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Effect of Infill Wall Opening Ratio on the Mechanical Characteristics of Reinforced Concrete Frames

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Abstract

This study investigated the influence of infill wall (IW) opening ratios on the mechanical performance of reinforced concrete (RC) frames using a novel numerical model. The proposed model incorporated stiffness degradation and a nonlinear "Gap Element" to simulate the interaction between RC frames and IWs under seismic loading. A 3D finite element model was developed in SAP2000 and calibrated using validated experimental data. Parameters such as IW thickness, opening ratio (0–100%), and opening position (symmetric, asymmetric, corner) were systematically varied to assess their effects on lateral displacement (Δ), fundamental period (T_1), shear force (Q), and bending moment (M). The results indicated that increasing the opening ratio significantly reduces frame stiffness, especially beyond 40%, and leads to substantial increases in displacement. Corner openings were found to have the most detrimental impact, while thicker walls (≥220mm) can partially mitigate stiffness loss. However, at ratios above 60%, even thick IWs failed to preserve structural performance. Based on these findings, a limit of 40% opening ratio was recommended for design purposes, and reinforcement was advised for higher ratios. The study provides a practical framework for optimizing the seismic and structural design of RC frames with openings in IWs, contributing new thresholds and modeling strategies for improved performance.

Keywords: Masonry Infill Walls; Reinforced Concrete Frames; Stiffness; Structural Behavior; Effects of Wall Openings.

1. Introduction

Reinforced concrete (RC) frames with infill walls (IW) are one of the most commonly used structural systems in civil and industrial construction projects in Vietnam as well as globally. IW, typically made of bricks or other building materials, do not directly contribute to the vertical load-bearing capacity of the structure but primarily serve to partition spaces and support the lateral load-resisting capacity of the frame system. Although not designed primarily for load-bearing, the presence of IW significantly alters the stiffness, load-bearing capacity, and dynamic characteristics of the RC frame. This directly impacts the structure's ability to withstand forces such as wind, earthquakes, and other lateral loads. Especially in areas prone to seismic activity, the interaction between the IW and the RC frame plays a crucial role in determining the stability and safety of the structure. The effects of IWs on RC frames can be quite complex due to factors such as wall thickness, the ratio of openings (e.g., doors and windows), material properties, and the distribution of IW within the frame. The stiffness of IWs generally enhances the lateral load resistance and reduces the overall displacement of the RC frame. However, the presence of openings in the walls can significantly affect their contribution to the structural response, potentially leading to local damage, weak-story mechanisms, or uneven stress

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distribution. A thorough understanding of these effects is essential for the design and safety of RC frames, particularly in earthquake-prone regions.

The impact of IWs on RC frames is nonlinear and depends on many factors, including the wall thickness, the opening ratio (such as doors and windows), material properties, the distribution of IW within the frame, and the boundary conditions of the structure. Previous studies have shown that IW significantly increases the stiffness of the frame, reduced horizontal displacement, and improves the lateral load-bearing capacity. However, the presence of openings in the IW could significantly reduce this effect, leading to a decrease in the overall stiffness of the system, uneven stress distribution, and potentially causing local damage or even weak-story failure. As the opening ratio increases, the load-transmitting ability of the IW is weakened, altering how the frame system responds to lateral loads. For example, Huệ [1] showed that the interaction between IWs and the surrounding RC frame under lateral loads increases the bending stiffness of the RC frame. This leads to a change in the basic design principle of "weak beam – strong column," as specified in seismic design codes, when the interaction with IWs is not considered. The results of this paper quantified the increase in stiffness and bending capacity of the RC frame when considering interaction with IWs under seismic loading. Based on these results, a new design condition was proposed for RC columns to ensure that the plastic failure mechanism occurs in RC frames under seismic loading according to Vietnamese code (TCVN 9386:2012 [2]).

The results from nonlinear static analysis of the infill frame system designed according to TCVN 9386:2012 [2] showed complete consistency with theoretical studies. Similarly, Dinh [3] modeled the improved equivalent strut (three-segment) which accurately simulated the internal force distribution in the IW during the elastic phase, with higher accuracy compared to previous single-strut models. This model was simple and easy to implement, significantly improving the lateral load resistance of RC frames with IW if the gap is appropriately designed. In experiments, the improved RC frame showed the highest maximum load capacity (P_{max}), and the wall and frame cracking occurred almost simultaneously. The stiffness of the IW after cracking did not decrease suddenly, allowing it to continue participating in load-bearing along with the RC frame. The failure modes observed in the experiments were similar to the results of previous studies. The "multi-strut" model combined with concentrated plastic joints and the "Gap-element" link element, proposed for push-over analysis, accurately simulated post-elastic behavior and predicted the ultimate lateral load capacity of the frame with IW under different boundary conditions. In the design and calculation of RC frames with IW, it is necessary to consider the stiffness of the IW to fully evaluate potentially dangerous scenarios.

Dalibor Burilo et al. [4] based their study on experimental results of a RC frame with brick IWs at a ratio of 1/2.5, consisting of three stories on a shaking table. The structure was tested with ten consecutive ground motions with progressively increasing acceleration ag/g, recorded at the Herzeg Novi station during the 1979 Montenegro earthquake with a magnitude of M6.9. The random eccentricity, considered a random variable, resulted from the uneven damage to the brick IWs in a structure that was originally symmetrical. Its effect, compared to other random (design) variables, was assessed using weighting factors and further evaluated through the provisions of construction codes and modern research findings. The analysis showed that random eccentricity, under certain conditions, could reach higher values than those prescribed by construction codes. This failure to meet seismic reliability requirements clearly indicates that the random torsion of RC frames with brick IWs under site conditions should be considered, even in conventional buildings. Muhammad Umar et al. [5] showed that IWs help to increase the stiffness and strength of RC frames, but they are often not considered during the design process. When IWs included in the design, the openings for doors and windows need to be taken into account. This study aims to evaluate the impact of openings in the IWs on the performance of RC frames with IWs. Specifically, the study examines the number of IWs in these frames. According to current construction practices in Pakistan, two RC frames with IWs at actual ratios were built in a laboratory. One frame has eccentric windows and doors (test specimen-1), while the other has windows at the center of the wall (test specimen-2). Both specimens were subjected to reversed cyclic loading (pseudo-static testing). Experimental results showed that the RC frame with IWs and fewer openings in the IW exhibited higher lateral load-bearing capacity, increased stiffness, and better energy dissipation compared to the frame with larger openings. Additionally, the displacement ductility and response factor also depend on the size and number of openings in the IWs of the RC frame.

Recent investigations have continued to explore the seismic behavior of RC frames with masonry infill walls. Zhang et al. [6] conducted a comprehensive study on the seismic performance of RC frame structures considering the effect of infilled walls. Their findings emphasize the significant impact of infill walls on the overall seismic response of structures, highlighting the necessity of incorporating infill effects in seismic design and analysis. The presence of openings in infill walls has been shown to influence the structural performance of RC frames significantly. A study by Kusonkhum et al. [7] examined the seismic performance of infilled RC frames with crumb rubber mortar wall panels, noting that openings can alter the stiffness and energy dissipation characteristics of the frames. Their research underscores the importance of considering opening configurations in the design process. Advancements in retrofitting methods have been made to enhance the seismic resilience of infilled RC frames. A notable study by Tekeli et al. [8] investigated the use of rebar-reinforced stucco layers to strengthen masonry-infilled RC frames with openings. The results demonstrated improved hysteretic behavior and energy dissipation capacity, suggesting this technique as an effective retrofitting solution. Choi et al. [9] explored the out-of-plane behavior of unreinforced masonry infill walls and assessed the effectiveness of various tie systems designed to enhance infill stability under seismic loading. Their experimental study revealed that full-length tie systems significantly improved out-of-plane performance, offering valuable insights into improving the seismic resilience of infilled RC frames. Shrestha et al. [10] analyzed the impact of irregular masonry infill walls on the seismic response of RC frame buildings using linear dynamic analysis. Their research highlighted that irregularities in infill walls could lead to uneven stress distributions and potential failure mechanisms, emphasizing the need for careful consideration of infill wall configurations in seismic design.

Although there have been numerous studies on the impact of IW on RC frame systems, most research has focused on the presence of IW without delving into the analysis of how the opening ratio and position affect the internal forces and displacements of the structure. In practice, the opening ratio in IW can vary significantly depending on the architectural requirements and functionality of the building. Therefore, it is essential to study the specific impact of the opening ratio and position on the mechanical properties of the RC frame system to better understand the structural behavior and propose suitable design solutions. This study focuses on analyzing the impact of the opening ratio in IW on lateral displacement, vibration cycles, shear force, and bending moments in RC frames. Through numerical simulations, the study evaluates changes in the mechanical properties of the system as the opening ratio increases from 0% to 100%, while also considering the impact of IW thickness and the position of the openings. The results obtained from this study will provide an important scientific basis for optimizing the design of RC frames with IW, thereby enhancing load-bearing capacity and ensuring the safety of the building structures.

The remainder of this paper is organized as follows. Section 1 introduces the background, significance, and research gaps concerning the effects of infill walls and their openings on the structural performance of RC frames. Section 2 presents a review of existing methods for modeling infill walls in RC frames. Section 3 introduces the proposed modeling approach, including the incorporation of stiffness degradation and the "Gap Element" for enhanced simulation accuracy. Section 4 details the numerical analysis conducted to evaluate the effect of infill wall opening ratios on key mechanical characteristics of RC frames. Section 5 discusses the results and provides design recommendations based on the findings. Finally, Section 6 concludes the paper with a summary of the main outcomes and suggestions for future research.

