

PERFORMANCE-BASED OPTIMIZATION FRAMEWORK CONSIDERING SHEAR WALL HEIGHT IMPACT ON STRUCTURAL BEHAVIOR OF HIGH-RISE BUILDINGS

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Abstract. *Shear walls play a crucial role in displacement control when included in moment-resisting tall frame buildings, and they provide an essential contribution to the lateral load resistance mechanism. This aspect has attracted significant attention into the structural optimization of frame-wall systems with the aim of minimizing their weight while enhancing structural performance. A promising approach involves the curtailment of shear walls at intermediate stories, instead of their continuation until the top of the frame building. The potential of this approach is that shear walls significantly contribute to displacement and stress control in lower stories, but their effectiveness decreases with height, and it can become detrimental.*

In this study, a parametric analysis is conducted analyzing the behavior of RC frames with shear walls curtailed at varying heights under wind and seismic loads. The displacement profiles, shear force diagrams, and bending moment diagrams are analyzed for 10, 12, and 14-floor frame buildings with different height shear walls. Interesting principles were individuated from the study of the obtained results.

The insights derived from the parametric analysis served as the basis for the definition of a preliminary performance-based optimization framework. The aim is to optimize the shear walls' layout and sizing, while also accounting for variations in wall height. The proposed framework outlines the definition of design variables, critical constraints, and effective strategies to enhance structural efficiency. This framework is expected to provide fundamental insights into the optimal balance between performance targets, stiffness requirements, and material consumption, paving the way for more efficient and sustainable structural solutions.

Keywords: Shear Walls, Optimization, Performance-Based, High-Rise, Earthquake

1 INTRODUCTION

Shear walls are a fundamental component in the structural design of high-rise buildings, reducing lateral displacements and inter-story drift. Their widespread adoption underscores their critical role in ensuring safety and serviceability of structures.

Consequently, the role of shear walls in structural systems has been extensively studied. [1] provided key insights into the design considerations of combined shear wall-frame systems, emphasizing their efficiency in resisting lateral loads. [2] reviewed previous research on shear wall structures, summarizing the main aspects of their behavior and load transfer mechanisms. [3] expanded upon these principles in the comprehensive work on tall buildings, providing guidelines for the analysis and design of the various typologies.

Given the importance of shear walls, the optimization of their placement and sizing has become a key research area. Effective optimization can reduce material usage, improve performance, and expedite the design process in early stages. In this regard, [4] introduced a practical framework for shear wall layout optimization based on the ESO method. In a related study, [5] developed a framework that integrates structural and architectural considerations using an evolutionary algorithm and the ground structure method. Other studies focused on integrating shear wall layout optimization with performance-based seismic design principles [6, 7]. In more recent studies, researchers have explored the use of neural networks for the intelligent generative design of shear wall buildings [8]. Although significant advances have been made in the field of shear wall optimization, most studies have focused exclusively on in-plan arrangement and base dimensions. Consequently, the potential benefits of in-height variations of shear walls remain unexploited.

A few studies addressed the effects of shear wall curtailment on the structural behavior of the frame. An early investigation into curtailed wall-frame structures was conducted by [9], who developed a mathematical solution for a continuum model and provided curves that specify the optimal level of curtailment under uniformly distributed loads. Subsequent research by [10] built upon this earlier investigation by correcting the optimal curtailment level curves. [11] examined the displacements of buildings with curtailed shear walls at varying heights under seismic loading conditions. Their findings indicated that extending beyond mid-height of the building has a negligible effect on top displacement.

These studies demonstrate that shear wall curtailment is a feasible design approach that has the potential to reduce weight while maintaining displacement and stress levels. It can even lead to a reduction in the reverse forces exerted by the wall on the frame at upper floors. Investigations into the optimal shear wall height under wind loading conditions have individuated valuable formulations. However, research focusing on seismic loading has failed to identify generalizable principles regarding optimal wall height. The majority of these studies overlooked the variation of shear and bending moment distribution along the height of the building, which are critical for the determination of wall curtailment effects.

