solutions in terms of structural weights are depicted as a function of building slenderness and for each design procedure. It is important to note that, for each design criterion, only the solution relative to the diagonal angle that provides the minimum weight is reported. The

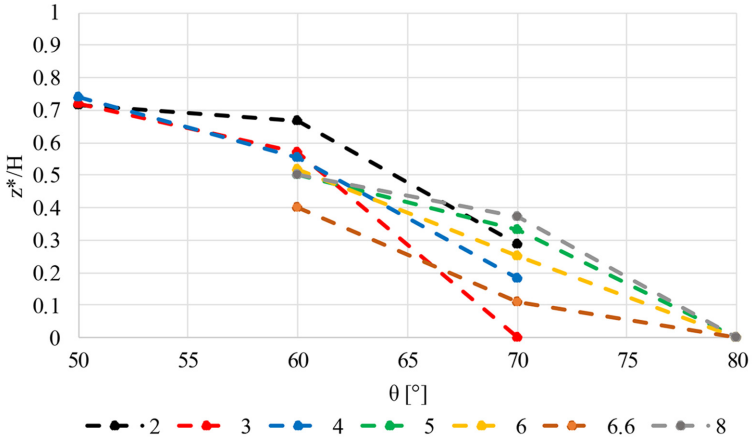


Figure 2. STF approach: height separating flange and web predominant behavior.

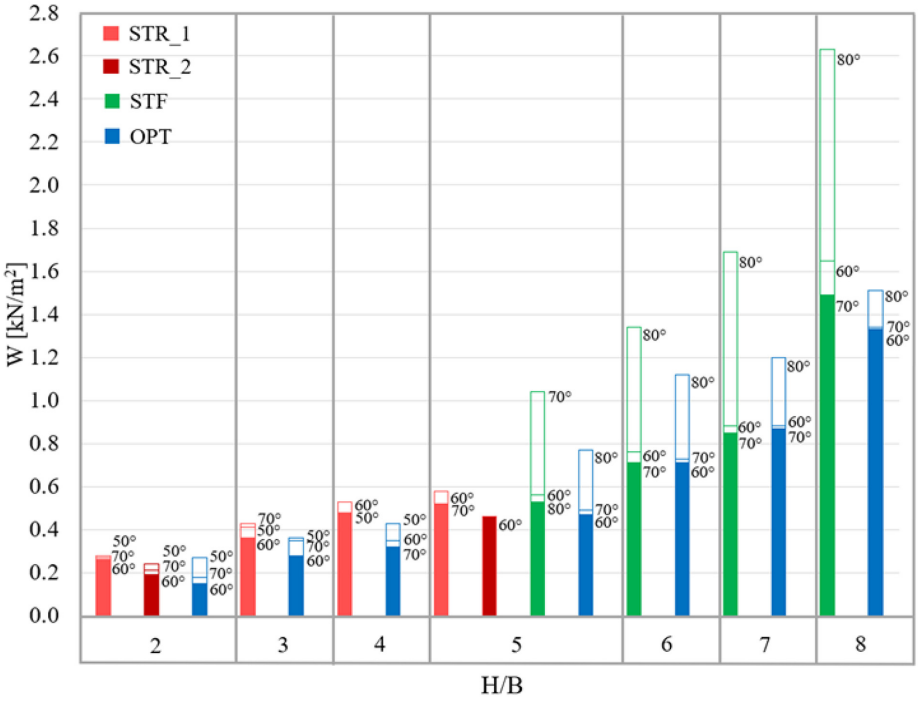


Figure 3. Structural weight of admissible solutions.

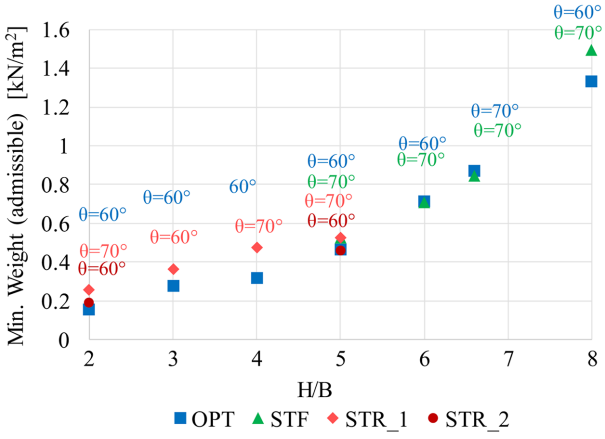


Figure 4. Minimum structural weight of admissible solutions.

graph suggests the premium-for-slenderness concept for diagrid structures, showing that the structural weight increases as a function of H/B, with an almost linear trend up to H/B=4, while for larger H/B the increase is more than linear. Further, it is evident that the diagonal angle of the best solutions throughout the H/B range are 60° and 70°, a compromise between the optimal angle to carry bending, 90°, and the optimal angle to carry shear, 45°.

