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ANALYTICAL INVESTIGATION OF MASONRY INFILL REINFORCED CONCRETE FRAMES UNDER AXIAL AND LATERAL LOADING

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Abstract

The structural behavior of framed reinforced concrete (RC) structures with and without infill is investigated in this work under axial and horizontal loading scenarios. Using sophisticated software and micro modelling approaches, the structural performance of RC frames of various geometrical performances lengths both bare and infilled is assessed, with a focus on rigidity, ductility, and load-bearing capacity. The RC frames were designed according to Euro code (EC) standards to ensure compliance with current design regulations, providing a reliable basis for analysis. The analysis thoroughly examines the structural behavior of these frames and how they react to combined loading situations. The findings imply that the frame slot space and the masonry infill have a major impact on the structures' lateral stiffness and load-bearing capability. The masonry infill within the RC exhibits enhanced resistance frames to horizontal forces, demonstrates with reduced significant horizontal displacement, were on the other hand, bare RC frames without infill show less stiffness and load-bearing ability, were highlights the importance of the slot space, RC frame length, and the infill in enhancing the overall structural performance. The investigation further emphasizes how important these elements are to improving the seismic resilience of RC frames. Across all frame lengths, infilled frames provide better stability and resistance to lateral stresses than plain frames. In order to ensure better performance, structural stability, and safety under both axial and lateral loading circumstances, this research advances optimum design methodologies for RC frames in seismic regions. The findings give engineers and designers important new information by showing how the thoughtful application of masonry infill and frame slot space variations can significantly improve the structural behavior of RC frames. These observations offer useful advice for enhancing stability and resilience in real-world engineering applications, and they can be applied to both new construction and retrofit projects.

Keywords: Reinforced concrete frames, infill walls, axial and lateral loading, structural performance, seismic performance, analytical investigations.

1. Introduction

Reinforced concrete (RC) frames represent a fundamental structural system widely employed in contemporary construction, particularly in seismic-prone areas. Their versatility, strength, and ability to withstand various types of loading make them an essential choice for high-performance buildings. However, optimizing their behavior under different loading scenarios requires a nuanced understanding of their interaction with non-structural components, such as infill walls. Infill walls, typically composed of masonry or bricks, are often integrated within RC frames to partition spaces and enhance lateral stiffness [1]. Despite being considered non-structural elements, these walls significantly influence the overall behavior of the frame, especially under lateral loading conditions [1, 2]. The presence of infill can increase stiffness, reduce displacements, and improve energy dissipation during seismic events. However, these benefits depend on factors such as material properties, wall placement, and the dimensions of the frame. The structural performance of RC frames also varies with their geometry and dimensions. Longer or taller frames may exhibit reduced stiffness and greater susceptibility to lateral displacements, whereas shorter frames tend to provide higher stability. Understanding how frame dimensions interact with infill characteristics is crucial for designing resilient structures capable of withstanding axial and lateral forces effectively. This study explores the complex interplay between RC frame dimensions, infill integration, and loading scenarios. Specifically, two frame configurations with dimensions of 2.5 m height by 4 m and 2.5 m height by 6 m width were analyzed. Comparing these configurations provides insights into the effect of varying frame lengths on performance metrics such as lateral stiffness, ductility, and load-bearing capacity. By employing advanced analytical tools and adhering to Eurocode standards, this work contributes to the development of safer and more efficient building systems for seismic regions. In this study, the analysis focuses on a single-story reinforced concrete frame with fixed supports at the base. Since the structure consists of just one story, the concept of interstory drift is not presented for evaluating its performance. Instead, the force-displacement diagrams are used to capture the structural response under lateral loads, which is sufficient for assessing the behavior of the frame in this context. This approach ensures a clear understanding of the frame's lateral stiffness and load-bearing capacity without the need for interstory drift considerations. Additionally, the findings hold relevance for both new construction projects and the retrofitting of existing buildings, ensuring compliance with modern engineering practices and safety requirements [3, 4, 5].

2. Methodology

The analysis was conducted using advanced finite element modelling techniques, leveraging state-of-the-art software to achieve accurate simulations. Micro-modelling was employed to capture the nuanced interaction between reinforced concrete (RC) frames and infill walls, ensuring a detailed representation of the structural behavior. The study considered various parameters, including frame lengths, to evaluate the impact of geometry on structural performance, and infill configurations, analyzing frames both with and without infill walls to assess their contribution to stiffness and load-bearing capacity. Realistic loading scenarios were applied, incorporating axial and lateral loads to simulate conditions such as seismic events. Structural performance metrics such as lateral stiffness, ductility, and load-bearing capacity were carefully evaluated to provide comprehensive insights into the behavior of the frames under different conditions [2, 7, 8].

2.1. Micro-Modelling in DIANA FEA

Micro-modelling in DIANA FEA is an advanced simulation approach used to capture detailed interactions within reinforced concrete frames and masonry infill walls. This methodology enables a precise representation of material behavior, geometric configurations, and boundary conditions. Micro modelling of infilled frames involves detailed representation of the reinforced concrete (RC) frame, the bricks infill material, and the interfaces between these components. This approach is essential for accurately capturing the nonlinear behavior of the frame and infill, including cracking, crushing, and interactions at the frame-infill interface. Brick infill exhibits distinct mechanical properties, such as its lightweight nature, low tensile strength, and relatively brittle behavior compared to traditional masonry. These characteristics pose challenges in finite element modelling, particularly under axial and lateral loading conditions. The strategy for finite element analysis of Brick-infilled RC frames is outlined in this chapter. To simulate real-world conditions and ensure a high level of precision in the analysis, fixed supports were implemented at the base of the RC frames to replicate realistic structural constraints, while interface elements were carefully employed to model the complex interaction between the RC frames and infill walls, accounting for parameters such as friction and cohesion to reflect the behavior of the interface under loading. Axial loads were applied vertically to represent the self-weight of the structure as well as additional gravity loads, while incremental lateral loads were introduced to simulate seismic forces and to assess the lateral stiffness, ductility, and overall structural response under extreme conditions. A fine meshing strategy was adopted for both the RC frames and the infill walls, with a particular focus on critical regions such as interfaces, corners, and stress concentration zones, enabling

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the accurate capture of localized stress distributions and potential failure mechanisms in nonlinear analyses, thereby providing reliable insights into areas prone to cracking or structural instability under combined loading scenarios [16, 17, 18, 19].

