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Diagrid systems coupled with closed- and open-section shear walls: Optimization of geometrical characteristics in tall buildings

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Abstract

Nowadays diagrid systems are employed worldwide for the realization of tall buildings since they allow to achieve remarkable architectural effects while providing an efficient mechanism to limit lateral displacements. Furthermore, being composed by an assembly of trusses on the exterior of the structure, they are suitable for optimization procedures if changing geometrical parameters, such as the inclination of the external diagonals. Such optimization procedures are generally carried out by means of Finite Element models, focusing mostly on diagrid lateral rigidity. In the last few decades, in order to perform the structural analysis of tall buildings, an analytical formulation, called General Algorithm (GA), was developed by some of the authors, which is much less time-consuming than FE calculations, while allowing to capture important insights on the structural behavior. Moreover, a matrix-based method has been recently proposed for the analysis of diagrid systems, which was shown to be suitable for insertion into the GA and able to provide information on the diagrid lateral and torsional flexibility. In this contribution, we analyze the structural behavior of external diagrid systems coupled with closed-section (CS) and open-section (OS) shear walls using the GA. The analysis was performed by considering lateral forces and torque moments distributed along the height of the building. By the GA, defined the building height and plan geometry, the optimal inclination of the external diagonals was sought, in order to minimize lateral displacements and torsional rotations. The effect of the shear wall type, i.e. CS or OS, was also investigated on the structural response, and it was found to have a significant impact on the torsional rotations.

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Keywords: Tall buildings; Geometrical optimization; Diagrid; Shear wall; General Algorithm; Analytical formulation.

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1. Introduction

In ordinary buildings and structures, the design choices are generally driven by the strength properties of the employed materials and deformability issues are usually checked *a posteriori* mainly in order to avoid significant damages on non-structural elements. Contrariwise, the need to limit lateral displacements strongly affects the design of high-rise buildings, because of the crucial importance of lateral actions due to wind and seismic loading conditions. To this purpose, deflection limits can be found in various international design codes, which are aimed at enhancing the serviceability properties of the structure as well as the occupant comfort [1,2], although the definition of these maximum values is still considered rather arbitrary as they should be specific for different structural systems [3]. Nevertheless, the need to minimize lateral displacements has significantly influenced the development of the most recent structural solutions for the realization of tall buildings [4].

Among these, diagrid systems have been widely exploited in the last few decades because of their efficacy in resisting lateral forces, minimizing lateral displacements, and their suitability to realize complex-shaped structures allowing to achieve remarkable architectural effects [5]. The resisting mechanism is based on the axial forces in diagonal members, which are able to carry both lateral actions and vertical loads, thus leading to the uselessness of conventional vertical columns. Plenty of research has been conducted in the last ten years investigating diagrid behavior and characteristics. For example, Moon *et al*. [6] proposed a simplified analytical methodology for the preliminary design of diagrid tube structures. Zhang *et al*. [7] generalized Moon's approach for the case of diagrid tubes composed of straight diagonals with gradually varying angles, whereas Mele *et al*. [8] proposed an hand-calculation methodology to investigate real case studies. More recently, Liu and Ma [9] made use of a modular method to evaluate the shear and bending stiffness for arbitrary polygonal diagrid tube structures, while Lacidogna *et al*. [10] developed a matrix-based method to perform the structural analysis of generic diagrid structures, providing information not only regarding the shear and bending behavior but also the torsional flexibility. In the literature it was also shown that diagrid structures are suitable for optimization procedures if changing geometrical parameters, such as the inclination of external diagonals [5,6]. For example, Montuori *et al*. [11] performed Finite Element (FE) analyses in order to investigate the effect of different geometrical patterns (regular, variable angle and variable density pattern) on the structural performance. FE calculations with similar aims were also carried out by Angelucci and Mollaioli [12] and Tomei *et al*. [13].