It is also worth noticing that when design is governed by strength, a wider range of allowable solutions is possible by adopting different steel grades for the diagonal members (e.g., S275 for STR_1, S355 for STR_2), with very lightweight solutions for high-strength steels.

5. Structural Analyses and Performance Assessment

The diagrid structural solutions obtained by means of hand calculation procedures (STF and STR) and sizing optimization process for the building models, characterised by H/B ranging from 2 to 8 and diagonal angle between 50° and 80°, are analysed using FEM numerical models. Factored gravity and wind loads previously specified (section 2) have been applied to the models.

In order to present a complete assessment of the structural performance exhibited by the different diagrids, some major response parameters are thoroughly examined and

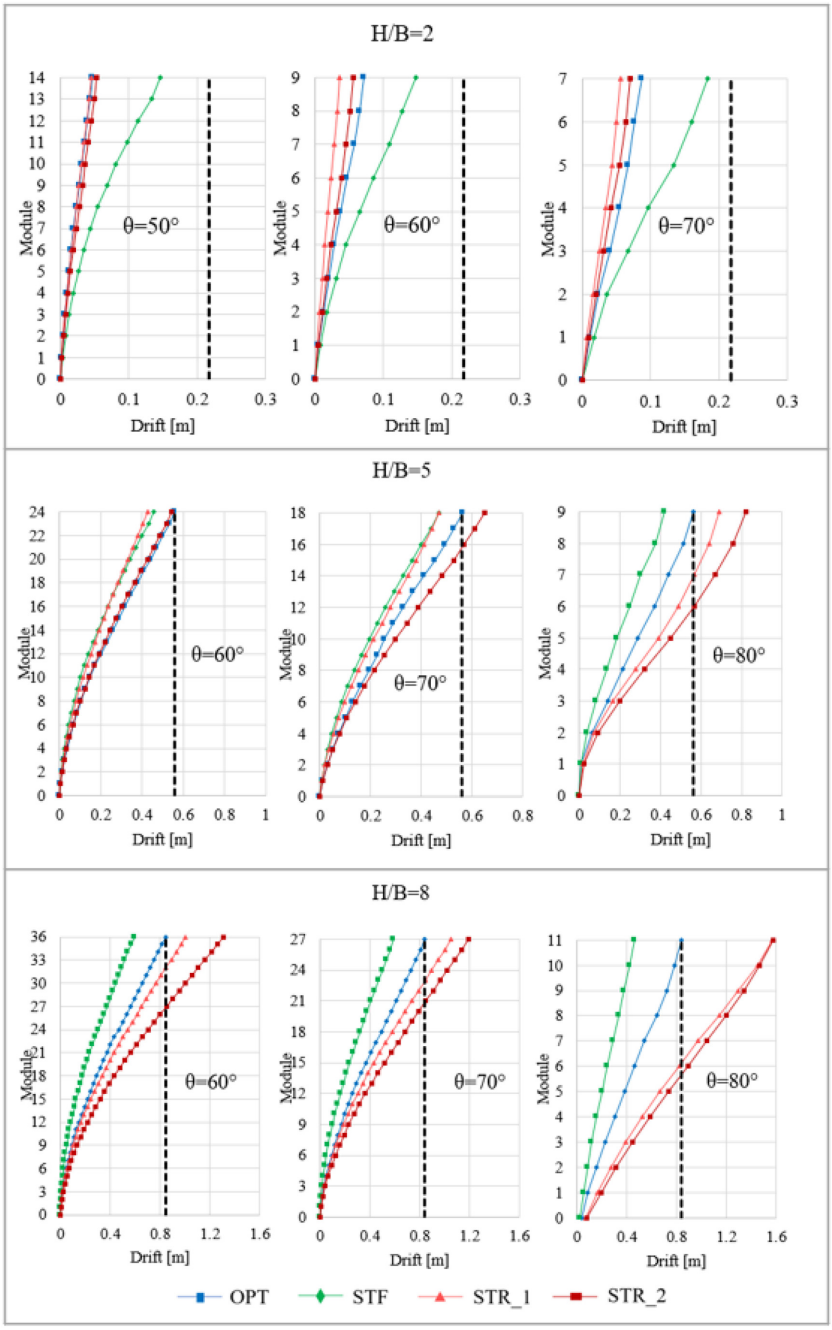


Figure 5. Lateral drifts.

compared, in particular: lateral drift; interstory drift ratio (IDR); strength demand to capacity ratio in the diagonal members (DCR, defined as the tension/compression axial force under design loads normalized to the yield/buckling capacity of the relevant member). The limit value for the above parameters are: top drift equal to H/500, IDR equal to 1/200, DCR equal to 1. For the sake of brevity, only the results obtained for H/B equal to 2, 5 and 8, are shown in the following figures; however, the discussion covers all design solutions and slenderness values.

