

# STRUCTURAL BEHAVIOR AND ROBUSTNESS ASSESSMENT OF TALL BUILDINGS: THE CASE OF DIAGRID SYSTEMS

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## **1. ABSTRACT**

Tall building structural design developed rapidly in the last decades, focusing among else on the sustainability improvement. In fact, sustainability in the urban and built environment is a key issue for the wellbeing of people and society, and sustainable development is nowadays a concern both for public authorities and for private investors. One of the evocative structural design solutions for sustainable tall buildings is embraced by the diagrid (diagonal grid) structural scheme. Diagrid, with a perimeter configuration characterized by a narrow grid of diagonal members, involved both in gravity and in lateral load resistance, has emerged as a new design trend for tall-shaped complex structures, since it requires less structural steel than a conventional steel frame, and thus, it provides for a more sustainable structure. This study focuses on the structural performance of a steel diagrid tall building, using FEM nonlinear analyses. Numerical comparisons are performed between different diagrid structures and a traditional outrigger structure for a tall steel building of 40 stories. The sustainability of the building (in terms of structural steel weight saving) is assessed, together with the structural behavior and the robustness.

## 2. INTRODUCTION

This study focuses on the Sustainability of Structural Systems. The inspiration arises from the impact that the construction industry has on the environment, in terms of use of resources and production of waste, and the social need that calls for investigating alternative sustainable solutions.

Diagrid is a perimeter structural configuration characterized by a narrow grid of diagonal members that are involved both in gravity and in lateral load resistance. Since it requires less structural steel than a conventional steel frame, it provides for a more sustainable structure. The diagrid system is not a new invention. In fact, an early example of today's diagrid-like structure is the 13-story IBM Building in Pittsburg of 1963. However, the implementation in a larger scale of such tall building was not practical due to high cost related to the difficult node connections. It is only in recent years that technology allowed a more reasonable cost of diagrid node connections [1].

In a diagrid structure, the perimeter configuration still holds the maximum bending resistance and rigidity, while, with respect to the braced tube, the mega-diagonal members are diffusely spread over the façade, giving rise to closely spaced diagonal elements and allowing for the complete elimination of the conventional vertical columns.

The difference between conventional exterior-braced frame structures and current diagrid structures is that for diagrid structures, almost all the conventional vertical columns are eliminated. This is possible because the diagonal members in diagrid structural systems can carry gravity loads as well as lateral forces due to their triangulated configuration in a distributive and uniform manner. Compared with conventional framed tubular structures without diagonals, diagrid structures are much more effective in minimizing shear deformation because they carry shear by axial action of the diagonal members, while conventional tubular structures carry shear by the bending of the vertical columns and horizontal spandrels [2].

A diagrid structure is modeled as a vertical cantilever beam on the ground, and subdivided longitudinally into modules according to the repetitive diagrid pattern. Each module is defined by a single level of diagrids that extend over multiple stories. Being the diagrid a triangulated configuration of structural members, the geometry of the single module plays a major role in the internal axial force distribution, as well as in conferring global shear and bending rigidity to the building structure.

The analysis of the diagrid structures can be carried out in a preliminary stage by dividing the building elevation into groups of stacking floors, with each group corresponding to a diagrid module. The reader is referred to Moon et al. [3], Moon [4] and Mele et al. [5] for theoretical formulations regarding the structural design of diagrid buildings.

Diagrid structures, like all the tubular configurations, utilize the overall building plan dimension for counteracting overturning moment and providing flexural rigidity. However, this potential bending efficiency of tubular configurations is never fully achievable due to shear deformations that arise in the building 'webs'. Thus, diagrid systems, which provide shear resistance and rigidity by means of axial action in the diagonal members, rather than bending moment in beams and columns, allows for a nearly full exploitation of the theoretical bending resistance.

### 3. STRUCTURAL ANALYSIS

The considered structure is a 40-story building, for a total height of 160m, and a footprint of about 36mx36m. Its function is for not-public offices. The building is located in Latina (Lazio, Italy). Regarding local wind and earthquake loading conditions, the area where the building is placed is characterized by a class of roughness “B” (urban and sub-urban areas) and a class of exposition to wind “IV”; the seismic zone corresponds II seismic level (PGA 0,15-0,25), in accordance with the Italian Building Code [6]. Two different structural design solutions are considered: outrigger and diagrid. Consequently, comparisons are performed to select the most efficient structural system and to reduce structural steel.

