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Stiffness Ratio Evaluation of Steel Exoskeletons Through Performance-Based Optimal Design

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Abstract. Among the various seismic retrofitting techniques, steel exoskeletons are distinguished by their non-invasive nature. However, only a few consolidated methodologies have been proposed for their design. The approach of several standard codes is based on the classification of elements according to their relative stiffness. In this way, a ratio between the stiffness of the exoskeletons and that of the building is taken as the main design parameter. In this study, a performance-based design approach was employed, with the inter-story drift of the building as the performance target. A sensitivity analysis was conducted to assess the impact of different inter-story drift thresholds on the structural behavior of the building-exoskeleton system. For each threshold, an optimization process was conducted to identify the optimal number of exoskeletons, their placement around the building, and the dimensions of their elements. Finally, the stiffness ratios were determined for each optimal configuration and were compared to the threshold provided by the regulations. This comparison yielded interesting insights into the differences in the approaches.

Keywords. Exoskeletons, seismic retrofit, optimization, sensitivity analysis, inter-storey drift, genetic algorithm

1. Introduction

In recent decades, steel exoskeletons have emerged as a promising solution for seismic retrofitting of reinforced concrete (RC) buildings [1]. In Europe, several buildings have been designed with outdated standards, without considering provisions to resist seismic excitation [2,3]. Moreover, the majority of these buildings have surpassed their design lifespan, resulting in durability issues and posing a potential safety hazard [4,5,6,7].

In this context where a great number of interventions are needed, the advantages of employing steel exoskeletons for retrofitting become crucial [8,9,10] even if a proper design of the pile foundations is needed [11]. The application of the exoskeleton from

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the exterior of the building prevents the interruption of the structure's use [12], avoiding downtime losses and relocation of inhabitants, thus reducing construction times and costs [13]. These structures increase the stiffness of the system against horizontal actions, thereby bearing a part of the seismic action and unloading the buildings [14].

The European standard regulation Eurocode8 [15] and the Italian NTC18 [16] provide guidelines that can be useful when designing interventions with exoskeletons. A classification of the structure's elements into primary and secondary is proposed based on their stiffness. Secondary elements are not required to meet the resistance requirements for horizontal actions generated by the seismic excitation. Nevertheless, the total contribution of the secondary elements to the stiffness and resistance to horizontal actions cannot exceed 15% of the analogous contribution of the primary elements. Moreover, due to the lack of knowledge about the stress distribution in the existing building, practitioners who follow this approach are often constrained to consider the entire existing structure as secondary. Consequently, in order to comply with the code provisions, the exoskeletons must have a stiffness of at least $K_{syst}/K_{str} = 100/15 = 6.67$ times that of the existing structure, where K_{syst} is the horizontal stiffness of the system (building and exoskeletons) and K_{str} is that of the building.

This raises the question of whether the stiffness ratio approach is the sole or most efficient method for ensuring the safety of the structure. In this study, a performance-based design approach was employed, with the inter-story drift of the building as the performance target. A sensitivity analysis was conducted to assess the impact of different inter-story drift thresholds on the structural behavior of the building-exoskeleton system. For each threshold, an optimization process was conducted to identify the optimal number of exoskeletons, their placement around the building, and the dimensions of their elements. The optimization tool aims to minimize the weight of the exoskeletons while respecting two constraints: the inter-storey drift threshold and the structural verifications of the exoskeleton elements. Subsequently, the stiffness ratios were determined for each optimal configuration and were compared to the threshold provided by the regulations.

2. Optimization framework

An optimization process was employed to determine the optimal number and spatial arrangement of exoskeletons, as well as the sizing of their members. The Objective Function is presented in Eq. 1, and the Design Variables are presented in Eq. 2.

$$\mathbf{min}\, f = W_{Ex} * \phi_1(D_i) * \phi_2(S_j) \tag{1}$$

$$\mathbf{x} = [\, x_1 \,,\, \dots \,,\, x_i \,,\, \dots \,,\, x_n \,,\, x_{n+1} \,,\, \dots \,,\, x_{n+j} \,,\, \dots \,,\, x_{n+m} \,] \tag{2}$$

The Objective Function is given by the minimization of the exoskeletons' weight, W_{Ex}, which is multiplied by two penalties, ϕ_1 and ϕ_2. These penalties represent the constraints of the optimization, designated as D_i and S_j. The first constraint, D_i represents the imposition of a maximum inter-storey drift allowable to all the nodes of the building. The threshold is defined as H/β, where H is the storey height and β is a factor. In this study, six different values of β were analyzed, ranging from 400 to 650, considering the thresholds proposed by [17] and [18]. In this way, a sensitivity analysis was conducted.

