EFFICIENZA STRUTTURALE DI EDIFICI ALTI IN ACCIAIO: CONFRONTO TRA DIFFERENTI TIPOLOGIE

STRUCTURAL EFFICIENCY OF HIGH-RISE STEEL BUILDINGS: COMPARISON AMONG DIFFERENT TYPOLOGIES

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ABSTRACT

In the present paper the structural efficiency of high-rise steel buildings is investigated. Five different structural typologies widely adopted in the European and many other world areas are considered, namely: Moment Resisting Frame [MRF], Concentrically Braced Frame [CBF], Braced Tube [BT], Diagrid Structure [DGR] and Outrigger Structure [OTR]. The structural efficiency is evaluated in terms of total structural weight with respect to slenderness (i.e. height-to-base dimension) ratio. For each typology, the height of a building with a squared plan (21 m x 21 m) is increased and the dimension of steel elements necessary for attaining a predefined level of structural safety are evaluated. Common assumptions are considered with reference to section types of structural elements and external actions. Then, FEM models are employed, and the dimensions of structural steel elements are varied for each structural typology and height to satisfy structural checks. At this purpose, a *trial-and-error* procedure is followed to optimize the structural configuration. The analyses allowed for defining qualitative "efficiency curves", relating, for each structural typology, the amount of steel weight necessary to ensure the minimum required structural safety.

SOMMARIO

Nel presente lavoro viene analizzata l'efficienza strutturale degli edifici in acciaio di grande altezza. A tal fine, vengono considerate cinque diverse tipologie strutturali ampiamente diffuse nel contesto europeo e mondiale: *Moment Resisting Frame* [MRF], *Concentrically Braced Frame*

[CBF], *Braced Tube* [BT], *Diagrid Structure* [DGR] and *Outrigger Structure* [OTR]. L'efficienza strutturale è valutata in termini di peso totale della struttura rispetto al rapporto di snellezza (cioè altezza/dimensione della base). Per ogni tipologia investigata, viene aumentata l'altezza di un edificio a pianta quadrata (21 m x 21 m) e stimate le dimensioni degli elementi in acciaio necessari a garantire una sufficiente sicurezza strutturale rispetto ai carichi verticali e orizzontali (sismici e da vento), nonché alle deformazioni. Con riferimento ai tipi di sezione degli elementi strutturali e alle azioni esterne vengono considerate assunzioni comuni. Vengono utilizzati quindi modelli agli elementi finiti, variando le dimensioni degli elementi strutturali in acciaio per ogni tipologia strutturale e per ogni altezza fino a garantire una capacità sufficiente nei confronti dei carichi esterni. A tale scopo, viene seguita una procedura *trial-and-error*, fino a definire la configurazione strutturale ottimizzata. Le analisi hanno permesso di definire "curve di efficienza" qualitative che mettono in relazione, per ogni tipologia strutturale, la quantità di acciaio necessaria per garantire una sufficiente sicurezza strutturale.

1 INTRODUCTION

Since ancient times, the height of buildings has been used to manifest power of civilisations. In more recent times, and particularly starting from the beginning of the 20th century, the adoption of high structures also met the need to reduce soil occupation for commercial, residential or mixed buildings, also thanks to the invention of the elevator and the use of new materials [1]. However, the strong revolution took place with the introduction of increasingly complex structural systems, which made possible the increasing of the height-to-base ratio of buildings greatly [2-5]. This permitted realizing not only increasingly taller buildings but also increasingly slender structures. In recent decades particular attention has been also given to sustainability in terms of cost and material use. In this sense, the adoption of steel for high-rise buildings represents an effective solution.

Based on these premises, in the current study, some of the most adopted steel structural systems retrieved from both American and Asiatic experiences are investigated to estimate their efficiency related to the height-to-base length ratio (H/b) [6]. Among the most common solutions, structural systems consisting of sole steel elements are considered. Therefore, the corresponding structural efficiency at different height levels, in terms of the amount of steel needed to guarantee a minimum structural capacity in facing both vertical (live) and horizontal (wind and earthquake) loads, is compared. Thus, for each considered structural system, several numerical analyses are performed to optimize by means of a *trial-and-error* procedure the choices of steel profiles and avoid excessive overstrength.