Regarding the outrigger structure, the building plant is symmetric with respect to the X axis; it has an octagonal footprint, approximated by a square of 35m x 35 m. The overall height of the structure is 160 m, while the distance between two consecutive floors is 4 m. The structure (and the model) have been realized in order to make a diagonal bracings system resist horizontal actions of the wind. The diagonal elements of the system consist in St. Andrew cross-bracings. In order to reduce the building deformability, a rigid plane (outrigger) is introduced, located at the 29th floor (between 112m and 116m), and realized by introducing braces expanded vertically for all façades in exam. These outriggers are located on two facades in direction X and on two cross-sections in direction Y at X=4m and X=31m.

Regarding the diagrid structures, the plant of the buildings is symmetric with respect to both the X and the Y axis, and it has a square footprint of 36mx36m. The overall height of the structure is 160 m, while the distance between two consecutive floors is 4 m.

Some general considerations are necessary. Typically, a diagrid structure is subdivided longitudinally into modules according to the repeated diagrid pattern. Each module is defined by a single level of diagrid that extends over multiple stories. In the buildings considered in this study, there are 4-story modules. The structural efficiency of diagrid for tall buildings can be maximized by configuring them to have optimum grid geometries. Since the optimal angle of the columns for maximum bending rigidity is 90 degrees and that of the diagonals for maximum shear rigidity is about 35 degrees, it is expected that the optimal angle of diagonal members for diagrid structures will fall in-between. Thus, three intermediate angles are considered: 42, 60 and 75 degrees respectively (Figure 1).

#### 3.1 Numerical modelling and results

The three diagrid buildings have two structural systems working in parallel: the first is internal and it is made of a rigid frame system which only reacts to gravity loads, while the second is perimetral and it is made of a diagonal grid system which reacts both to vertical and horizontal loads.

The internal structure, as any other ordinary frame structure, is composed by columns and main and secondary beams, while, the external one is composed by diagonal and horizontal elements (without columns). All the components of the internal system are placed at a distance of 6m in plant, thus creating square footprints of 6mx6m. The internal columns transmit vertical loads to the ground, while the perimetral ones do not. In fact, their function is to link the generic diagrid module to the floors included in it. Basically, the external columns receive the loads from the perimetral beams and they transfer these loads

to the horizontal elements of the module. The extension of the external columns is four-story length as the diagrid module. Passing from one module to the consecutive one, the perimetral beams are replaced by the horizontal diagrids. Therefore, the two structures “communicate” every four floors.

All of the vertical elements are tapered every four stories, since the size of each diagrid module changes. While Italian profiles are used for interior structure, American ones are used for the perimetral structure.

The computational code SAP2000 (version 16.0.0) has been used for all analysis. The structural model takes into count the real distribution of the masses, while the effect of non-structural elements on the global stiffness has not been considered.