2.2. Geometry Definition

The geometry of structure illustrates a reinforced concrete frame with masonry infill, designed for both 4.0 m (Model M1.1) and 6.0 m (Model M2.1) lengths, with the only variation being the frame width. The frame consists of two vertical columns with cross-sectional dimensions of 50x30 cm, connected by a horizontal beam with a T-shaped cross-section, having a flange width of 40 cm and a depth of 20 cm. The overall height of the frame is 260 cm, while the foundation beneath the columns has a rectangular cross-section of 110x60 cm to provide stability and support for load distribution. The masonry infill spans the space between the columns and beam, with a height of 240 cm. For the 4.0 m frame, the masonry infill has a width of 350 cm, while in the 6.0 m frame, it spans 550 cm. The infill is composed of bricks with dimensions of 20x10x5 cm, arranged in a uniform bonded pattern to ensure structural integrity and efficient load transfer. Both models share the same reinforcement and structural design, maintaining a uniform reinforcement ratio of 1.2%. This approach ensures comparable performance in terms of stiffness, load-bearing capacity, and interaction between the frame and infill, while accommodating the differing frame lengths to study their behavior under various loading scenarios.

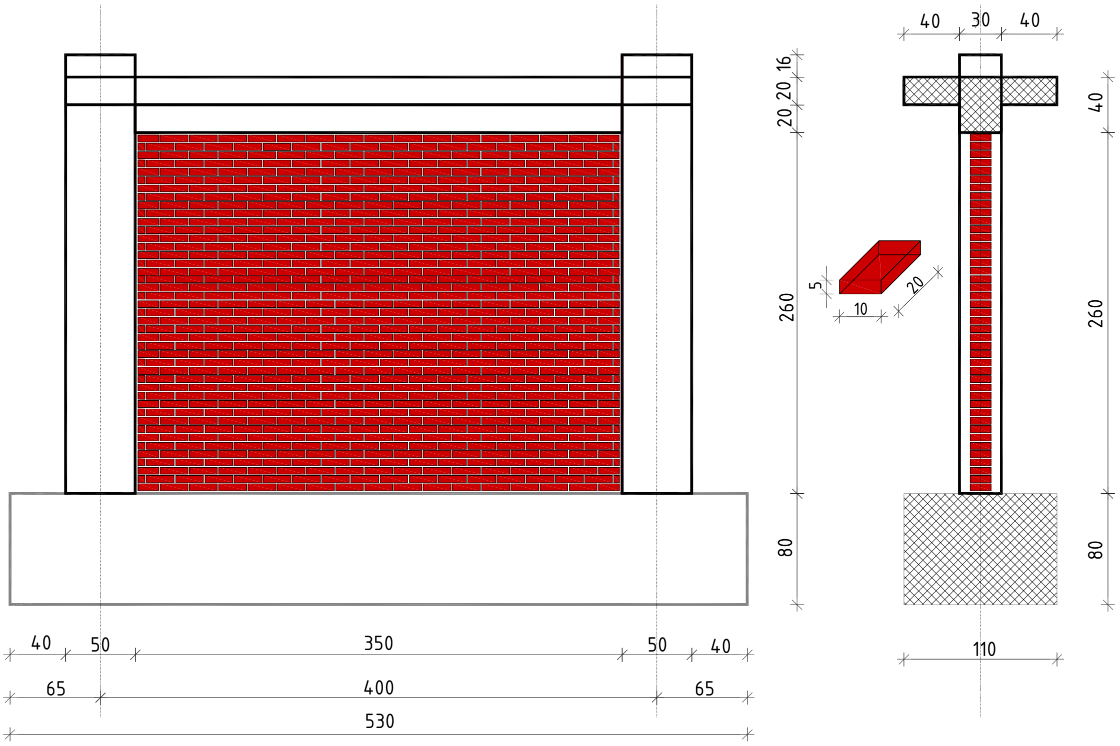

Figure 1. Geometry of Infilled RC frame (4m' length)

The reinforcement for the RC frame (Fig. 2) is designed with a consistent reinforcement ratio of 1.2%, utilizing specific bar diameters to ensure structural integrity across all elements. Columns are reinforced with Ø18 mm and Ø16 mm longitudinal bars, supported by Ø12 mm stirrups for shear resistance and confinement. Beams incorporate Ø20 mm longitudinal bars for both the top and bottom reinforcement, complemented by Ø10 mm stirrups to provide adequate shear capacity. Foundations are reinforced with Ø20 mm longitudinal bars, along with Ø12 mm stirrups or ties for shear stability, ensuring axial and bending resistance. Beam-to-column connections are strengthened with Ø16 mm bars to enhance joint ductility and structural performance. Both Model M1 and Model M2 utilize the same reinforcement

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design, with the only difference being their lengths. This consistent approach ensures reliability and compliance with design standards while addressing the unique demands of different frame lengths.

