Influence of the geometrical shape on the structural behavior of diagrid tall buildings under lateral and torque actions

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Abstract:	Diagrid structural systems are more and more exploited worldwide for the realization of tall buildings, due to their versatility, their capability to realize complex-shaped constructions, and their efficiency in limiting lateral displacements. Plenty of research has been carried out in the last decade aimed at analyzing the structural behavior of these systems, mainly considering buildings with square or rectangular floor plans and commonly investigating only the lateral deformability of the structure. In this paper, we investigate the influence of some geometrical parameters on the structural response of diagrid tubular buildings, under both lateral and torque actions. To this aim, we make use of a matrix-based method (MBM), which was recently developed for the structural analysis of generic diagrid structures.
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Dear Editor,

I am very glad to resubmit the manuscript: “Influence of the geometrical shape on the structural behavior of diagrid tall buildings under lateral and torque actions” by Giuseppe Lacidogna, Domenico Scaramozzino and Alberto Carpinteri, for consideration of publication within the “Developments in the Built Environment” Journal.

This paper deals with the numerical investigation of the structural response of diagrid structures when subjected to both lateral and torque actions. In particular, the influence of geometrical parameters, such as the inclination of external diagonals, the floor plan shape and the building aspect ratio, on the diagrid structural behavior is investigated. The calculations have been carried out by means of a matrix-based procedure, recently published by the Authors, which allows for a quick evaluation of the overall behavior of the diagrid structure. Moreover, to the best of the Authors’ knowledge, this is the first time that the diagrid torsional behavior is thoroughly addressed and analyzed.

The original paper has been modified to overcome the criticalities emerged from the review process. In the revised version of the manuscript, we provided detailed explanations performing relevant references to the reviewers' observations. All the modified and new parts are highlighted in yellow in the updated text. We hope that the Editorial Board will agree on our opinion.

Sincerely Yours,

Giuseppe Lacidogna

on behalf of the Authors

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Highlights:

- The comprehension of the structural response of diagrid systems under both lateral and torque actions is vital for correct optimization purposes.

- The lateral and torsional deformability of diagrid structures is investigated, by changing geometrical parameters like the inclination of external diagonals, the floor plan shape and the building aspect ratio.

- The inclination of external diagonals plays a central role in modifying both the lateral and torsional deformability, whereas the floor plan shape affects the structural response usually when the diagonal angle is not within the optimal range.

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Referring to the submission of the article "Influence of the geometrical shape on the structural behavior of diagrid tall buildings under lateral and torque actions" to the "Developments in the Built Environment" Journal, the Authors declare no conflict of interest.

Sincerely Yours,

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Influence of the geometrical shape on the structural behavior of diagrid tall buildings under lateral and torque actions

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Abstract

Diagrid structural systems are more and more exploited worldwide for the realization of tall buildings, due to their versatility, their capability to realize complex-shaped constructions, and their efficiency in limiting lateral displacements. Plenty of research has been carried out in the last decade aimed at analyzing the structural behavior of these systems, mainly considering buildings with square or rectangular floor plans and commonly investigating only the lateral deformability of the structure. In this paper, we investigate the influence of some geometrical parameters on the structural response of diagrid tubular buildings, under both lateral and torque actions. To this aim, we make use of a matrix-based method (MBM), which was recently developed for the structural analysis of generic diagrid structures. Various building configurations, differing for the aspect ratio, the inclination of the external diagonals, and the floor plan shape, are considered and the structural solutions which allow to minimize the lateral displacements and torsional rotations are thoroughly surveyed.

Keywords: Diagrid, Tall buildings, Geometrical shape, Lateral displacements, Torsional rotations.

1. Introduction

Nowadays the increasing growth of global population associated with the intense urbanization phenomenon claims for more spaces intended for housing and office services within the cities. This inevitably leads governors and designers to consider a more efficient and rational usage of the city land, which is causing a tireless growing and development of tall buildings [1]. Although tall buildings can provide a positive answer to the spacing problem and they can constitute successful solutions in defining the skyline of modern cities, they pose a variety of sustainability challenges which must be taken into account throughout the whole design and construction process [2-4]. The sustainability of a tall building should be investigated considering three main dimensions, namely the social, economic and environmental dimension [4], and it should be addressed via a multidisciplinary approach involving various disciplines. From a purely Structural Engineering point of view, aiming to the sustainability of a tall building implicates to find the optimal design solutions which allow to use the minimum amount of material while enhancing the global performance of the structure [5]. Such performance is usually evaluated by controlling the lateral displacements, since the need to limit the lateral deformability of tall structures plays a pivotal role in the design phases and has a strong impact in defining the principal resisting elements.

Among the different solutions adopted to increase the structural performance and sustainability of tall buildings, diagrid systems have been one of the most widely exploited in the last decade [6-8]. These are composed by tubular truss systems which are located on the exterior of the building and allow to reach high structural performances by exploiting the axial resisting mechanism of inclined mega-diagonals. Moreover, being composed by an assembly of triangular modules on the building façade, they allow to realize complex-shaped structures achieving noteworthy architectural effects [9], like in the case of the Swiss Re Tower in London, the Tornado Tower in Doha, etc.

Many researchers have dealt with the structural behavior and performance of diagrid systems. Moon *et al*. firstly proposed an analytical methodology for the preliminary design of diagrid tubes and showed that there exists an optimal inclination of the external diagonals in order to minimize the lateral displacement [10]. Subsequently, complex-shaped diagrid systems, such as twisted, tilted and freeform diagrid towers, were also analyzed by means of Finite Element (FE) calculations [11]. Zhang *et al*. explored the optimal diagonal inclination in diagrid tube buildings composed of straight diagonals with gradually varying angles [12], whereas Montuori *et al*. investigated the influence of stiffness- and strength-based criteria on the design of the diagonal members [13]. Real case studies, such as the Hearst Tower in New York, the Swiss Re Tower in London and the Guangzhou West Tower in Guangzhou, were also surveyed by Mele *et al*. via simplified hand calculations [14]. The influence of some geometrical patterns was also investigated on the structural behavior [15-19], and special secondary bracing systems were also proposed by Montuori *et al.* in order to minimize the effect of local structural issues which could undermine the building performance, such as the stability of interior columns and the excessive inter-story drift [20].

As for the methodologies which have been used for the structural analysis of diagrid buildings other than FE calculations, Liu and Ma proposed an analytical approach, based on the modular method, in order to calculate the shear and bending rigidity of polygonal diagrid tubes [21]. More recently, Lacidogna *et al.* developed a matrix-based method (MBM), for the investigation of generic diagrids, in order to obtain information not only regarding the lateral deformability of the diagrid structure but also concerning its torsional behavior [22]. In particular, the MBM was developed by the authors with the aim of providing a methodology, more expeditious than FE modelling and analysis, which allowed to obtain the fundamental information on the global behavior of the diagrid structure. The MBM was set up within a more general analytical framework, called General Algorithm, which was extensively developed by some of the authors in recent years in order to perform the structural analysis of tall buildings. By means of the General Algorithm, the interaction between various vertical resisting elements could be deeply analyzed, including unconventionally-shaped structures [23], open- and closed-section shear walls [24,25] and buildings of different height [26,27]. The General Algorithm also allowed to investigate real case studies [28,29].

As can be found out by analyzing the literature concerning diagrid systems, a lot of research has been carried out regarding diagrid tubes made up of square floor plans, but little attention has been paid when it comes to different floor shapes, such as polygonal or circular floor plans [19,21]. Moreover, although plenty of calculations has been performed regarding lateral displacements, the analysis of the diagrid torsional behavior has received no consideration at all. Here, we make use of the recently developed MBM in order to investigate the influence of some geometrical parameters, such as the diagonal inclination and the floor plan shape, on the structural response of diagrid buildings under both lateral and torque actions. In particular, after performing the analysis for four different building aspect ratios, we show that the diagonal inclination plays the key role in governing the diagrid behavior as far as lateral displacements and torsional rotations are concerned, whereas minor differences are observed when changing the floor plan shape, especially when it comes to the lateral displacements.

2. Methodology

In this Section, the fundamentals of the MBM, used to perform the structural analysis of the diagrid structures, are briefly recalled. The details of the different generated diagrid buildings, obtained by changing the total height of the building, the floor plan shape and the inclination of the external diagonals, are also shown.

2.1 The matrix-based method (MBM) for the structural analysis

The MBM is based on the following assumptions, which are meant to simplify the mathematical formulation while allowing to capture the global structural behavior: the diagonals are supposed to be only subjected to axial force, remaining into the linear elastic regime; the floors included within the triangular modules are neglected, thus the local bending and shear deformations of the diagonals are not taken into account; the considered floors, i.e. the ones lying at the end of the pinned diagonals, are assumed to remain plane after deformation, so that they can be treated as rigid bodies in the space characterized by six degrees of freedom [22]. The structure, which is considered into a three-dimensional reference system XYZ, is subjected to concentrated forces and moments, acting at the level of the floor centroids, which are grouped into the 6*N* generalized force vector $\{F\}$, being *N* the number of floors. Accordingly, the building undergoes floor displacements and rotations, which can be grouped into the 6*N* generalized displacement vector $\{\delta\}$. The linear structural problem can then be formulated through the following matrix relation:

$$\begin{Bmatrix} \{F_x\} \\ \{F_y\} \\ \{M_z\} \\ \{M_x\} \\ \{M_y\} \\ \{F_z\} \end{Bmatrix} = \begin{bmatrix} [K_{F_x\delta_x}] & [K_{F_x\delta_y}] & [K_{F_x\varphi_z}] & [K_{F_x\varphi_x}] & [K_{F_x\varphi_y}] & [K_{F_x\delta_z}] \\ [K_{F_y\delta_x}] & [K_{F_y\delta_y}] & [K_{F_y\varphi_z}] & [K_{F_y\varphi_x}] & [K_{F_y\varphi_y}] & [K_{F_y\delta_z}] \\ [K_{M_z\delta_x}] & [K_{M_z\delta_y}] & [K_{M_z\varphi_z}] & [K_{M_z\varphi_x}] & [K_{M_z\varphi_y}] & [K_{M_z\delta_z}] \\ [K_{M_x\delta_x}] & [K_{M_x\delta_y}] & [K_{M_x\varphi_z}] & [K_{M_x\varphi_x}] & [K_{M_x\varphi_y}] & [K_{M_x\delta_z}] \\ [K_{M_y\delta_x}] & [K_{M_y\delta_y}] & [K_{M_y\varphi_z}] & [K_{M_y\varphi_x}] & [K_{M_y\varphi_y}] & [K_{M_y\delta_z}] \\ [K_{F_z\delta_x}] & [K_{F_z\delta_y}] & [K_{F_z\varphi_z}] & [K_{F_z\varphi_x}] & [K_{F_z\varphi_y}] & [K_{F_z\delta_z}] \end{bmatrix} \begin{Bmatrix} \{\delta_x\} \\ \{\delta_y\} \\ \{\varphi_z\} \\ \{\varphi_x\} \\ \{\varphi_y\} \\ \{\delta_z\} \end{Bmatrix}. \tag{1}$$

In Eq. (1), $\{F_x\}$, $\{F_y\}$ and $\{F_z\}$ represent the vectors containing respectively the floor forces along X, Y and Z direction, $\{M_z\}$ is the vector of the floor torque moments, whereas $\{M_x\}$ and $\{M_y\}$ represent the vectors containing respectively the out-of-plane floor moments along X and Y axes. As for the displacements, $\{\delta_x\}$, $\{\delta_y\}$ and $\{\delta_z\}$ represent the vectors containing the displacements along X, Y and Z direction respectively, $\{\varphi_z\}$ is the vector of the in-plane torsional rotations, whereas $\{\varphi_x\}$ and $\{\varphi_y\}$ represent the vectors containing the out-of-plane rotations along X and Y axes respectively. The global stiffness matrix is a symmetric $6N \times 6N$ matrix, which is reported in Eq. (1) by a partition based on the six degrees of freedom of each floor. Each $N \times N$ submatrix stands for the stiffness matrix which links each force/moment vector to each displacement/rotation vector. Given the properties of the diagrid building, i.e. the structure geometry and diagonals' properties, each submatrix is analytically computed by applying unitary displacements/rotations to selected floors and calculating the total reaction forces/moments arising at the other floors. For more details about the procedure for the evaluation of the stiffness matrices, the reader can refer to [22].

