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Structural optimization of an unbraced steel system designed for a parking structure

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Abstract – **The aim of the present study is to perform a comparative analysis of four structural solutions for the columns of a multi-storey parking structure. The objective is to analyse the ratio between the final mass of the structure and its load-bearing capacity to determine the most suitable solution, leading to structural optimization. The analysis will consider the verification requirements related to both strength and stability. Parking structures are subjected to low-frequency but high-consequence hazards such as vehicle-induced impacts and fire scenarios, both of which can initiate progressive collapse mechanisms.**

Keywords – accidental actions, cruciform sections, robustness, steel parking structures.

1. INTRODUCTION

Advances in steel section design have enabled the development of increasingly complex and efficient structures. These developments stem from the need for lightweight, structurally efficient systems, with off-site steel prefabrication improving precision and reducing construction time. [1]

Growth in on-demand mobility and anticipated autonomous vehicles highlight the need to regulate emerging parking-sector innovations, which can support sustainable development; without regulation, parking practices may worsen existing urban quality-of-life issues. [2] Multi-storey car parks with steel structures aim to optimize vertical space to maximize land use, a resource that is particularly limited in urban centres. [3]

Stiffened cruciform sections are increasingly used as building columns due to their high compressive strength and balanced bending properties about both principal axes. They offer key advantages such as easy beam connections and accessible continuity plate assembly. Unlike I-sections prone to flexural buckling, cruciform sections are mainly governed by torsional buckling. Their ductility and energy dissipation capacity make them suitable for seismic applications. [4]

Keintjem et al. emphasize the influence of column height on the structural efficiency of cruciform sections. For short columns (approximately 2 m), all steel sections demonstrate similar behaviour because slenderness effects remain limited. As height increases, the advantages of cruciform geometries become more substantial. In medium-height members (around 3 m), cruciform sections maintain their efficiency compared with

H-sections, whereas I-sections show reduced performance. For tall columns (4–5 m), the "king cross" configuration surpasses both the "queen cross" and conventional profiles due to its optimized geometry, which improves load-carrying capacity and buckling resistance. These results highlight the importance of geometric optimization for enhancing material efficiency and stability in slender compression members. [1]

Failure of vertical load-bearing elements, such as columns, can trigger progressive collapse in a structure. Preventing this requires alternative load paths to redistribute forces. In parking structures, vehicle fires pose a critical risk by severely heating nearby elements, which may reduce their load capacity and compromise overall stability. [5] Steel is frequently the material of choice for multi-storey car parks. However, although steel and composite parking structures can be designed for conventional loading using well-established provisions, their performance under extreme actions remains an active area of investigation.[6]

2. CASE STUDIES

The key properties that must be assessed when designing a structural system subjected to seismic actions are ductility, strength and stiffness. Sufficient ductility is required to avoid collapse and ensure that earthquake-induced damage remains economically repairable. Seismic design therefore aims to enforce a controlled plastic mechanism that dissipates energy and prevents structural failure. [7]

This study evaluates the structural efficiency of cruciform column sections in comparison with conventional H- and I-shaped profiles, focusing on their applicability in steel parking structures, a typology of increasing relevance in contemporary practice.

The structural solution consists of HEM 400/IPE 500 columns or cruciform sections made from the same profiles, and IPE 400 beams. The secondary beams are also made from IPE 200 profiles. The floor slab is reinforced concrete C30/37, and the roof is considered non-accessible.

In unbraced frames, horizontal actions are resisted primarily through bending, with the dissipative zones located at beam ends near the beam–column joints, where energy is dissipated by cyclic flexural yielding. Dissipative regions may also develop in the columns when they are intentionally assigned at the base, at the top storey of multi-storey buildings, or at both the top and the base in single-storey structures for which $N_{Ed}/N_{pl,Rd} < 0.3$.[8]