Since such analyses are generally performed by FE calculations which are much time-consuming, especially regarding the construction of the models, there remains the need to have a faster methodology for a quick evaluation of the global structural behavior. To this purpose, a General Algorithm (GA) was initially developed by A. Carpinteri and An. Carpinteri [14], which was based on an analytical formulation embedding the most common features of typical resisting elements in tall buildings, such as moment-resisting frames and closed-section (CS) shear walls [15-18]. Further on, the GA was also made suitable to analyze open-section (OS) shear walls [19], whose behavior is based on the Vlasov's theory [20], as well as structures of different heights [21,22] and unconventionally shaped systems, such as tapered and twisted resisting elements [23]. The GA also allowed to investigate the dynamic behavior of tall buildings [24] as well as to perform the analysis of real case studies [25-27]. Finally, diagrid systems were also studied following the GA approach and they were shown to be suitable for insertion into the GA [10].

In this contribution, the structural analysis of an external diagrid system coupled with internal CS and OS shear walls is carried out by means of the GA. The procedure for inserting the diagrid stiffness matrix within the GA numerical code is briefly described and an application to a 40-story building is presented. The structural behavior is investigated under both lateral forces and torque moments distributed along the height of the building. Different inclinations of the external diagonals are also considered, in order to explore the effect of this geometrical parameter on the lateral and torsional flexibility. Furthermore, the effect of the shear wall type, i.e. CS or OS, is investigated on the structural response. Finally, a description of a multi-parameter approach, to be developed in future works, is briefly presented, which allows to take into account variable inclinations of the external diagonals and considers a large set of possible geometrical patterns.

2. Methodology

In the GA framework, a building made up of N stories and M vertical resisting elements is considered within a three-dimensional XYZ reference system. Each floor is subjected to external horizontal forces and torque moments, and it consequently undergoes lateral displacements and torsional rotations. The relationship between the global forces acting on the floors and the global displacements can be formulated as follows:

$$\{F\}=[K]\{\delta\} \tag{1}$$

In Eq. (1), $\{F\} = \{p_x, p_y, m_z\}$ represents the force vector, which is constituted by the $2N$ transverse forces p_x and p_y in the X and Y directions, respectively, and the N torque moments m_z respect to the vertical axis, $\{\delta\} = \{\xi, \eta, \vartheta\}$ stands for the displacement vector, which is constituted by the $2N$ transverse displacements ξ and η in the X and Y directions, respectively, and the N torsional rotations ϑ respect to the vertical axis, whereas $[K]$ denotes the $3N \times 3N$ global stiffness matrix of the building. An analogous relationship can be written for the ith resisting element as follows:

$$\{F_i\}=[K_i]\{\delta\} \tag{2}$$

being $\{F_i\} = \{p_{x,i}, p_{y,i}, m_{z,i}\}$ the horizontal forces acting on the ith vertical bracing and $[K_i]$ the $3N \times 3N$ stiffness matrix of the ith element referred to the global reference system. Considering M vertical bracings, the equilibrium condition yields the definition of the global stiffness matrix of the structure as a sum of the M elements' stiffness matrices:

$$\{F\}=\sum_{i=1}^{M}\{F_i\}=\left(\sum_{i=1}^{M}[K_i]\right)\{\delta\}=[K]\{\delta\} \tag{3}$$

For further details, the reader can refer to [14,19,21-27]. As briefly mentioned in the Introduction, a matrix-based method was developed in [10] for the structural analysis of diagrid systems which is suitable for insertion into the GA. This is possible if the diagrid stiffness matrix, which is initially calculated considering six degrees of freedom per floor, is reduced to a $3N \times 3N$ matrix, obtainable by considering only horizontal forces and torque moments, and by condensing the contribution of the out-of-plane rotations and vertical displacements (see [10] for more details).

Moreover, when the diagrid is associated to other internal resisting elements within the GA framework, the rows and columns of the diagrid stiffness matrix associated to the intra-module floors are filled with zeros: this means that the bending mechanisms of the diagonals are neglected (coherently with other analytical methodologies developed in the literature [6,7,9]). Following the mentioned numerical operations, the diagrid stiffness matrix was then inserted within the GA numerical code, in order to analyze the structural response of an external diagrid coupled with a central shear wall.