2.2 The generated models with changing geometrical parameters

In order to study the influence of the geometrical shape on the structural behavior of diagrid systems, various buildings with different geometrical parameters (diagonal inclination and floor plan shape) were investigated and analyzed by means of the MBM. For each structural model, some geometrical and material parameters were kept constant, which are the following ones: inter-story height equal to 3.5 m, total floor area equal to 900 m^2, diagonals' elastic modulus equal to 210 GPa and cross-sectional area equal to 380 cm^2 for all the diagonals (Tab. 1). Note that, in real diagrid structures, diagonals usually exhibit tapered cross sections towards the top of the building. For sake of completeness, this case has also been considered and the results are reported in the Appendix. As is shown in that section, considering a different distribution for the diagonal cross-sectional area does not affect the main conclusions of the present analysis.

Tab. 1. Main parameters of the generated diagrid buildings.

Parameter	Value
Inter-story height [m]	3.5
Total floor area [m^2]	900
Diagonals' elastic modulus [GPa]	210
Diagonals' cross-sectional area [cm^2]	380
Total building height [m] (total number of floors [-])	126 (36), 168 (48), 210 (60), 252 (72)

Four different heights of the building were taken into account, namely 126 m, 168 m, 210 m and 252 m, which correspond to four different numbers of floors, i.e. 36, 48, 60 and 72 respectively (Tab. 1). For each building height, four different floor plan shapes were investigated, namely square, hexagonal, octagonal and circular. Six different diagonal inclinations were adopted by considering different numbers of floors included within the diagonal module, namely 1, 2, 3, 4, 6 and 12 intra-module floors. Therefore, twenty-four diagrid models were investigated for each building height (Tab. 2), for a total of ninety-six structures. Each diagrid module was comprised of twenty-four diagonals, placed all over the exterior of the building. The details of the investigated models with changing geometrical parameters are also observable from Fig. 1.

Thus, each structure was assumed to be subject to an horizontal load of 30 kN/m along the X axis and a torque load of 70 kNm/m, uniformly distributed along the height of the building, as shown in Fig. 2. The distributed loads were then correspondingly converted into concentrated forces and moments acting at the floor level, and the lateral displacements and torsional rotations of the floor were finally obtained by the application of the MBM. It is worthing to note that this particular load distribution is not affecting the results of our analysis. In the Appendix, the case of a reverse triangle load pattern is also reported and, as is shown in that section, considering a different load distribution is found not to affect the main conclusions of the present analysis.

Tab. 2. Variable geometrical parameters of the different structures.

Structure	Floor plan shape	Number of intra-module floors [-]	Diagonal angle [°]
SQ.1	Square	1	34.99
SQ.2		2	54.46
SQ.3		3	64.54
SQ.4		4	70.35
SQ.6		6	76.61
SQ.12		12	83.21
HE.1	Hexagon	1	36.97
HE.2		2	56.40
HE.3		3	66.11
HE.4		4	71.63
HE.6		6	77.51
HE.12		12	83.68
OC.1	Octagon	1	37.57
OC.2		2	56.98
OC.3		3	66.57
OC.4		4	72.00
OC.6		6	77.77
OC.12		12	83.82
CI.1	Circle	1	38.37
CI.2		2	57.73

CI.3	3	67.17
CI.4	4	72.48
CI.6	6	78.11
CI.12	12	83.99

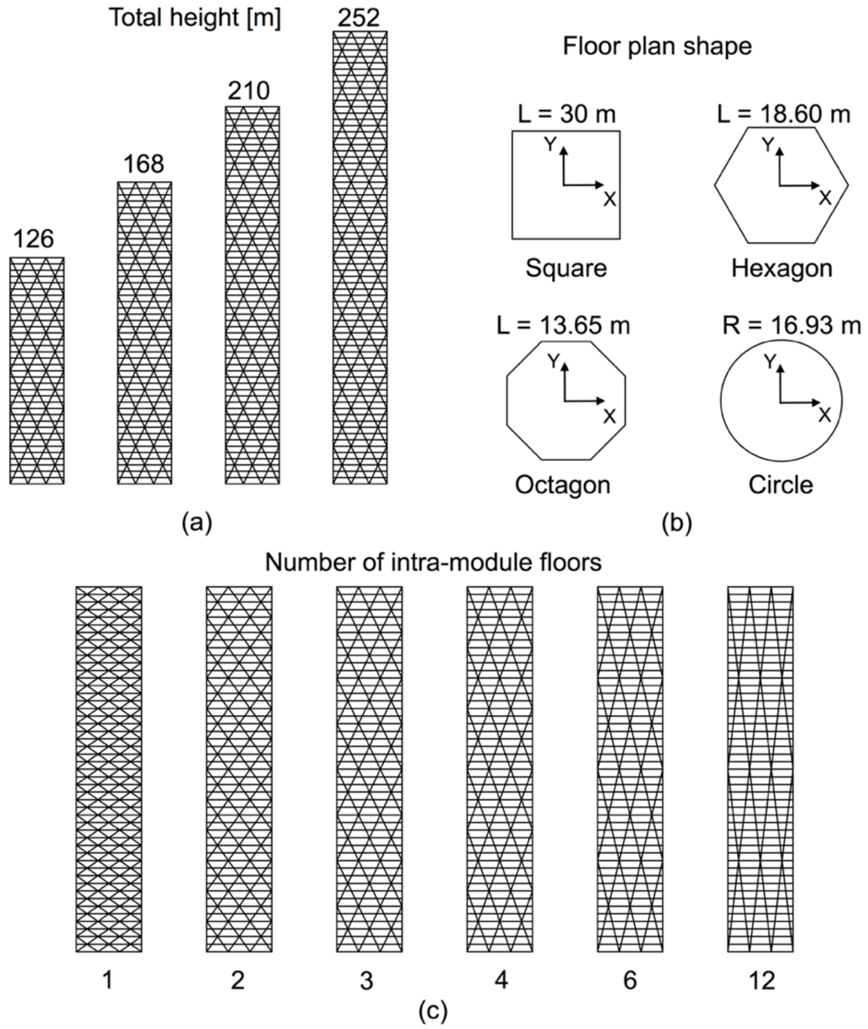

Fig. 1. Geometry of the generated diagrid buildings: (a) four different total heights; (b) four different floor plan shapes; (c) six different diagonal inclinations.

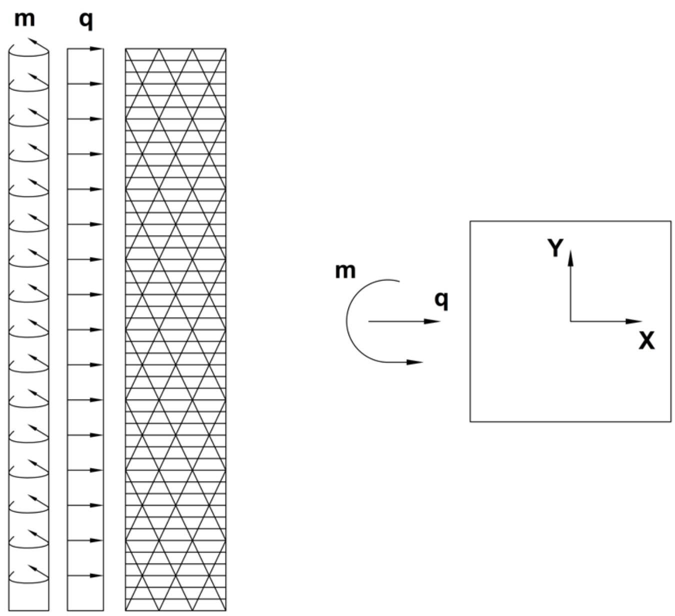

Fig. 2. Uniform load pattern: *q* refers to the distributed horizontal load, *m* to the distributed torque moments.

3. Results and Discussion

In this Section the results arising from the application of the MBM to the generated diagrid structures are reported, for the four different heights of the building.

3.1 36-story building

In Tab. 3 and Fig. 3, the results are shown for the twenty-four diagrid structures referring to the 36-story 126 meters-high building. Tab. 3 reports the total number of diagonal modules along the height of the building (which only depends on the number of intra-module floors), the resulting total mass of the diagonals, and the lateral displacements and torsional rotations evaluated at the top of the structure. To better visualize the results, the displacements and the rotations are also displayed in Fig. 3. In Figs. 3a and 3b the obtained lateral displacements are reported depending on the number of intra-module floors and the diagonal inclination, respectively, whereas in Figs. 3c and 2d the torsional rotations are shown.

Tab. 3. Displacements and rotations for the 36-story building (minimum values of displacements and rotations for each floor plan shape are in bold).

Structure	Total number of modules [-]	Diagonals' total mass [ton]	Lateral displacement [m]	Torque rotation [E-4 rad]
SQ.1	36	1563	0.186	**0.34**
SQ.2	18	1101	0.071	0.47
SQ.3	12	993	**0.060**	0.77
SQ.4	9	952	0.063	1.21
SQ.6	6	921	0.082	2.47
SQ.12	3	903	0.207	9.29
HE.1	36	1490	0.168	**0.29**
HE.2	18	1076	0.070	0.44
HE.3	12	980	**0.062**	0.75
HE.4	9	944	0.066	1.18
HE.6	6	918	0.090	2.44
HE.12	3	902	0.235	9.28

OC.1	36	1470	0.159	**0.28**
OC.2	18	1069	0.069	0.43
OC.3	12	977	**0.062**	0.74
OC.4	9	942	0.068	1.18
OC.6	6	917	0.094	2.43
OC.12	3	902	0.251	9.26
CI.1	36	1443	0.153	**0.27**
CI.2	18	1060	0.068	0.43
CI.3	12	927	**0.063**	0.74
CI.4	9	939	0.069	1.19
CI.6	6	915	0.097	2.48
CI.12	3	901	0.264	9.45

As can be observed from Tab. 3 and Fig. 3, the optimal solution to minimize lateral displacements corresponds to the configuration with three intra-module floors for each floor plan shape (Fig. 3a). Correspondingly, the optimal diagonal inclination to minimize the lateral displacement stands in the range 64°-67° (Fig. 3b). By examining Fig. 3a and Tab. 3, it is evident how the solutions related to two and four intra-module floors are not far from the optimal condition, leading to lateral displacements just 10% higher than the minimum ones. However, increasing the diagonal inclination, the total amount of employed material decreases (Tab. 3). A balance between the need to limit the lateral displacement and reduce the amount of employed material is then needed, when selecting the optimal structural solution in the preliminary design stages. In the optimal diagonal configuration (three intra-module floors), no significant differences can be observed when changing the plan shape. The absolute minimum displacement corresponds to the square shape (60 mm) while the highest arises from the circular one (63 mm), which is just 5% higher. The influence of the specific plan shape is otherwise important far from the optimal diagonal configuration, e.g. when considering one intra-module floor or more than six floors included within the diagonal module. In this case, as shown in Figs. 3a-b, changing the floor plan geometry can lead to not negligible differences in terms of lateral flexibility (up to 30% difference).

Different conclusions can be drawn when looking at the torsional flexibility of the building. In fact, the optimal solution to minimize torsional rotations corresponds to one intra-module floor, which is related to the minimum diagonal inclination (Tab. 3, Figs. 3c-d). This is due to the fact that torsional rigidity is related to the shear rigidity of the diagonal modules, and the latter has already been shown to achieve the highest value for low diagonal inclinations, close to 35° [10]. Note that, although the configuration associated with one intra-module floor is optimal to reduce torsional rotations, it is the one which exhibits the highest amount of employed material and leads to lateral displacements much higher than the optimal ones (Tab. 3). The results of the calculations also show that the optimal floor plan geometry to withstand torque actions corresponds to the circular shape. In fact, among the structures with the optimal diagonal inclination (one intra-module floor), the circular building exhibits the lowest torsional rotations (2.7×10^{-5} rad), the other ones providing higher values (up to 26% higher for the square building).