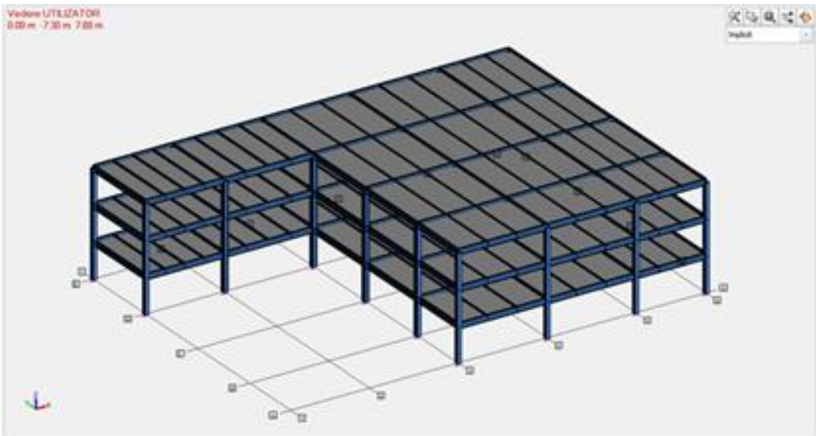

Fig. 1. Isometric view of the structure

The analysed structure is a steel parking facility located in Constanța, configured as a ground floor plus two-storey system (GF+2F). The structural layout comprises spans ranging from 6.40 m to 8.10 m and bay widths between 5.70 m and 7.20 m. Each storey has a height of 3.15 m, resulting in an overall building height of 9.45 m. The structure is designed for ductility class DCM and assigned to Importance Class III, corresponding to Importance Category C ("normal").

The load assessment incorporates permanent loads of 1.454 kN/m² for the typical floor slab and 2.027 kN/m² for the non-accessible roof terrace, together with an imposed load of 2.5 kN/m² corresponding to Category F parking and light-vehicle traffic areas [9]. The characteristic snow load for Constanța is taken as 1.2 kN/m². [10]

Seismic action is defined using a design ground acceleration ag = 0.20g and the elastic response spectrum with TB = 0.14 s, TC = 0.70 s and TD = 3.00 s. [7] Load combinations are established according to SR EN 1990 and P100-1/2013, applying $\psi_2 = 0.6$ for imposed loads and including the overstrength factor ΩT for non-dissipative elements such as columns.

3. RESULTS AND SIGNIFICANCES

3.1. Comparative assessment of column solutions in terms of strength

Following the strength verification under maximum loading, all four structural configurations were found to meet the required strength criteria. However, the structure composed of simple IPE500 rolled sections is at the lower limit of the minimum acceptable resistance capacity.

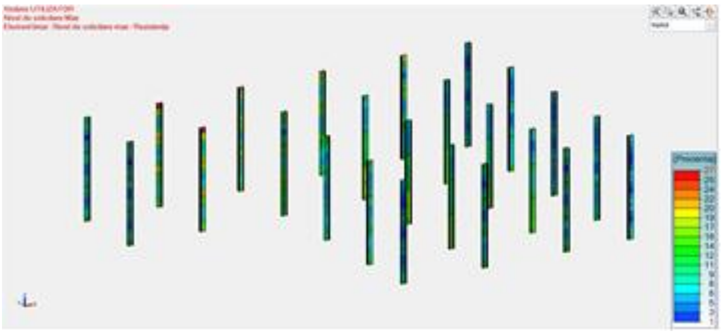

Fig. 2 Strength verification under peak demand conditions for HEM400 columns

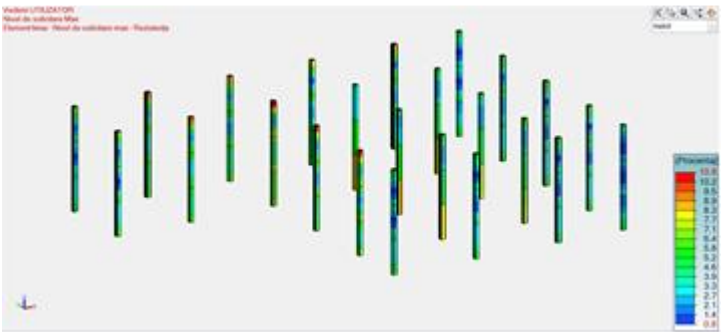

Fig. 3 Strength verification under peak demand conditions for HEM400 cruciform columns