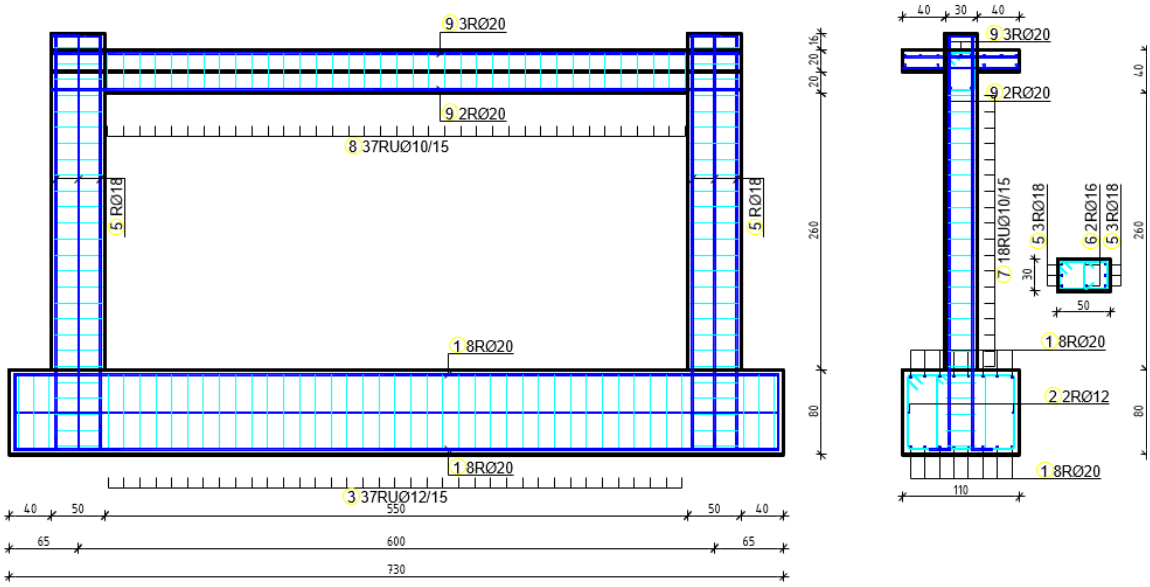

Figure 2. Reinforcement of RC frame (6m’ length)

2.3. Material Properties

The material properties used in the analysis were obtained from established literature, ensuring they are well-founded and appropriate for accurately modelling the structural behavior under the specified loading conditions [2, 7, 16].

Table 1. Material used for analysis

Material	Property	Value
Concrete (RC Frame)	Compressive Strength (fc)	30 MPa
	Young's Modulus (E)	25,000 MPa
	Poisson's Ratio (ν)	0.2
Masonry (Infill)	Compressive Strength (fc)	10 MPa
	Tensile Strength (ft)	0.5 MPa
	Young's Modulus (E)	5,000 MPa
	Poisson's Ratio (ν)	0.15
Reinforcement Steel	Yield Strength (fy)	500 MPa
	Young's Modulus (E)	200,000 MPa
	Density (ρ)	7,850 kg/m³

Table 2. Material properties used for analysis in software

Material	Property	Value
Brick (Linear Elastic)	Young’s Modulus	1.74E+10 N/m²
	Poisson’s Ratio	0.15
	Mass Density	1700 kg/m³
Total strain module	Young’s Modulus (X)	4E+9 N/m²
	Young’s Modulus (Y)	6E+9 N/m²

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	Shear Modulus	2E+9 N/m²
	Mass Density	1700 kg/m³
	Tensile Strength (Bed Joint)	250,000 N/m²
	Compressive Strength	8.5E+6 N/m²
	Fracture Energy in Compression	15,000 N/m
Brick (Nonlinear)	Young's Modulus	1.74E+10 N/m²
	Poisson's Ratio	0.15
	Mass Density	1700 kg/m³
	Tensile Strength	250,000 N/m²
	Compressive Strength	8.5E+6 N/m²
	Fracture Energy in Compression	15,000 N/m
Concrete	Young's Modulus	3E+10 N/m²
	Poisson's Ratio	0.15
	Mass Density	2200 kg/m³
Linear Interface	Normal Stiffness	1.0E+12 N/m³
	Shear Stiffness	1.0E+12 N/m³
Interface (Plastic Model)	Normal Stiffness	8.3E+10 N/m³
	Shear Stiffness	3.6E+10 N/m³
	Tensile Strength	250,000 N/m²
	Fracture Energy	18 N/m
	Compressive Strength	8.5E+6 N/m²
Interface (Friction)	Normal Stiffness	8.3E+10 N/m³
	Shear Stiffness	3.6E+10 N/m³
	Friction Angle	0.643501 rad
Interface (No Tension)	Normal Stiffness	8.3E+10 N/m³
	Critical Normal Interface Opening	3E-6 m
	Normal Stiffness Reduction Factor	1E-5

3. Results and Discussion

In reinforced concrete (RC) frame systems, masonry infills significantly contribute to enhancing the load-bearing capacity of the structure. However, it is important to clarify that the infill should not be considered a structural element or a rigid surface. While masonry infills are brittle, weak, and have a reduced load-bearing capacity compared to the RC frame, they play a crucial role in improving the overall performance of the frame by enhancing its lateral stiffness. The RC frame, being made of reinforced concrete, has significantly higher shear strength and load-bearing capacity than the masonry wall. As such, the design of the system must ensure that lateral displacements remain within limits, preventing excessive forces from being transmitted to the infill that could lead to failure. This is especially crucial, as masonry walls have a limited ability to resist shear forces and large displacements. There is a substantial body of research demonstrating the beneficial contribution of masonry infills to RC frame systems. However, it is important to note that this contribution varies depending on factors such as the type of masonry units used, the construction methods, mortar layers, and the dimensions of the infill walls. This interaction is evident when comparing the displacement values of frames with and without masonry infills, considering variations in wall height and length.