In Fig. 5, the lateral drift at the levels of the modules' top is depicted, for H/B=2, 5, and 8, respectively. For each slenderness value, the solutions obtained for the different angle values according to the different design procedures are compared. Looking at the diagrids with H/B=2, and, in general, with H/B≤4, it can be stated that all design strategies guarantee solutions exhibiting top drift well within the limit of H/500. For slenderness equal to 5, in particular for the diagonal slope θ of 60° and 70°, all design strategies (except for STR_2) provide solutions with top drifts less than H/500; in particular, STR_1 and STF procedures provide top drifts much lower than H/500, while

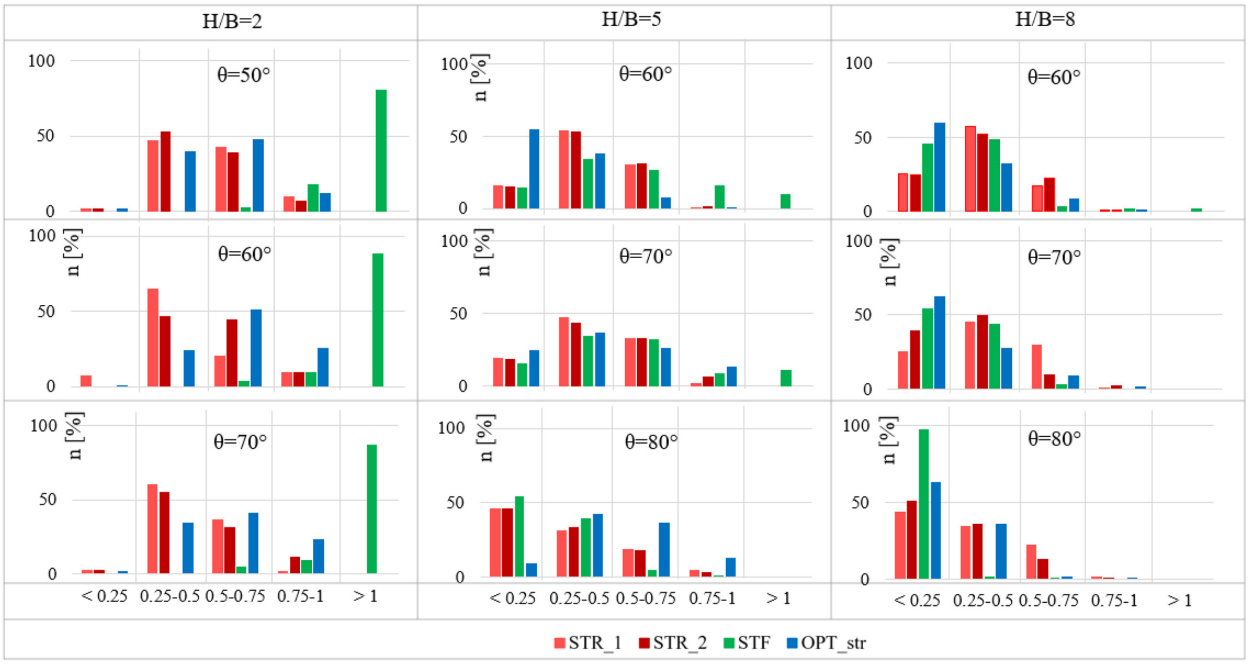


Figure 6. DCR values.

the OPT design gives a top drift very close to it. For θ= 80°, the strength approach (both STR_1 and STR_2) does not provide acceptable results in term of top drift, while the STF approach gives, also in this case too, a top drift value much lower than the target value. Finally, for slenderness values from 6 to 8, STR approach is no longer adequate to design satisfactory solutions, while STF approach provides top drift quite lower than the imposed limit; the OPT solutions, instead, always show top drifts that assume exactly the limit value.