2. Methods for Modeling Infill Walls

2.1. Equivalent Diagonal Strut Model

This model allows for replacing the IW with one or more equivalent diagonal struts, simplifying the structural analysis process. This model can be divided into two types:

Single diagonal strut model: the IW is replaced by a single diagonal strut, with its width and stiffness determined based on the geometric and material properties of the wall. This method is simple and easy to apply for linear analyses, as it requires relatively simple calculations, reducing the complexity of solving mechanical problems in the structure. In studies on modeling RC frames with IW, there are two main approaches:

- *The first group*: this group proposes a method for modeling the infill wall as a single diagonal strut. The width of the diagonal strut (w_m) is determined as a fixed portion of the diagonal length of the infill wall panel (δ_m). This method has been developed by authors such as Holmes [11], Smith [12], Moghaddam & Dowling [13], Smith & Coull [14], Paulay & Priestley [15], Angel et al. [16], Fardis [17], etc. More specifically, in this method, the IW in the RC frame is replaced by a single diagonal strut. This diagonal strut has its width and stiffness determined based on the geometric and material properties of the wall. To determine the width of the diagonal strut, the ratio between the length of the diagonal of the IW (d_m) and the width of the diagonal strut (w_m) is used. This means that the width w_m is not an entirely free value but is linked to the length of the IW panel, simplifying the calculation process and reducing the complexity of the analysis. The studies from the first group mainly focus on determining how to calculate the stiffness of the replacement diagonal strut in a way that accurately simulates the load-bearing characteristics of the infill wall under lateral loads. Specifically, the stiffness of the diagonal strut (k) is calculated based on factors such as:
    - Material properties of the IW: different materials (brick, stone, mortar, etc.) have varying stiffness and elasticity, which directly affect how the IW transmits and withstands loads.
    - Geometry of the IW: The thickness of the wall, the length, and the configuration of the infill wall also influence how the wall distributes the loads onto the frame. These geometric factors are incorporated into the formulas used to determine the stiffness of the diagonal strut.

This method is very useful in linear analyses, where the goal is to assess the structural strength under normal loads. By replacing the infill wall with a single diagonal strut, the calculation process becomes simpler and more straightforward, saving time and effort in the structural analysis. However, this method has limitations in accurately simulating the nonlinear effects of the infill wall, especially when the wall is subjected to large loads or when there are significant changes in the wall's behavior under different loading conditions. Therefore, subsequent studies have shown that this model is only suitable for preliminary and linear analyses and cannot fully reflect complex situations or dynamic loads.

- The second group: this group proposes a method for modeling the infill wall by determining the width of the diagonal strut (w_m) through more precise mathematical expressions, based on the geometric and mechanical properties of the infill frame system. This method has been developed and studied by several authors, such as, Smith [18, 19], Smith and Carter [20], Mainstone [21], Abdul-Kadir [22], Dawe & Seah [23], Decanini et al. [24], Flanagan and Bennet [25], Asteris et al. [26], etc. Unlike the first group, the second group's method not only simply replaces the IW with a single diagonal strut, but the width of the strut (w_m) is determined more accurately through mathematical expressions, combining the geometric and mechanical factors of the infill frame system. This approach provides a better simulation of the interaction between the IW and the RC frame under complex loading conditions. The factors influencing the determination of the width w_m in this method include:
    - *Stiffness ratio between the frame and the IW*: the stiffness of the frame and the IW has a significant impact on how the loads are transmitted between them. The stiffness ratio between these components largely determines the width of the diagonal strut. If the IW is stiffer than the frame, the diagonal strut will have a larger width, and vice versa.
    - *Elastic properties of the IW along the diagonal direction*: an important factor is the distribution of the elastic properties of the IW along the diagonal direction, meaning how the wall deforms when subjected to lateral loads. These elastic properties may vary in different parts of the wall and directly affect its ability to transmit force.
    - *Vertical loads from the frame to the IW*: when the frame transmits vertical loads to the infill wall, this affects how the wall bears the load. These vertical loads need to be calculated accurately to determine how the force and deformation are distributed in the infill frame system. The study by Amato et al. [27] indicates that vertical loads are an essential factor when determining the width of the diagonal strut in this model.

The method of the second group offers higher accuracy compared to the first group, allowing for better simulation of the nonlinear behavior of IWs under lateral loads. This is crucial in detailed analyses, especially when the infill wall is subjected to large loads or when the frame interacts complexly with the wall. However, due to the complexity in determining the precise geometric and mechanical properties, this method requires the use of more complex mathematical formulas and more accurate computational models. As a result, applying this method can be time-consuming and requires advanced simulation software, but in return, it provides a more accurate simulation of the IW's behavior in RC frame systems.

Multi-strut model: in this model, the IW is represented by several parallel diagonal struts, which allows for a more accurate simulation of the nonlinear behavior of the wall under lateral loads. While this method is more complex than the single diagonal strut model, it enables a more detailed and accurate simulation of the interaction between the infill wall and the frame. This model is commonly used in more detailed analyses, especially when considering uneven stress distributions and deformations. As mentioned, the interaction between the IW and the frame is primarily localized in the regions where the two parts come into contact. In these regions, the transfer of loads from the IW to the frame can cause brittle shear failure in the components of the RC frame. Brittle shear failure typically occurs when the forces transferred from the infill wall to the frame cause sudden failure at the contact points, reducing the load-bearing capacity of the frame components, particularly under large or sudden loading conditions. Studies by authors such as, Saneinejad & Hobbs [28], and Buonopane & White [29] indicate that the single diagonal strut model cannot accurately distribute the bending moments and shear forces, nor can it precisely determine the locations of potential plastic hinge zones in the frame components. The single diagonal strut model simply replaces the entire IW with a single diagonal strut, and thus cannot accurately reflect the force distribution across the entire structural system, especially in regions where the wall and frame come into contact. For this reason, to overcome the shortcomings of the single diagonal strut model, various authors have proposed more complex multi-strut macro-models.

These models simulate the interaction between the infill wall and the frame through multiple parallel diagonal struts, allowing for more accurate load distribution and better simulation of the nonlinear behavior of the IW under lateral loads. Each diagonal strut in this model represents a small part of the infill wall and can have its own physical and mechanical properties, helping to simulate the force distribution and deformation more accurately in the frame components. Multi-strut models allow for a more detailed determination of bending moments, shear forces, and potential plastic hinge regions in the RC frame. This is particularly important in detailed analyses, especially when the frame and IW are subjected to complex or time-varying loads. The use of multi-strut models helps improve the accuracy of predicting the behavior of the structural system, thus ensuring safety and optimizing the design. However, due to the higher level of complexity, multi-strut models require powerful computational tools and advanced numerical simulation software. The computation and analysis process becomes more complicated due to the need to address multiple variables and various influencing factors, including the interaction between the struts, uneven material properties, and changing load conditions. Despite this, it remains a superior method for structural analyses that require high accuracy and the ability to accurately reflect the behavior of the RC frame combined with the IW.

2.2. Finite Element Model

This method uses finite element analysis to model the detailed behavior of the IW and its interaction with the RC frame. The finite element model allows for the analysis of nonlinear behavior, including cracking and failure of the IW. However, this method requires extensive input data and high computational capacity, making it suitable for in-depth studies. The Finite Element Method (FEM) is a powerful tool in structural analysis that allows for the detailed simulation of the IW behavior and its interaction with the RC frame. By discretizing the structure into smaller elements, FEM enables the analysis of nonlinear behavior, including cracking and failure of the infill wall. FEM allows for accurate simulation of the material and geometric properties of the infill wall, providing a better understanding of the structural behavior under load. Specifically, the nonlinear analysis capability of FEM helps predict phenomena such as cracking, large deformations, and failure, which linear analysis methods cannot perform. Furthermore, FEM can be applied to complex structures with diverse shapes and boundary conditions, making it suitable for various types of buildings. However, this method also has some drawbacks and requirements. Firstly, it requires detailed input data, including information about the material, geometry, and boundary conditions of both the IW and the RC frame to ensure the accuracy of the simulation. Additionally, FEM analysis requires specialized software and high computational capacity, especially when simulating large or complex structures. Moreover, the time and cost involved are significant factors to consider, particularly in in-depth studies or when optimization of the design is required.

Many studies have applied FEM to analyze the behavior of RC frames with IWs [3, 30-33]. In this study, the authors used FEM with an idealized compressive equivalent link element to model the interaction between the frame and the IW, providing a deeper understanding of the nonlinear behavior of the structural system. However, applying FEM in the analysis of IWs and RC frames requires a deep understanding of FEM theory, as well as experience in model building and result interpretation. Therefore, this method is typically used in in-depth studies or when detailed analysis of the structural behavior under complex loading conditions is needed.

2.3. Concentrated Plastic Hinge Model

This method assumes that plastic deformation occurs only at the plastic hinges at the ends of the components, while the rest of the component remains elastic. The IW is modeled as either simple elastic or nonlinear elements, helping to minimize the complexity in the analysis. This method is commonly used in nonlinear static analysis (pushover analysis) to assess the load-bearing capacity of the structural system. In this approach, plastic deformation is assumed to occur only at the plastic hinges, which are transition points where the component changes from an elastic state to a plastic state. These plastic hinges are usually the connection points between the elements of the structure. This simplification helps reduce the complexity of the analysis and creates a simple model that still accurately simulates the behavior of the structure under load. The IW in this method is generally modeled as simple elastic or nonlinear elements, with the assumption that the wall only cracks or fails in certain regions (such as at the plastic hinges). The remaining parts of the wall and frame elements maintain elastic properties, reducing the complexity in modeling and calculations. This makes the method suitable for preliminary studies or analysis of structures under simple loads.

The concentrated plastic hinge model is particularly useful in nonlinear static analysis (pushover analysis), a popular method for assessing the load-bearing capacity of structures under dynamic loads or any changes in loading conditions. Pushover analysis helps identify potential plastic hinge regions in the structure and the system's load-bearing capacity as the load increases until the structure reaches its limit state. This method is often used in cases requiring quick and simple calculations of a structure's load-bearing capacity, such as evaluating the strength of structures under earthquake loads, wind loads, or other static impacts. However, this method has limitations when dealing with more complex scenarios or structures that require a more detailed analysis of nonlinear behavior in regions outside of the plastic hinges [34-37].