For the current study, a series of models should be constructed to experimentally validate the theoretical analysis, with a focus on assessing the contribution of masonry infills in improving lateral stiffness and

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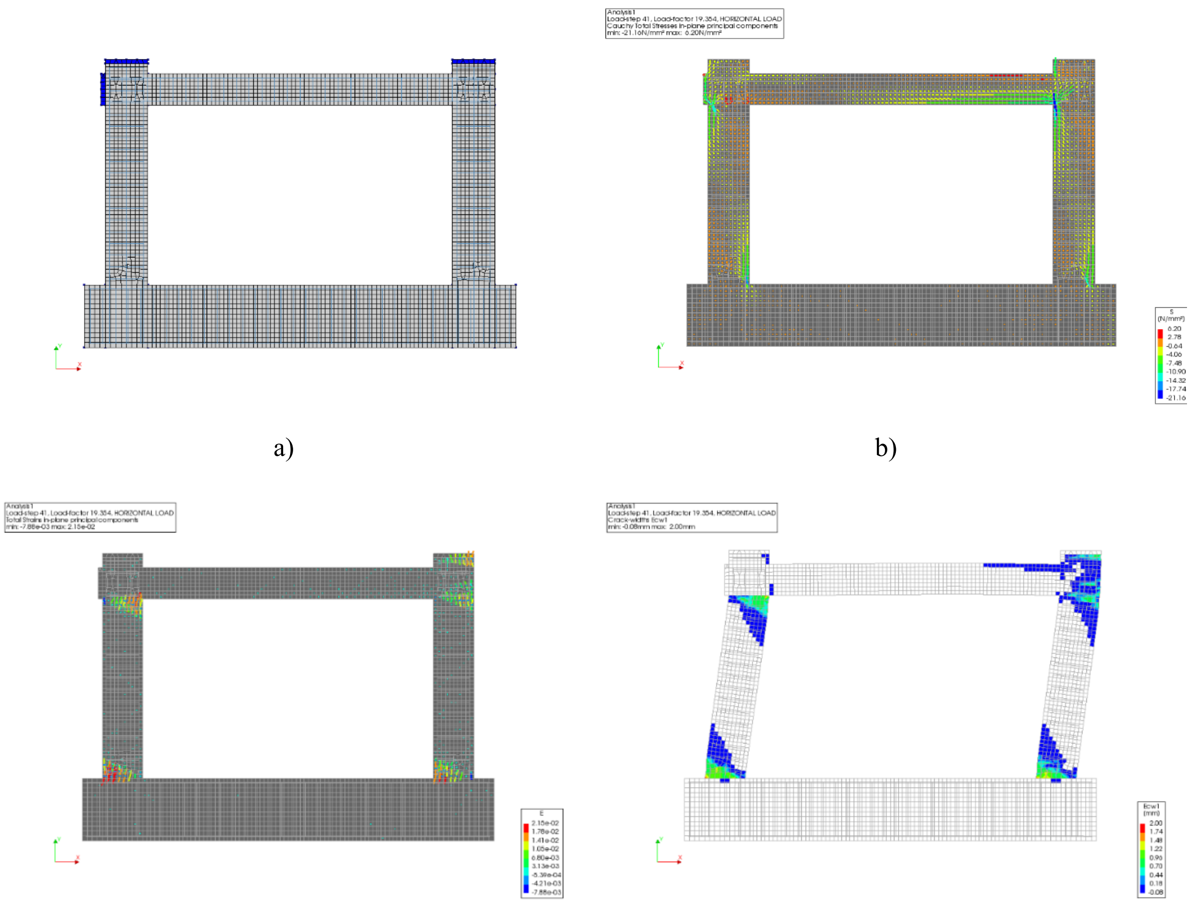
load-bearing capacity under axial and lateral loads. It should be noted that, for single-story frames, the effects of interstory drift are not as prominent. However, this analysis is particularly relevant in the context of multi-story buildings. Lastly, it is important to emphasize that the RC frame in this analysis is considered in-plane, not out-of-plane, as out-of-plane behavior of masonry infills is outside the scope of this study.

Fig. 3a (Model 1) illustrates the meshed structural model used for finite element analysis. The mesh is carefully constructed to ensure that the structural response to various loading conditions can be accurately simulated, providing a foundation for the assessment of stresses, strains, and deformations. Fig. 3b presents the stress distribution across the structure, offering a visual representation of how internal forces are distributed as the structure reacts to applied loads. This allows for an understanding of the load-bearing capacity and the regions where stresses are concentrated. Fig. 3c depicts the strain distribution, demonstrating the extent of deformation experienced by the structure under the specified loading conditions. This visualization is crucial for identifying potential zones of significant deformation or instability. Lastly, fig. 3d shows the crack patterns that develop in the structure as a result of the applied forces. The depiction of crack propagation provides insights into the structural integrity, durability, and the areas most affected by the loading, aiding in evaluating the overall performance of the structure [7, 8, 16, 17, 18].



a) b) c) d)

Figure 3. a) The meshed structural model used for finite element analysis; b) Stress distribution across the structure; c) The strain distribution; d) The crack patterns

The graph in Fig. 4 illustrates the force-displacement response of Model M1 (L=4.0m) under one-way loading. Initially, the steep rise in the curve represents the elastic behavior, where the frame resists load with minimal deformation. The peak force of approximately 260 kN marks the maximum load-bearing

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capacity, followed by a gradual decline indicating nonlinear behavior due to cracking or plastic deformations. The plateau region reflects the post-yield behavior, showcasing the frame's ability to sustain resistance under increased displacements. This diagram highlights the frame's stiffness, strength, and ductility under one-way loading [7, 16, 17].