As an application, a 40-story building was considered, whose geometry is shown in Fig. 1. The typical floor is a 25 m × 25 m square plan and the inter-story height is equal to 4 m, leading to a total building height of 160 m and an aspect ratio equal to 6.4. A diagrid tube is present on the exterior of the structure, made up of steel diagonals (Young's Modulus equal to 210 GPa), having the same inclination and cross-sectional area (0.1 m^2) along the height of the structure. A 9 m × 9 m square shear wall, made up of concrete (Young's Modulus equal to 30 GPa) and 0.80 m thick, is placed at the center of the floor. In order to study the influence of the shear wall type on the structural response, both CS and OS shear walls are also considered (Fig. 1a). Moreover, six different diagrid models are studied, considering six different diagonal inclinations (Fig. 1b). In conclusion, given the overall geometry of the building, twelve models are analyzed changing the shear wall type and inclination of the diagonals (Tab. 1). As for the loading conditions, the structure is subjected to 100 kN horizontal forces along the X direction and 1000 kNm torque moments, distributed along the height of building.

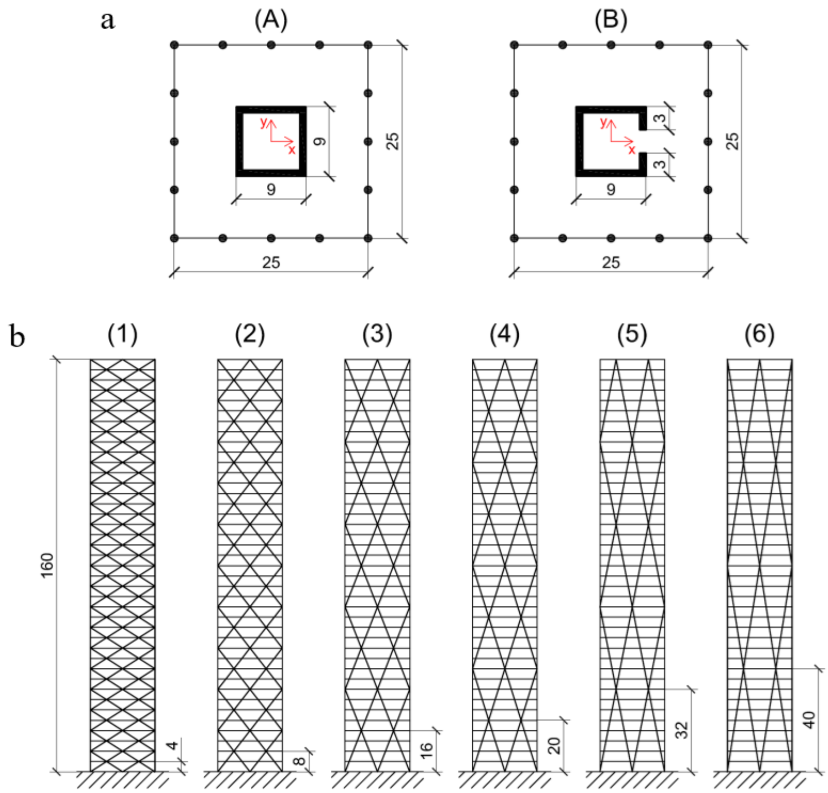

Fig. 1. Building geometry: (a) floor plans, (b) lateral views.

Table 1. Considered models.

Model	1A	2A	3A	4A	5A	6A	1B	2B	3B	4B	5B	6B
Shear wall type	CS	CS	CS	CS	CS	CS	OS	OS	OS	OS	OS	OS
Number of intra-module stories	1	2	4	5	8	10	1	2	4	5	8	10
Angle of diagrid diagonals [°]	32.6	52.0	68.7	72.7	79.0	81.1	32.6	52.0	68.7	72.7	79.0	81.1

3. Results and Discussion

In Figs. 2 and 3, the lateral displacements and torsional rotations obtained by the GA are shown, for the case of diagrids coupled with CS and OS shear wall, respectively. As can be clearly seen in the figures, both the lateral displacements and torsional rotations are affected by the inclination of the external diagonals.