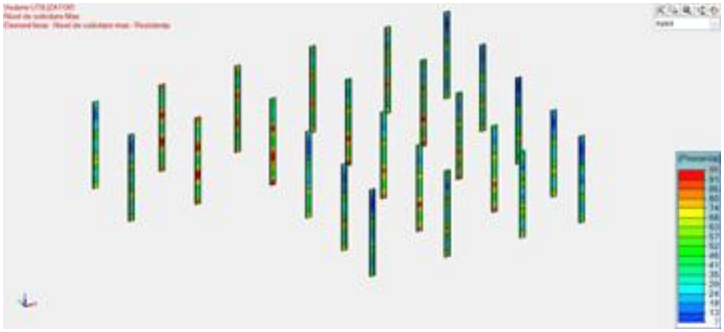

Fig. 4 Strength verification under peak demand conditions for IPE500 columns

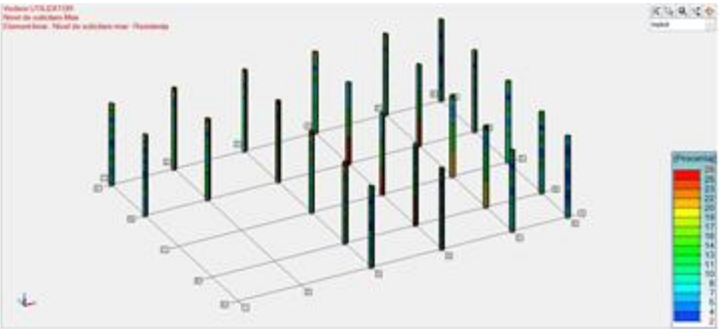

Fig. 5 Strength verification under peak demand conditions for IPE500 cruciform columns

3.2. Comparative assessment of column solutions in terms of stability

Following the stability verification under maximum loading, only three of the analyzed structural configurations meet the stability requirement. Columns made from IPE500 rolled sections lose stability under the specific loading conditions. The three compliant configurations exhibit a considerable structural reserve in terms of stability, ensuring that the columns possess sufficient overstrength to allow the formation of the plastic mechanism.

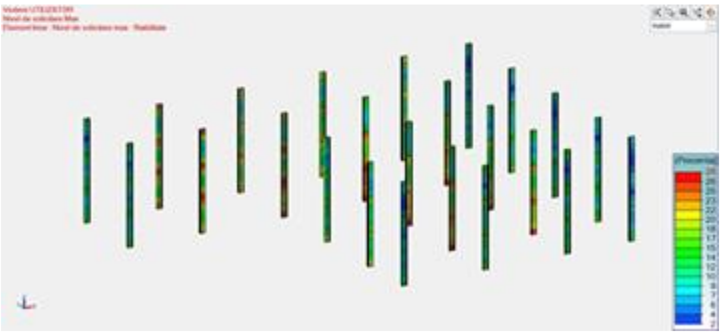

Fig. 6 Stability verification under peak demand conditions for HEM400 columns

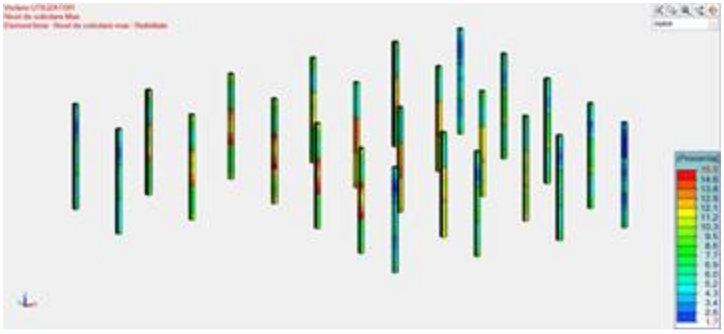

Fig. 7 Stability verification under peak demand conditions for HEM400 cruciform columns

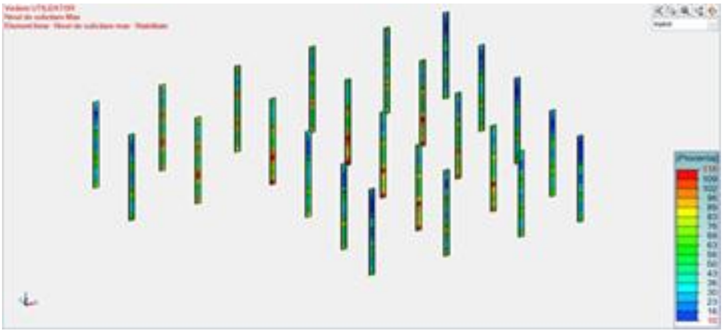

Fig. 8 Stability verification under peak demand conditions for IPE500 columns

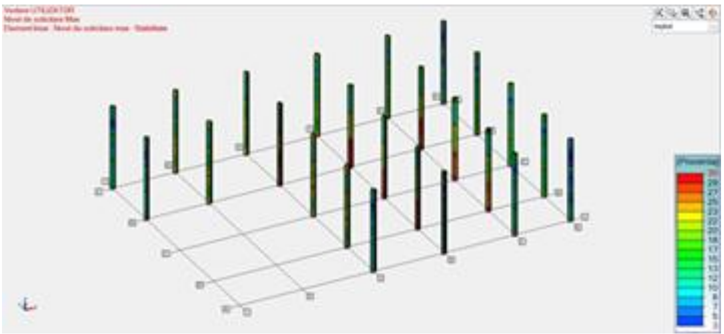

Fig. 9 Stability verification under peak demand conditions for IPE500 cruciform columns

3.3. Comparative assessment of column solutions in terms of stability

To determine the most economically advantageous solution, we will compare only the column weight summaries, since the rest of the structure remains the same.