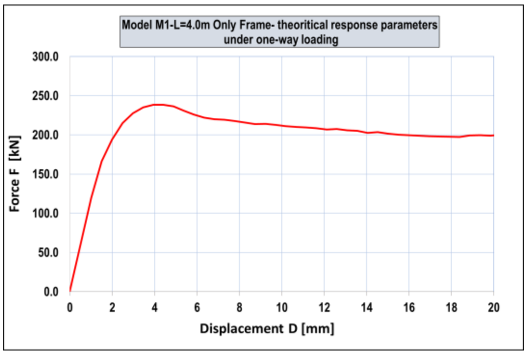
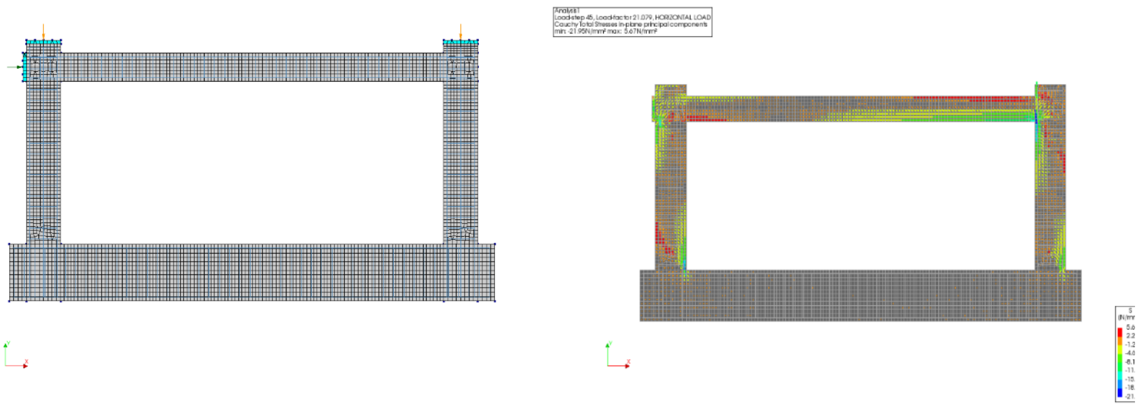


Fig 4. Force-Displacement Diagram for Model M1 (L=4.0m) Under One-Way Loading

The results presented in Fig. 5 (Model 2) provide a comprehensive understanding of the structural behavior of the RC frame with a 6 m length under applied loading conditions. The meshing ensures detailed analysis and accurate representation of the frame's response. The stress distribution illustrates how forces are transferred within the structure, highlighting areas of internal resistance. The strain distribution reflects the deformation experienced by the frame, offering insights into its structural flexibility and potential weaknesses. The crack pattern visualization identifies the development and propagation of cracks, which are critical for assessing the structural integrity and overall performance of the frame under applied forces. Together, these results demonstrate the frame's capacity to handle loading conditions while revealing potential vulnerabilities and areas for improvement.



a) b)

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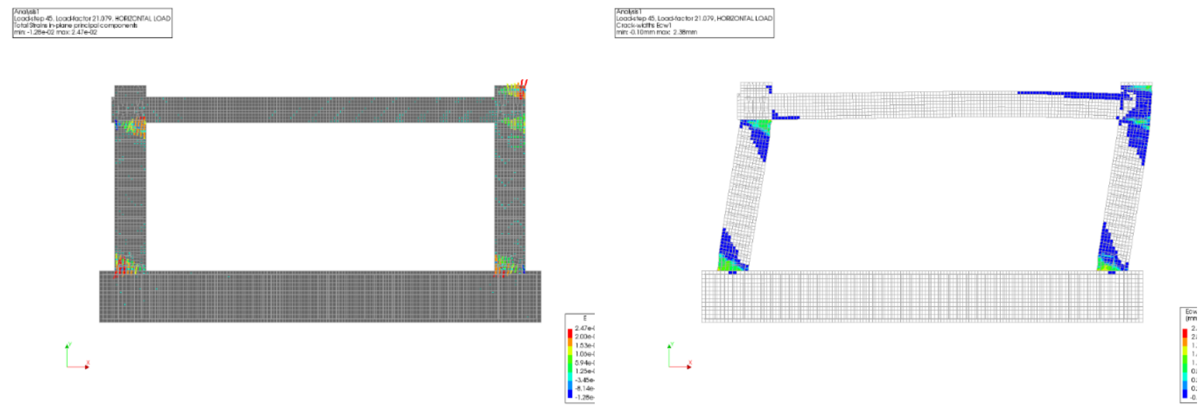

c) d)

Figure 5. a) The meshed structural model used for finite element analysis (L=6m'); b) Stress distribution across the structure; c) The strain distribution; d) The crack patterns

The graph shown in Fig. 6 represents the force-displacement diagram for Model M2 (L=6.0m) under one-way loading, capturing the structural response of the frame during the application of lateral forces. The curve shows an initial steep increase, indicating the elastic behavior of the structure, where the frame resists applied forces with minimal deformation. The peak force, around 250 kN, represents the maximum load-bearing capacity of the frame. Beyond this point, a slight drop in force is observed, marking the transition to nonlinear behavior caused by material cracking, localized failures, or yielding in critical sections. Following this, the curve transitions into a nearly horizontal plateau, indicating post-yield behavior, where the frame maintains a consistent resistance to increasing displacements.

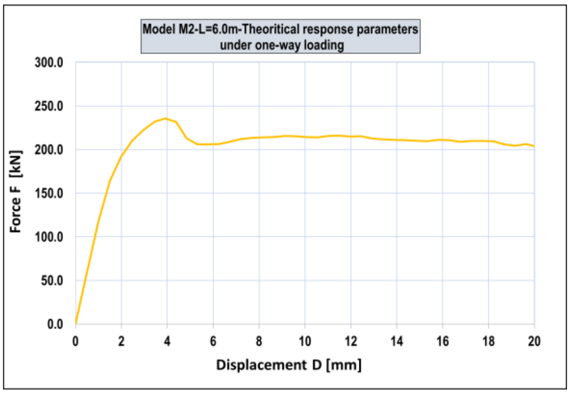

Figure 6. Force-Displacement Diagram for Model M2 (L=6.0m) Under One-Way Loading

Fig. 7 illustrates the analysis results for the RC frame with a length of 4 meters, infilled with masonry (Model 1.1). These results provide a comprehensive understanding of the structural behavior under applied horizontal loading. The meshed model represents the finite element discretization, ensuring accurate simulation of the interaction between the frame and the infill. The distribution of stresses offers valuable insights into how forces are transferred throughout the structure, highlighting the interplay between the frame and the infill under external loading conditions. Similarly, the strain distribution reflects the deformation characteristics of the structure, demonstrating the material's response to the applied forces and identifying areas of potential weakness or instability. The crack pattern visualization further complements this understanding by showcasing the extent and progression of cracking within the frame and infill. Together, these results allow for a detailed assessment of the structural integrity, durability, and overall performance of the system, providing critical information for evaluating the structural behavior and its capacity to withstand horizontal loads [16, 17, 18].