2.4. Micro Modeling

The micro-modeling approach simulates the detailed behavior of each component of the infill wall, including the bricks, mortar joints, and their interaction with the RC frame. Each component of the wall, from the brick material to the mortar layer, is modeled separately, and the forces acting between them are calculated in detail. This method allows for accurate analysis of the IW's behavior under lateral loads, including phenomena such as cracking, deformation, and failure of individual elements within the wall. Micro-modeling helps realistically reproduce the material properties of the IW, enabling precise analysis of the interaction between the different material components in the wall and with the RC frame. This method can simulate complex mechanical responses, such as uneven deformation of the wall, crack development, and the propagation of stress through the bricks and mortar layer. Therefore, micro-modeling is a powerful tool for understanding the detailed behavior of IWs under lateral loads. However, micro-modeling requires extensive data on materials, geometry, and interaction factors, leading to high computational demands and the need for advanced simulation software. The detailed simulation of each brick-and-mortar joint also significantly increases the complexity of the model. As a result, this method is typically used in scientific research or when detailed analysis of specific mechanical phenomena is required, which simpler models cannot accurately simulate [19, 38, 39].

The choice of the appropriate modeling method depends on the analysis objectives, the complexity of the structure, and the required accuracy. In preliminary analyses or standard designs, models such as the equivalent diagonal strut model or the concentrated plastic hinge model may be sufficient to assess the load-bearing capacity of the structure. These methods are simpler and easier to apply to basic structures. However, for critical buildings or when detailed analysis of the behavior of IWs and RC frames under complex loading conditions is required, finite element models or micro-modeling may be preferred. Although these methods require more data and higher computational capabilities, they provide greater accuracy and reliability, helping to optimize the design and ensure the safety of the structure.

3. Proposed Model

The proposed model for simulating the behavior of reinforced concrete (RC) frames with infill walls (IWs) was developed by the authors, building upon the studies of Huy [40], and the ACI 318-19 Code [41]. To accurately capture stiffness degradation within the structural system, the model employs the concept of effective moment of inertia to adjust the stiffness of beams, columns, and IWs. Specifically, the effective moment of inertia is assumed to be 70% of the gross section's inertia for columns and IWs, and 35% for beams, in accordance with experimental findings and design standards. A three-dimensional finite element model (FEM) was constructed in SAP2000, in which the RC frame and IWs are modeled as distinct components interacting through nonlinear connections. This separation allows the model to explicitly account for the complex role of IWs: while they can enhance global stiffness, they may also induce local separation or detachment under seismic or large lateral loads. To simulate this phenomenon, the authors introduced the "Gap Element," a nonlinear component designed to model loss of contact or local separation between IWs and the surrounding RC frame members.

This modeling strategy enhances the accuracy of structural performance assessment, particularly under lateral loads, and informs the development of improved design methodologies for RC structures with IWs. The use of the "Gap Element" is essential due to the typical lack of full contact between IWs and the RC frame. Factors such as construction tolerances, thermal effects, and intentional design provisions often result in an initial gap between these components. The "Gap Element" explicitly represents this gap, allowing for simulation of the initial separation and subsequent contact behavior under loading. Under lateral loads—such as those induced by wind or earthquakes; the degree of contact between the IW and the frame varies with deformation. The "Gap Element" is therefore governed by a compression-only constitutive law: it transmits compressive forces when the IW is in contact with the frame, but permits separation under tensile conditions. This approach effectively models the detachment and cracking of the IW, thereby improving the fidelity of the simulation.

The theoretical framework underpinning this study is grounded in the nonlinear behavior of RC frames with IWs subjected to lateral loading, particularly in cases involving wall openings. Central to the modeling approach is the interaction between the RC frame and the IW, which exerts a profound influence on both global stiffness and structural failure modes. To capture this interaction, the study adopts a hybrid modeling strategy that integrates three key theoretical components:

- Stiffness degradation theory: the progressive reduction of stiffness in beams, columns, and IWs is modeled using empirical relationships derived from experimental data. The effective moment of inertia, I_{eff}, is reduced at successive loading stages to simulate the effects of cracking, yielding, and post-peak behavior. This methodology aligns with the principles of ACI 318-19 [41] and contemporary nonlinear analysis approaches, capturing the full range of structural response from elasticity to plasticity.

- Gap Element theory: a distinguishing feature of the model is the incorporation of the "Gap Element," which reflects the partial and evolving contact between IWs and the RC frame. Governed by a compression-only law, this element accurately represents real-world conditions—including construction imperfections, thermal effects, and material incompatibilities—by permitting contact only when compressive forces are present. This concept, rooted in contact mechanics, is widely employed in seismic analyses to simulate separation and pounding phenomena.

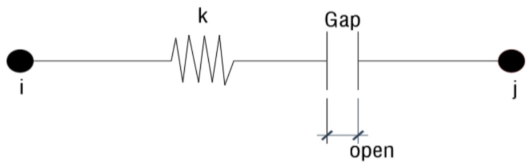
- Nonlinear FEM: the overall structural response is evaluated through nonlinear static (pushover) analysis within the FEM framework (SAP2000). The model incorporates geometric and material nonlinearities, as well as nonlinear interaction effects via the Gap Elements. This comprehensive approach captures both global displacement behavior and localized effects, such as stress concentrations around openings, through numerical methods grounded in continuum mechanics and the solution of partial differential equations governing structural deformation.

The interaction between the brittle, crack-prone IW and the ductile RC frame introduces significant complexity into the system's behavior. The nonlinear modeling of this interaction—facilitated by the Gap Element—is particularly critical in analyses involving large or cyclic loads. The inclusion of the Gap Element thus enhances the model's ability to accurately represent the interaction dynamics between IWs and RC frames, providing a robust foundation for advancing structural analysis, design optimization, and load-bearing capacity assessment in practical engineering applications. The configuration of the proposed model is illustrated in Table 1 and Figure 1.

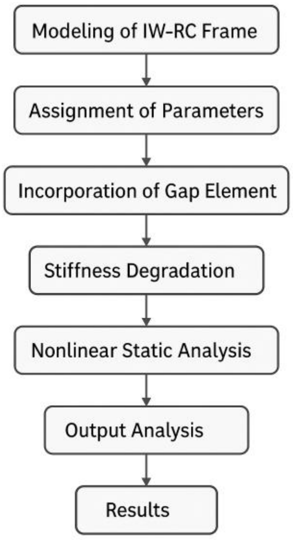
Table 1. Proposed model

No.	Point	Values	Stiffness (EI)			Gap element
			Beam	Colum	IW	
1	0	0	1.00	1.00	1.00	x
2	C (Crack point)	$0.1V_{peak}$	1.00	1.00	1.00	x
3	Y (Yield point)	$0.75V_{peak}$	0.35	0.70	0.70	x
4	P (Peak point)	V_{peak}	0.30	0.35	0.35	x
5	D (Degradation point)	$0.85V_{peak}$	0.2	0.3	0.3	x

Note: the V_{peak} value is determined using the finite element method with elastic parameters.



(a) Gap element



(b) Proposed model flowchart

Figure 1. Proposed model

Model validation: the proposed model was validated with experimental results from the authors [4, 5]. The validation results are shown in Figures 2 and 3. It can be seen that the proposed model accurately simulates the behavior of the RC frame both with and without IWs.

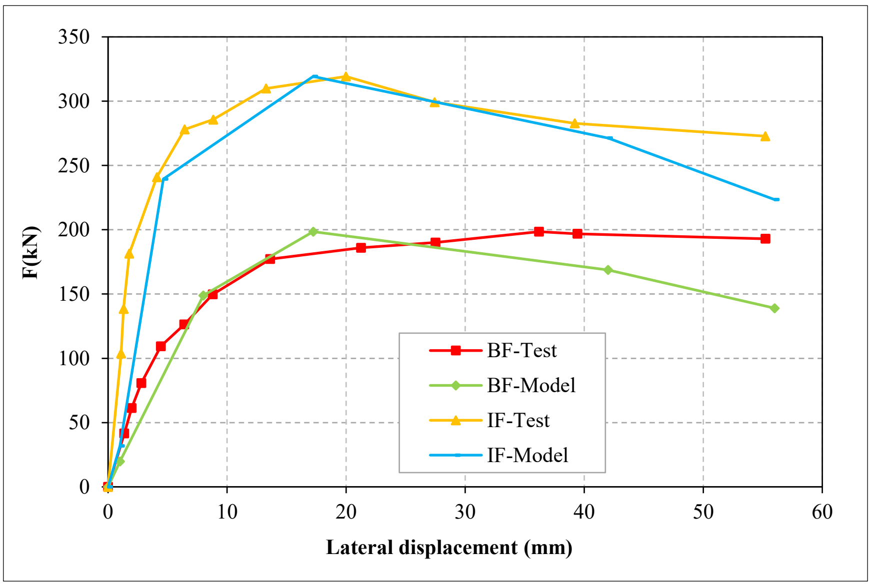


Figure 2. Model validation with experimental results from-Burilo et al. [4]