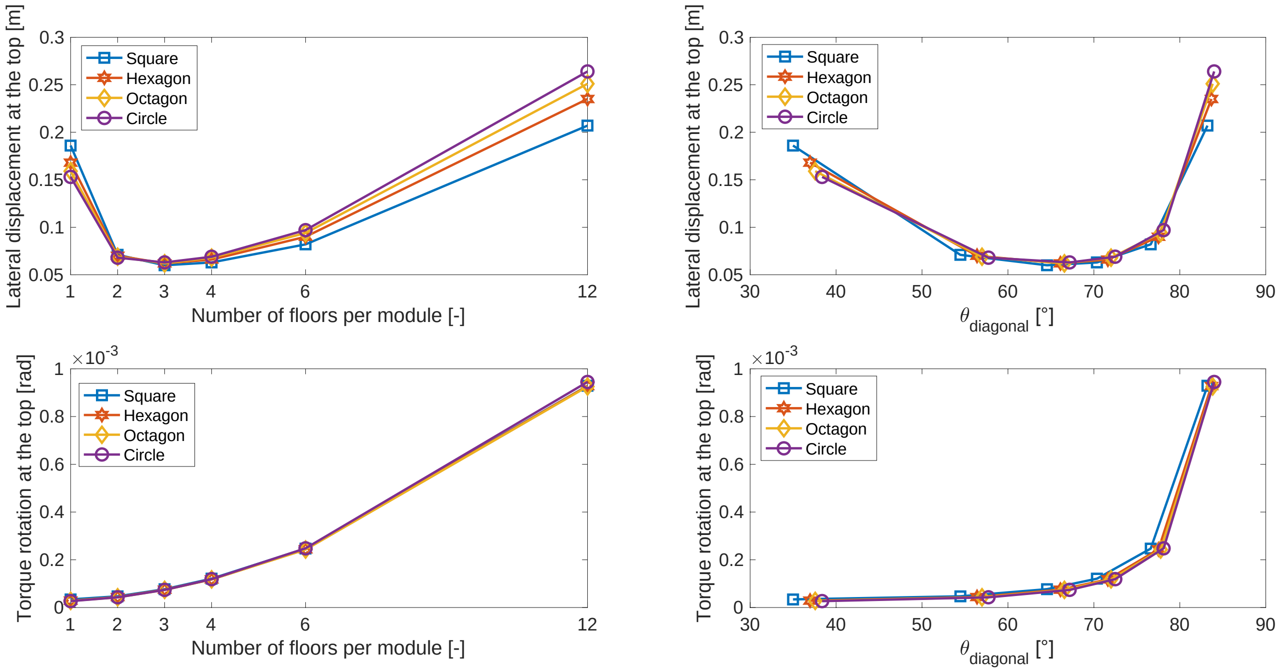

Fig. 3. Displacements and rotations for the 36-story building: (a-b) lateral displacements; (c-d) torsional rotations.

3.2 48-story building

The results obtained for the 48-story 168 meters-high diagrid buildings are shown in Tab. 4 and Fig. 4. In this case, the optimal solution to minimize lateral displacements is found to be associated to four intra-module floors for the square floor plan geometry and three intra-module floors for the other plan shapes (hexagonal, octagonal and circular). Accordingly, the optimal diagonal inclination is found to lie in the range 64°-70° (Fig. 4b). The case of the square building demonstrates that, by increasing the aspect ratio of the building, higher diagonal inclinations are expected in order to minimize the lateral displacement. Again, as in the case of the 36-story building, the influence of the specific plan geometry is significant only in the region which is far from the optimal solution, e.g. for one, six or twelve intra-module floors (Fig. 4a), and it leads to negligible differences in the region of the optimal diagonal inclination (3.5% difference).

As far as the torsional behavior is concerned, in line with the outcomes of the 36-story building, the optimal solution to reduce torsional rotations corresponds to the configuration with one intra-module floor and the circular plan shape (Tab. 4, Figs. 4c-d).

Tab. 4. Displacements and rotations for the 48-story building (minimum values of displacements and rotations for each floor plan shape are in bold).

Structure	Total number of modules [-]	Diagonals' total mass [ton]	Lateral displacement [m]	Torque rotation [E-4 rad]
SQ.1	48	2084	0.578	**0.60**
SQ.2	24	1469	0.214	0.83
SQ.3	16	1324	0.171	1.37
SQ.4	12	1269	**0.168**	2.15
SQ.6	8	1228	0.193	4.39
SQ.12	4	1204	0.414	16.52
HE.1	48	1987	0.522	**0.52**
HE.2	24	1434	0.209	0.78
HE.3	16	1307	**0.174**	1.32
HE.4	12	1259	0.175	2.11

HE.6	8	1224	0.212	4.35
HE.12	4	1202	0.466	16.49
OC.1	48	1960	0.494	**0.49**
OC.2	24	1425	0.203	0.76
OC.3	16	1302	**0.172**	1.31
OC.4	12	1257	0.176	2.09
OC.6	8	1223	0.218	4.33
OC.12	4	1202	0.494	16.46
CI.1	48	1925	0.474	**0.48**
CI.2	24	1413	0.201	0.76
CI.3	16	1297	**0.173**	1.32
CI.4	12	1253	0.179	2.12
CI.6	8	1221	0.225	4.41
CI.12	4	1202	0.518	16.81

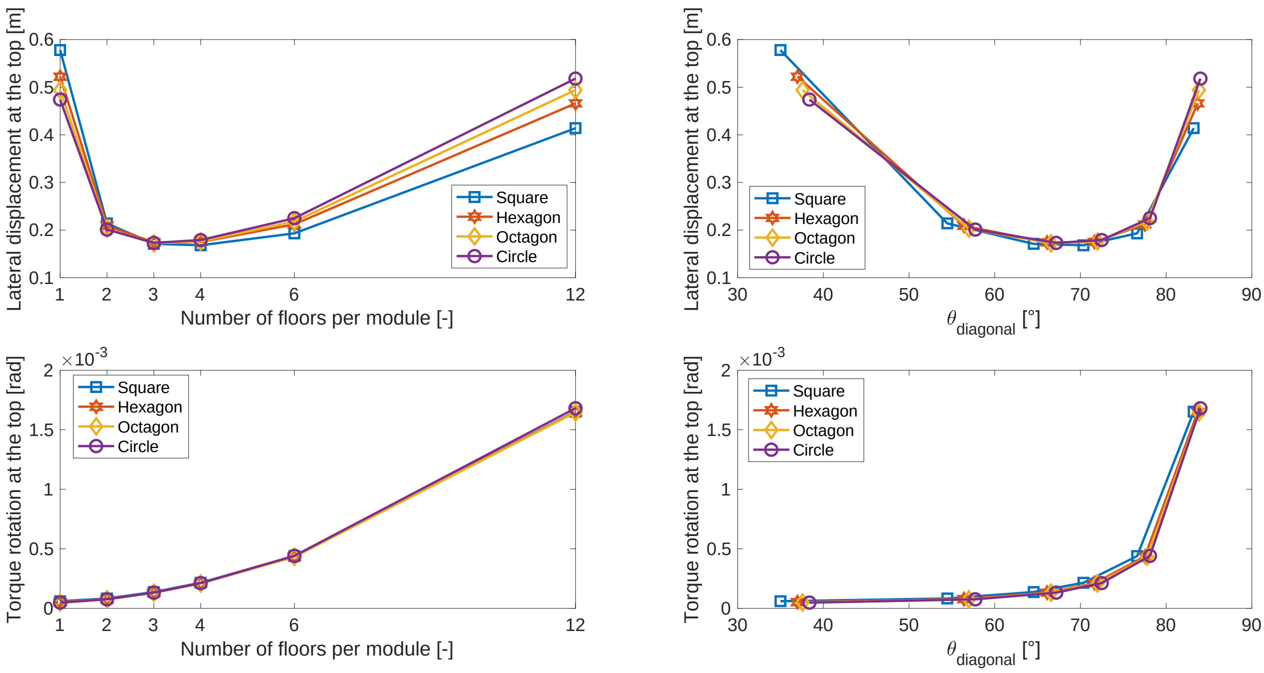

Fig. 4. Displacements and rotations for the 48-story building: (a-b) lateral displacements; (c-d) torsional rotations.

3.3 60-story building

In Tab. 5 and Fig. 5, the results are displayed which are related to the 60-story 210 meters-high diagrid buildings. In this case, the configurations associated to four intra-module floors are found to be the optimal ones in order to minimize lateral displacements for both the floor plan geometries. Again, the influence of the specific plan shape is not negligible only when considering one or more than six intra-module floors (Fig. 5a). In this case, the diagonal inclination associated to the minimum lateral displacements is found to lay in the range 70°-72° (Fig. 5b). As can be seen, increasing the aspect ratio of the building leads to higher values of the optimal diagonal angle.

Analyzing the results related to the torsional flexibility, the optimal solution to minimize the torsional rotations involves again considering only one intra-module floor and the circular floor geometry (Tab. 5, Figs. 5c-d).

Tab. 5. Displacements and rotations for the 60-story building (minimum values of displacements and rotations for each floor plan shape are in bold).

Structure	Total number of modules [-]	Diagonals' total mass [ton]	Lateral displacement [m]	Torque rotation [E-4 rad]
SQ.1	60	2605	1.402	**0.93**
SQ.2	30	1836	0.509	1.30
SQ.3	20	1655	0.394	2.15
SQ.4	15	1586	**0.375**	3.36
SQ.6	10	1536	0.410	6.86
SQ.12	5	1504	0.744	25.81
HE.1	60	2484	1.263	**0.81**
HE.2	30	1793	0.495	1.22
HE.3	20	1634	0.399	2.07
HE.4	15	1574	**0.387**	3.29
HE.6	10	1530	0.437	6.80
HE.12	5	1503	0.828	25.77
OC.1	60	2450	1.196	**0.78**
OC.2	30	1782	0.481	1.19
OC.3	20	1628	0.393	2.05
OC.4	15	1571	**0.386**	3.27
OC.6	10	1528	0.443	6.77
OC.12	5	1503	0.870	25.72
CI.1	60	2406	1.148	**0.75**
CI.2	30	1767	0.476	1.19
CI.3	20	1621	0.395	2.06
CI.4	15	1567	**0.392**	3.31
CI.6	10	1527	0.455	6.89
CI.12	5	1502	0.909	26.26

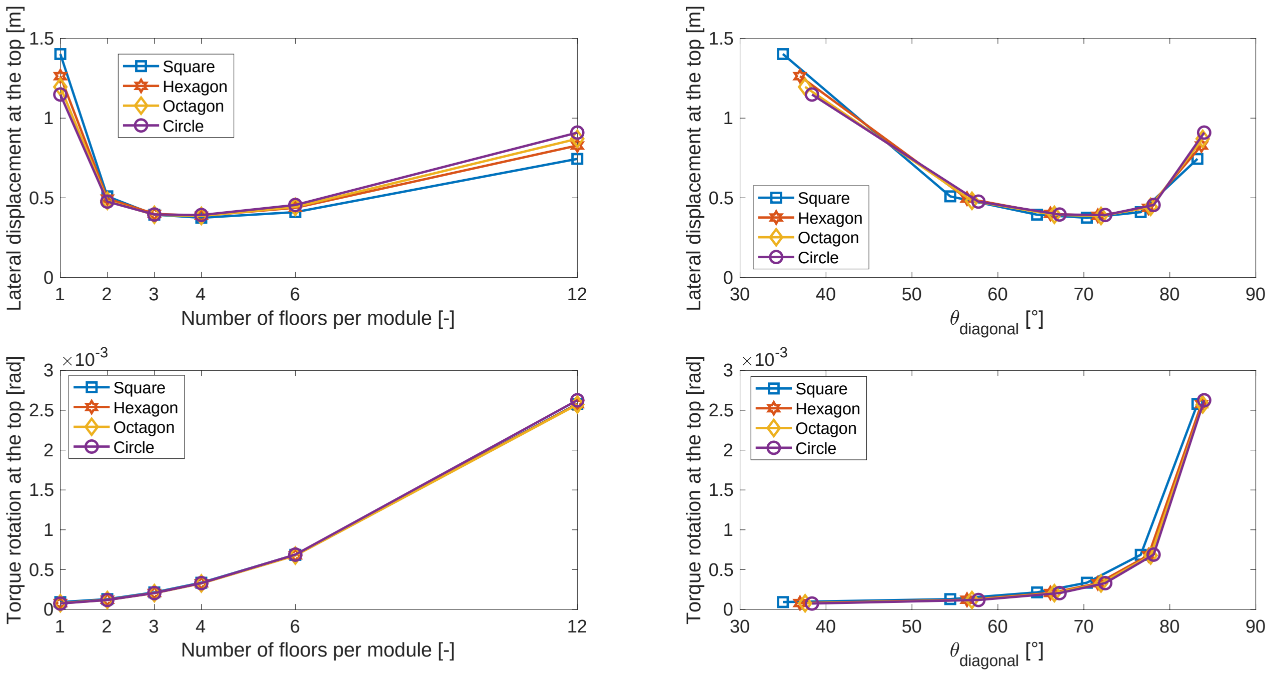

Fig. 5. Displacements and rotations for the 60-story building: (a-b) lateral displacements; (c-d) torsional rotations.