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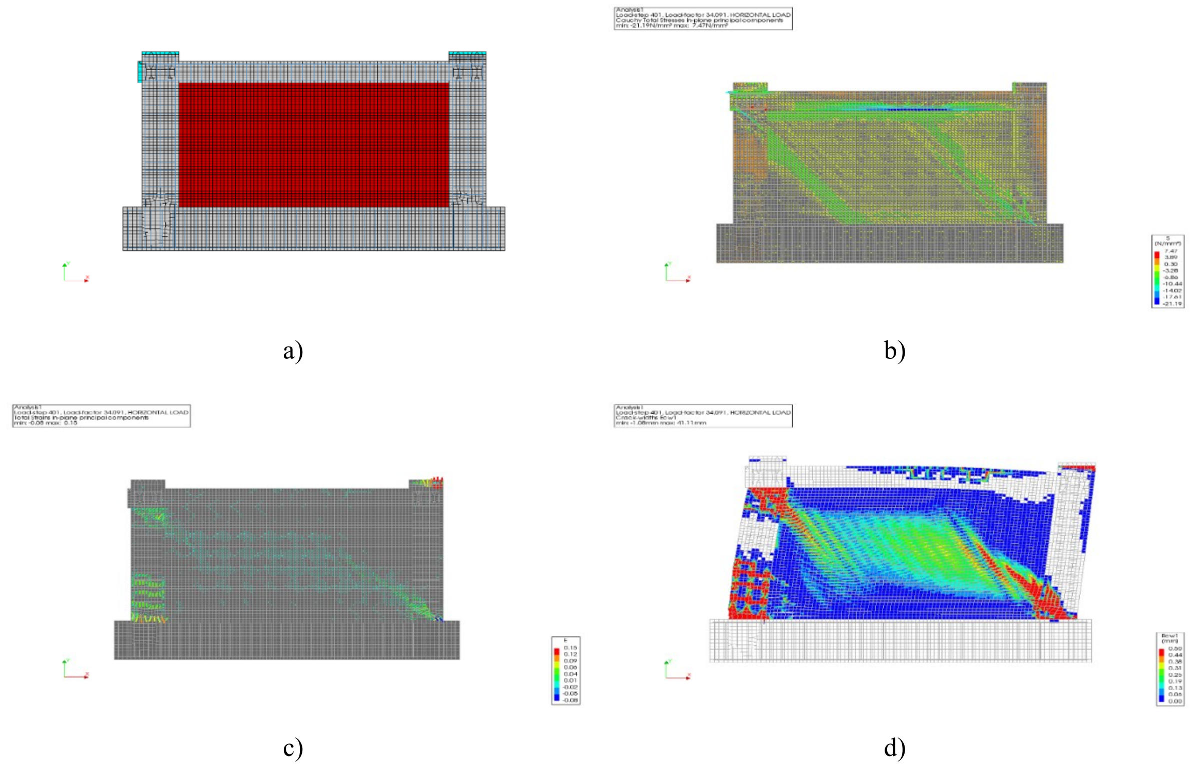

Figure 7. a) The meshed structural model used for finite element analysis RC Frame with infill (L=4m'); b) Stress distribution across the structure; c) The strain distribution; d) The crack patterns

Fig. 8 represents the force-displacement diagram for Model M1.1 (L=4.0m) with an infill under one-way loading. The curve exhibits an initial steep rise, indicating the elastic behavior of the frame with infill as it resists applied forces. The peak force of approximately 550 kN demonstrates the enhanced load-bearing capacity due to the presence of the infill, significantly higher compared to the bare frame. Beyond the peak, the curve transitions into a near-horizontal plateau, showcasing the post-yield behavior where the structure maintains consistent resistance despite increasing displacements. This diagram highlights the significant role of the infill in improving the stiffness, strength, and overall performance of the frame under lateral forces, reflecting its ability to enhance structural resilience and maintain stability during loading. The results for the RC frame with an infill and a length of 6 meters provide a detailed understanding of the structural behavior under horizontal loading (fig 9). The meshed model ensures a precise representation of the geometry, allowing for accurate simulation of interactions between the frame and the infill [3, 7]. The stress distribution highlights how forces are transferred and concentrated within the structure, reflecting the response of the materials under the applied loads. The strain visualization demonstrates the deformation characteristics, showing the extent of material elongation and compression. Finally, the crack pattern and width distribution reveal critical insights into the structural integrity, illustrating areas of crack initiation, propagation, and potential failure. These results collectively offer a comprehensive view of the structural performance, emphasizing the frame's load-bearing capacity, flexibility, and durability under horizontal forces.

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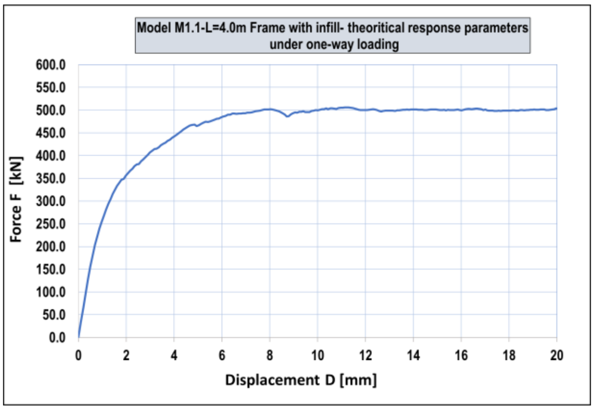
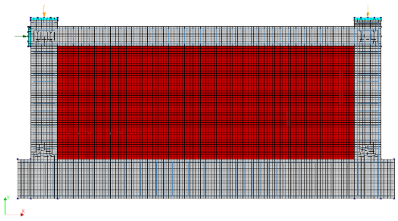