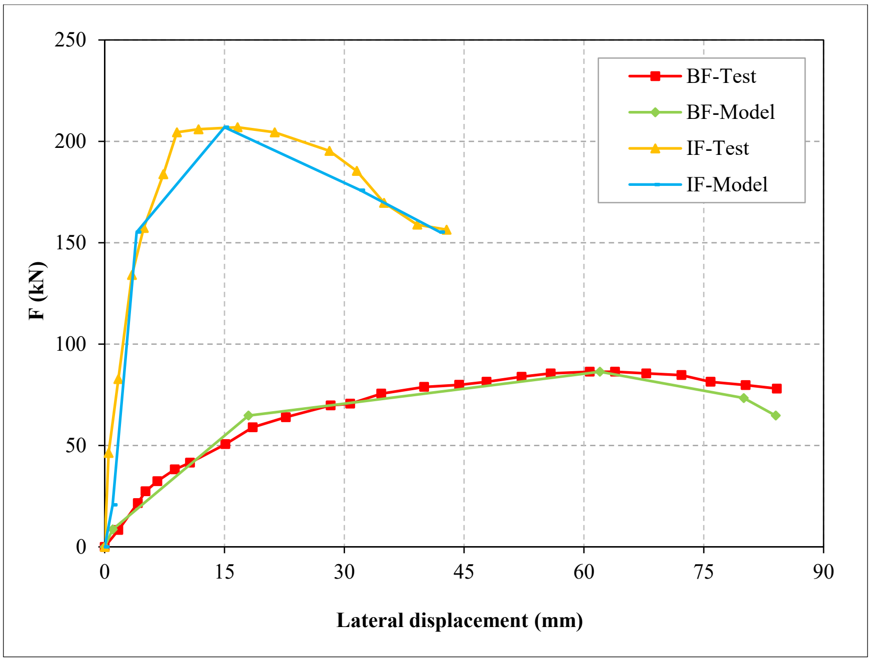
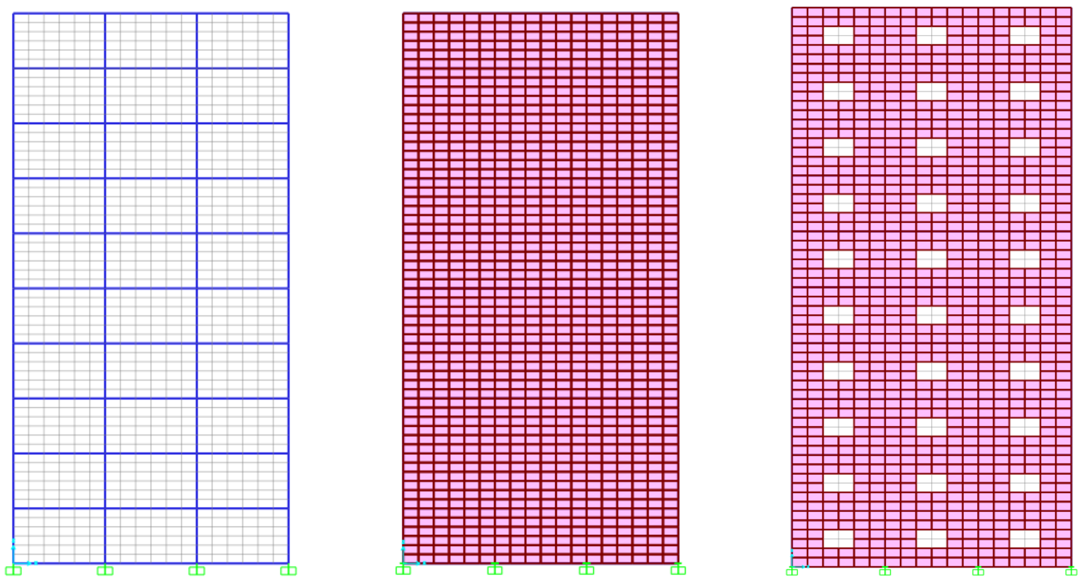


Figure 3. Model validation with experimental results from Umar et al. [5]

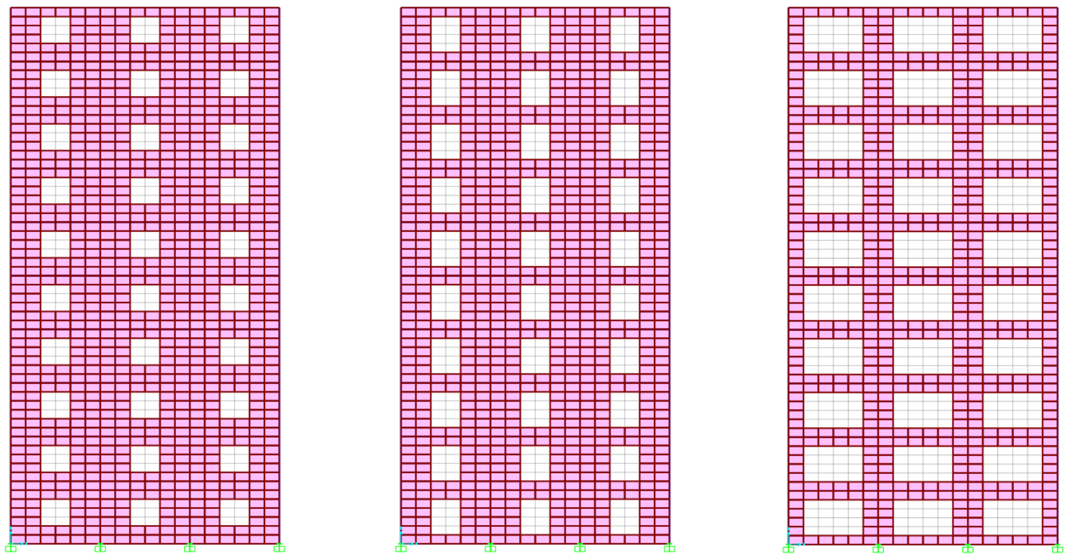
4. Effect of Opening Ratio in IW on Performance of RC Frames

To evaluate the impact of IWs on the performance of RC frames, especially in the case of openings in the wall, the authors based their analysis on the proposed model and conducted an analysis on a ten-story, three-bay RC frame with a span of L = 6 m and story height of h = 3.6 m. The structural system includes beams with dimensions (300 × 600) mm and 5ϕ25 rebar arranged at the span and beam supports, and columns with dimensions (400 × 800) mm and longitudinal steel reinforcement of 10ϕ25 arranged along the perimeter. The frame is subjected to primary loads, including dead load from the weight of the structure itself, dead load from the weight of the IW, live load from usage, and earthquake load according to Vietnamese's code (TCVN 9386:2012 [2]).

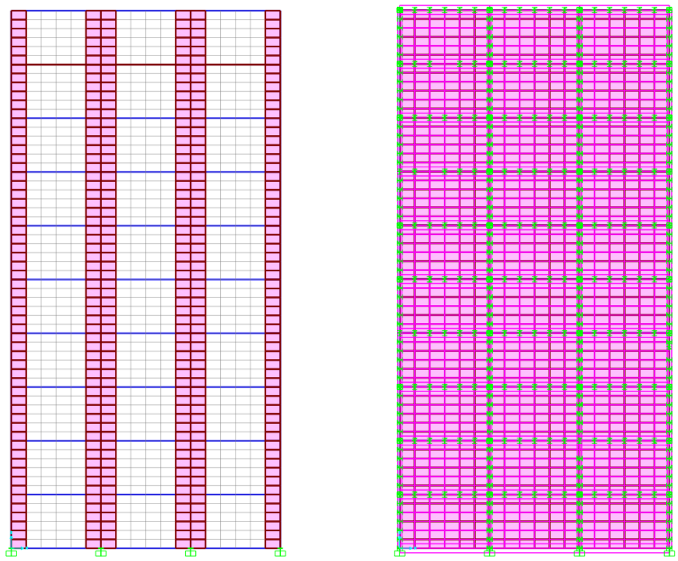
In the study, the IWs constructed using clay bricks with 6 holes, which were common in Vietnam, with dimensions (170 mm × 140 mm × 60 mm), compressive strength of 5.0 MPa, and an elasticity modulus of 3360 MPa. To evaluate the effect of openings in the IW, three scenarios considered: window openings (symmetrical openings), door openings (asymmetrical openings), and soft story (with the first floor having no IW). These scenarios are illustrated in Figures 4 and 5.



(a) RC Frame without IW (b) RC Frame with IW (c) RC Frame with IW and openings of 2×1.2 m

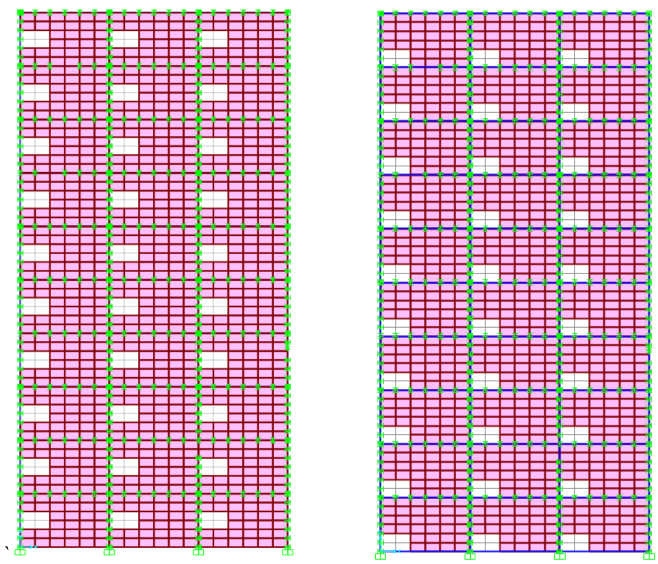


(d) RC Frame with IW and openings of 2×1.8 m (e) RC Frame with IW and openings of 2×2.4 m (f) RC Frame with IW and openings of 4×2.4 m



(g) RC Frame with IW and openings of 4×3.6 m (h) RC Frame with IW using Gap Element

Figure 4. Symmetrical opening scenarios



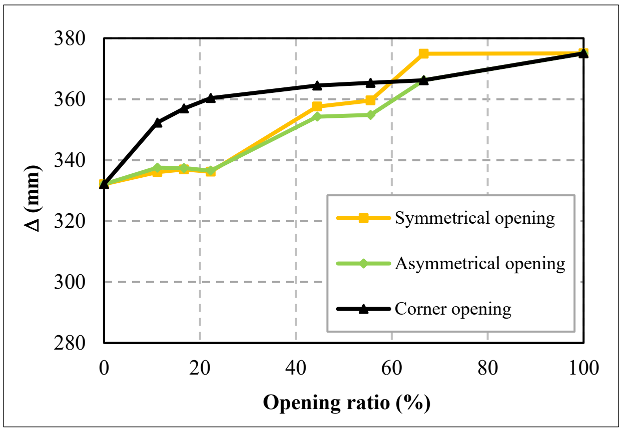
(a) Asymmetrical openings (b) Corner openings

Figure 5. Asymmetrical opening scenarios

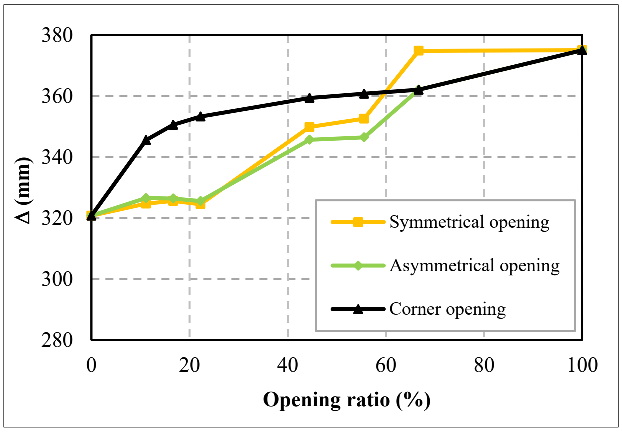
During the simulation, to account for the formation of gaps between the IW and the RC frame components (beams, columns), the authors used the "Gap Element" with key parameters including stiffness (2000 MPa) and an initial gap (Open) of 0.02 m. The Gap Element allows for accurate simulation of the nonlinear interaction between the IW and the RC frame, where the IW can either be in contact with or detach from the frame depending on the load level. This model enables an accurate assessment of local detachment phenomena as well as the change in overall stiffness of the structural system, providing scientific foundations for improving design methods and assessing the load-bearing capacity of RC frame structure.