On the other hand, the second constraint is related to the structural verification of the exoskeleton's elements. These concern the combined bending and axial compression, accounting for buckling, according to EC3 6.3.3.(6.61-6.62) and the combined shear force and torsional moment, according to EC3 6.2.7.(6.25) and (6.28).

The design variables (Eq. 2) from x_1 to x_n are binary DVs, from which the amount and position of exoskeletons are determined. Conversely, the design variables from x_{n+1} to x_{n+m} define the size of the exoskeleton's elements. These select a standard Circular Hollow Section (CHS) for each element from a standard list in accordance with the European code EN10219-2 [19].

The described optimization process is applied through a Genetic Algorithm with case-specific modifications, developed by Olivo et al. [20]. In order to evaluate the fitness of each individual, it is necessary to determine the stresses and displacements of the system that result from the application of the seismic excitation. To obtain these results, multimodal spectral analyses were conducted using SAP2000 OAPI (Open Application Programming Interface). The utilization of this software facilitated the automatic generation and modification of the structural models, which were controlled by the algorithm in MatLab. The characteristics of the building and the exoskeletons, as well as the loads implemented in the model, are described in the following section.

3. Case study

For this research, the building to be retrofitted is a reinforced concrete moment-resisting frame building. It has three bays of five meters in each direction and three storeys of four meters each, providing a square-shaped building of 15 x 15 x 12 meters. The stairs located in one of the modules generate an irregularity in plant, while maintaining the regularity in height. The building is composed of beams and columns fully restrained to each other, the columns are fully restrained to the foundation, and the floors are considered to behave as rigid diaphragms.

The building was designed for this study with the aim of representing a typical real-world building constructed prior to the introduction of seismic design standards. The structure has been designed to comply with the structural verifications corresponding to the Ultimate Limit State (ULS) in front of gravitational loads, in accordance with the NTC18. Conversely, several elements of the building result non-verified when subjected to seismic action corresponding to the Life Safety Limit State (LSLS). The seismic excitation was determined in accordance with the NTC18, considering the building located in Foggia, Italy. In this case, a significant number of elements are overstressed, presenting a maximum demand-capacity ratio (DCR) of 2.15 and an average DCR among all the elements of 1.37.

The exoskeletons are non-dissipative steel frames that function as truss bracing systems, positioned perpendicular to the building's façade and connected to the column-beam nodes of the building. The exoskeletons are entirely composed of S355 steel Circular Hollow Sections (CHS). A size optimization is conducted to determine the optimal cross-sectional area for each element, from a list of standard CHS profiles in accordance with the European code EN10219-2. Moreover, the number of exoskeletons to be placed and their respective locations are also determined through the optimization process, as detailed in Section 2.

4. Results and discussion

The application of the optimization procedure to the case study, with consideration of different inter-storey drift thresholds, yielded insights into the behavior of a building retrofitted with steel exoskeletons.

Fig. 1 depicts the final configuration obtained from the optimization process for each considered inter-storey drift (ISD) threshold. Furthermore, the structural verifications of the reinforced concrete building were conducted in accordance with the Italian Standard Regulation NTC18. The demand-capacity ratios (DCR) of each element are presented as color maps in the same figure for all the considered cases, ranging from an ISD allowable of H/400 (Fig. 1(a)) to H/650 (Fig. 1(f)).

The unretrofitted building is characterized by the presence of several critical elements, as illustrated in Fig. 2. The maximum DCR among the elements is 2.15, while the average of all the elements' DCRs is 1.37. A comparison of Figures 2 and 1 reveals that an exoskeleton-based intervention results in a notable reduction in the forces bared by the building, thereby enabling their elements to comply with the structural verification requirements.

Moreover, the maximum and average DCRs corresponding to each case study were presented in Fig. 3, for each ISD threshold. This figure illustrates the impact of maximum inter-storey drift on the structural verification of reinforced concrete (RC) elements, along with the required steel weight for each case. Interesting insights are obtained comparing the values of maximum and average DCR obtained for each inter-storey drift threshold with the ones of the unretrofitted building, which were 2.15 and 1.37, respectively. Both the maximum and the average DCR decrease significantly with the introduction of the exoskeletons, with reductions ranging from 48% to 60%, corresponding to the ISD thresholds of H/400 and H/650, respectively.

The unloading of the building after the retrofit is evident from the results presented in Figure 4. The base shears were calculated in the X and Y directions, and the forces taken by the unretrofitted building were compared to the forces taken by the building and by the exoskeletons, after the retrofit. It is noteworthy that as the ISD threshold is reduced, becoming more restrictive, the exoskeletons tend to be stiffer, attracting more force and unloading the building to a greater extent.