3.4 72-story building

Finally, the results arising from the analysis of the 72-story 252 meters-high buildings are shown in Tab. 6 and Fig. 6. In this case, the same outcomes observed for the 60-story structures are found: the best configurations which minimize the lateral displacements imply four intra-module floors for all the plan geometries (Fig. 6a), the optimal diagonal angle lies in the range 70°-72° (Fig. 6b) and the differences among the different floor plan shapes are not negligible just for one, six or twelve intra-module floors (Fig. 6a). Again, as far as the torsional behavior is concerned, the one intra-module floor circular building is the most capable one to withstand torque actions, since it provides the lowest torsional deformability (Tab. 6, Figs. 6c-d).

Tab. 6. Displacements and rotations for the 72-story building (minimum values of displacements and rotations for each floor plan shape are in bold).

Structure	Total number of modules [-]	Diagonals' Total mass [ton]	Lateral displacement [m]	Torque rotation [E-4 rad]
SQ.1	72	3126	2.896	**1.34**
SQ.2	36	2203	1.040	1.88
SQ.3	24	1985	0.793	3.09
SQ.4	18	1904	**0.738**	4.84
SQ.6	12	1843	0.771	9.88
SQ.12	6	1805	1.239	37.17
HE.1	72	2981	2.611	**1.16**
HE.2	36	2152	1.010	1.75
HE.3	24	1961	0.799	2.98
HE.4	18	1889	**0.759**	4.74
HE.6	12	1836	0.813	9.79
HE.12	6	1804	1.367	37.11
OC.1	72	2940	2.468	**1.12**

OC.2	36	2138	0.979	1.72
OC.3	24	1954	0.785	2.95
OC.4	18	1885	**0.752**	4.70
OC.6	12	1834	0.820	9.75
OC.12	6	1803	1.425	37.04
CI.1	72	2888	2.368	**1.08**
CI.2	36	2120	0.968	1.71
CI.3	24	1945	0.788	2.97
CI.4	18	1880	**0.761**	4.77
CI.6	12	1832	0.838	9.92
CI.12	6	1803	1.483	37.82

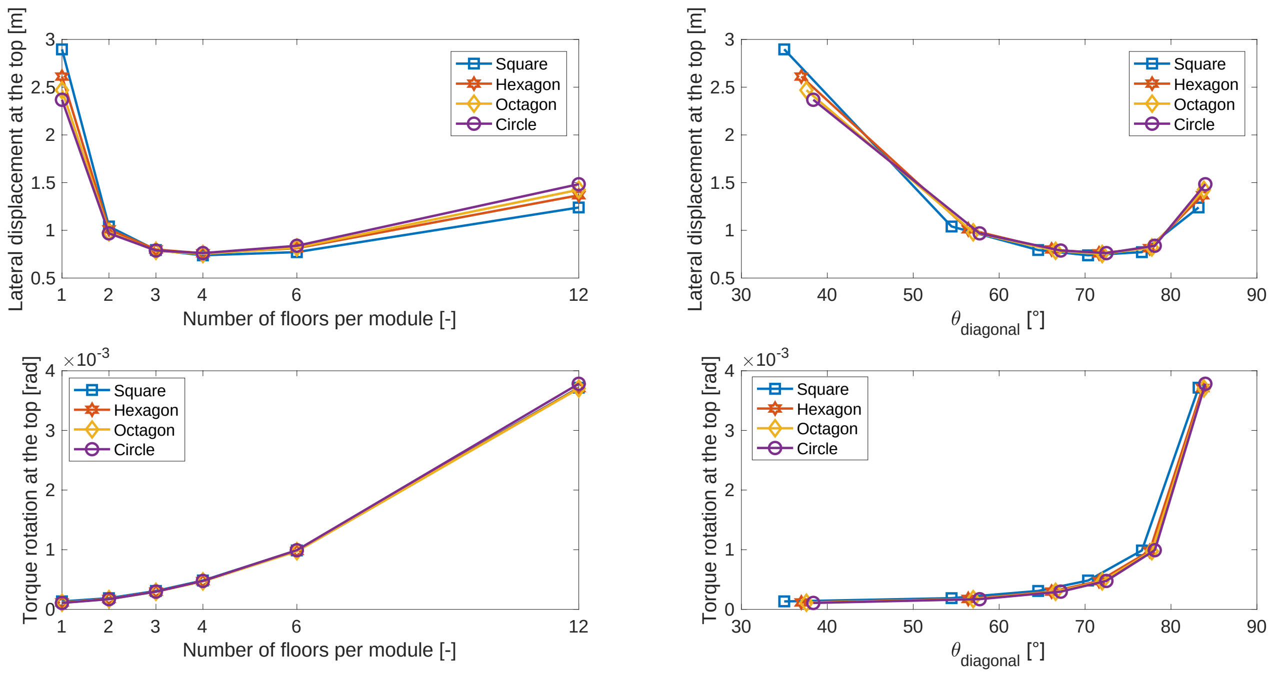

Fig. 6. Displacements and rotations for the 72-story building: (a-b) lateral displacements; (c-d) torsional rotations.

3.5 Influence of the total height of the building

As described in Sections 3.1-3.4, the total height of the building has an influence mostly on defining the optimal structural configurations to minimize lateral displacements. In fact, as recalled in Tab. 7, by increasing the total height of the building, the number of intra-module floors which leads to the minimum lateral displacements increases from three to four, for each plan shape. As a consequence, the optimal range for the diagonal inclination increases from 64°-67° to 70°-72°. This is due to the fact that both shear and bending rigidity compete to define the lateral stiffness of the building. As shown by Moon *et al.* [10], the shear rigidity of the diagrid modules reaches the highest value for a diagonal inclination of about 35° and it decreases significantly for higher diagonal angles; contrariwise, bending rigidity is maximum if the diagonal angle is 90° and decreases for lower inclinations. By the competition of shear and bending rigidity, the optimal solution is usually found between these two angle values, depending on the building aspect ratio. Since shear behavior prevails for lower buildings and bending behavior for taller buildings, increasing the total high of the building leads to an increasing predominance of bending rigidity over shear rigidity. Therefore, by increasing the height of the building, the diagonal inclination which provides the lowest lateral displacement exhibits higher values (Tab. 7, Figs. 3-6b).

Contrariwise, no competition between shear and bending rigidity occurs when dealing with the torsional behavior because, as mentioned above, this is governed only by the shear rigidity of the diagrid modules. For this reason, the diagonal inclination which leads to the lowest torsional rotations is always found to be the lowest one, in the range 35°-38° (Tab. 7).

Tab. 7. Optimal number of intra-module floors and diagonal inclination to minimize lateral displacements and torsional rotations (configurations providing the absolute minimum displacements and rotations are in bold)

Total height of the building [m]		126	168	210	252
Number of intra-module floors which minimizes lateral displacements [-]	**Square**	**3**	**4**	**4**	**4**
	Hexagon	3	3	4	4
	Octagon	3	3	4	4
	Circle	3	3	4	4
Diagonal inclination which minimizes lateral displacements [°]	**Square**	**64.54**	**70.35**	**70.35**	**70.35**
	Hexagon	66.11	66.11	71.63	71.63
	Octagon	66.57	66.57	72.00	72.00
	Circle	67.17	67.17	72.48	72.48
Number of intra-module floors which minimizes torsional rotations [-]	Square	1	1	1	1
	Hexagon	1	1	1	1
	Octagon	1	1	1	1
	Circle	**1**	**1**	**1**	**1**
Diagonal inclination which minimizes torsional rotations [°]	Square	34.99	34.99	34.99	34.99
	Hexagon	36.97	36.97	36.97	36.97
	Octagon	37.57	37.57	37.57	37.57
	Circle	**38.37**	**38.37**	**38.37**	**38.37**

With regards to the influence of the floor plan geometry on the structural response, as shown in Sections 3.1-3.4, this is usually found to be very small when the diagonal inclination lies in the optimal range. Although the differences are usually lower than 5%, it is interesting to note that the configurations which lead to the minimum lateral displacements are always associated to the square buildings (Tabs. 3-7). At first sight, this result seems in contrast with the findings of Mirniazmandan *et al*. [19], where the buildings with square geometry were not included in the list of the most performant solutions for the limitation of the lateral displacements. However, this difference mainly arises from the different choice of keeping different geometrical parameters constant when changing the floor plan shapes. As a matter of fact, in the present work, we choose to keep the total floor area constant (this being one fundamental parameter for architectural purposes), whereas Mirniazmandan *et al*. [19] decided to keep the total external perimeter constant in their calculations. Choosing different geometrical parameters to be constant leads to different results in terms of floor dimensions. For example, by taking the circle geometry as the reference, considering the external perimeter constant leads to obtain a square geometry which is 12% smaller than it would be in the case of considering the total floor area constant. Since the base dimensions play a key role in governing the stiffness of the building, as they strongly affect the bending rigidity, this difference is the one which make our results deviate from the ones of Mirniazmandan *et al*. Anyway, from both our analysis and the one of Mirniazmandan *et al*., it is evident how the geometrical characteristic which mostly affects the lateral flexibility of the diagrid is the diagonal inclination, whereas the influence of the plan shape geometry is less evident. Conversely, far from the optimal number of intra-module floors, the differences between the different floor plan shapes is found to be significant; for a number of intra-module floors lower than the optimum ones the optimal geometry is usually associated to the circular plan shape, whereas for higher numbers of intra-module floors the square plan geometry is the one providing the highest stiffness of the building (Figs. 3a-6a). The hexagonal and octagonal plan geometries always exhibit structural responses in between.

Regardless the total height of the building, the optimal configuration which leads to the highest torsional stiffness is always associated to the circular plan geometry with the lowest inclination of the diagonals (one intra-module floor). As already remarked above, this is due to the torsional mechanism of the diagrid structure, which only involves the shear rigidity of the diagonal modules, and not their bending rigidity as in the case of lateral deformability. So far, all the researchers have focused their attention only on the limitation of the lateral displacements, not considering the torsional rotations [10-19]. Sometimes, torque actions can be particularly severe, e.g. in the case of a strong asymmetry in the resisting elements placed in the interior of the building which leads to a not negligible eccentricity between the mass and stiffness centroids of the floors. In these cases, the torsional rotations induced by these actions should be taken into account. Unfortunately, in the present analysis, we have shown that a unique diagonal inclination which minimizes the lateral displacement and the torsional rotation at the same time does not exist. Therefore, when adopting the diagonal inclination which minimizes the lateral displacements, attention should be paid to the corresponding torsional rotations, as they might create problems to the façade elements as well.

4. Conclusions

The influence of geometrical parameters, such as the inclination of external diagonals, the floor plan shape, and the building aspect ratio, on the structural response of diagrid tall buildings was investigated. In particular, a previously developed matrix-based method (MBM) was used in order to perform the structural analysis of diagrid tube structures, under both horizontal forces and distributed torque moments. Lateral displacements and torsional rotations were calculated by the MBM for a variety of diagrid structures, with changing geometrical parameters, and the following conclusions were drawn.