5. Results and Discussion

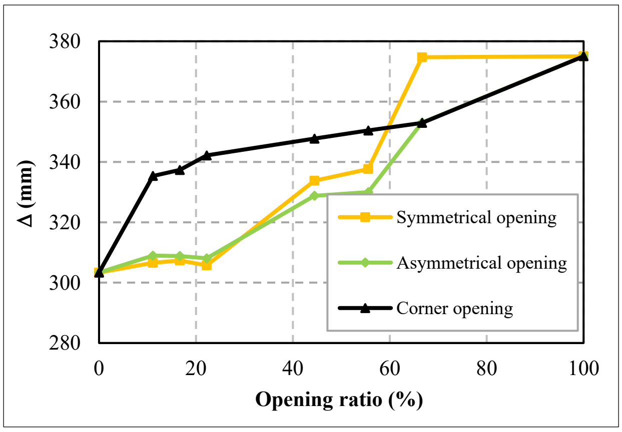
The analysis was performed using SAP2000 version 26 [42] in conjunction with the code on Matlab [43]. The calculation results are presented in Figures 6 to 11.



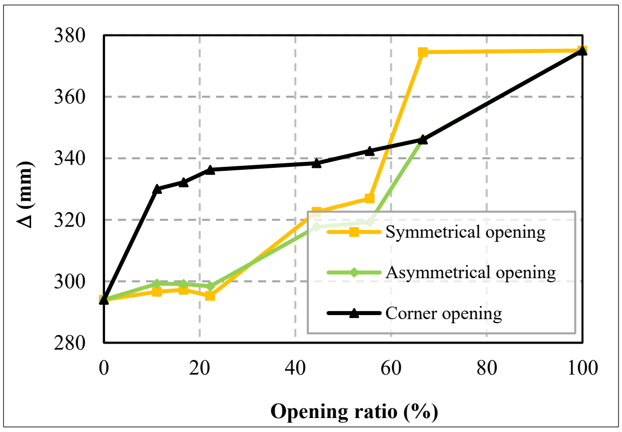
(a) IW with $d = 70\ mm$



(b) IW with $d = 110\ mm$

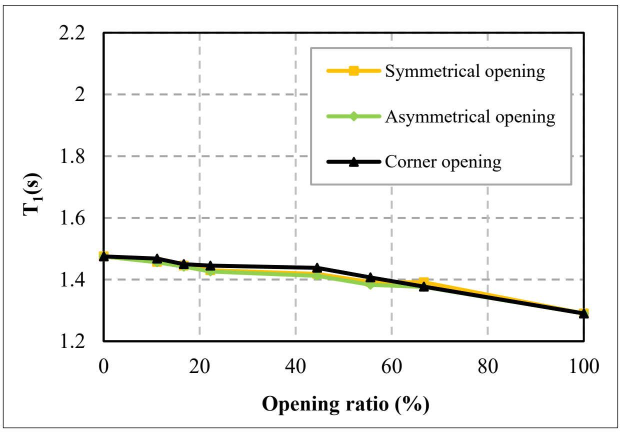


(c) IW with $d = 220\ mm$

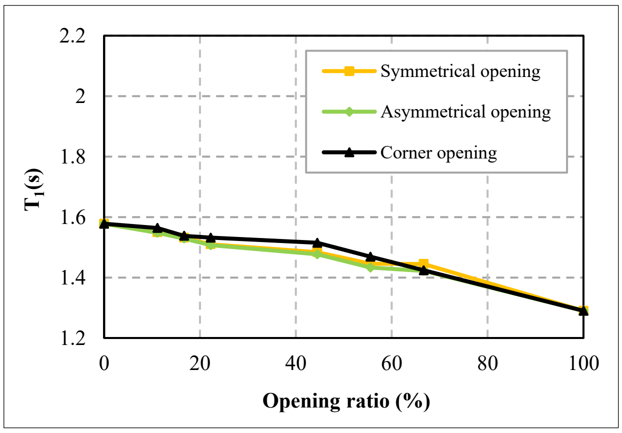


(d) IW with $d = 330\ mm$

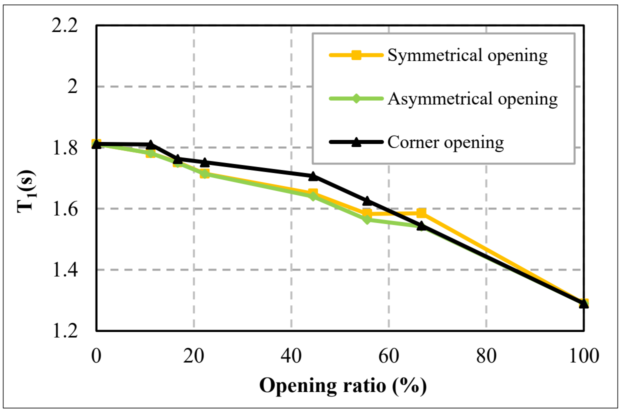
Figure 6. The effect of openings in the IW on the lateral displacement (Δ) of the RC frame



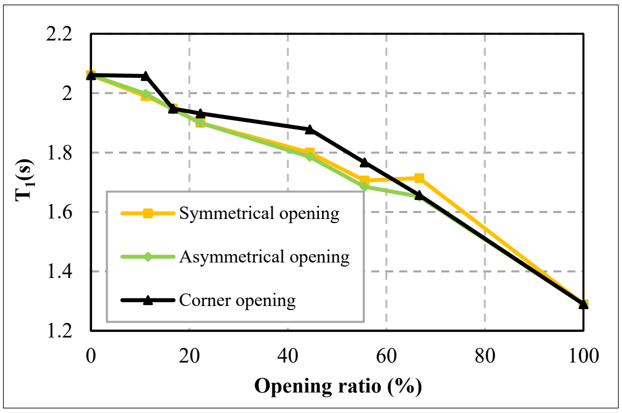
(a) IW with $d = 70\ mm$



(b) IW with $d = 110\ mm$

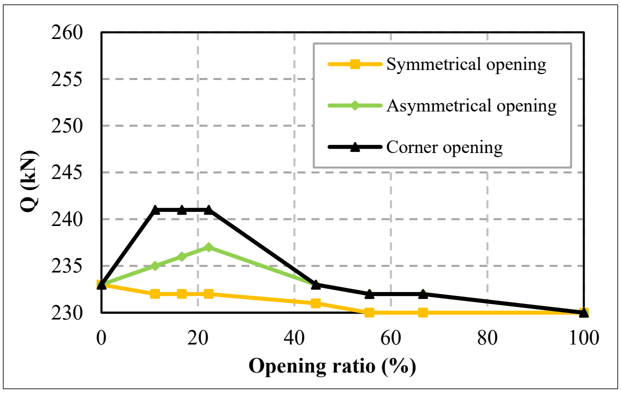


(c) IW with $d = 220\ mm$

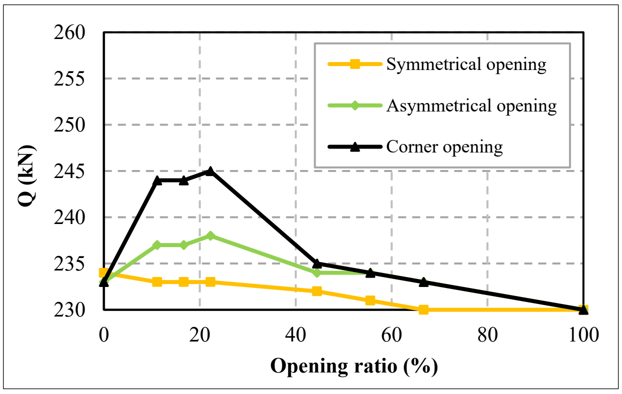


(d) IW with $d = 330\ mm$

Figure 7. The effect of openings in the IW on the first vibration period (T_1) of the RC frame



(a) IW with $d = 70\ mm$



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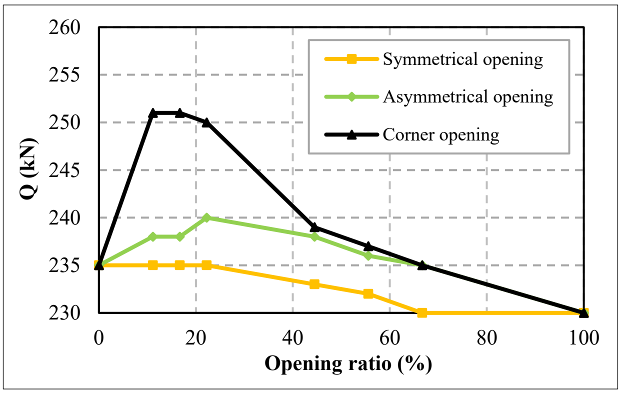