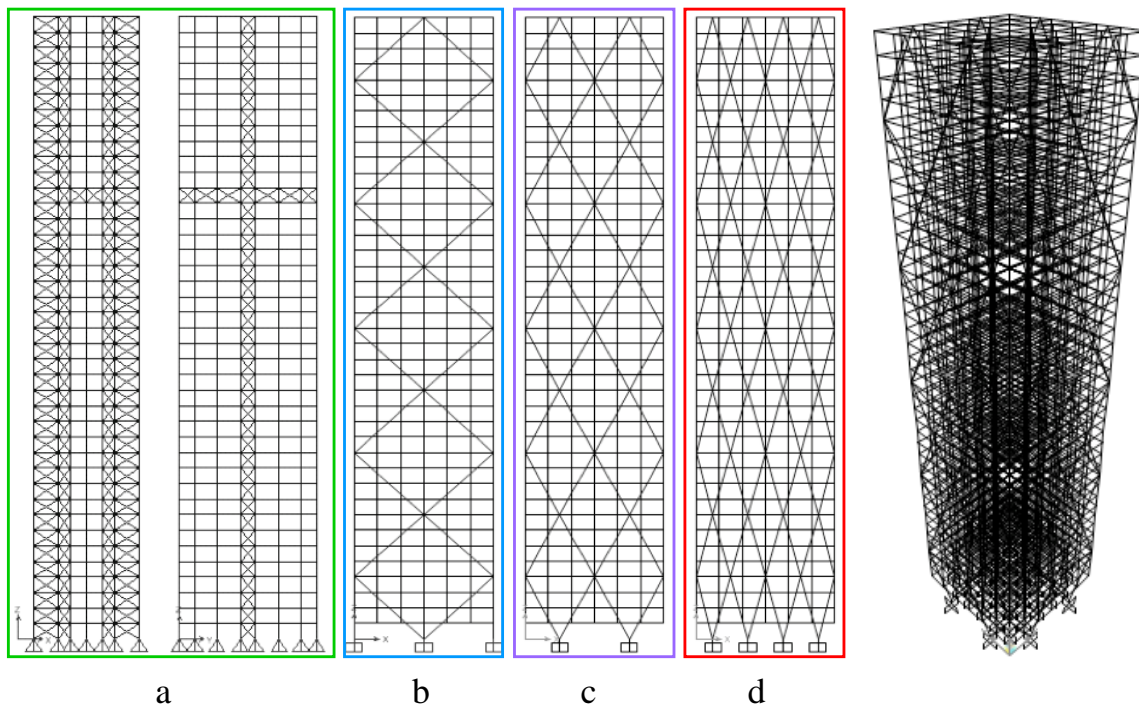


Fig. 1 Structural Models (a- Outrigger Structure; b- Diagrid Structure  $\alpha=42^\circ$ ; c- Diagrid Structure  $\alpha=60^\circ$ ; d- Diagrid Structure  $\alpha=75^\circ$ ) and a generic FEM model

For all diagrid structural systems an important weight saving occurs. The weight of the structures is calculated without considering the floors. Table 1 provides a comparison and the percentage of savings is calculated compared to the weight of the outrigger structure.

Structure	Structural weight (ton)	Weight-reduction (%)
Outrigger	8052	-
Diagrid $42^\circ$	6523	19
Diagrid $60^\circ$	5931	26
Diagrid $75^\circ$	5389	33

Table 1. Structural weight and weight reduction

The structural configurations are verified for both Serviceability Limit States (SLS) and Ultimate Limit States (ULS).

For SLS, the absolute horizontal displacements are considered. The points of control used are placed every four stories (16m). These displacements are compared with threshold values provided by the Italian Building Code [6]. All structures are verified by a great margin. Results are omitted for the sake of brevity.

For ULS, in order to evaluate the ductility of the structures, a non-linear static (Pushover) analysis is conducted. A lamped plasticity model has been implemented taking into account the material non-linearity. The Pushover analysis is conducted on the 3D model for all structures with the same static loads and hinges, in order to have a direct comparison of the results.

For the pushover analyses, a nominal horizontal triangular load is applied to the structure, increasing with height. The concentrated forces, are applied to the geometric centers of each floor and represent the normalized equivalent static forces. To simulate the non-linearity of material, plastic hinges are introduced. Two different kinds of hinges are considered: axial hinges, used for all elements of the outrigger structures and the perimetral system in the diagrid structures, and, bending hinges for the internal columns in the diagrid structures.

In order to consider the effect of geometric non-linearity in the structural behavior, a P-Delta non-linear static analysis is introduced.

As an example, Figure 2 reports the comparison of the pushover capacity curves of all structures, considering also vertical (dead) loads accounting for the P-Delta effect. This particular pushover analysis is in fact the most realistic. As can be seen, the 60° diagrid system gives the best overall results.