The diagonal inclination is the main geometrical parameter affecting the structural behavior of the building. For the investigated diagrid structures, its optimal values are found to lie in the range 64°-72° in order to minimize lateral displacements and these increase when the aspect ratio of the building increases, due to the competition between shear and bending rigidity. Contrariwise, the diagonal inclinations which provide the highest torsional stiffness are always found in the range 35°-38° and do not depend on the total height of the building, since torsional behavior is only affected by the shear rigidity of the diagrid modules.

The influence of the floor plan geometry was also investigated, by considering four different plan shapes for each structure, i.e. square, hexagonal, octagonal, and circular, by keeping the floor area constant. It is observed that the specific plan geometry does not affect significantly the structural response, when the diagonal inclination is in the optimal range for limiting the lateral displacements. In these cases, the differences among the adoption of different plan shapes is found to be lower than 5% for all the investigated buildings. Contrariwise, significant differences can be found when far from the optimal diagonal inclinations. In this case, adopting different floor geometries leads to bigger differences in terms of lateral displacements (up to 25%). As far as the torsional behavior is concerned, when the diagonal inclination is optimized to minimize torsional rotations, the circular plan geometry is always found to be the most suitable for withstanding torque actions.

The outcomes reported in this paper showed that the structural solutions which lead to the minimum lateral displacements and torsional rotations are not the same. Furthermore, besides limiting the structure deformability, it is essential for sustainability purposes to minimize the amount of employed material as well. Other parameters to take into account should also be the axial loads in the diagonals and the story drifts. For these reasons, a multi-objective multi-parameter approach is going to be developed in future work to address this problem. Various geometrical parameters are going to be considered to find the *best* diagrid solutions among numerous *good* solutions, in order to find a compromise to limit both lateral displacements, torsional rotations, amount of employed material, diagonal axial loads and story drifts.

Finally, it is needed to remark that the outcomes shown in this paper are based on the linear elastic regime of the diagrid structure. Although this is common in the literature [10-21], nonlinearities might play a crucial role, especially under moderate or severe earthquake motions. As a matter of fact, some diagonals may enter into plastic state and the force distribution within the diagrid may change drastically, affecting the structural response. All these aspects should be taken into account for a more detailed design and analysis of diagrid structure, which was not the aim of the present analysis. For this reason, future research works will also consider enriching the MBM in order to investigate the structural response of the building in the nonlinear regime, considering both geometrical and material nonlinearities.

Appendix

A1. Effect of considering a variable cross-sectional area for the diagonals along the height of the building

In this section we report the results obtained when considering the diagrid buildings, with different floor shapes and diagonal inclinations, with a variable cross-sectional area of the diagonals along the height of the building. Specifically, the cross-sectional areas of the diagonals belonging to the ground module and the top module were assumed to be 1000 cm^2 and 100 cm^2, respectively. A gradual linear interpolation was considered for the other modules. Except for this parameter, all the parameters reported in Tab. 1 were used for the diagrid structures. In Tabs. A1-A4 and Figs. A1-A4 the results are shown for the four buildings. In Tab. A5, the best solutions to minimize the lateral displacements and torsional rotations are reported. As can be observed from the results, the main conclusions which were drawn when considering a uniform distribution of the cross-sectional areas are still valid. Therefore, considering a different diagonal cross-sectional area distribution is found not to affect the main outcomes of the present analysis.

Tab. A1. Displacements and rotations for the 36-story building (minimum values of displacements and rotations for each floor plan shape are in bold) – Variable cross-sectional area.

Structure	Total number of modules [-]	Diagonals' total mass [ton]	Lateral displacement [m]	Torque rotation [E-4 rad]
SQ.1	36	2262	0.090	**0.21**
SQ.2	18	1594	0.036	0.30
SQ.3	12	1437	**0.031**	0.50
SQ.4	9	1377	0.034	0.79
SQ.6	6	1333	0.049	1.68
SQ.12	3	1306	0.169	8.03
HE.1	36	2157	0.082	**0.18**
HE.2	18	1557	0.035	0.28
HE.3	12	1419	**0.032**	0.48
HE.4	9	1367	0.036	0.77
HE.6	6	1329	0.054	1.67
HE.12	3	1305	0.194	8.01
OC.1	36	2128	0.078	**0.18**
OC.2	18	1547	0.034	0.27
OC.3	12	1414	**0.032**	0.47
OC.4	9	1364	0.037	0.77
OC.6	6	1327	0.056	1.66
OC.12	3	1305	0.203	8.00
CI.1	36	2090	0.075	**0.17**
CI.2	18	1534	0.034	0.27
CI.3	12	1408	**0.033**	0.48
CI.4	9	1360	0.038	0.78
CI.6	6	1326	0.058	1.67
CI.12	3	1304	0.214	8.17

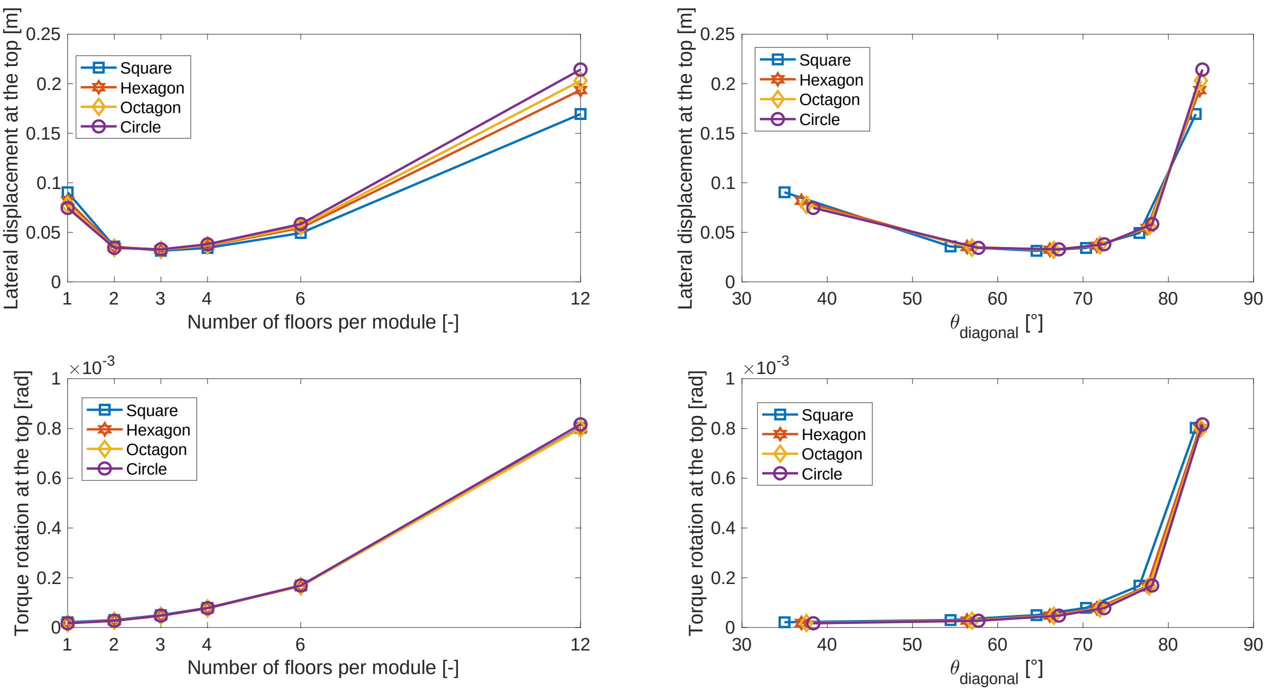

Fig. A1. Displacements and rotations for the 36-story building: (a-b) lateral displacements; (c-d) torsional rotations – Variable cross-sectional area.

Tab. A2. Displacements and rotations for the 48-story building (minimum values of displacements and rotations for each floor plan shape are in bold) – Variable cross-sectional area.

Structure	Total number of modules [-]	Diagonals' total mass [ton]	Lateral displacement [m]	Torque rotation [E-4 rad]
SQ.1	48	3016	0.281	**0.38**
SQ.2	24	2126	0.105	0.53
SQ.3	16	1916	**0.860**	0.88
SQ.4	12	1837	0.872	1.38
SQ.6	8	1778	0.110	2.89
SQ.12	4	1742	0.290	12.42
HE.1	48	2876	0.253	**0.33**
HE.2	24	2077	0.103	0.49
HE.3	16	1892	**0.088**	0.85
HE.4	12	1823	0.091	1.35
HE.6	8	1772	0.119	2.86
HE.12	4	1740	0.328	12.39
OC.1	48	2837	0.240	**0.31**
OC.2	24	2063	0.100	0.48
OC.3	16	1885	**0.087**	0.84
OC.4	12	1819	0.092	1.34
OC.6	8	1770	0.122	2.85
OC.12	4	1740	0.340	12.37
CI.1	48	2786	0.230	**0.30**
CI.2	24	2046	0.100	0.48
CI.3	16	1877	**0.088**	0.84
CI.4	12	1814	0.094	1.36
CI.6	8	1768	0.126	2.90
CI.12	4	1739	0.358	12.63

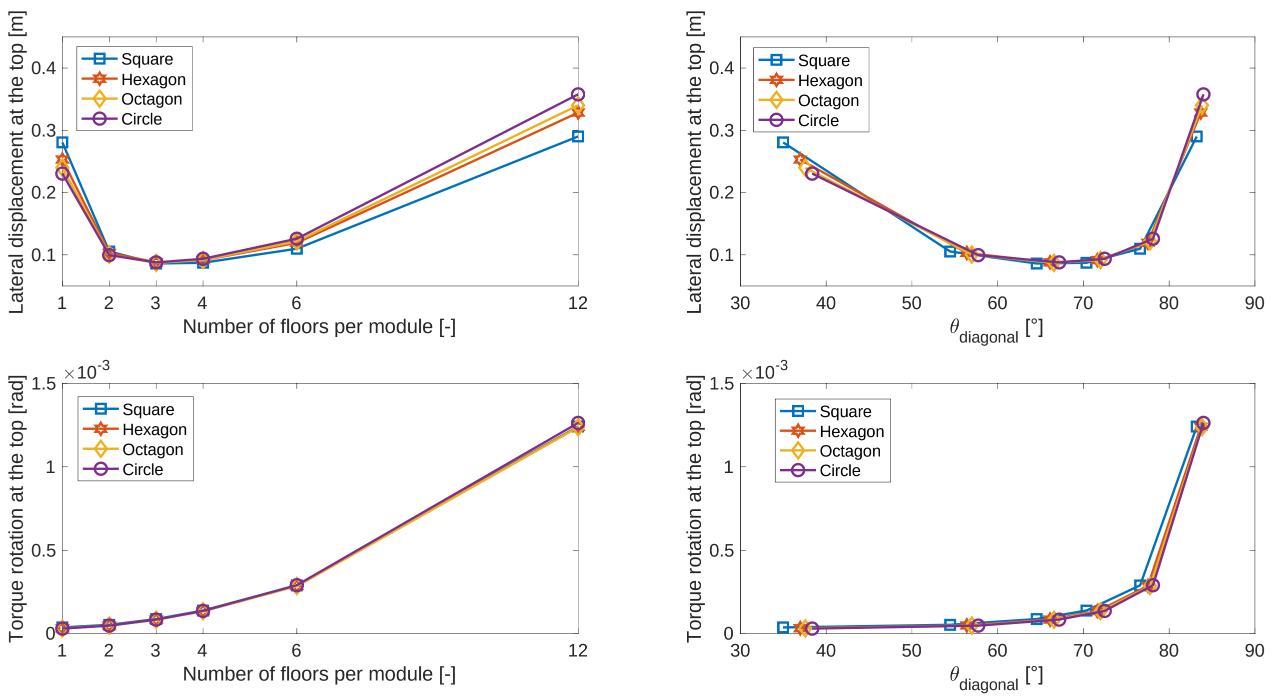

Fig. A2. Displacements and rotations for the 48-story building: (a-b) lateral displacements; (c-d) torsional rotations – Variable cross-sectional area.

Tab. A3. Displacements and rotations for the 60-story building (minimum values of displacements and rotations for each floor plan shape are in bold) – Variable cross-sectional area.