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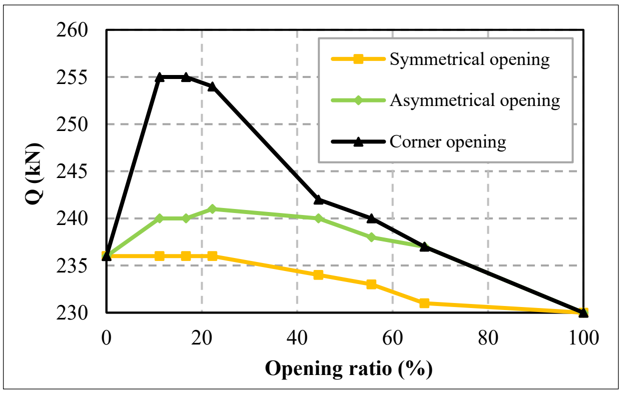
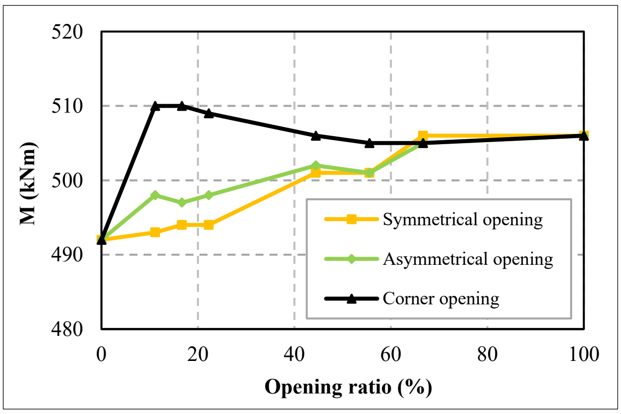
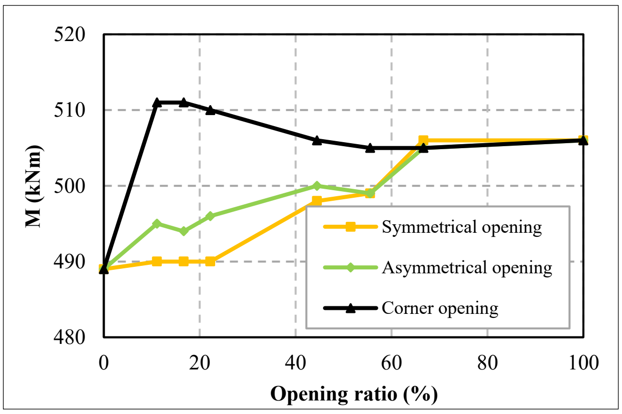


(d) IW with $d = 330\ mm$

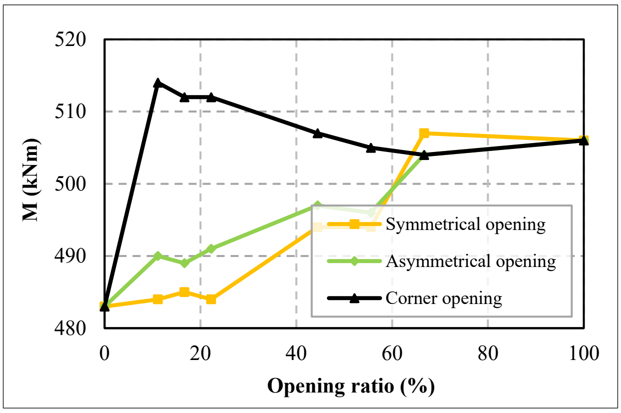
Figure 8. The effect of the opening ratio on shear force (Q) at the column base



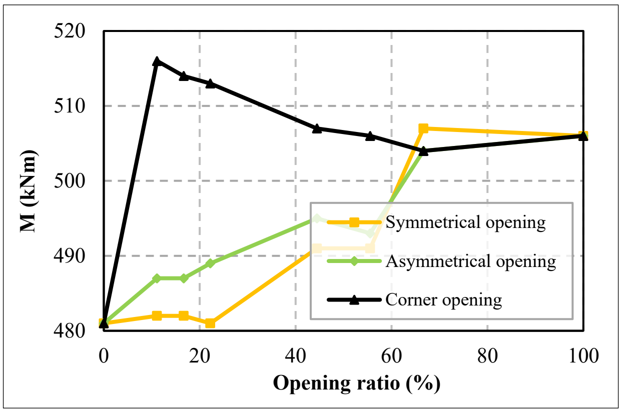
(a) IW with $d = 70\ mm$



IW with $d = 110\ mm$

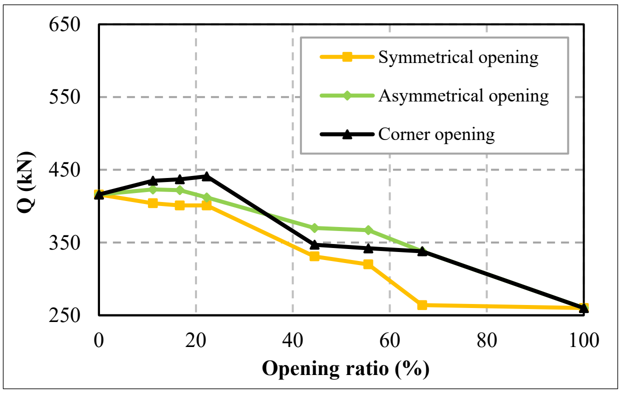


(c) IW with $d = 220\ mm$

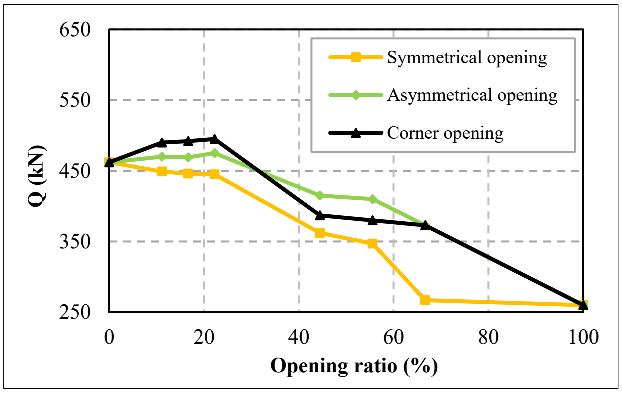


(d) IW with $d = 330\ mm$

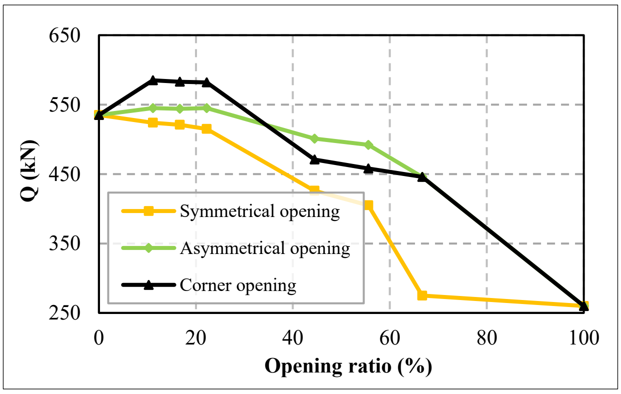
Figure 9. The effect of openings in the IW on the moment (M) of the column base



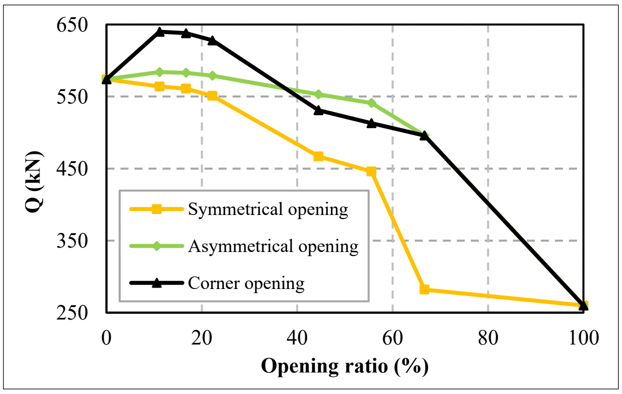
(a) IW with $d = 70\ mm$



(b) IW with $d = 110\ mm$

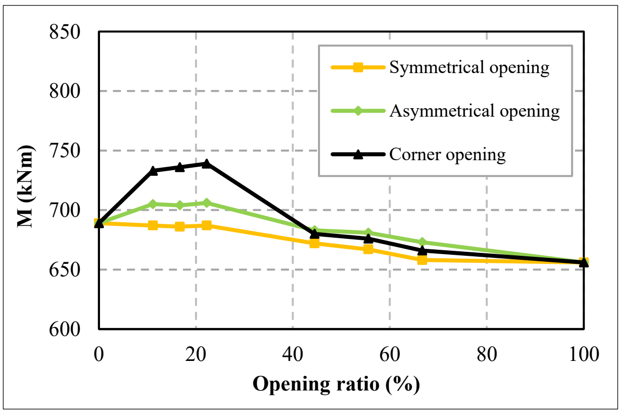


(c) IW with $d = 220\ mm$

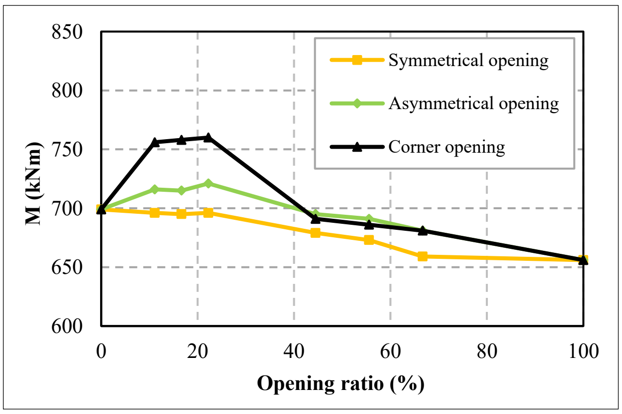


(d) IW with $d = 330\ mm$

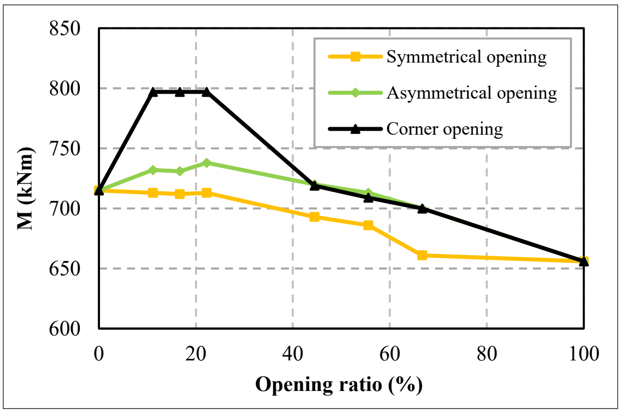
Figure 10. The effect of openings in the IW on the shear force (Q) of the beam