Analysing the DCR values (Fig. 6), the STR and OPT design criteria provides structures with DCR lower than one for all members, throughout the range of building slenderness. On the contrary, the STF solutions designed

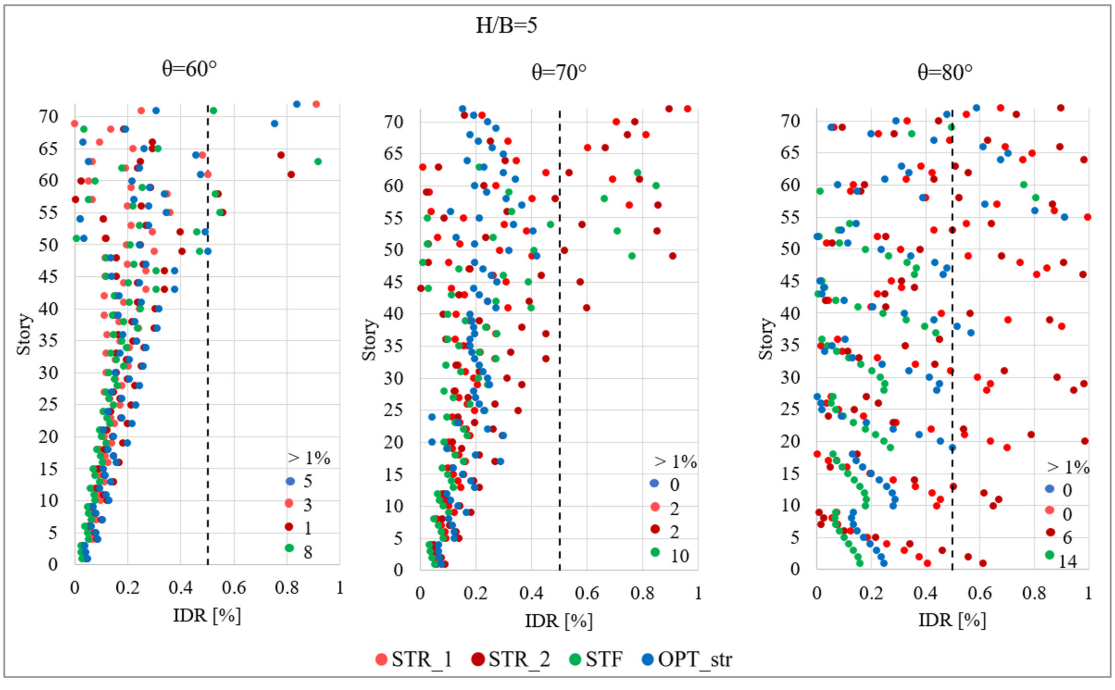


Figure 7. IDRs.

for H/B<5 have a very high percentage of elements with DCR larger than one, while, for the cases with higher slenderness (H/B≥5), the STF criterion provides acceptable solutions in terms of DCR values. In general, the OPT design criteria dominated by strength, provides a more uniform distribution, thus a higher average value, of DCRs, with respect to the hand calculation procedures.

In Fig. 7, the interstory drift ratios (IDR) are depicted, only for the case H/B=5. It can be observed that almost all diagrid structures designed according to the STR and STF procedures, and in particular the ones characterized by the steepest diagonal angles, show unsatisfactory performance in terms of interstory drift, with IDR exceeding the limit value of 1/200. The OPT solutions, instead, are less, or almost not, affected by this problem.

This is an important and recurrent design issue, arising in all structure types characterized by a primary bracing system employing mega-diagonals which span over multiple floors, as in diagrids, braced tubes and exoskeleton systems. In fact, in the diagrid module, concentrated lateral loads are applied along the diagonal length, at the locations where intermediate floors intersect the diagonal member. Therefore, while the overall lateral stiffness of the building structure, thanks to the triangle configuration, strictly depends on the axial stiffness of the diagonal members, on the contrary, the lateral stiffness within the module length only relies on the flexural stiffness of the diagonals, which could not be adequate. In (Montuori et al., 2014b) this problem has been thoroughly addressed and solved, by means of a secondary bracing system (SBS), and a simplified procedures for the consequent SBS member design. This problem has been also solved in (Tomei et al., 2018), by means of a structural optimization process, explicitly involving constraint conditions on the IDR maximum value.

6. Conclusions

The effect of slenderness on the structural design of tall buildings is a major concern. Increasing the building slenderness the demand for lateral stiffness, and, in turn, the structural material consumption, usually increase with a remarkable gradient. Diagrid structures, emerged as innovative solutions merging structural efficiency and aesthetic quality, are excellent candidate for the structural system of slender buildings, as in the case of the super-slender tower at 53rd West 53rd Street of NYC, also known as MoMA Tower. Designed by Jean Nouvel, this building is characterized by a pyramidal form and by an aspect ratio equal to 12; it is founded on the aesthetics of exposed elements arranged in an almost random pattern of diagonal elements, an irregular diagrid, which provides stiffness and strength.