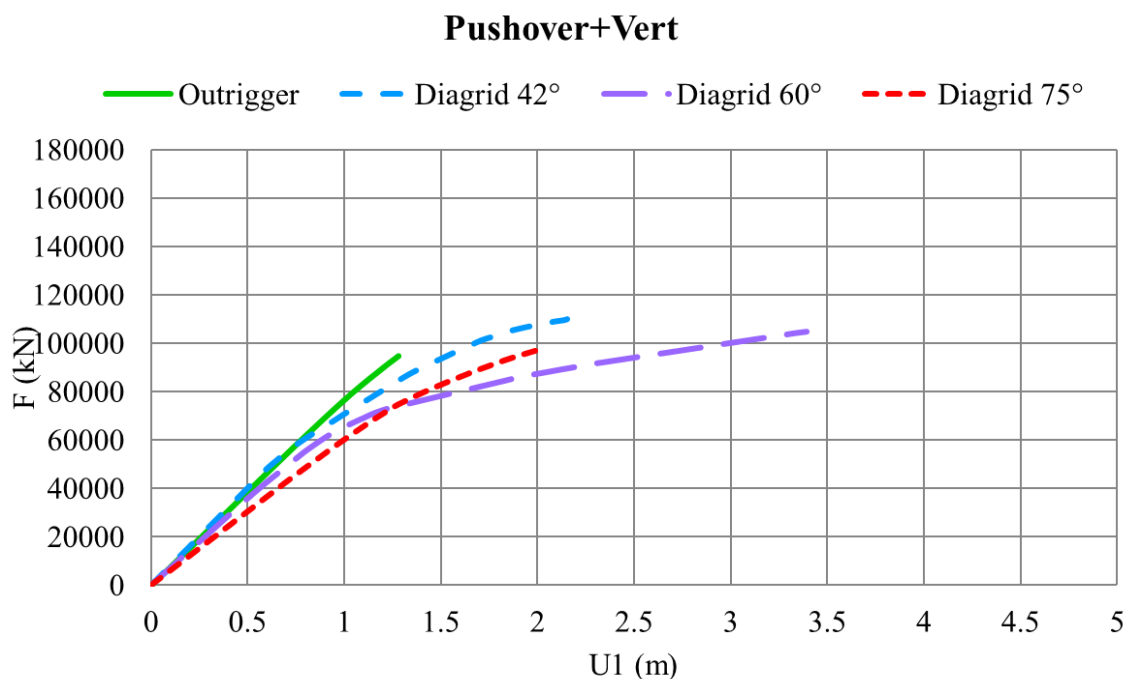


Fig. 2 Comparison of 'Pushover+Vert' capacity curves

Based on the capacity curves of the previous paragraph, it is possible to obtain three of the four values from which the model with the best behavior is identified. These properties are:

- Strength (R)
- Stiffness (K)
- Ductility ( $\mu$ )

Using these properties as well as the weight of the structure, the buildings are compared and the best structure is chosen through an equation defined in the following paragraph. All these features are calculated for the ‘Pushover+Vert’ case, since it is the most realistic case.

An equation that helps to identify the structure with the best behavior is defined below. All terms of this equation are normalized to the features of the outrigger structure (the reference building). These terms are multiplied with amplification coefficients. For the weight, a coefficient equal to 1.2 is considered, since weight is very important for the sustainable aspect while. The higher the outcome, the better the behavior of the structure. In the equation, the subscript “0” identifies the features relative to the outrigger structure. Given that the behavior improves for a reduced weight, a higher expression is used.

$$\frac{R}{R_0} + \frac{K}{K_0} + \frac{\mu}{\mu_0} + 1,2 \left[ \frac{(P-P_0)}{P_0} + 1 \right] \quad (1)$$

In order to have a clearer view, is possible to represent the terms of eq. (1), multiplied for the relative coefficients, on the axes of a radar chart (Figure 3).