In the present study, a novel philosophy for the optimization framework of shear walls is proposed, leveraging the advantages of shear wall curtailment. To establish the foundations for this approach, a better understanding of the wall height impact on structural behavior is required. To this end, a parametric analysis is conducted on RC moment-resisting frame buildings with varying wall curtailment heights, under wind and seismic loads. The insights gained from the parametric analysis guided the definition of the optimization framework. Key design variables, relevant constraints, and critical considerations are defined. In particular, effective strategies to enhance structural efficiency are derived from the observed effects of wall curtailment.

2 METHODOLOGY

The parametric analysis is designed to systematically evaluate the structural behavior of a moment-resisting frame with shear walls curtailed at different heights under both wind and seismic loading. In this way, the influence of wall curtailment on key structural parameters is assessed. The analyses are conducted using the SAP2000 OAPI through a MATLAB script that enables automatic model generation and modification, as well as results extraction.

Due to the high in-plane stiffness of the slabs, which ensures uniform horizontal displacement across the frame, the model is simplified as a planar frame with rigid diaphragms at each floor. The shear wall is modeled using thin shell elements. Figure 1 presents the model and characteristics of the frame with full-height, 11-floor, and 7-floor walls. Gravitational and horizontal loads have been defined according to the European Standard Regulation. Horizontal loads include seismic and wind loads, the latter of which have been modeled as a uniformly distributed load concentrated at each floor level.

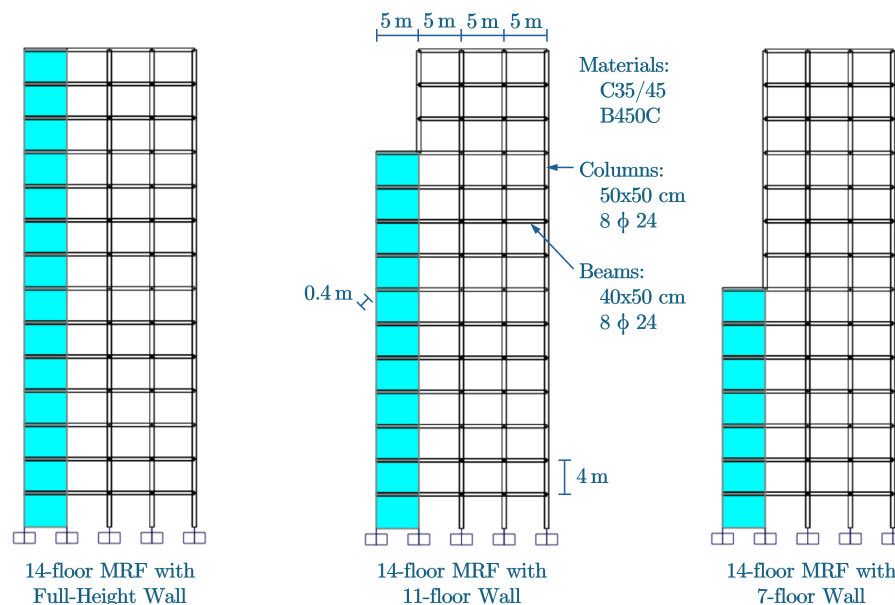


Figure 1: Model of the 14-floor moment-resisting frame with full-height, 11-floor, and 7-floor shear walls. Geometric and material characteristics are indicated.

The study's objective is to assess key structural performance indicators, including floor displacements, shear forces, and bending moments in both the wall and the frame. These are analyzed at each floor level to provide insight into the redistribution of internal forces and the overall effectiveness of wall curtailment in reducing material usage without compromising structural behavior.

3 RESULTS OF THE PARAMETRIC ANALYSIS

This section presents the results of the parametric analysis conducted on a moment-resisting frames with shear walls curtailed at different heights, under wind and seismic loads. The results focus on three key response parameters: displacement profiles, shear force diagrams, and bending moment diagrams. The displacement profiles illustrate how wall height influences global lateral deformation. The shear force and moment diagrams offer insights into the redistribution of internal forces between the frame and the wall as the curtailment height varies. Due

to the extensive number of analyzed scenarios, a representative selection has been made for presentation.

The displacement profiles presented in Figure 2 consistently show that curtailing the shear wall up to a certain height, which is generally close to the mid-height of the frame building, improves top displacement control. However, beyond this point, further extensions of the wall provide negligible additional reductions in top displacement. Therefore, further extensions are structurally inefficient in terms of displacements. This behavior is evident in both wind and earthquake loading cases.