In particular, the torsional flexibility is found to be deeply influenced by the adopted diagrid geometry. In fact, by observing Figs. 2b and 3b, it can be noted that by increasing the diagonal angle the torsional flexibility of the structure increases remarkably. This means that, by increasing the inclination of the diagonals, the contribution of the diagrid in withstanding the external torque actions and governing the modes of torsional deformation becomes less and less important. For example, for diagrid scheme (1), i.e. lowest diagonal inclination, almost no differences are found when considering a CS or OS shear wall (Figs. 2b and 3b), since it is the diagrid that dominates the torsional behavior. Contrariwise, for scheme (6), i.e. highest diagonal angle, important differences arise both in terms of numerical values and deformation shapes, and this is due to the fact that, in this case, the contribution of the shear walls becomes more important. As a result, one may observe, in models 5B and 6B, the presence of an inflection point in the torsional deformation, which is due to the warping effect of the OS shear wall (Fig. 3b).

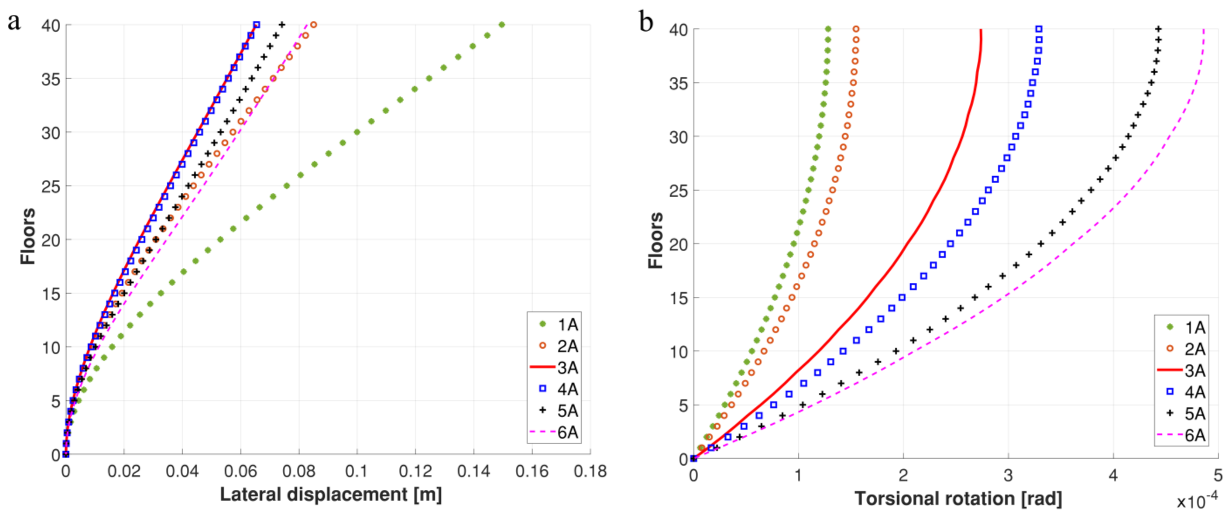

Fig. 2. Diagrid tube coupled with closed-section shear wall: (a) lateral displacements, (b) torsional rotations.