2 METHODOLOGIES

2.1 General assumptions

Six different pure-steel structural systems have been investigated. A common geometry has been identified consisting of buildings having a 21 m x 21 m square plan, divided into three 7 m bays and an inter-storey height of 3,50 m. For each structural system, starting from an initial number of storeys equal to 6, which means a total height H= 21 m and a height-to-base length ratio H/b=1, the total height has been increased by adding 6 storeys in each step. Every configuration has been thus assembled in Midas/GEN, and by means of the design tool, an optimization procedure has been performed to achieve a safety index (demand-to-capacity ratio) in the range 0.9-0.99 of the most stressed elements. For the purposes of this study, a unique profile is chosen for each structural element typology (i.e. columns, beams and braces). Conversely, the same steel grade was considered, namely *S355*.

An automatic procedure for structural checks has been implemented by considering both strength and deflection limits imposed by both European and Italian codes [7,8]. After this first procedure, additional user checks have been performed to avoid excessive displacements of the investigated structures (both in terms of inter-story and total drifts). In several cases, the latter led to assume over-resistant structural profiles to comply with the code displacement limitations.
As for the assembly of the models, floor diaphragms have been introduced for each story, thus simulating the presence of sufficiently stiff slabs. The following loads have been considered:

- Steel self-weight (defined by assuming a density of 7850 kg/m^3);
- Permanent structural loads G_1=3.25 kN/m^2;
- Permanent non-structural loads G_2=1.30 kN/m^2;
- Live loads Q=4.00 kN/m^2;
- Wind loads defined according to [9], by assuming fundamental basic wind velocity of 27 m/s;
- Seismic loads defined according to [10] assuming a design response spectrum with a return period of 475 years and characterized by a PGA of 0.20 *g* on a flat rigid soil and a behavior factor of 1.5.

It is worth mentioning that the seismic loads have been simulated by means of linear static analyses and, at this aim, modal analyses have been also performed. Moreover, the loads have been combined according to the *fundamental* and *seismic* combinations of the Italian code.
As regards the adopted profiles, common sections of structural elements were assumed to obtain comparable results. In particular, square-section hollow profiles were used for columns, while I-H and tube sections were adopted for beams and braces, respectively. Also, limits on the profile dimensions were considered and in particular:

- For hollow profiles with square cross-section a maximum of 900x900x50 mm;
- For I-H profiles, the use of IPE, HEA, HEB, HEM, up to HEM 900;
- For tube profiles a maximum of 1168x30 mm.

2.2 The investigated structural systems

The following structural system are analysed in this study:

- Moment Resisting Frame [MRF];
- Concentrically Braced Frame [CBF];
- Braced Tube [BT];
- Diagrid (type 1) [DGR1];
- Diagrid (type 2) [DGR2];
- Outrigger [OTR].

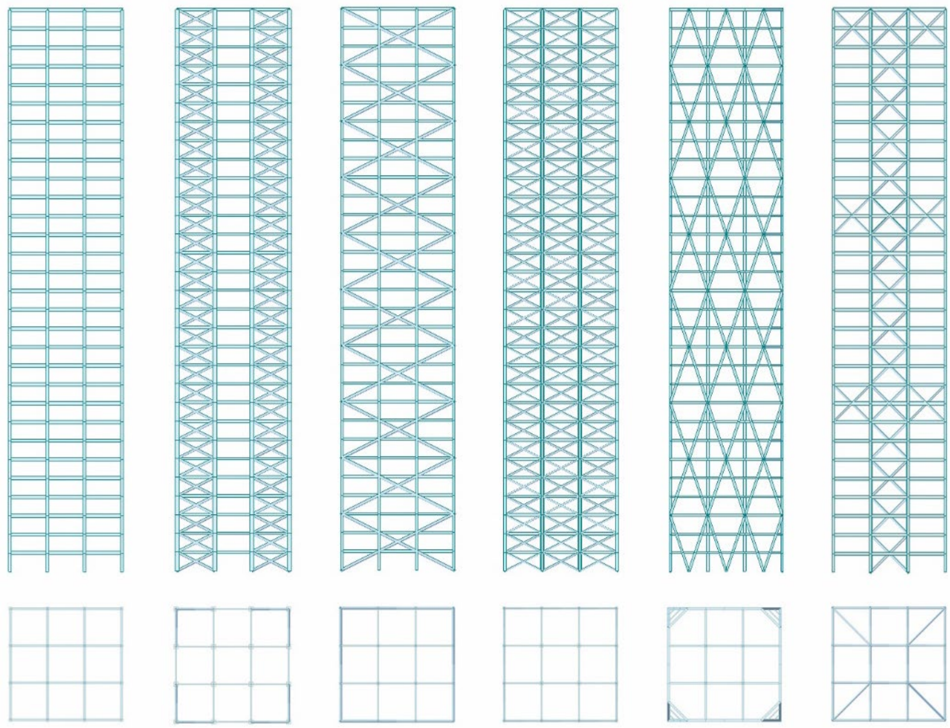
According to an existing typological classification [6], it can be stated that [MRF] and [CBF] belong to the so-called 1st generation systems and [BT] to the 2nd generation systems, while diagrid and outrigger systems can be identified as 3rd generation systems.
Moment Resisting Frame [MRF] models were set up with frames having perfect-rigid connections between columns and beams.
For the [CBF] (Concentrically Braced Frames) structural system, St. Andrew's braces were considered in the corner bays of all stories.
As for the Braced Tube structure, which is characterized by X-shaped braces in the perimetric frames of the structures, the diagonal elements were considered covering 3 stories.
The Diagrid structure consists of a “mesh” of triangular elements arranged to create a rigid tube. Two different Diagrid structures were considered:

- [DGR1]: diagonal braces inclined with an angle of 23° placed on all the outer bays;

- [DGR2]: diagonal braces inclined with an angle of 69° placed on the outer bays and covering six storeys; in this case also the corner portions are eliminated, actually providing a bevelled shape in plan.

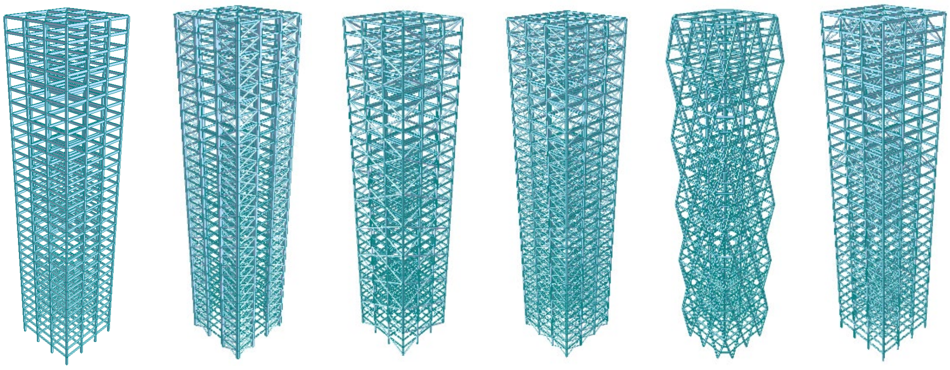
Finally, for the [OTR] structure, diagonal braces were placed in the sole central bays of the outer frames covering two storeys. Moreover, every eight storeys, the system is extended to each bay of two storeys, forming the real outrigger system.

General plans and frontal views of the considered systems are proposed in Fig. 1, while in Fig. 2 3d views of the adopted numerical models are shown.



(a) (b) (c) (d) (e) (f)

Fig. 1 Examples of plans and frontal views of the investigated structural systems: (a) [MFR], (b) [CBF], (c) [BT], (d) [DGR1], (e) [DGR2], and (f) [OTR]



(a) (b) (c) (d) (e) (f)

Fig. 2 Examples of 3d views of the adopted numerical models: (a) [MFR], (b) [CBF], (c) [BT], (d) [DGR1], (e) [DGR2], and (f) [OTR]

3 RESULTS AND DISCUSSION

The results obtained for each considered configuration are summarized in Table 1 and Fig. 3, where the total weight W_{tot} of the optimized structures is reported in relation to the *H/b* ratio. Fig. 3 clearly shows the parabolic trends of the total weight with respect to the *H/b* ratio, for each structure typology. For low height levels, the systems returned similar outcomes, while significant differences of the efficiency of the systems can be appreciated for $H/b \geq 4$. Generally, the [CBF] structural system resulted less efficient, as no solutions were found for $H/b>5$ with the considered assumptions. This could be strongly related to geometry and profile assumptions, given that mostly compressed diagonal elements having a significant length are present, with consequent buckling issues. Thus, it cannot be excluded that by assuming different plan configurations, better performance of this system would be obtained. With [MRF], a maximum *H/b* ratio up to 8 was reached. Despite this, for ensuring positive verifications significant dimensions of the beam and columns profiles were needed, which lead to admit the unsuitability of such structural system for significantly high-rise buildings.