Furthermore, particularly under seismic loads, shorter walls demonstrate an enhanced ability to control displacements in the lower stories of the building, though this effect is less pronounced than the variations observed in top displacement. Consequently, if an optimal curtailment point is identified, the displacements of both the upper and lower stories can be reduced simultaneously.

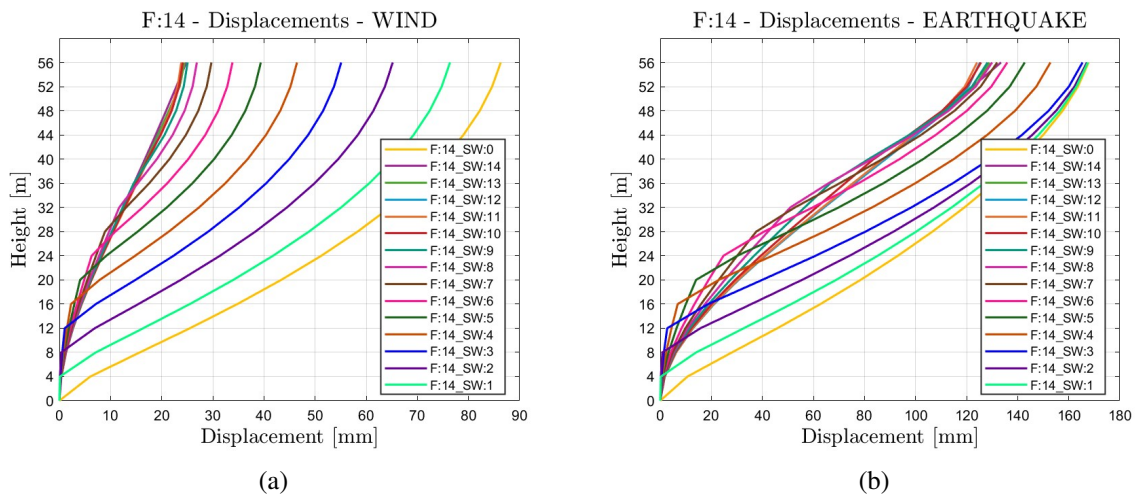


Figure 2: Displacement profiles of the moment-resisting frame building with varying wall height, under (a) wind and (b) earthquake loading conditions.

The shear force diagrams are presented in Figure 3, illustrating the redistribution of shear force deriving from wall curtailment. The diagrams for the full-height wall (Fig. 3(a)(b)) reveal the distribution of forces between frame and wall under seismic loading. It is evident from these diagrams that the wall has a higher participation in the resistance to horizontal actions in lower stories, while the frame becomes central in the upper stories.

Particularly, under wind loading (Fig. 3(a)), there is a distinct point where the shear force in the wall changes direction. At this location, the wall begins to exert counterforces onto the frame, indicating that the ideal curtailment position to avoid adverse force interactions would be below this point, as explained in [9]. However, under seismic loading (Fig. 3(b)), the forces on the wall remain positive throughout the entire height. Consequently, this distinct point is not observed.

Examining the curtailed wall cases (Fig. 3(c)-(f)), it can be appreciated that reducing the wall height leads to a localized increase in shear forces in the frame columns immediately above the curtailment level. This effect is observed in both wind and seismic cases, with the intensity of the shear increase growing as the curtailment height decreases. Under wind loading, the frame shear above the cut matches the total shear, which also coincides with the shear distribution of the bare frame. This implies that shear redistribution in the frame can be directly predicted

from the full-height case. In contrast, for seismic loads, predicting the increase in frame shear is not straightforward. This is due to the influence of the modal properties of the system on the seismic forces, which in turn are influenced by the wall height.

The bending moment diagrams are presented in Figure 4 in the same way as for the shear diagrams. It is evident from these diagrams that the contribution of the shear wall decreases with height. In particular, for the full-height wall, the wind load case (Fig. 4(a)) exhibits a clear inflection point, marking the transition from positive to negative moments in the wall. According to [9], this inflection point serves as the lower bound of the optimal range for curtailment, aiming at minimizing top displacement. However, this trend does not hold for seismic loading (Fig. 4(b)), where no clear inflection point is observed.