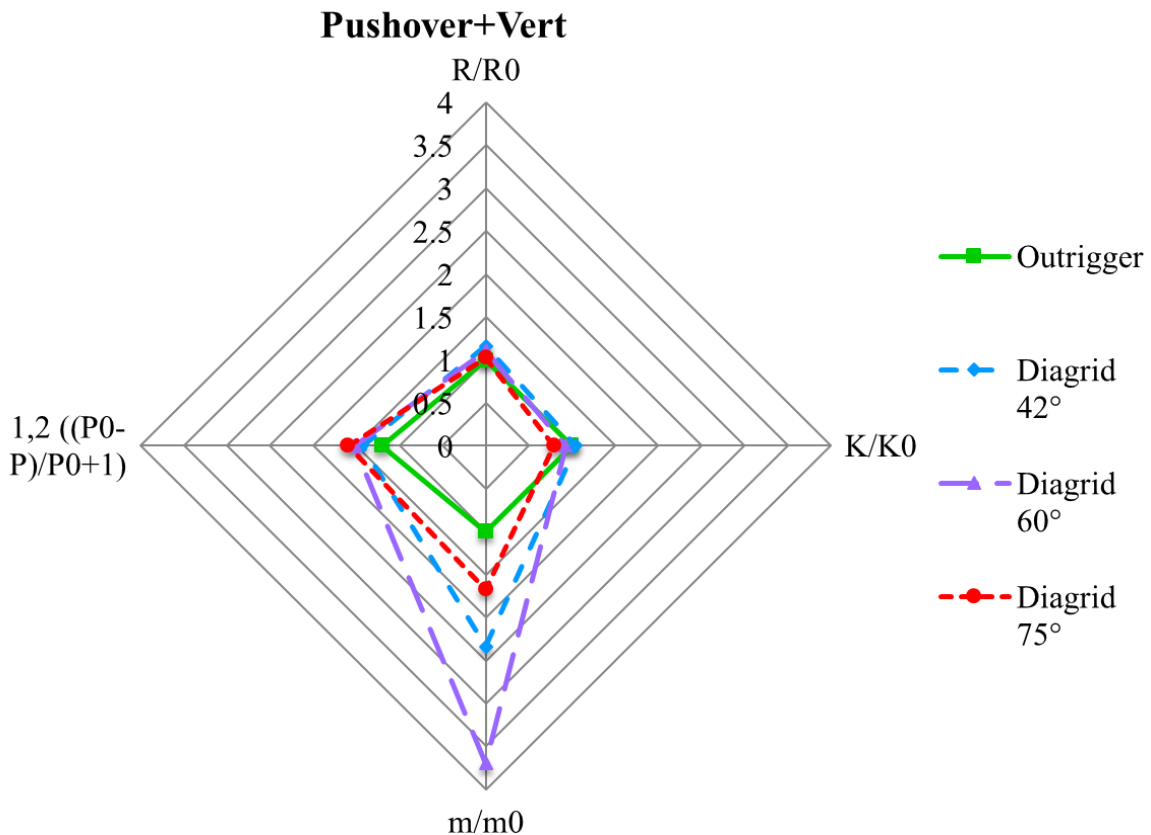


Fig. 3 Comparison of the performance for the ‘Pushover+Vert’ case

From the chart, it is possible to observe that the model with the best behavior is the diagrid structure with diagonal members having an inclination of 60°.

Thus, the diagrid structure with an intermediate inclination results as the best model. In fact this structure leads to an important saving of weight while at the same time, offers a high performance in terms of strength, stiffness and ductility.

### 3.2 Robustness checks

Structural robustness has been thoroughly studied in the last years (see for example [7]). Even though a variety of terms have been used in literature, robustness in structural engineering is commonly defined as the “insensitivity of a structure to initial damage”.

Steel truss structures have been the subject of recent research on what concerns their robustness, by means of different methods and metrics. The structural robustness of the Diagrid 60° is assessed for six different scenarios. The scenarios account for the elimination of one or two diagonal elements, at different heights. L1 indicates a single damage, while L2, the cumulative damage of both elements.

Figure 4 provides the results for the pushover analysis, considering only the horizontal loads.

As can be seen, the safety margins are distinctively lower for the elimination of elements at the base, something also expected. The other pushover analyses results are omitted for the sake of brevity, although it should be stated that when considering the P-Delta effects the results are less marked.