Figure 8. Force-Displacement Diagram for Model M1.1 (L=4.0m) Under One-Way Loading



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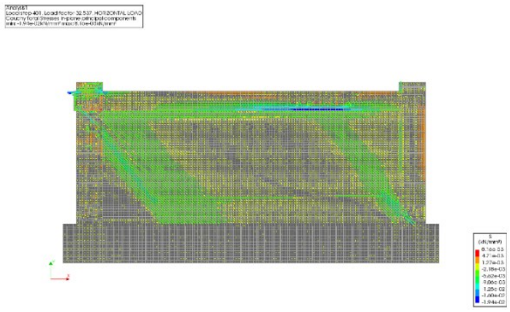

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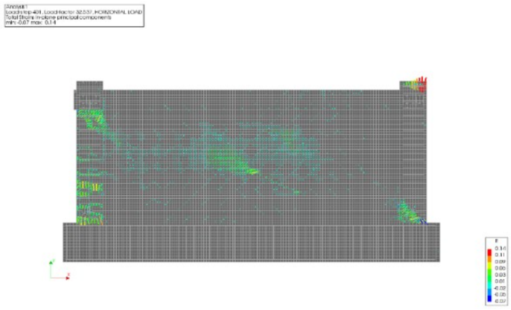

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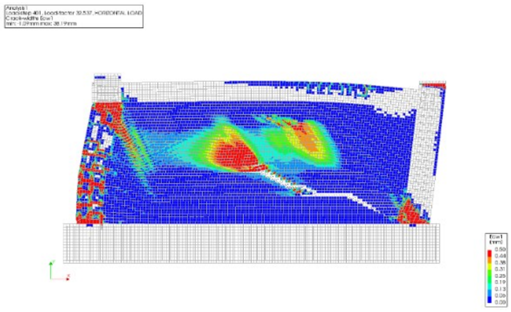

d)

Figure 9. a) The meshed structural model used for finite element analysis RC Frame with Infill (L=6m'); b) Stress distribution across the structure; c) The strain distribution; d) The crack patterns

Force-displacement response for Model M2.1 (L=6.0m) with an infill under one-way loading conditions is prescribed in Fig 10. The curve begins with a sharp rise, indicating the elastic behavior of the structure as it resists increasing loads with minimal deformation. The peak force, around 550 kN, demonstrates the frame's enhanced capacity due to the infill's contribution, which significantly improves its strength. Following the peak, the curve flattens into a plateau, representing the post-yield phase, where the structure continues to bear load despite increased displacements. This response reflects the combined action of the frame and infill, which contributes to the stability, ductility, and sustained load-bearing performance of the structure, even under extensive deformation. The diagram emphasizes the importance of infill in maintaining structural integrity and overall resilience in longer frames under lateral loads.

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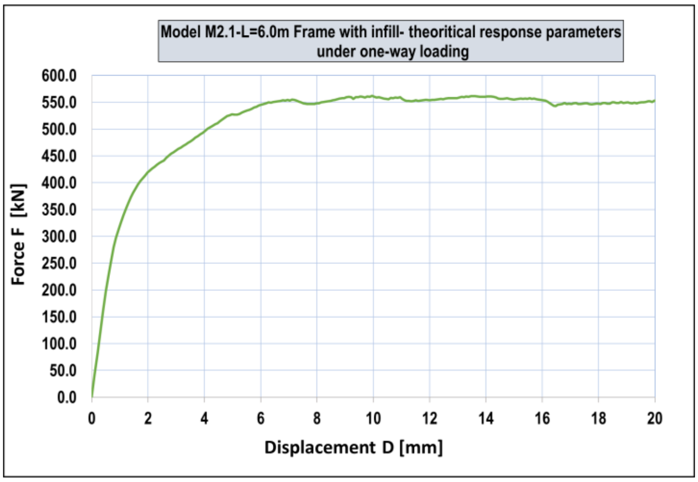

Figure 10. Force-Displacement Diagram for Model M2.1 (L=6.0m) Under One-Way Loading

3.1. Results discussion

The comparative analysis of Model M1, Model M1.1, Model M2, and Model M2.1 highlights the significant impact of masonry infill and frame length on the structural performance of reinforced concrete frames under one-way loading conditions. Model M1 (4.0 m frame without infill) shown in Fig. 11a, and Model M1.1 (4.0 m frame with infill) demonstrate the critical role of infill in enhancing structural stiffness and load-bearing capacity, as evidenced by the steeper initial slope and higher peak force in the force-displacement curve for Model M1.1. The inclusion of infill not only improves stiffness but also provides greater residual strength and ductility, enabling the frame to better resist lateral forces. Similarly, the comparison between Model M2 (6.0 m frame without infill) and Model M2.1 (6.0 m frame with infill) reveals that masonry infill significantly enhances stiffness, peak force, and residual strength (Fig 11b). The infill in Model M2.1 contributes to a more uniform stress distribution, lower strain concentrations, and reduced crack development, whereas Model M2 exhibits localized stress and strain concentrations, along with larger and more severe cracks near beam-column joints and column bases. When comparing Model M1.1 and Model M2.1, which both include infill but differ in frame length, the results demonstrate that the longer frame (Model M2.1) achieves a higher peak force and improved post-peak performance. This can be attributed to the larger dimensions of the masonry infill, which enhance load transfer and lateral stiffness, as well as the longer span allowing for a more distributed stress pattern. Model M1.1, with a shorter length, reaches its residual strength more quickly, indicating higher stress concentrations and reduced load distribution (Fig 11c). Overall, the comparative analysis underscores the critical influence of masonry infill and geometric dimensions on the structural performance of reinforced concrete frames. Numerous studies demonstrate the contribution of masonry infills to RC frames, but there is variability based on factors like the type of masonry units used, the construction methods, mortar layers, and the dimensions of the walls. Additionally, studies from earthquakes, such as those in Durrës in 2019, show how large displacements of the frame could cause significant damage to infill walls, especially when the walls are constructed with certain masonry units or improperly oriented.