Analyzing the results, the total base shear of the building after the retrofit, for the configuration obtained with the ISD threshold of H/400, is 66% of that of the unretrofitted building, in the X direction, and 52% in the Y direction. In contrast, the base shears for the ISD threshold of H/650, which is more rigorous than H/400, are 53% and 42% of that of the unretrofitted building, in the X and Y directions, respectively. These values indicate that, as previously stated, the more restrictive the ISD threshold, the greater the unloading of the building.

Finally, the stiffness ratios (K_{syst}/K_{str}) of the configurations corresponding to the different ISD thresholds are presented in Table 1 for the X and Y directions. The ratios in question are calculated as the stiffness of the system constituted by the building and the exoskeletons, divided by the stiffness of the building alone. The stiffnesses against horizontal actions were considered for each direction independently. It is evident that the obtained stiffness ratios are considerably lower than the threshold values prescribed by the Italian and European standard regulations, which is 6.67, presenting reductions ranging from the 60% to the 72%. This reduction in the stiffness ratio indicates that less

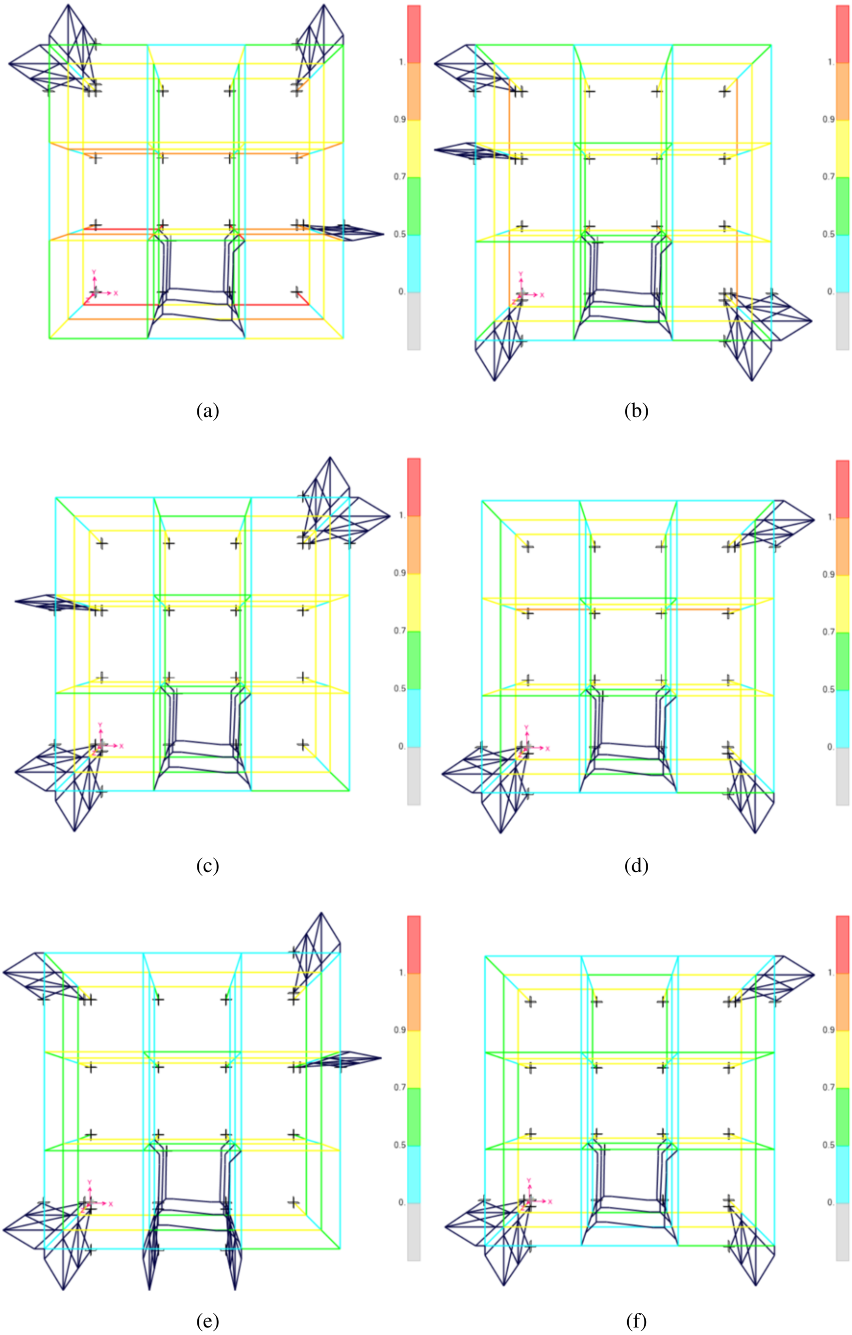

Figure 1. Color map of the structural verifications of the obtained configurations corresponding to the different inter-storey drift ratios, from H/400 (a) to H/650 (f)