An examination of the case involving curtailed wall at the 7th floor (Fig. 4(c)-(f)) reveals that, in contrast to shear forces, the redistribution of stresses after the curtailment does not result in substantial increases in column moments. Even if the moment increase resulting from curtailing the wall at lower floors is higher than that from curtailing the wall at upper floors, moment variation remains relatively minor. This finding suggests that the primary structural concern when curtailing shear walls is the redistribution of shear forces, rather than the localized increment in bending moment.

In summary, the parametric analyses indicate that the curtailment of shear walls up to certain heights can optimize displacement control without adverse effects on structural behavior. Shear redistribution in the frame at the curtailment level is a crucial consideration, particularly under seismic loads where predictions are less straightforward due to the load's dependency on modal properties. Conversely, moment redistribution does not pose a significant concern. These findings contribute to a fundamental understanding of the effects of wall height variation and serve as key inputs for the development of the optimization framework.

4 OPTIMIZATION FRAMEWORK: A NEW PHILOSOPHY

The optimization of shear walls in moment-resisting frame buildings is a crucial step in enhancing structural efficiency while minimizing material usage in high-rise buildings. This study proposes a preliminary framework for optimizing shear walls in frame structures, considering not only their layout and sizing but also variations in height. Unlike conventional approaches that assume full-height shear walls, this framework incorporates the possibility of curtailing walls at specific heights. In some cases, curtailment may even improve performance by reducing top displacement and preventing adverse counterforces from the walls on the frame at upper levels.

Furthermore, in recent years, seismic design has undergone a paradigm shift toward performance-based approaches. The performance objectives are defined by establishing acceptable levels of structural and non-structural damage for different hazard levels. Given the critical role of shear walls in controlling lateral stiffness and strength, the optimization framework is designed around a performance-based seismic optimization strategy.

The primary objective function of the optimization process is to minimize structural weight, thereby reducing the total material consumption of both the frame and the shear walls. Additionally, a multi-objective optimization strategy could also be explored to incorporate sustainability metrics [12], such as embodied carbon, or to minimize structural complexity, which directly affects constructability and costs [13]. The design variables in the proposed framework include the number and distribution of shear walls within the building footprint and their height, as well as the cross-sectional dimensions and reinforcement of both the walls and the frame elements.

In the context of performance-based seismic design, damage thresholds are defined to ensure