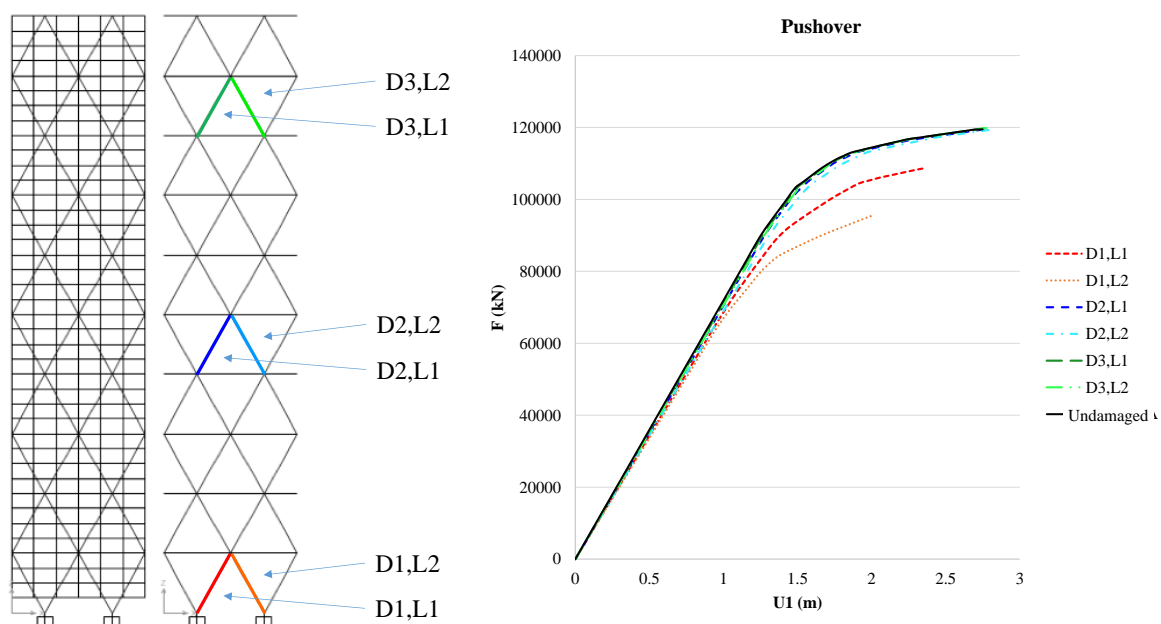


Fig. 4 Considered damage scenarios (left) and corresponding 'Pushover' curves (right)

## 4. CONCLUSION

In this study, the performance of diagrid structures has been assessed, not only in terms of material reduction, but also in terms of safety, serviceability and structural robustness.

Between the diagrid structures considered the one with the best overall behavior results to be the one with  $60^\circ$  diagonal element inclination. Although the results can only be considered as preliminary due to the complexity of the problem, the initial results provide a starting point and contribute obtaining an initial assessment of the sustainability of diagrid tall buildings.

## 5. REFERENCES

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## **ΠΕΡΙΛΗΨΗ**

Η αειφορία είναι ένα σημαντικό στοιχείο, τόσο του χωροταξικού και πολεοδομικού σχεδιασμού, όσο και του δομικού σχεδιασμού, όπου δίνεται έμφαση στην μελέτη και τον σχεδιασμό κτιρίων με ελαχιστοποίηση της εμπεριεχόμενης ενέργειας των υλικών καθώς και της κατανάλωσης φυσικών πόρων. Σε αυτό το πλαίσιο, η δομική και μορφολογική ανάλυση υψηλών κτιρίων γνωρίζει μεγάλη άνθηση. Ένα από τα πιο εμβληματικά σχέδια υψηλών κτηρίων των τελευταίων ετών χαρακτηρίζεται από χρήση διαγώνιου πλέγματος από χάλυβα (γνωστό και ως πλαίσιο "diagrid"). Στην παρούσα εργασία, γίνεται μελέτη της στατικής ανελαστικής συμπεριφοράς ενός ψηλού κτηρίου diagrid με την βοήθεια αριθμητικού προσομοιώματος. Αξιολογείται τόσο η αειφορία του κτιρίου (με όρους εξοικονόμησης του βάρους του δομικού χάλυβα), όσο και η στατική ασφάλεια του, λαμβάνοντας υπόψιν την αλληλεπίδραση ανάμεσα στο εσωτερικό και εξωτερικό πλαίσιο. Παρουσιάζονται επίσης αποτελέσματα σχετικά με την ευρωστία του κτηρίου, σε σενάρια βλάβης δομικών του στοιχείων.