Table 1. Total weights of the optimized structures

		Total weight [kN]					
No. of Storeys	*H/b*	[MRF]	[CBF]	[BT]	[DGR1]	[DGR2]	[OTR]
6	1	1291	1569	1508	1504	1151	
12	2	3872	4184	3201	3677	2446	3071
18	3	7949	7189	6659	7442	4120	5429
24	4	14471	16081	9888	10907	8733	10026
30	5	24921	38147	17697	16249	11308	14280
36	6	34793		26712	22193	16637	21920
42	7	50225		35481	31899	27342	33533
48	8	63876		51310	46951	41035	48399
54	9			73960	73100	60334	69848
60	10				93547	89405	97090
66	11				175360		

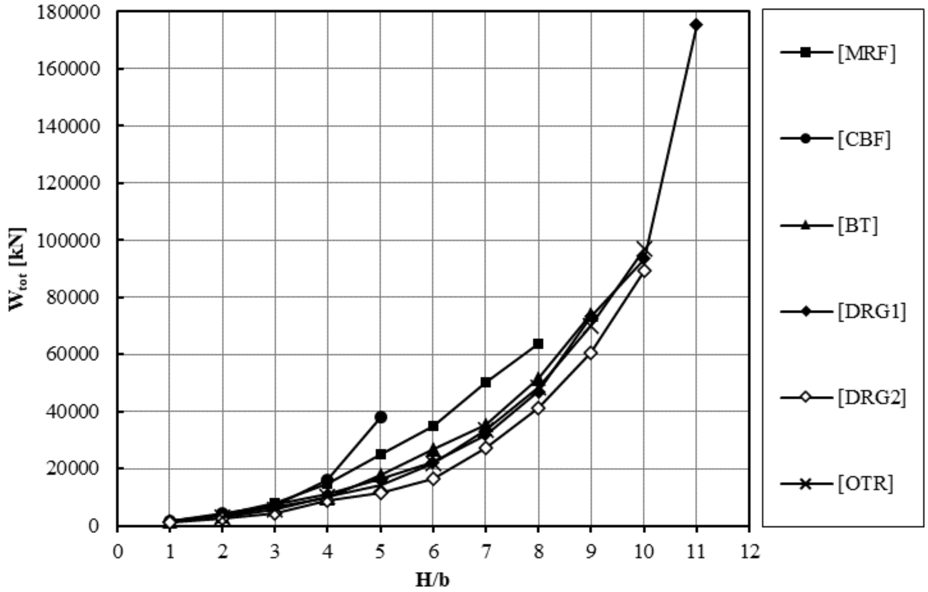


Fig. 3 Total weight of each considered structures.

On the other hand, the [DGR2] system returned the lowest values of total weight for all considered number of storeys, while the [DGR1] system was the only one that allowed to reach the maximum total height corresponding to H/b=11.
To provide a clearer interpretation of the results, in Fig. 4 the total weights obtained for each height level and structural system are normalized with respect to the system exhibiting the lowest amount of steel needed for complying with the considered standards, $W_{tot,min}$.