Structure	Total number of modules [-]	Diagonals' total mass [ton]	Lateral displacement [m]	Torque rotation [E-4 rad]
SQ.1	60	3770	0.679	**0.59**
SQ.2	30	2657	0.249	0.82
SQ.3	20	2395	0.196	1.36
SQ.4	15	2296	**0.190**	2.15
SQ.6	10	2223	0.219	4.45
SQ.12	5	2177	0.471	18.19
HE.1	60	3595	0.613	**0.51**
HE.2	30	2596	0.242	0.77
HE.3	20	2365	0.199	1.31
HE.4	15	2278	**0.197**	2.10
HE.6	10	2214	0.235	4.41
HE.12	5	2175	0.529	18.16
OC.1	60	3546	0.580	**0.49**
OC.2	30	2579	0.235	0.75
OC.3	20	2356	**0.196**	1.30
OC.4	15	2273	0.196	2.09
OC.6	10	2212	0.238	4.39
OC.12	5	2175	0.549	18.12
CI.1	60	3483	0.557	**0.47**
CI.2	30	2557	0.233	0.75
CI.3	20	2346	**0.197**	1.31
CI.4	15	2267	0.200	2.12
CI.6	10	2210	0.245	4.47
CI.12	5	2174	0.575	18.50

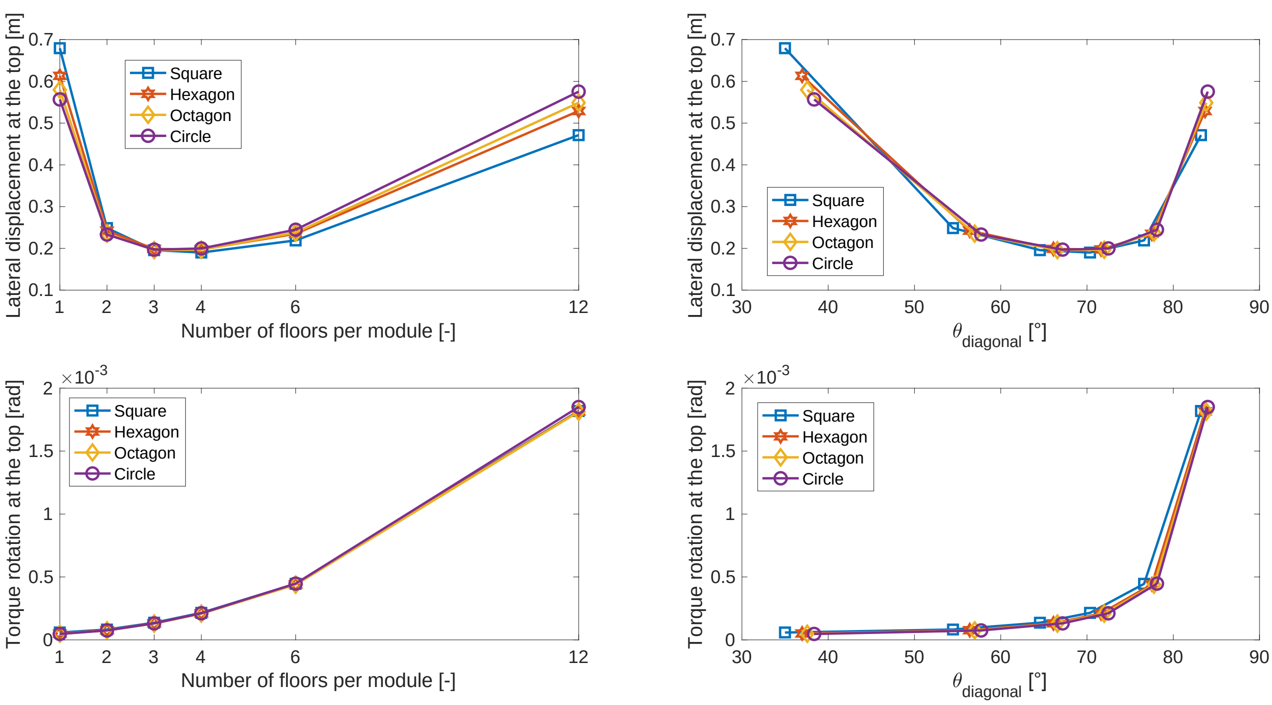

Fig. A3. Displacements and rotations for the 60-story building: (a-b) lateral displacements; (c-d) torsional rotations – Variable cross-sectional area.

Tab. A4. Displacements and rotations for the 72-story building (minimum values of displacements and rotations for each floor plan shape are in bold) – Variable cross-sectional area.

Structure	Total number of modules [-]	Diagonals' total mass [ton]	Lateral displacement [m]	Torque rotation [E-4 rad]
SQ.1	72	4524	1.403	**0.84**
SQ.2	36	3189	0.506	1.19
SQ.3	24	2874	0.390	1.96
SQ.4	18	2755	**0.369**	3.08
SQ.6	12	2667	0.400	6.36
SQ.12	6	2613	0.742	25.31
HE.1	72	4314	1.265	**0.73**
HE.2	36	3115	0.492	1.11
HE.3	24	2838	0.394	1.89
HE.4	18	2734	**0.381**	3.02
HE.6	12	2657	0.425	6.30
HE.12	6	2610	0.826	25.26
OC.1	72	4255	1.196	**0.70**
OC.2	36	3095	0.477	1.08
OC.3	24	2828	0.387	1.87
OC.4	18	2728	**0.377**	2.99
OC.6	12	2655	0.428	6.27
OC.12	6	2610	0.851	25.22
CI.1	72	4179	1.148	**0.68**
CI.2	36	3069	0.472	1.08
CI.3	24	2815	0.389	1.88
CI.4	18	2721	**0.382**	3.03
CI.6	12	2651	0.439	6.39
CI.12	6	2609	0.889	25.75

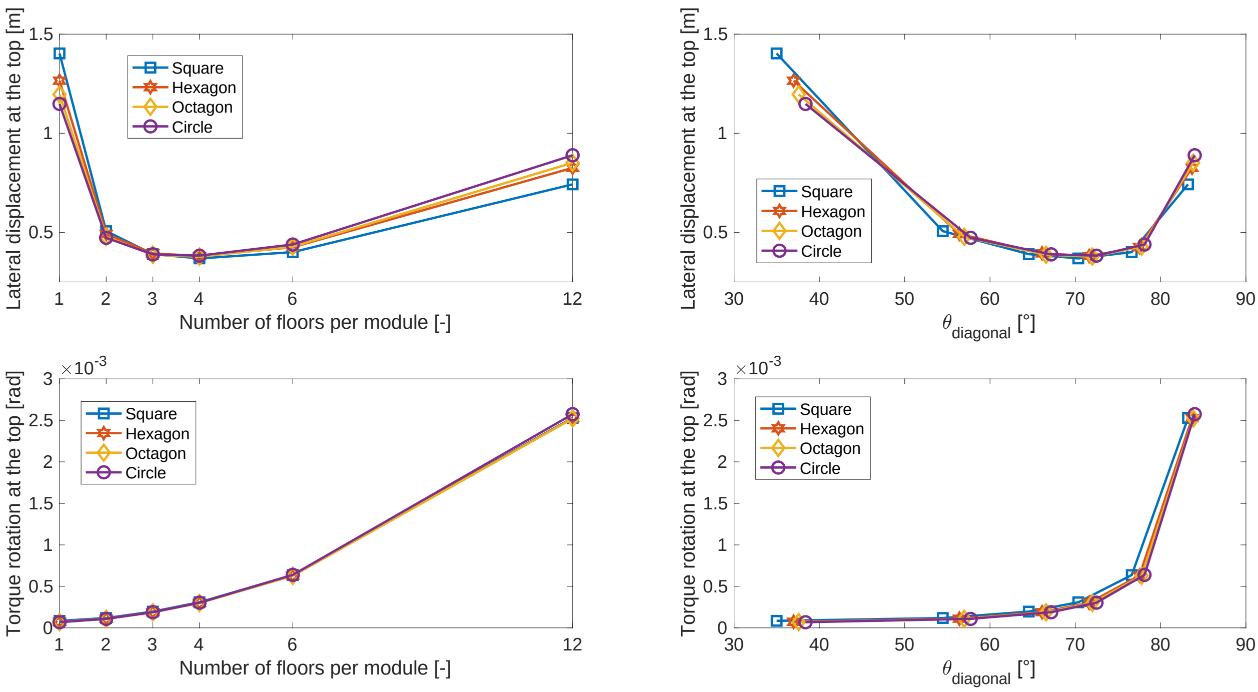

Fig. A4. Displacements and rotations for the 72-story building: (a-b) lateral displacements; (c-d) torsional rotations – Variable cross-sectional area.

Tab. A5. Optimal number of intra-module floors and diagonal inclination to minimize lateral displacements and torsional rotations (configurations providing the absolute minimum displacements and rotations are in bold) – Variable cross-sectional area.

Total height of the building [m]		126	168	210	252
Number of intra-module floors which minimizes lateral displacements [-]	Square	**3**	**3**	**4**	**4**
	Hexagon	3	3	4	4
	Octagon	3	3	3	4
	Circle	3	3	3	4
Diagonal inclination which minimizes lateral displacements [°]	Square	**64.54**	**70.35**	**70.35**	**70.35**
	Hexagon	66.11	66.11	71.63	71.63
	Octagon	66.57	66.57	72.00	72.00
	Circle	67.17	67.17	72.48	72.48
Number of intra-module floors which minimizes torsional rotations [-]	Square	1	1	1	1
	Hexagon	1	1	1	1
	Octagon	1	1	1	1
	Circle	**1**	**1**	**1**	**1**
Diagonal inclination which minimizes torsional rotations [°]	Square	34.99	34.99	34.99	34.99
	Hexagon	36.97	36.97	36.97	36.97
	Octagon	37.57	37.57	37.57	37.57
	Circle	**38.37**	**38.37**	**38.37**	**38.37**

A2. Effect of considering a reverse triangle load pattern along the height of the building

In this section we report the results obtained when considering the diagrid buildings, with different floor shapes and diagonal inclinations, subjected to a reverse triangle load pattern along the height of the building. Specifically, as shown in Fig. A5, the maximum values for the lateral and torque distributed load were assumed 30 kN/m and 70 kNm/m, respectively, at the top of the building. A linear decrease was applied up to the ground floor. Except for this condition, all the parameters reported in Tab. 1 were used for the diagrid structures. In Tabs. A6-A9 and Figs. A6-A9 the results are shown, for the four buildings. In Tab. A10, the best solutions to minimize the lateral displacements and torsional rotations are reported. As can be observed from the results, the main conclusions which were drawn when considering a uniform load distribution along the height of the building are still valid. Therefore, considering a different load scheme is not found to affect the main outcomes of the present analysis.

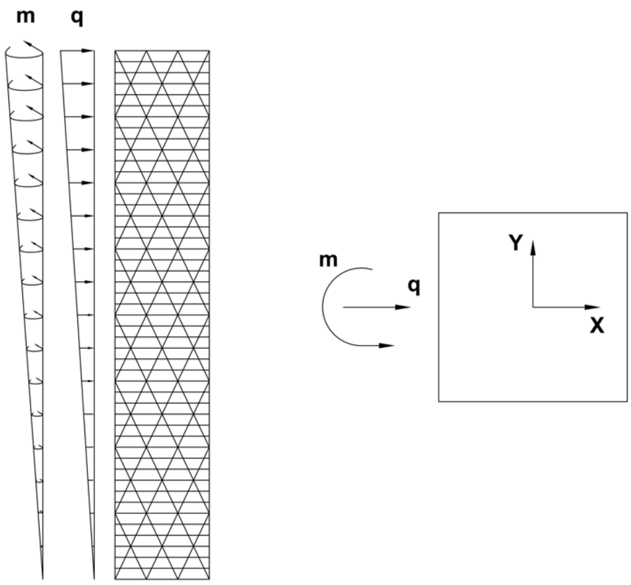

Fig. A5. Reverse triangle load pattern: *q* refers to the distributed horizontal load, *m* to the distributed torque moments.

Tab. A6. Displacements and rotations for the 36-story building (minimum values of displacements and rotations for each floor plan shape are in bold) – Reverse triangle load.