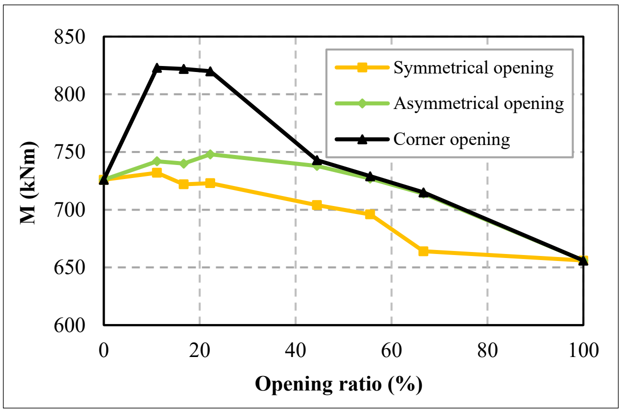
(a) IW with $d = 70\ mm$



(b) IW with $d = 110\ mm$



(c) IW with $d = 220\ mm$



(d) IW with $d = 33\ mm$

Figure 11. The effect of openings in the IW on the bending moment (M) of the beam

The effect of the opening ratio in IWs on the horizontal displacement of RC frames:

From Figure 6, the effect of the opening ratio in IWs on the lateral displacement (Δ) of RC frames is analyzed, and it can be observed that:

- Effect of opening ratio: as the opening ratio increases, Δ significantly increases, indicating a decrease in the overall stiffness of the structural system. At low opening ratios (<20%), Δ changes little, but once the opening ratio exceeds 30%, Δ increases more rapidly, especially for symmetrical and asymmetrical openings. When the opening ratio exceeds 60%, the increase in Δ becomes more pronounced, leading to significant instability of the frame system.
- Effect of opening type: among the types of openings, corner openings have the most negative impact, significantly weakening the load-bearing capacity of the frame, while asymmetrical openings have a lesser effect, especially when the opening ratio is below 60%.
- Effect of wall thickness: thicker walls result in smaller Δ, helping to maintain better stiffness. The 70 mm wall is most affected, with Δ increasing rapidly as the opening ratio increases. The 110 mm wall improves stiffness compared to the 70 mm wall but still experiences significant effects when the opening ratio exceeds 50%. In contrast, the 220 mm and 330 mm walls maintain more stable horizontal displacements, though their effectiveness diminishes when the opening ratio exceeds 60%.

In summary, to maintain the stiffness of the frame and prevent a rapid increase in horizontal displacement, the opening ratio should be kept below 40%. If larger openings (>60%) are required, thicker walls (≥220 mm) should be used to minimize the reduction in stiffness and lateral load-bearing capacity. Corner openings should be limited, particularly in buildings requiring high stiffness, due to their substantial negative impact on the stability of the structural system. Symmetrical openings cause larger horizontal displacements than asymmetrical openings, so careful placement is crucial to minimize adverse effects. In buildings with high lateral load and stability requirements, optimizing the placement of openings and combining them with appropriate reinforcement methods is essential to mitigate the negative impacts of openings. The results from this study provide a solid scientific basis for improving the design of RC frame systems with IWs, enhancing the stability and load-bearing capacity of structures under lateral loads. The increase in opening ratio causes a clear rise in lateral displacement of the RC frame. This reflects a progressive reduction in lateral stiffness, especially beyond the 40% opening ratio, where the infill wall's contribution is significantly weakened. For thin walls (70 mm), the structural frame behaves nearly like a bare frame after 60% openings. In contrast, thick walls (220–330 mm) sustain stiffness longer, indicating that wall thickness can partially compensate for strength loss due to openings. Corner openings are especially detrimental due to their location near critical stress pathways.

The effect of the opening ratio in IW on the first vibration period (T_1) of RC frames:

Figure 7 shows the effect of openings in the IW on the first vibration period (T_1) of the RC frame, from which the following observations can be made:

- Effect of opening ratio: the analysis results show that as the opening ratio in the IWs increases, T_1 of the RC frame decreases significantly, indicating a reduction in the overall stiffness of the structural system. For small opening ratios (<20%), the change in T_1 is negligible. However, when the opening ratio increases to 30–60%, T_1 decreases more rapidly, demonstrating a noticeable impact of the openings on the structure's stiffness. When the opening ratio exceeds 60%, the frame loses substantial lateral load resistance, leading to a sharp reduction in the vibration period, which directly affects the ability to resist vibrations and the overall stability of the structure.

- Effect of wall thickness: thicker walls result in a larger T_1, indicating higher overall stiffness of the structural system. Thinner walls (70 mm and 110 mm) are more affected by openings, with T_1 decreasing rapidly as the opening ratio increases. In contrast, thicker walls (220 mm and 330 mm) help maintain T_1 stability better. However, when the opening ratio exceeds 60%, even thicker walls cannot preserve their original stiffness.
- Effect of opening type: corner openings maintain better stiffness than symmetrical and asymmetrical openings when the opening ratio is below 40%, due to their position, which helps redistribute stress within the frame. However, when the opening ratio exceeds 60%, the difference between the types of openings gradually diminishes, and all types negatively impact the stiffness of the structural system.

In conclusion, to ensure structural stability and minimize the negative impact on the load-bearing capacity of the RC frame, the opening ratio should be limited to below 40%. When the opening ratio exceeds 60%, thicker walls (≥220 mm) should be used to reduce stiffness degradation and maintain the stability of the structure. Corner openings should be limited, especially in buildings requiring high vibration resistance. Symmetrical openings should be preferred to ensure uniform stress distribution, helping to maintain a more stable vibration period. In earthquake-prone areas, the effect of openings should be carefully considered to prevent a reduction in overall stiffness, which could lead to structural instability under lateral loads. T_1 increases with larger openings, especially after 30–40% ratios. A longer fundamental period indicates reduced stiffness and a shift in the dynamic response of the structure. In seismic design, this affects the demand on energy dissipation mechanisms. Thicker walls delay the increase in T_1 but cannot prevent it entirely once openings exceed 60%, confirming that geometric changes in the IW substantially influence global dynamics.

The effect of the opening ratio in IW on shear force (Q) at the column base:

Figure 8 shows the effect of the opening ratio on shear force (Q) at the column base, from which the following key findings are derived:

- Effect of wall thickness: the thickness of the IW is crucial in maintaining the load-bearing capacity of the structure when there are openings. Thinner walls (70 mm) exhibit a lower initial shear force, which decreases rapidly as the opening ratio increases, indicating a higher susceptibility to stiffness and load-bearing degradation. Thicker walls (110 mm, 220 mm, 330 mm) maintain better performance with higher initial shear forces, minimizing stiffness degradation and sustaining load-bearing capacity. The 330 mm wall achieves the highest shear force in all cases, highlighting the importance of wall thickness in mitigating the negative effects of openings. Walls thicker than 220 mm significantly reduce shear force degradation compared to thinner walls.
- Effect of opening ratio: as the opening ratio increases, Q decreases for all opening types (symmetrical, asymmetrical, corner), indicating a substantial reduction in stiffness and load-bearing capacity as the opening area expands. When the opening ratio is between 0% and 20%, shear force increases slightly for thicker walls (220 mm, 330 mm), particularly with corner openings. This may be due to the combined effect of the wall and frame early on. Once the opening ratio exceeds 40%, shear force drops sharply, especially for thinner walls and corner openings. At a 100% opening ratio, Q reaches very low levels, indicating the structure loses almost all support from the IW. When the opening ratio exceeds 40%, strengthening measures or thicker walls are necessary to ensure the system's load-bearing capacity.
- Effect of opening type: corner openings have the most negative impact, causing rapid shear force reduction as the opening ratio increases due to the loss of critical connection between the IW and the frame. Asymmetrical openings cause moderate shear force reduction, with less severe effects compared to corner openings. Symmetrical openings maintain the highest shear force among all types, providing greater stability due to more even stress distribution. Symmetrical openings are the most effective in minimizing negative effects, while corner openings should be limited to prevent damage to the frame's stiffness.

To summarize, when the opening ratio exceeds 40%, strengthening measures or the use of thicker walls are necessary to maintain the system's load-bearing capacity, particularly for structures with corner openings. As the opening ratio increases, the base shear decreases, particularly with corner openings. A reduced shear force capacity implies a lower lateral load resistance of the frame. The stress redistribution caused by openings leads to early cracking and detachment of the IW from the frame, especially when using thinner walls. Symmetrical openings retain more shear force due to balanced stress paths, while corner openings disrupt them severely.

The effect of the opening ratio in IW on bending moment (M) at the column base:

Figure 9 illustrates the effect of openings in the IW on the moment (M) at the column base, from which several noteworthy insights can be drawn:

- Effect of wall thickness: the thickness of the IW significantly affects the distribution of the bending moment in the structure, with thicker walls helping to minimize the change in moment when openings are present. Thinner wall (70 mm) has a lower initial bending moment and tend to increase slightly as the opening ratio increases, though this increase is not significant due to the substantial reduction in the system's overall stiffness. Thicker walls (110 mm, 220 mm, 330 mm) exhibit higher initial moments and maintain better performance as the opening ratio increases, with the 330 mm thick wall reaching the highest bending moment, indicating better load-bearing capacity.

- Effect of opening ratio: M tends to increase as the opening ratio increases, especially for symmetrical and asymmetrical openings. This is likely due to the redistribution of stresses within the structural system as the IW no longer directly supports the frame. When the opening ratio is between 0% and approximately 20%, the bending moment increases most rapidly for corner openings, as the structural system retains some load-bearing capacity from the remaining portion of the IW. When the opening ratio exceeds 60%, the bending moments for symmetrical and asymmetrical openings tend to converge to the same value, indicating that the structural system nearly entirely relies on the RC frame rather than the IW.
- Effect of opening type: corner openings cause a sharp increase in the bending moment when the opening ratio is low (<20%), but the moment gradually decreases as the opening ratio increases. This is due to the significant weakening of structural stiffness as the corner openings expand. Asymmetrical openings show a more gradual increase in the bending moment with the opening ratio and tend to stabilize more than corner openings. Symmetrical openings exhibit a steady increase in the bending moment with the opening ratio and maintain the most stable values at higher opening ratios, suggesting that uniform stress distribution helps maintain better load-bearing capacity.