Furthermore, the interaction between the RC frame and infill is critical. This can be observed when comparing displacement values for frames with and without masonry infills, considering the length and height of the walls.

These findings highlight the importance of optimizing both material properties and geometric configurations to achieve superior structural performance in reinforced concrete frames [9, 10]. The comparison fig 11.c illustrates the slight variation in stiffness and ductility between the two models (M1 and M2), useful for evaluating structural resilience. Both models exhibit a steep elastic phase followed by a peak load (around 260 kN), with Model M1 showing a slightly higher stiffness. Post-peak behavior

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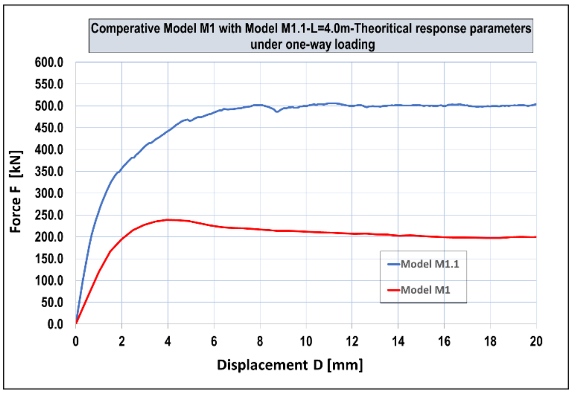
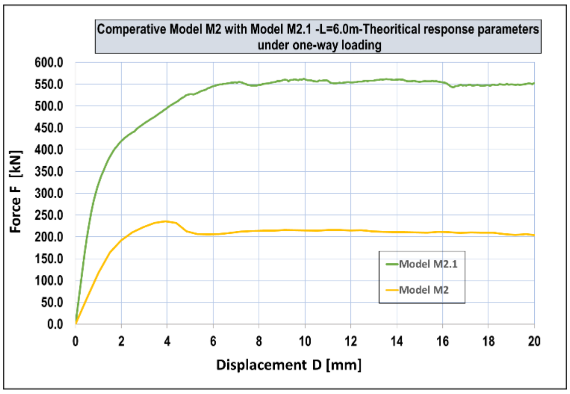
indicates a gradual decline, highlighting material cracking or plastic deformations, with both models maintaining a comparable plateau phase [2, 3, 4].





a)

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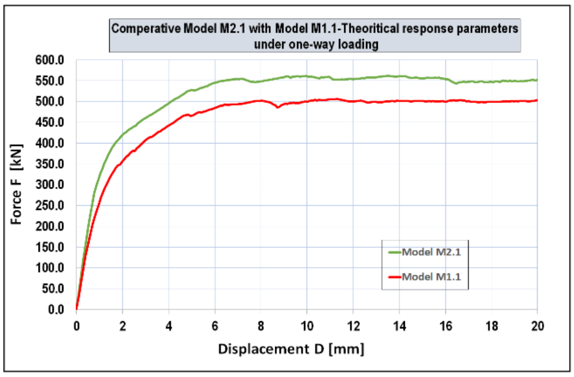

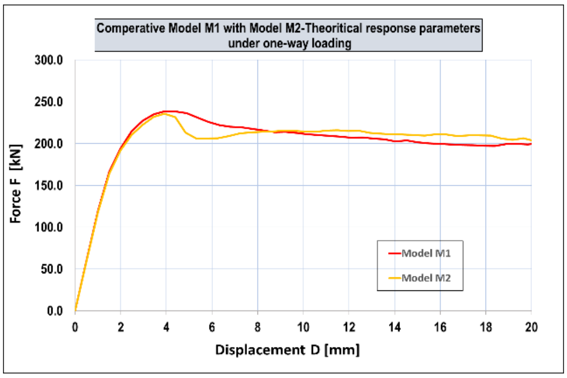

Figure 11. a) Force-Displacement Diagram for Model M1 and Model M1.1; b) Force-Displacement Diagram for Model M2 and Model M2.1; c) Force-Displacement Diagram for Model M2.1 and Model M1.

4. Conclusions

- In reinforced concrete (RC) frame systems, masonry infills provide significant contributions to increasing the load-bearing capacity of the structure. However, it's important to recognize that masonry infills should not be treated as structural elements or rigid surfaces. While the infill is brittle and has reduced load-bearing capacity compared to the RC frame, it still plays a crucial role in enhancing the lateral stiffness of the system. The frame itself, made from reinforced concrete, possesses much higher shear strength and capacity compared to the masonry wall. The engineer must design the system in such a way that lateral displacements are kept within limits so that the infill does not experience excessive forces that could cause failure. This is especially important because masonry walls have a limited capacity to withstand large shear forces.
- Infill walls significantly influence the seismic behavior of reinforced concrete (RC) frames, often with contradictory findings in the literature. While infills may enhance the lateral stiffness and load-bearing capacity of frames, numerous studies and experimental campaigns highlight their potential to cause adverse effects during earthquakes. A critical aspect is the infill/frame interaction, which can induce additional shear forces on RC columns. This phenomenon is particularly detrimental in cases of short columns, where the increased shear demand can lead to brittle failure.

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- Longer frames, such as Model M2.1 (6.0 m), exhibit greater load capacity and more distributed stress patterns compared to shorter frames like Model M1.1 (4.0 m), demonstrating the critical role of geometric dimensions in structural performance.
- Longer frames with infill experience more evenly distributed and less severe cracking, while shorter frames show higher stress concentrations and localized crack formations near beam-column joints and column bases.
- Advanced finite element modelling and micro-modelling techniques provided detailed insights into the structural response under varying lengths, infill configurations, and loading scenarios, accurately capturing critical performance metrics like stiffness, ductility, and energy dissipation

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