Structure	Total number of modules [-]	Diagonals' total mass [ton]	Lateral displacement [m]	Torque rotation [E-4 rad]
SQ.1	36	1563	0.136	**0.22**
SQ.2	18	1101	0.052	0.31
SQ.3	12	993	**0.043**	0.52
SQ.4	9	952	0.045	0.81
SQ.6	6	921	0.058	1.67
SQ.12	3	903	0.149	6.54
HE.1	36	1490	0.123	**0.19**
HE.2	18	1076	0.051	0.29
HE.3	12	980	**0.045**	0.50
HE.4	9	944	0.047	0.79
HE.6	6	918	0.064	1.65
HE.12	3	902	0.169	6.53
OC.1	36	1470	0.116	**0.19**
OC.2	18	1069	0.050	0.29
OC.3	12	977	**0.044**	0.49
OC.4	9	942	0.048	0.79
OC.6	6	917	0.066	1.65
OC.12	3	902	0.179	6.51
CI.1	36	1443	0.112	**0.18**
CI.2	18	1060	0.049	0.29
CI.3	12	927	**0.045**	0.50
CI.4	9	939	0.049	0.80
CI.6	6	915	0.068	1.68
CI.12	3	901	0.188	6.65

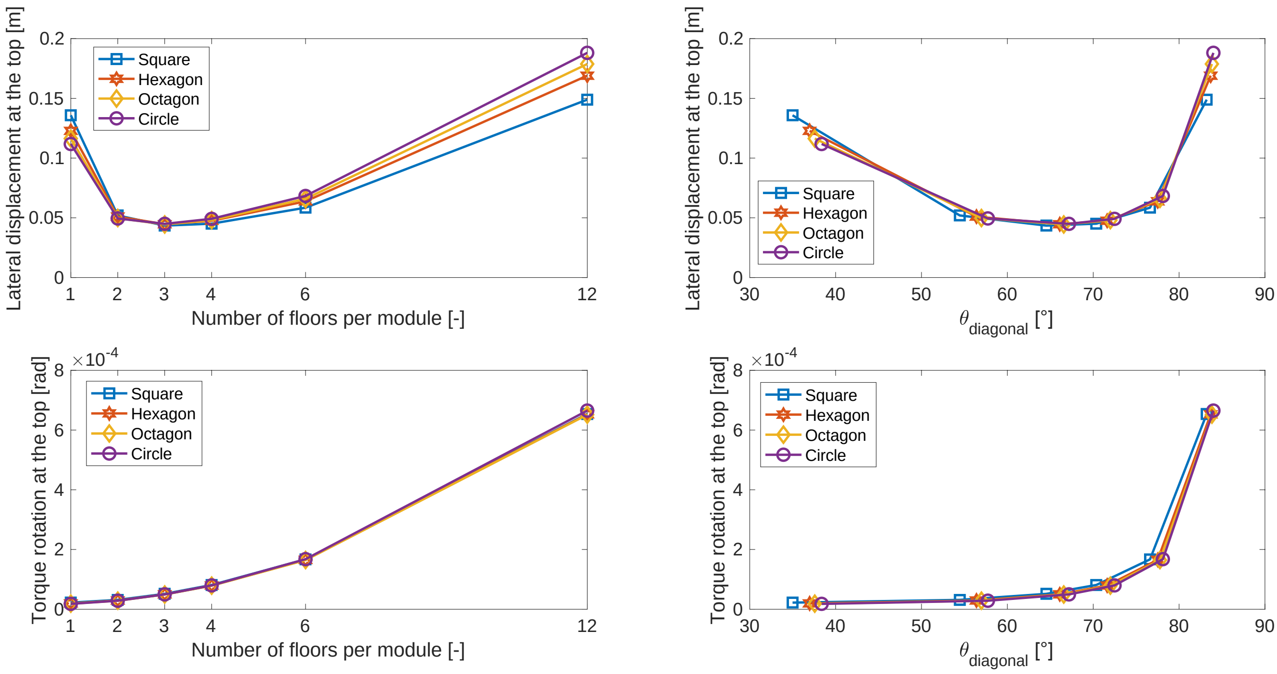

Fig. A6. Displacements and rotations for the 36-story building: (a-b) lateral displacements; (c-d) torsional rotations – Reverse triangle load.

Tab. A7. Displacements and rotations for the 48-story building (minimum values of displacements and rotations for each floor plan shape are in bold) – Reverse triangle load.

Structure	Total number of modules [-]	Diagonals' total mass [ton]	Lateral displacement [m]	Torque rotation [E-4 rad]
SQ.1	48	2084	0.423	**0.40**
SQ.2	24	1469	0.156	0.56
SQ.3	16	1324	0.124	0.92
SQ.4	12	1269	**0.121**	1.44
SQ.6	8	1228	0.141	2.95
SQ.12	4	1204	0.294	11.36
HE.1	48	1987	0.382	**0.35**
HE.2	24	1434	0.152	0.52
HE.3	16	1307	**0.126**	0.89
HE.4	12	1259	0.126	1.41
HE.6	8	1224	0.151	2.92
HE.12	4	1202	0.330	11.34
OC.1	48	1960	0.361	**0.33**
OC.2	24	1425	0.148	0.51
OC.3	16	1302	**0.124**	0.87
OC.4	12	1257	0.126	1.40
OC.6	8	1223	0.154	2.91
OC.12	4	1202	0.347	11.32
CI.1	48	1925	0.347	**0.32**
CI.2	24	1413	0.147	0.51
CI.3	16	1297	**0.125**	0.88
CI.4	12	1253	0.128	1.42
CI.6	8	1221	0.159	2.96
CI.12	4	1202	0.364	11.56

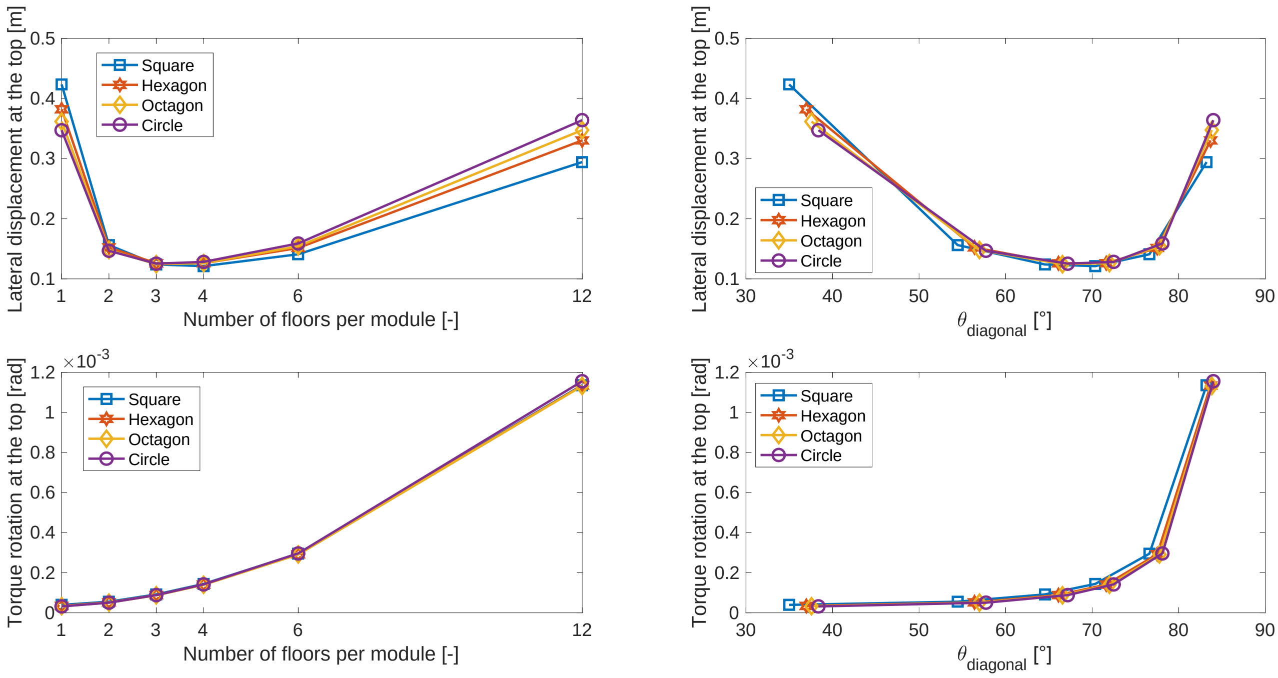

Fig. A7. Displacements and rotations for the 48-story building: (a-b) lateral displacements; (c-d) torsional rotations – Reverse triangle load.

Tab. A8. Displacements and rotations for the 60-story building (minimum values of displacements and rotations for each floor plan shape are in bold) – Reverse triangle load.

Structure	Total number of modules [-]	Diagonals' total mass [ton]	Lateral displacement [m]	Torque rotation [E-4 rad]
SQ.1	60	2605	1.027	**0.62**
SQ.2	30	1836	0.372	0.87
SQ.3	20	1655	0.287	1.43
SQ.4	15	1586	**0.272**	2.25
SQ.6	10	1536	0.295	4.60
SQ.12	5	1504	0.527	17.55
HE.1	60	2484	0.926	**0.54**
HE.2	30	1793	0.362	0.81
HE.3	20	1634	0.290	1.38
HE.4	15	1574	**0.281**	2.20
HE.6	10	1530	0.313	4.55
HE.12	5	1503	0.585	17.52
OC.1	60	2450	0.876	**0.52**
OC.2	30	1782	0.351	0.80
OC.3	20	1628	0.285	1.37
OC.4	15	1571	**0.279**	2.82
OC.6	10	1528	0.316	4.54
OC.12	5	1503	0.610	17.49
CI.1	60	2406	0.841	**0.50**
CI.2	30	1767	0.347	0.79
CI.3	20	1621	0.287	1.37
CI.4	15	1567	**0.282**	2.21
CI.6	10	1527	0.324	4.62
CI.12	5	1502	0.636	17.86

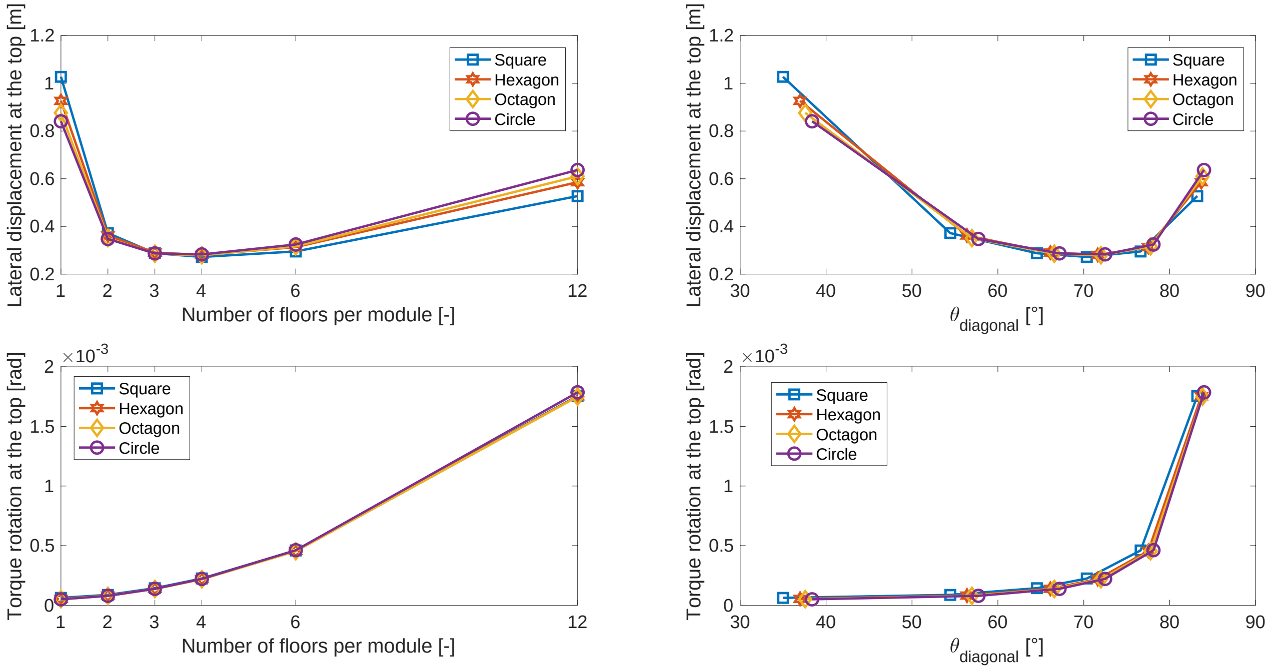

Fig. A8. Displacements and rotations for the 60-story building: (a-b) lateral displacements; (c-d) torsional rotations – Reverse triangle load.