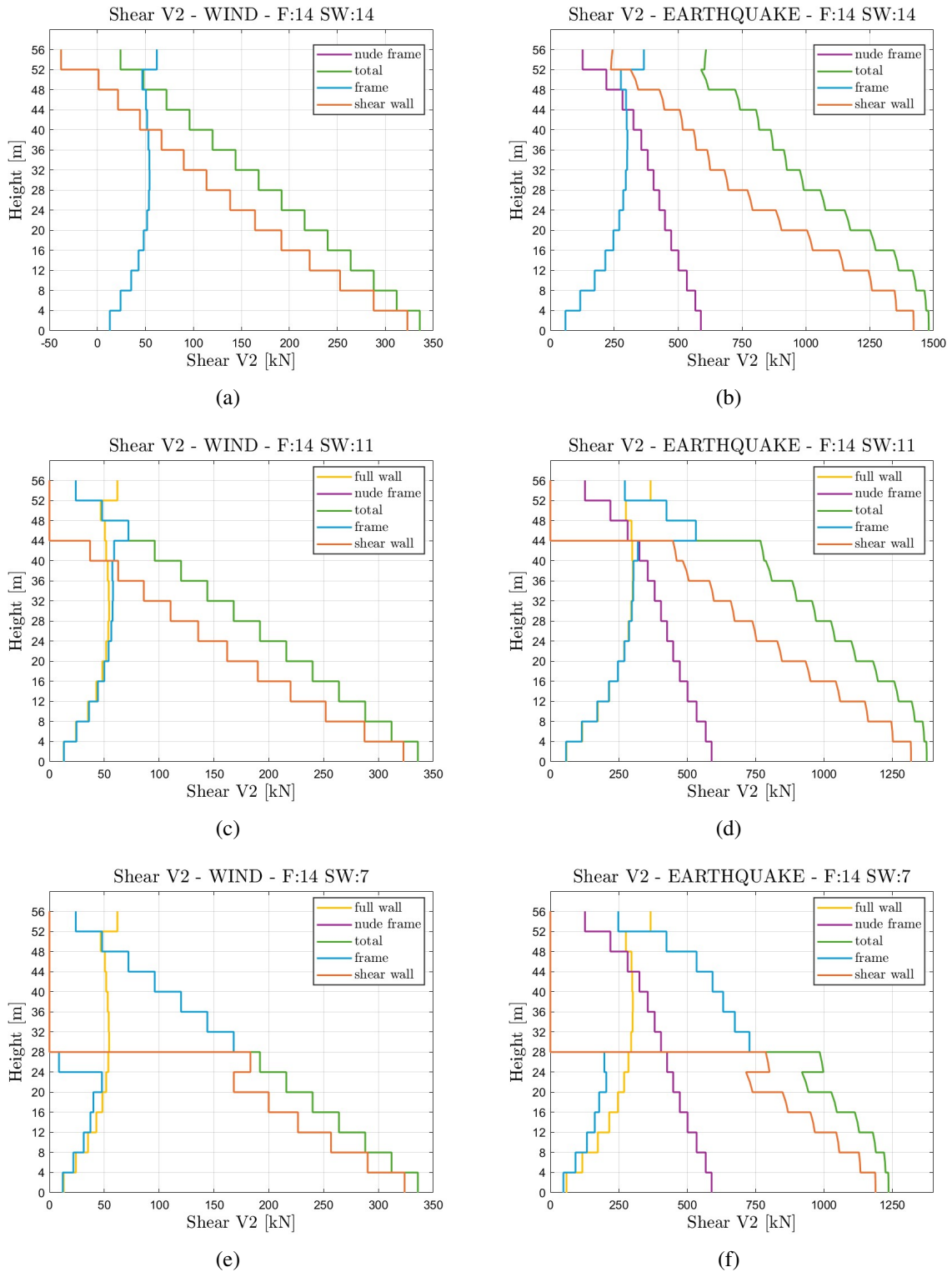


Figure 3: Shear force diagrams, under wind and earthquake loading conditions, of the moment-resisting frame building with (a-b) full height shear wall, and the shear wall curtailed at the (c-d) 11th floor and the (e-f) 7th, as well as the total shear. The values corresponding to the frame without shear wall (nude frame) and those of the frame with the full-height wall (full wall) are included.