Given that the option using IPE500 rolled profiles does not meet the strength and stability requirements, it will be excluded. The remaining viable options are cruciform columns made from IPE500 or HEM400 profiles, and the simple HEM400 section. The cruciform solution using HEM400 profiles proves to be highly disadvantageous economically. Therefore, we will compare the cost difference between the simple HEM400 section and the composite IPE500 cruciform section.

Average steel price considered was €1.8/kg. The IPE500 composite solution has a total steel weight of 41,142 kg, compared with 57,853 kg for the simple HEM400 section. The resulting weight reduction of 16,711 kg corresponds to an approximate cost saving of €30,000.

4. CONCLUSIONS

This study, which analysed a multi-storey parking structure from the perspective of optimizing the column section, led to the following conclusions:

1. In the case of typical parking loads, a moderate seismic zone, and medium column height, cruciform "Malta cross" sections made from HEM profiles are not justified due to an unfavourable weight-to-strength ratio.
2. Columns made from standard I-shaped rolled sections do not ensure sufficient load-bearing capacity. They are vulnerable to in-plane buckling due to low minor-axis stiffness and are designed primarily for bending, not axial loads.
3. The most economically efficient solution is the cruciform column made from IPE sections, offering an optimal mass-to-capacity ratio and reducing overall structural costs by approximately €30,000 compared to equivalent HEM sections.

Cruciform columns also allow rigid joints in all directions, improving structural redundancy. This enhances robustness and reduces the risk of progressive collapse-particularly important for multi-storey parking structures, where fire or impact hazards are higher.

6. REFERENCES

[1] M. Keintjem, R. Suwondo, and M. Suangga, *Efficiency Assessment of Cruciform Steel Columns: Balancing Axial Capacity and Weight*, Eng. Technol. Appl. Sci. Res., vol. 15, no. 2, pp. 21342–21347, Apr. 2025, doi: 10.48084/etasr.10107

[2] J. Rosenblum, A. W. Hudson, and E. Ben-Joseph, *Parking futures: An international review of trends and speculation*, Land Use Policy, vol. 91, p. 104054, Feb. 2020, doi: 10.1016/j.landusepol.2019.104054

[3] S. Xiang, Y. He, T. Golea, V. Denoël, and J.-F. Demonceau*, Simplified methods to predict the robustness of steel parking-structure joints*, J. Constr. Steel Res., vol. 213, p. 108355, Feb. 2024, doi: 10.1016/j.jcsr.2023.108355

[4] H. Naderian, R. Sanches, O. Mercan, P. J. Kushner, M. Azhari, and H. Ronagh, *Stability of stiffened cruciform steel columns under shear and compression by the complex finite strip method*, Thin-Walled Struct., vol. 136, pp. 221–234, Mar. 2019, doi: 10.1016/j.tws.2018.12.023

[5] J. M. Adam, F. Parisi, J. Sagaseta, and X. Lu, *Research and practice on progressive collapse and robustness of building structures in the 21st century*, Eng. Struct., vol. 173, pp. 122–149, Oct. 2018, doi: 10.1016/j.engstruct.2018.06.082

[6] J.-F. Demonceau et al., *Robustness of car parks against localised fire. Communauté Europèene,* 2012

[7] Cod de proiectare seismică. Partea I. Prevederi de proiectare pentru clădiri, indicativ P 100-1/2013

[8] F. Țepes-Onea, *Construcții metalice*. București: MatrixRom, 2023

[9] SR EN 1991-1-1 - Eurocod 1: Acțiuni asupra structurilor Partea 1-1 : Acțiuni generale - Greutați specifice, greutăți proprii, încărcări utile pentru clădiri.
[10] Cod de proiectare. Evaluarea acțiunii zăpezii asupra construcțiilor, indicativ CR 1-1-3/2012