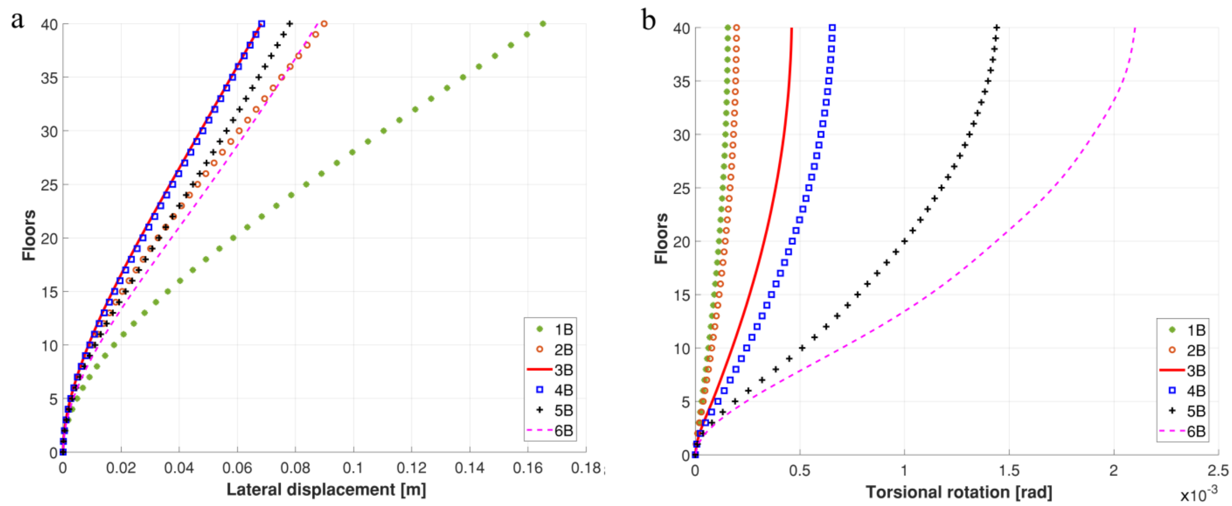

Fig. 3. Diagrid tube coupled with open-section shear wall: (a) lateral displacements, (b) torsional rotations.

In order to compare the models in Fig. 1 and Tab. 1, the lateral displacements and torsional rotations at the top of the building are reported in Fig. 4, depending on the angle of diagrid diagonals. As can be seen from Fig. 4a, the optimal solution in order to limit the horizontal displacements is found to correspond to schemes (3) or (4) for the external diagrid structure (Fig. 1), leading to optimal diagonal angles around 70°, in accordance with previous findings in the literature [6]. Moreover, the two diagrid solutions need similar amounts of employed material (Tab. 2), with a difference lower than 2.5%, so they are the best candidates to minimize transverse displacements.

Contrariwise, by observing Fig. 4b, the most suitable diagrid scheme to minimize torsional rotations is the one with the lowest diagonal angle, i.e. scheme (1). However, taking into account also the amount of employed material (Tab. 2), scheme (1) is found to need approximately 46% more steel material than scheme (2), whereas the obtained torsional rotations between scheme (1) and (2) are not so different. For this reason, considering both torsional flexibility and amount of material, it is believed that the best solution to withstand torque actions is provided by diagrid scheme (2).