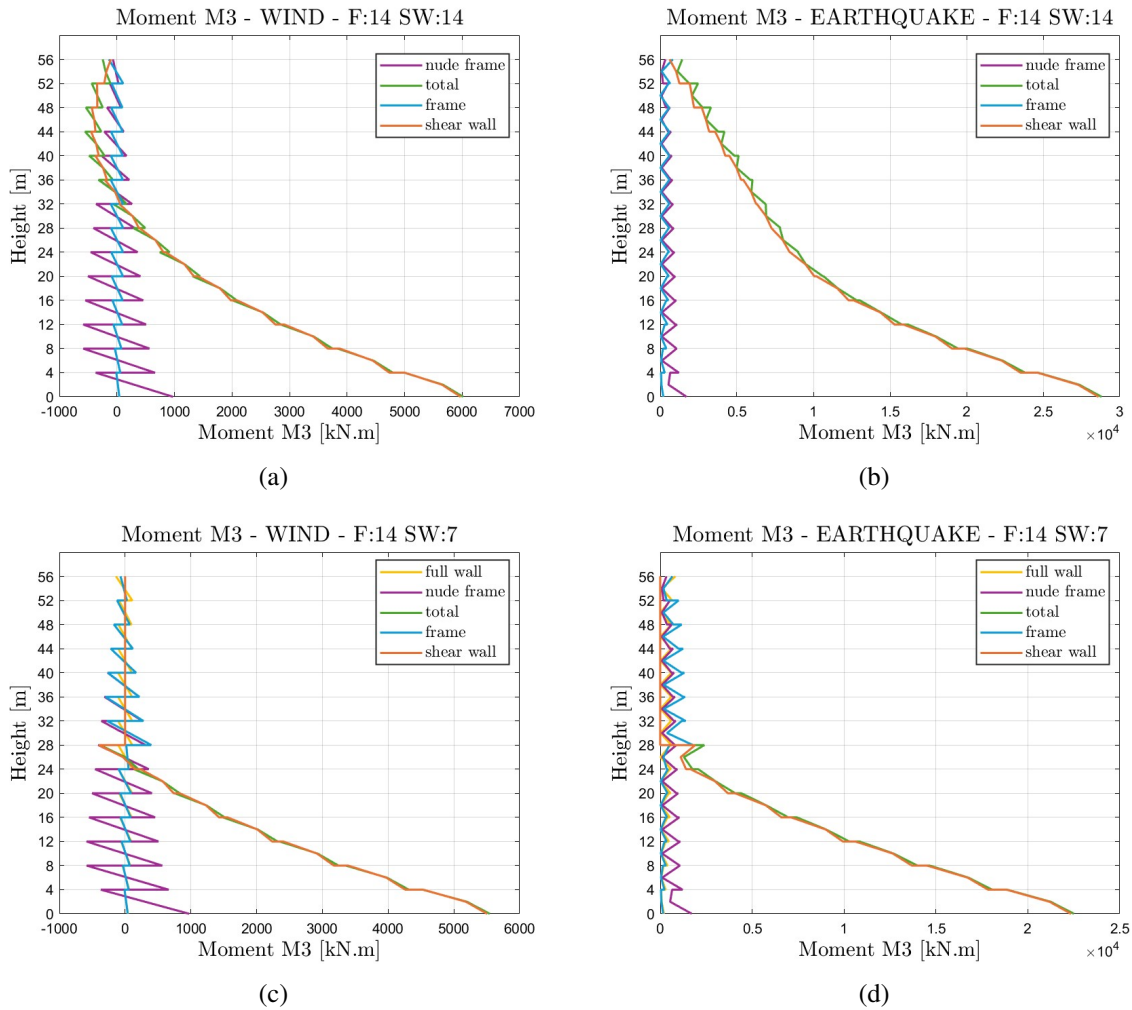


Figure 4: Bending moment diagrams, under wind and earthquake loading conditions, of the moment-resisting frame building with (a-b) full height shear wall, and (c-d) the shear wall curtailed at the 7th floor, as well as the total moment. The values corresponding to the frame without shear wall (nude frame) and those of the frame with the full-height wall (full wall) are included.

the desired behavior of the structure for various limit states (OP, IO, LS, CP). The control of these damage levels is achieved through the implementation of performance indicators. Specifically, inter-story drifts are adopted as performance indicators for this application. The drift thresholds associated with the desired level of damage are incorporated into the optimization process as constraints, and a penalty system is adopted to account for them in the Objective Function [14]).

In addition to the control of drift, the structural verification of reinforced concrete elements constitutes a fundamental constraint. These verifications encompass compliance checks for axial, bending and buckling, shear and torsional resistance. Subsequently, the structural verifications are incorporated as constraints within the optimization framework, as in the case of the constraint associated with drift control [15].

A pivotal aspect of the proposed framework regards the integration of shear wall variations in height. As previously discussed, this aspect offers a substantial potential for weight reduction. Moreover, if the optimal curtailing point is accurately identified, the impact on the system's performance is not adverse, and the displacements can undergo further reductions.

To consider the curtailment of shear walls, two well-differentiated cases can be established associated with the loading conditions. Significant differences arise in structural behavior depending on whether the governing action is a uniformly distributed load, designated here as wind load, or a seismic load. The disparity in behavior is attributed to the fact that, while wind loads are independent of wall height, seismic loads are highly dependent on the eigenvalues and eigenvectors of the system, which vary with wall height.

- **Uniformly Distributed Load: Independent of Modal Properties**

Under wind loading, the applied forces remain independent of shear wall height, making it possible to identify clear behavioral trends associated with different levels of curtailment. These patterns were observed in Section 3, and an optimal range of curtailment heights can be identified. Specifically, the optimal curtailment zone lies between two points that can be identified in the stress diagrams of the corresponding full-height structure. These are the inflection point of the bending moment diagram of the wall and the point of zero wall shear. Curtailing the wall within this range minimizes the top displacement while ensuring that internal force redistributions do not induce significant stress increases in the frame.