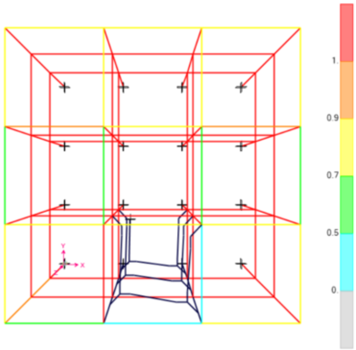

Figure 2. Color map of the structural verifications of the unretrofitted building

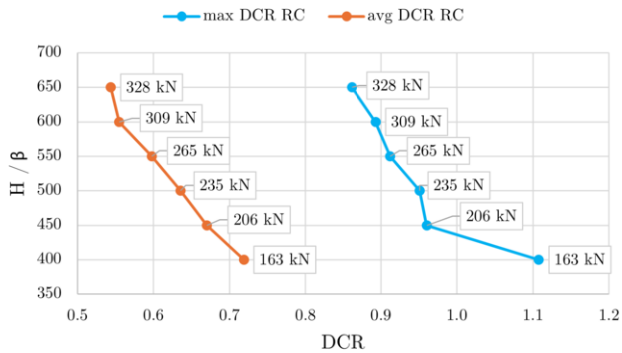

Figure 3. Sensitivity analysis of the effect of the imposed inter-storey drift threshold on the structural verifications of the RC building's elements, in terms of maximum and average demand-capacity ratios

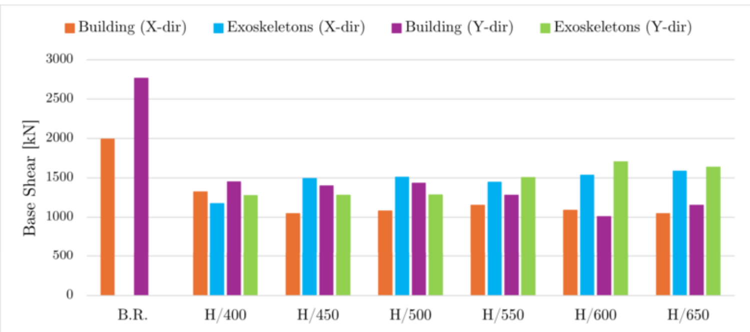

Figure 4. Base shears bared by the building and by the exoskeletons, before (B.R.) and after the retrofit

stiff exoskeletons can lead the existing building to comply with all the structural verifications against horizontal actions. In conclusion, the lower the imposed ISD threshold, the greater the participation of the existing building in the resistance to horizontal actions, and the more lightweight and cost-efficient the solution.

Table 1. Stiffness ratios (K_{syst}/K_{str}) obtained for the different inter-storey drift thresholds (H/β).

H/β	K_{syst}/K_{str}	
	X-dir	Y-dir
H/400	1.89	1.88
H/450	2.43	1.91
H/500	2.40	1.89
H/550	2.25	2.17
H/600	2.41	2.69
H/650	2.51	2.42

5. Conclusions

Some standard regulations propose a stiffness-based approach for the design of an exoskeleton system. This approach is based on the control of the ratio between the horizontal stiffness of the exoskeletons and that of the building. In this paper, an alternative approach is explored, adopting a performance-based approach for the design, relying on the inter-storey drift (ISD) as the main performance target.

In order to perform a sensitivity analysis, different ISD thresholds were considered. These thresholds were incorporated as constraints in an optimization process, performing one optimization for each. The optimization aims to find the lightest solution while complying with the allowable ISD and meeting the structural verification requirements for the exoskeleton elements. Through this process, the optimal number and placement of the exoskeletons are determined, as well as their sizing. Finally, the structural verifications were conducted on the resulting configurations, and their stiffness ratios were determined.

The stiffness ratios of the resulting configurations were determined by dividing the horizontal stiffness of the retrofitted system by that of the building alone. These values were then compared with the threshold provided by the standard regulation, obtaining reductions in the stiffness ratio ranging from 60% to 72%. The results suggest that an exoskeleton solution obtained through the imposition of an inter-storey drift limit can guarantee the structural safety of the building while providing reduced weight and cost of the exoskeletons. This is due to the fact that the building still contributes to the resistance of horizontal actions, in a proportion determined by the selected ISD threshold.

The optimal ISD threshold to be selected for the design is highly dependent on the characteristics of the building to be retrofitted, and it has a strong influence on the resulting behavior of the system. The analysis of buildings with different characteristics and irregularities may yield valuable insights into the performance and applicability of this design approach.

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