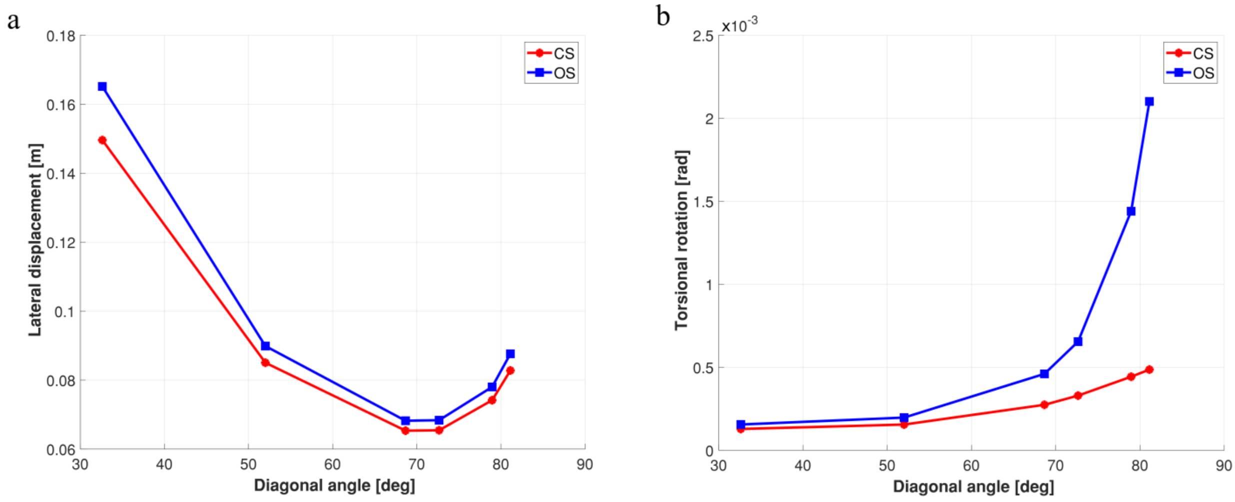

Fig. 4. Influence of diagonal inclination on: (a) top lateral displacements, (b) top torsional rotations.

In conclusion, the best diagrid solutions are the ones associated to schemes (2), (3) and (4). However, scheme (2) should be adopted just in case torque actions are particularly severe, since it leads to higher lateral displacements and amount of diagrid material than schemes (3) and (4). Conversely, schemes (3) and (4) provide essentially the same results both in terms of lateral flexibility and amount of material, but scheme (4) can lead to high torsional rotations, especially if the external diagrid is associated to an internal OS shear wall. Finally, in order to take into account both lateral flexibility, torsional rotations and amount of material, the best solution seems to be scheme (3), which constitutes a sort of compromise between the three considered variables (Tab. 2).

Table 2. Lateral displacements, torsional rotations and diagrid steel tonnages for each model.

Model	1A	2A	3A	4A	5A	6A	1B	2B	3B	4B	5B	6B
Lateral displacement at the top [cm]	15.0	8.5	6.5	6.5	7.4	8.3	16.5	9.0	6.8	6.8	7.8	8.8
Torsional rotation at the top [10^{-4} rad]	1.28	1.55	2.74	3.29	4.43	4.86	1.55	1.97	4.60	6.54	14.4	21.0
Diagrid steel mass [ton]	3728	2550	2157	2105	2048	2034	3728	2550	2157	2105	2048	2034

Finally, in Fig. 5, the stiffness contribution of the diagrid system and the central shear wall is shown, both regarding lateral (Fig. 5a) and torsional (Fig. 5b) stiffness. In order to obtain such values, the horizontal and torque actions have been applied to the separate models, i.e. the diagrid, the CS and OS shear walls, and the displacements at the top of each structure have been measured. Defining the global lateral (torsional) stiffness as the ratio between the total horizontal force (torque moment) at the base and the displacement (rotation) at the top of the structure, the relative stiffness between the diagrids and the shear walls could be simply evaluated as a ratio between the calculated stiffness values. In the graphs a thicker line identifies the angles of inclination of the diagonals where the diagrids and the CS or OS shear walls stiffness are equal.

As shown in Fig. 5a, the lateral stiffness of the diagrid is always higher than the shear walls' ones with the exception of scheme (1), where the diagrid is found to be more flexible. The difference between the two shear walls (red and blue curve) is just due to the reduction of the moment of inertia due to the opening in the OS shear wall.

As regards the relative torsional stiffness, it can be observed from Fig. 5b (red curve) that the diagrid schemes (1) and (2) are more rigid than the CS shear wall, schemes (3) and (4) exhibit basically the same stiffness, whereas schemes (5) and (6) are much more flexible. Contrariwise, as far as the stiffness comparison with the OS shear wall