These principles can be leveraged to enhance computational efficiency by significantly reducing the search space within the optimization process. To achieve this, a two-step analysis approach is introduced for each individual in the optimization framework. First, a model with a full-height shear wall is analyzed to determine the optimal curtailment height range based on the shear and bending moment diagrams. Once this range is identified, the values that the height-related variables can take are restricted accordingly, eliminating non-optimal solutions from consideration.

A second analysis is then performed on the configuration with the walls curtailed at the identified heights. The results from this model are subsequently used to evaluate constraint compliance and compute the objective function. While this methodology requires two structural analyses per individual, it offers a substantial reduction in computational effort by limiting the search space.

- **Seismic Load: Dependent on Modal Properties**

Conversely, the behavior under seismic loads presents a more complex challenge. Unlike wind loads, total seismic forces are highly sensitive to the structural configuration, as they are influenced by the modal properties of the frame-wall system. Due to these interdependencies, it is not possible to establish an optimal curtailment point or range based on the response of the structure with the full-height wall, as was possible for wind loads. In such circumstances, the use of an optimization tool is particularly advantageous to manage the complex interaction between the various factors that influence structural behavior. The optimization process must therefore treat the height of the shear wall as a free variable, allowing the evolution of the algorithm to find the optimal balance between stiffness, displacement control, and cost. By enabling such exploration, the framework facilitates the identification of trends in the relationship between wall curtailment and seismic performance, providing valuable insights into the most effective design solutions.

Another crucial consideration is the shear redistribution in the columns located directly above the curtailed shear wall. A localized increase in shear demand is observed at the discontinuity

level, which must be controlled through the careful selection of the curtailment point (see Fig. 3). Nevertheless, the optimization tool needs to balance the numerous and often conflicting interests under consideration. For this reason, in some cases, it may prioritize solutions that sacrifice shear control to minimize top displacement or structural weight.

In such scenarios, additional verifications must be implemented to prevent brittle failure mechanisms. Ensuring a ductile failure mode requires the application of capacity design principles. This concept can be integrated into the optimization process either as explicit constraints or as formulations that guide the generation of new individuals. By embedding these principles, the framework ensures that brittle failure mechanisms are avoided and that the integrity of the load-bearing system is maintained.

With the considerations discussed in this section, the proposed framework seeks to establish a balance between material efficiency, structural performance, and computational feasibility. The complexity of the seismic response, in particular, underscores the value of an optimization-based approach, as it allows for the simultaneous consideration of multiple interacting factors that cannot be easily predicted through analytical methods.

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

Shear walls play a crucial role in enhancing the lateral resistance of reinforced concrete moment-resisting frame buildings, making their efficient design a key aspect of structural optimization. The curtailment of shear walls offers a promising approach to achieving an optimal balance between structural performance and material efficiency. However, determining the ideal curtailment height requires a deeper understanding of the systems' response interaction. This study addresses this challenge by systematically analyzing the behavior of RC frames with shear walls curtailed at different heights under wind and seismic loads.

The parametric analyses revealed that curtailing the shear wall up to a height near mid-height of the building can effectively reduce top displacements, while further extensions beyond this point provide negligible additional benefits. Regarding internal force redistribution, the results showed that shear forces in the frame columns experience a localized increase at the curtailment level, with more pronounced effects for lower wall terminations. However, bending moment redistribution was found to be less critical.

Building upon these findings, a preliminary optimization framework has been proposed for the performance-based design of shear walls in high-rise moment-resisting buildings, with a focus on incorporating variations in wall height. This framework outlines critical design variables, essential constraints, and effective strategies to enhance structural efficiency. By integrating these considerations, the optimization has the potential to achieve an optimal balance between performance targets, stiffness requirements, and material consumption, paving the way for more efficient and sustainable structural solutions.

Future research should further explore the relationship between modal properties and the effects of shear wall curtailment under seismic loads. A deeper understanding of how wall height influences the dynamic response could help define optimal curtailment principles, which reduce the search space in the optimization process. Another crucial next step is the full development and application of the proposed optimization framework. By implementing this framework in practical scenarios, the results can provide valuable insights into the optimal trade-offs between performance, stiffness, and material efficiency. Finally, extending this study to three-dimensional structures will be essential to assess the influence of torsional effects.

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