Tab. A9. Displacements and rotations for the 72-story building (minimum values of displacements and rotations for each floor plan shape are in bold) – Reverse triangle load.

Structure	Total number of modules [-]	Diagonals' Total mass [ton]	Lateral displacement [m]	Torque rotation [E-4 rad]
SQ.1	72	3126	2.122	**0.89**
SQ.2	36	2203	0.761	1.25
SQ.3	24	1985	0.578	2.06
SQ.4	18	1904	**0.536**	3.23
SQ.6	12	1843	0.556	6.61
SQ.12	6	1805	0.879	25.12
HE.1	72	2981	1.913	**0.78**
HE.2	36	2152	0.739	1.17
HE.3	24	1961	0.583	1.99
HE.4	18	1889	**0.551**	3.16
HE.6	12	1836	0.586	6.55
HE.12	6	1804	0.967	25.08
OC.1	72	2940	1.808	**0.74**
OC.2	36	2138	0.715	1.14
OC.3	24	1954	0.572	1.97
OC.4	18	1885	**0.546**	3.14
OC.6	12	1834	0.588	6.52
OC.12	6	1803	1.001	25.04
CI.1	72	2888	1.735	**0.72**
CI.2	36	2120	0.708	1.14
CI.3	24	1945	0.573	1.98
CI.4	18	1880	**0.551**	3.18
CI.6	12	1832	0.600	6.64
CI.12	6	1803	1.040	25.56

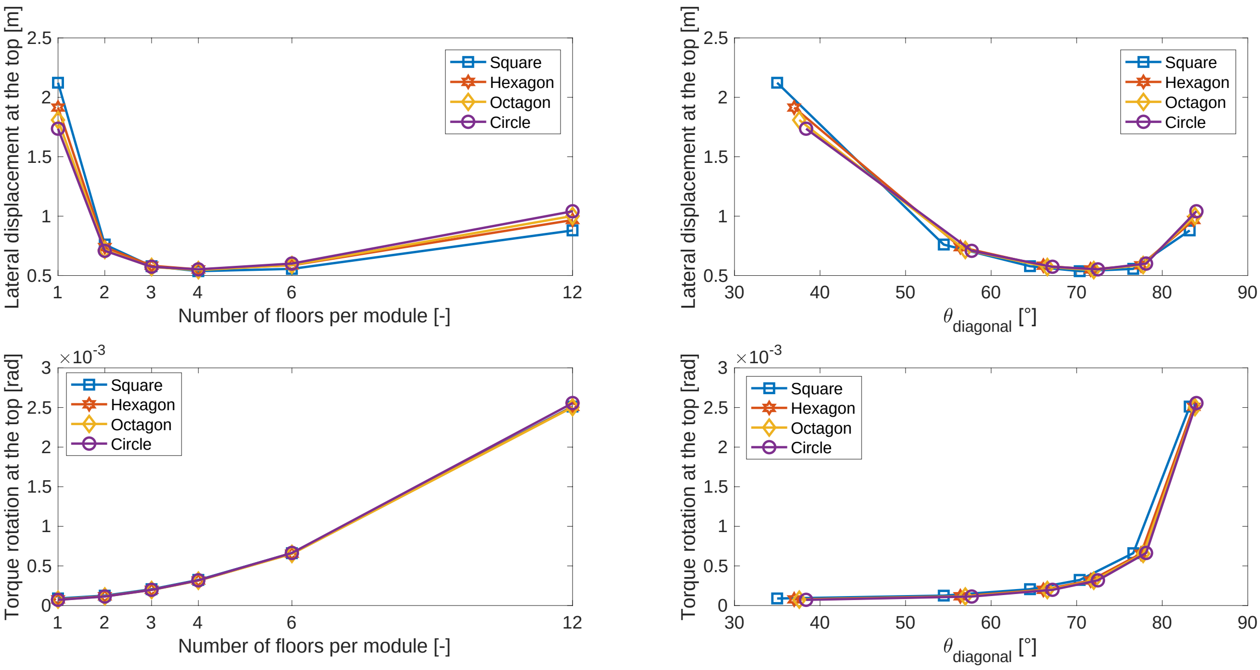

Fig. A9. Displacements and rotations for the 72-story building: (a-b) lateral displacements; (c-d) torsional rotations – Reverse triangle load.

Tab. A10. Optimal number of intra-module floors and diagonal inclination to minimize lateral displacements and torsional rotations (configurations providing the absolute minimum displacements and rotations are in bold) – Reverse triangle load.

Total height of the building [m]		126	168	210	252
Number of intra-module floors which minimizes lateral displacements [-]	Square	**3**	**4**	**4**	**4**
	Hexagon	3	3	4	4
	Octagon	3	3	4	4
	Circle	3	3	4	4
Diagonal inclination which minimizes lateral displacements [°]	Square	**64.54**	**70.35**	**70.35**	**70.35**
	Hexagon	66.11	66.11	71.63	71.63
	Octagon	66.57	66.57	72.00	72.00
	Circle	67.17	67.17	72.48	72.48
Number of intra-module floors which minimizes torsional rotations [-]	Square	1	1	1	1
	Hexagon	1	1	1	1
	Octagon	1	1	1	1
	Circle	**1**	**1**	**1**	**1**
Diagonal inclination which minimizes torsional rotations [°]	Square	34.99	34.99	34.99	34.99
	Hexagon	36.97	36.97	36.97	36.97
	Octagon	37.57	37.57	37.57	37.57
	Circle	**38.37**	**38.37**	**38.37**	**38.37**

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RESPONSES TO THE REVIEWERS' COMMENTS
on the manuscript
"Influence of the geometrical shape on the structural behavior of diagrid tall buildings under lateral and torque actions" by
Giuseppe Lacidogna, Domenico Scaramozzino, Alberto Carpinteri
(DIBE-D-19-00050)

First of all, the authors wish to thank the anonymous Reviewers who helped to improve the quality of the proposed manuscript by their valuable comments. We performed a scrupulous work trying to fulfil all the points remarked by the Reviewers. The manuscript has been modified to overcome the criticalities emerged from the review process. In the following, we provide detailed responses to the comments, trying to answer to their observations and to make the relevant references to the revised version of the manuscript. All the modified and new parts are highlighted in yellow in the updated text.

Reviewer #1 comments.
The paper presents a numerical investigation on the diagrid structures. The authors have employed a previously developed matrix-based method (MBM) to analyze several diagrid tube structures to investigate the effects of floor plan, number of stories, the inclination of external diagonals on the response of these systems. The paper merely reports findings from a straightforward set of analysis and does not advance the state-of-the art in diagrid structure design. Lateral displacement and torsional rotation responses have been studied without providing design recommendations that take into account both the effects. In other words, the paper does not answer the question of what should be the angle of inclination of diagonals when both the lateral displacement and torsion criteria have to be satisfied. Furthermore, as mentioned in the text the authors have selected cases where the cross sectional area of the diagonals are constant along the height of the building.
This is a significant limitation of the study which prevents the conclusions to be generalized. This reviewer does not recommend publication of the article in its present form in Developments in the Built Environment.

Answers to the Reviewer #1 comments.
The reviewer points out that the paper does not answer the question of what should be the diagonal inclination to minimize both lateral displacements and torsional rotations. The outcomes of the present analysis have exactly shown that, unfortunately, a unique diagonal inclination to minimize both the variables does not exist. This is due to the different lateral and torsional deformability mechanisms of the diagrid modules. So far, researchers have only considered the minimization of lateral displacement. The present analysis suggests that such optimal angle can lead to higher torsional rotations, which might cause problems to the façade elements when torque actions are particularly intense and, especially, when the building plan dimensions are small. Additional comments regarding this problem have been added in the Results and Conclusions sections.

The reviewer also points out that considering a constant cross-sectional area of the diagonals along the height of the building might prevent the generalization of the results. The choice of not considering a cross-sectional variation was made here in order to investigate only the effect of the other geometrical parameters (floor shape, inclination of the diagonals, building aspect ratio) on the structural response, and it is consistent with other parametric studies, e.g. Mirniazmandan et al. (2018). However, acknowledging that this might affect the outcomes, in the revised version of the manuscript, we have added a dedicated Appendix. In the first paragraph of that section, we show the results when variable cross sections are considered along the height of the building. As can be seen, the main conclusions which were drawn previously are still valid in the case of variable cross sections.

Reviewer # 2 comments.

In this paper, a variety of diagrid structures with different geometrical parameters was analyzed using matrix-based method (MBM). The influence of the inclination of external diagonals, the floor plan shape and the total building height on the structural response of diagrid tall buildings was investigated. This research derived the main geometrical parameter affecting the structural behavior of diagrid structures and proposed the optimal diagonal inclination to minimize lateral displacements. The research is more-or-lesss of importance for the preliminary design of diagrid tubes.

Nevertheless, knowledge and findings obtained from the research is still within the scope of the knowledge of counterparts of researchers both in depth and in width. All the research done by the author is based on linear elastic analysis, but some critical portion of the structure may yield and change the force distribution of the structure. In addition, the performance of diagrid structures is only evaluated in terms of lateral displacements and torsional rotations, other key indices such as storey drifts and axial load distribution of diagonals, etc should be taken into account. Frankly speaking, the author's research tends to be simple and idealized.

In the following are some notes and advices that could help the authors to improve the quality of the paper:

1. The matrix-based method (MBM) adopted by the author can only be used for linear elastic analysis. However, under moderate or severe earthquake motions, some diagonals in the corner of diagrid structures may enter into plastic state and spread from the bottom to the top. Please supplement the premise of this research.

2. Please explain why the load combination a horizontal load of 30 kN/m and a torque load of 70 kNm/m was used for structural analysis?

3. Please add a schematic diagram to show the load pattern applied to the structure.

4. With increasing building height, the effect of high-order vibration modes on structural response tends to be more significant. However, static analysis with simple concentrated load or uniform load cannot reflect this effect. The author is suggested to use more realistic load combinations for analysis.

Answers to the Reviewer #2 comments.

The point-by-point responses are reported as follows:

1. As recognized by the reviewer, the MBM only takes into account the linear elastic regime of a diagrid tall building. This is in accordance with several analyses carried out in the last decade, e.g. by Moon et al. (2007), Zhang et al. (2012), Mele et al. (2014), Liu and Ma (2017), etc. However, we are planning to extend this method also to take into account geometrical and material non-linearities in future research works. In order to highlight the limitation and purposes of MBM, additional comments about the effect of plasticization and nonlinear response have been added in the Conclusions sections.
2. A horizontal load of 30 kN/m has been considered assuming a uniform horizontal pressure of 1 kN/m^2 acting on the frontage of the building, which is 30 meters wide. A torque load of 70 kNm/m has been considered assuming an eccentricity of the horizontal load equal to 2.3 meters with respect to the floor centroid. However, we need to point out that, since here our aim is to compare the structural response of different geometry under the same conditions and within the linear elastic regime, the absolute values of the loads are not important for the purposes of this analysis. The choice of considering arbitrary load values, not meant to represent real design values, has also been adopted in other parametric studies, e.g. Liu and Ma (2017).

3. A new Figure (Fig. 2) was inserted into the revised version of the manuscript, showing the uniform loading distribution applied to the building.
4. We acknowledge that more realistic load combinations should be considered for detailed design and analysis. However, for the purpose of this research, the particular load distribution is not affecting the results of our analysis. As a matter of fact, we have added an Appendix section where, in the second paragraph, we show the outcomes where a reverse triangle load scheme is considered along the height of the building. As can be seen, the main conclusions which were drawn previously remain the same. Therefore, considering more complex load schemes does not affect the overall results of our analysis, as long as we remain in the elastic regime.