In summary, when the opening ratio exceeds 60%, the structural system almost entirely relies on the load-bearing capacity of the RC frame, making it necessary to implement reinforcement measures or design optimization to ensure durability and stability. Corner openings have the most negative impact, causing a sharp initial increase in the moment, followed by a decrease as the opening ratio increases.

The effect of the opening ratio in IW on shear force (Q) in beams:

Figure 10 illustrates the effect of openings in the IW on the shear force (Q) of the beam, from which the following observations can be drawn:

- Effect of wall thickness: the thickness of the IW is crucial in maintaining shear force in the beams, with thicker walls helping to minimize the negative impact when openings are present. Thinner walls (70 mm) experience a rapid decrease in shear force as the opening ratio increases, especially with corner openings, indicating weaker structures more prone to stiffness degradation. Thicker walls (110 mm, 220 mm, 330 mm) exhibit higher initial shear forces and maintain better performance as the opening ratio increases, slowing the rate of shear force reduction.
- Effect of opening ratio: as the opening ratio increases, Q in the beam decreases, reflecting the critical role of the IW in supporting the frame system. When the opening ratio is small (<20%), shear force remains high, but when it exceeds 40%, the decrease becomes noticeable, especially with corner openings. When the opening ratio exceeds 60%, the reduction in shear force becomes significant for all types of openings, reflecting the negative impact of losing IW support. At a 100% opening ratio, shear force converges to the same low value for all cases, indicating that the structural system now fully relies on the frame, without support from the IW.
- Effect of opening type: corner openings cause the fastest decrease in shear force as the opening ratio increases, particularly when it exceeds 40%, due to a significant loss of connection between the IW and the structural system. Asymmetrical openings lead to a more gradual reduction in shear force and are more stable than corner openings. Symmetrical openings maintain shear force better than the other types, indicating a more uniform stress distribution.

In summary, when the opening ratio exceeds 40%, reinforcement or design optimization should be considered to maintain the system's durability and load-bearing capacity.

The effect of the opening ratio in IW on bending moment (M) in beams:

Figure 11 illustrates the effect of openings in the IW on the bending moment (M) of the beam, and the observations from Figure 11 are as follows:

- Effect of wall thickness: the thickness of the IW wall plays a crucial role in controlling the reduction of bending moment, with thicker walls helping to minimize the negative impact. Thinner walls (70 mm) experience a faster reduction in M as the opening ratio increases, particularly with corner openings, indicating poorer structural performance when using thinner walls. Thicker walls (110 mm, 220 mm, 330 mm) exhibit higher initial bending moments and decrease more slowly as the opening ratio increases, demonstrating better maintenance of the load-bearing capacity of the frame.

- Effect of opening type: corner openings cause significant fluctuations in M, especially when the opening ratio is between 10% and 30%, after which M decreases rapidly. This is likely due to a sudden change in stress distribution as much of the wall's stiffness is weakened. Asymmetrical openings lead to a more gradual and stable reduction in bending moment compared to corner openings. Symmetrical openings show the most stable decrease in M, indicating a more uniform load distribution compared to the other two types of openings.
- Effect of opening ratio: when the opening ratio exceeds 40%, the bending moment decreases significantly, requiring reinforcement measures or design optimization to ensure the durability and stability of the structure. At a 100% opening ratio, all types of openings have nearly identical bending moments, indicating that the structural system primarily relies on the load-bearing capacity of the frame and beams rather than the IW.

Overall, as the opening ratio increases, the bending moment in the beam decreases, especially when the opening ratio exceeds 40%, reflecting the weakening of the IW and the increased load transmitted to the beam. Bending moments increase up to a point with the opening ratio, then plateau or reduce. Initially, with small openings, the infill wall provides lateral support, concentrating bending demand on columns. As openings grow, the IW loses its bracing effect, and the moment is redistributed throughout the frame. After 60%, the system transitions to a frame-dominant response, where moments stabilize but displacement increases rapidly. This transition is crucial for understanding potential failure mechanisms.

Based on the numerical analysis conducted in this study, a set of design recommendations is proposed to optimize the structural performance of RC frames with masonry IWs containing openings. When the opening ratio is maintained at or below 40%, the structural system remains within a safe performance range, exhibiting only moderate stiffness degradation and no significant compromise in lateral load resistance. However, in the critical transition range of 40% to 60%, the system begins to exhibit more pronounced stiffness reduction and potential instability, necessitating the implementation of reinforcement measures to sustain structural integrity. When the opening ratio exceeds 60%, the RC frame enters a high-risk zone where the infill wall's contribution to lateral stiffness is significantly diminished. In such cases, the use of thicker infill walls (≥220 mm) and localized strengthening elements—such as tie-columns, reinforced lintels, or boundary frame elements—is strongly recommended to mitigate adverse effects. Additionally, the location of openings plays a crucial role in overall performance. Among the configurations examined, symmetric and asymmetric openings were found to induce less stiffness loss and stress concentration compared to corner openings, which should be avoided in regions of high seismic demand or lateral load sensitivity.

The results of the present study are consistent with and extend the findings of previous research on the effects of openings in infill walls on the mechanical performance of RC frames. Specifically, the observed reduction in lateral stiffness and corresponding increase in lateral displacement with increasing opening ratios aligns with the findings of Umar et al. [5], who reported significant stiffness degradation in RC frames due to wall openings. Our results further quantify critical thresholds at which such degradation becomes pronounced, particularly at opening ratios exceeding 40% and 60%. Moreover, the detrimental impact of corner openings on structural stability corroborates the conclusions of Kusonkhum et al. [7] and Tekeli et al. [8], who highlighted that non-central and asymmetrical openings lead to adverse stress redistributions and diminished energy dissipation. The increase in the fundamental vibration period observed in our study is also in agreement with the findings of Zhang et al. [6], who emphasized the influence of infill wall configurations on dynamic performance under seismic loads. Our analysis adds that thicker walls can mitigate this effect to some extent, although their efficacy diminishes at higher opening ratios. Furthermore, the reduction in base shear and alterations in bending moment patterns identified in our simulations are consistent with the work of Smith [19], who proposed strength and stiffness reduction factors for infilled frames with openings. This study extends the current understanding by providing a more detailed analysis of different opening configurations and wall thicknesses. These comparative insights confirm the validity of the present findings and contribute new quantitative benchmarks for the structural design and optimization of RC frames with infill walls.

6. Conclusions

The paper proposed a simple model combining stiffness degradation and the "Gap element" to simulate the behavior of RC frames with and without IW. This study also analyzes the impact of the opening ratio in the IW on the mechanical characteristics of the RC frame system, including horizontal displacement, vibration period, shear force, and bending moment. The results show that as the opening ratio increases, the overall stiffness of the structural system decreases significantly, leading to an increase in horizontal displacement and a reduction in the load-bearing capacity of the frame. At small opening ratios (<20%), the impact of the openings is not significant; however, when the ratio exceeds 30%, horizontal displacement begins to increase rapidly, especially with symmetrical and asymmetrical openings. When the opening ratio exceeds 60%, the frame loses significant lateral load resistance, the vibration period decreases sharply, and the structure becomes less stable. Regarding the thickness of the IW, thinner walls (70 mm) are most significantly affected by openings, while thicker walls (≥220 mm) help maintain better stiffness and reduce the degradation of shear force and bending moment. However, when the opening ratio exceeds 60%, even thicker walls cannot maintain their initial stiffness, leading to overall weakening of the structural system.

In terms of the opening types, corner openings have the most negative impact, significantly weakening the frame's load-bearing capacity and creating larger horizontal displacements compared to other opening types. Symmetrical openings cause larger horizontal displacements than asymmetrical openings when the opening ratio exceeds 50%, indicating an uneven redistribution of stress within the frame. Asymmetrical openings have less impact but still cause significant stiffness degradation when the opening ratio exceeds 40%. Based on these results, the study recommends that to maintain the stability of the frame system, the opening ratio should not exceed 40%, and if openings larger than 60% are necessary, thicker IW (≥220 mm) should be used to minimize the negative effects. Specifically, corner openings should be limited in buildings requiring high stiffness, while symmetrical openings should be placed strategically to avoid destabilizing the frame system. This study provides a scientific basis for optimizing the design of RC frame systems with IW, helping to enhance the stability and load-bearing capacity of structures under lateral loads.

Although the study provides valuable insights into the effect of openings on RC frames with IW, there are some limitations to be considered. The study primarily relies on numerical simulations and lacks experimental testing to validate the results. Additionally, the study focuses on static responses and does not fully address the effects of earthquake loads or cyclic loading. Furthermore, only a few common opening types are analyzed, while there are many different shapes and arrangements of openings that may affect the results. Future research should focus on conducting experimental tests to validate the simulation results and develop nonlinear models to more accurately predict the impact of openings on frame structures. Furthermore, the impact of dynamic loads and various boundary conditions, especially in high seismic risk areas, should be considered. Lastly, reinforcement solutions, such as using additional steel reinforcement around the openings or applying composite materials, should also be explored to optimize the load-bearing capacity and stability of the structural system when openings are present in the IW.

7. Declarations

7.1. Author Contributions

Conceptualization, C.V.L.; methodology, P.A.H.P.; software, P.A.H.P.; validation, P.A.H.P.; formal analysis, P.A.H.P.; investigation, P.A.H.P.; resources, V.T.N.; data curation, C.V.L. and V.T.N.; writing—original draft preparation, P.A.H.P. and C.V.L.; writing—review and editing, P.A.H.P. and C.V.L.; visualization, P.A.H.P. and V.T.N.; supervision, P.A.H.P.; project administration, P.A.H.P. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

8. References

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