This paper has been focused to assess the effect of slenderness on the structural behavior and on the optimal design parameters of diagrid tall buildings. For this aim, a parametric design of diagrid structures characterized by different aspect ratios and diagrid angles has been carried out, according to hand-calculation procedures (stiffness-based and strength-based) and sizing optimization methods. The outcomes of the parametric design phase and the results on FE analyses developed for the design solutions, suggest the following major conclusions and design implications.

The inherent stiffness of diagrid structures leads to an impact of slenderness on design solutions less remarkable than for traditional structural systems utilized for tube configurations. Considering, as an example the framed tube system, and in particular the paradigmatic and refined structural design of the WTC Twin Towers, characterized by an aspect ratio H/B equal to 6.6, the dramatic efficiency of the diagrid system can be even better appreciated. In fact, from the analyses carried out by De Luca et al. (2003), also confirmed by the comprehensive results obtained by NIST in the extensive post-WTC-collapse research (Sadek, 2005), some interesting considerations can be extracted. With a unit steel weight of 1.77 kN/m^2, the WTC structure exhibits values of cumulative drift under original design wind loads in the range of H/300-H/200, quite larger than H/500, proving a certain inefficiency of the frame tube structural type in this slenderness range. On the contrary, the diagrid structures designed in this paper for H/B=6.6 have unit steel weight in the range of 0.8-0.9 kN/m^2, and exhibit top drift equal to or lower than H/500.

Looking more specifically at the effect of slenderness on the governing design criterion and on the design outcomes, the following observations can be made. For building aspect ratio equal to 2, 3 and 4 (corresponding to number of stories between 27 and 55), the design is mainly governed by member strength demand rather than by global stiffness requirements, independently on the diagrid angle. Further, a slight weight premium for slenderness can be observed in this range, since the unit structural weight increases as a gentle linear function of H/B. For aspect ratios from 6 to 8 (corresponding to number of stories between 80 and 108), the structural design is mainly governed by stiffness for all diagrid angles, and the weight increases as a more-than-linear function of H/B. Aspect ratio around 5 (number of stories: 72) is the threshold separating the design solutions governed by local strength demand from the ones controlled by the global stiffness requirements. In this particular case, of H/B=5, the stiffness and strength based solutions have comparable weight.

While the predominant design criteria (strength or stiffness) mainly depends on the building slenderness and does not depend on the diagrid angle, the latter strongly affects the efficiency of the structural solutions, particularly the ones controlled by stiffness requirements. Throughout the parametric range of H/B, the diagonal angles of the least weight, i.e., the most efficient, solutions are always between 60° and 70°.

A design strategy based on sizing optimization techniques has been proposed as either an alternative to, or a refinement of, the preliminary design methods. The approach here proposed can also be used for complex and non conventional patterns, like the one of the MoMA Tower, which can be hardly analyzed through simplified procedures. An interesting feature of the optimization process is that it can take into account at the same time both strength and stiffness criteria, thus providing solutions that respect both limits. Furthermore, the analysis of the strength demand to capacity ratios calculated for the diagonal members shows that a better exploitation of the member strength and buckling capacity is obtained in the optimized solutions with respect to the conventionally designed solutions.

Finally, the optimized structural solutions are always characterized by comparable or lower weight than the solutions designed according to procedures suggested in literature, but the distribution of diagonal cross sections along elevation is generally quite different; this gives rise to a superior performance of the optimized solutions, and, therefore, to an increase of structural efficiency. In particular, while large interstory drifts usually arise at the upper modules of the diagrid solutions conventionally designed, the optimization process gives rise to solutions that are almost not affected by this local flexibility effect. Indeed, the hand-calculation solutions provide cross-sectional areas of the module diagonals that decrease along elevation, from the bottom to the top, on the basis of the decreasing value of shear and overturning moment, and of the relevant stiffness demands. The flexural stiffness of the diagonals at upper modules, therefore, is quite limited and not sufficient to control the lateral deformations arising at the floor levels within the module height, giving rise to large interstory drifts. On the contrary, in the optimization process, this local flexibility effect at upper modules is recognized and prevented by increasing the corresponding diagonal sections, which consistently have areas larger than the counterparts in the hand-calculation solutions.

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