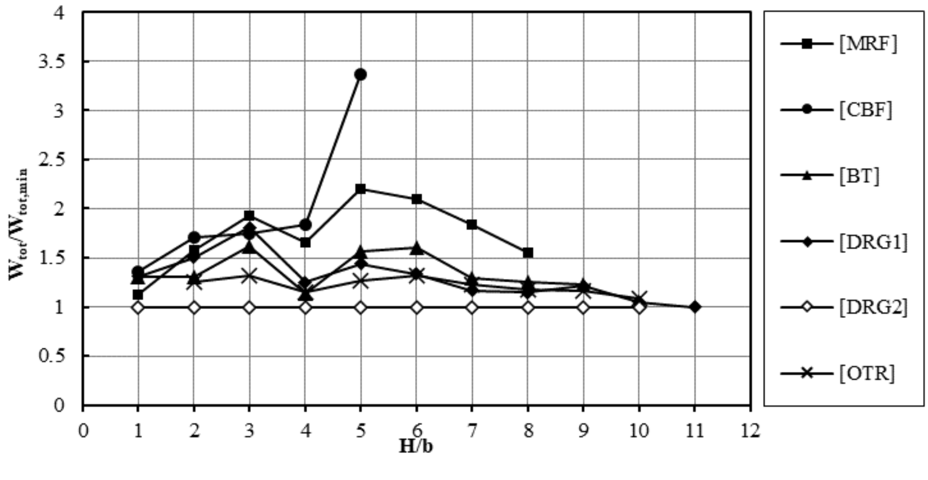


Fig. 4 Total weight of each considered structures.

The significant difference in terms of total weight between 1st generation systems and the other systems can be appreciated. Generally, these results are consistent with the observed data reported in past studies, where the slenderness of high-rise steel buildings were investigated according to real buildings.
Another aspect which is worthy of mention is that the higher the height of the considered structures the stronger the influence of deformations on the choices of the profiles. In the histogram of Fig. 5, such an aspect is shown by reporting, for each considered configuration, the ratio between the total weights of the structures and those obtained disregarding the deformation limits (maximum top displacement and inter-storey drifts), namely $W_{tot}/W_{strength}$.

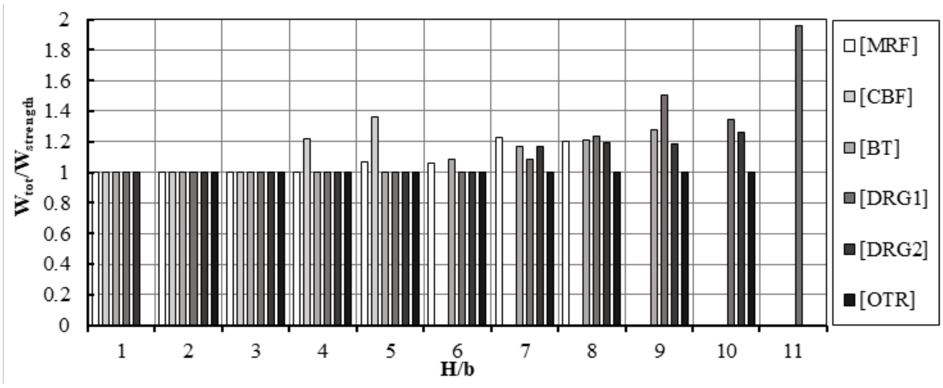


Fig. 5 Influence of deformation limits on total weight of the structures

It can be observed that the effects of deformation limits become predominant with respect to strength capacity at different height levels, and in particular:

- 1st generation systems exhibited deformation issues for $H/b \geq 4$;
- in [BT] (2nd generation system) the displacement design resulted necessary for $H/b \geq 5$;
- 3rd generation systems (diagrid) needed updates of profiles for taking into account of high horizontal displacements starting from $H/b=6$;
- outrigger structural system seems not to be affected by excessive deformation.

Generally, this evidence confirms that 3rd generation systems are usually more suitable for reaching higher rising of steel buildings.

CONCLUSIONS AND FUTURE DEVELOPMENT

In the present study, a parametric investigation aimed at identifying efficient steel structural systems for high-rise buildings has been presented. Common assumptions have been considered to effectively compare the efficiency of each investigated structural type in term of total structural weight. On the whole, the good efficiency of 3rd generation systems (i.e. diagrid and outrigger) has been highlighted, corroborating the evidence of past typological and observational studies.
Nonetheless, the present study must be intended as a preliminary investigation, given that several aspects have been, inevitably, disregarded. For instance, it cannot be excluded that by changing the plan configurations, the study would have returned different results. Also, the effect of the joints on the total weight of the structures has been neglected. Therefore, other aspects, including also hybrid systems with concrete elements, will be further investigated in order to provide typological *abacuses* aimed at identifying, for each level of slenderness, the structural performance.

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KEYWORDS

High-rise buildings, skyscrapers, structural systems, Moment Resisting Frame, Concentrically Braced Frame, Braced Tube, Diagrid Structure, Outrigger Structure