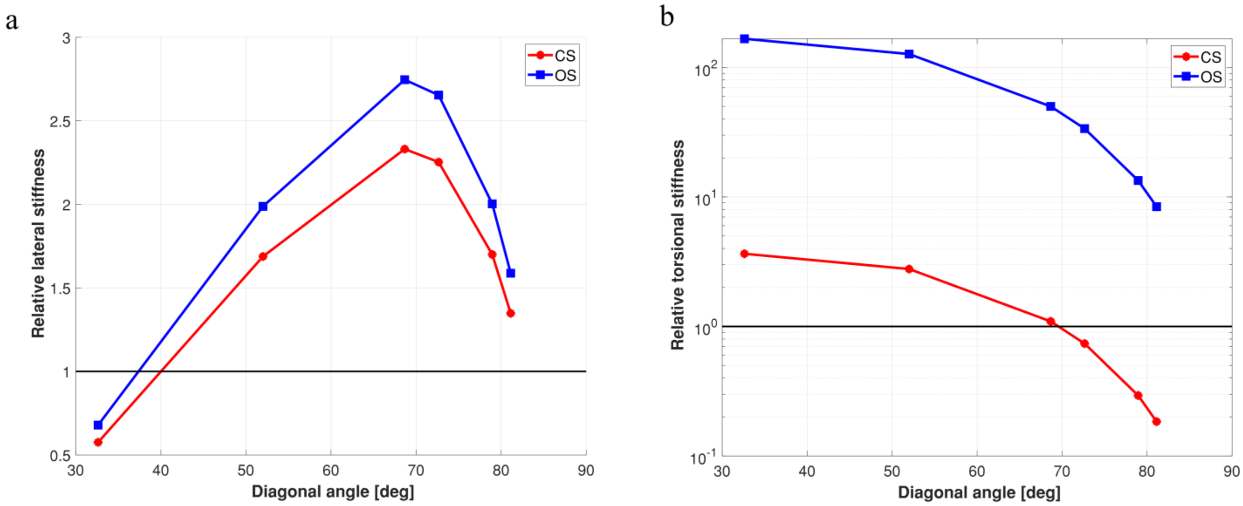

Fig. 5. Relative stiffness of diagrid and shear wall: (a) lateral stiffness, (b) torsional stiffness.

is concerned (blue curve), each diagrid scheme is much more rigid than the shear wall, and this is due to the remarkable reduction of torsional rigidity of the OS shear wall because of the opening. It is worth noting that, even if the diagrid schemes (5) and (6) are found to be approximately 10 times more rigid than the OS shear wall, the torsional deformations (Fig. 3b) are significantly affected by the shear wall since they show the inflection point due to the warping effect, as briefly commented above.

4. Conclusions and Future Developments

In this contribution, we made us of the GA, which is much less time-consuming than FE calculations, to perform the structural analysis of external diagrid systems coupled with central CS or OS shear wall. In particular, the building response to external lateral and torque actions was investigated, and the influence of the inclination of the external diagonals, as well as the shear wall type, on the structure flexibility was analyzed. In accordance to other studies present in the literature, we found that an optimal diagonal angle around 70° should be used in order to minimize lateral displacements; lower angles should be conversely used to minimize torsional rotations. Therefore the best solution should be chosen in order to find a compromise to minimize both lateral displacements, torsional flexibility and the amount of material. Finally, it was shown that the relative stiffness of the diagrid with respect to the shear walls significantly varies by changing the inclination of the external diagonals, especially as regards the torsional stiffness and in presence of an internal OS shear wall.

The case of constant inclination of the external diagonals was treated here, which is a typical solution in most real diagrid structures, but it could be not the only one since diagrids allow to create various geometrical patterns. As briefly commented in the Introduction, the most common procedure for searching the optimal solution is usually to generate a rather limited set of structures, having different geometrical patterns, perform the structural analysis by means of FE calculations and choose the optimal solution [11-13]. However, the computational advantages of the matrix-based method proposed for diagrid systems [10], coupled with the GA numerical code, allow the search for the optimal solutions taking into account a larger set of feasible structures. For this reason, we are now planning to integrate the combinatorics theory, in order to generate several combinations of external diagonal arrangements, with structural analysis outcomes, so that we can automatically obtain the optimal diagonal arrangement, in order to minimize the building flexibility while reducing the amount of materials. The first step of this research will consider variable inclinations of external diagonals along the height of the building, allowing to consider thousands of different structures and obtaining the optimal solutions almost in real time.

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