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Numerical Investigation of In-Plane Response of Un-grouted Reinforced Masonry Walls

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ABSTRACT

In conventional masonry construction, the use of grout significantly increases construction costs and time due to the additional material, labour, and curing processes required. This numerical study aims to identify alternatives to conventional fully grouted reinforced masonry (FGRM) walls that use less or no grouting, without bonding the vertical reinforcement. To demonstrate this, the effect of grout and bonding, on the in-plane (IP) behaviour of masonry walls was studied. A total of 20 walls were analysed which were categorized into five groups. In addition, to capture different failure modes (e.g., flexural, shear), four different aspect ratios i.e., 2, 1.44, 1 and 0.86 were considered. The numerical simulations were conducted in the general-purpose finite element software ABAQUS using the simplified micro modelling strategy, in which the individual components (e.g., concrete block, grout, reinforcements) were explicitly represented. The results indicated that when compared with URM masonry, un-grouted RM walls have higher strength and ductility. However, the un-grouted walls with unbonded reinforcement exhibit complex failure patterns and relatively lower in-plane capacities than conventional FGRM walls due to the absence of grout. It was also observed that the grouted unbonded masonry walls with a smaller aspect ratio are inherently stable with maximum loads comparable to those of conventional bonded RM walls. Based on the above numerical modelling and analyses, it is concluded that the use of unbonded reinforcement would save construction time and labour costs, particularly when constructing non-slender masonry walls.

KEYWORDS

Masonry Construction, Un-grouted Masonry, Unbonded Reinforcement, In-Plane Behaviour, Numerical Modelling

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INTRODUCTION

Masonry is one of the oldest and most extensively used construction forms. It is generally used for low-rise structures, including residential, commercial, educational and recreational buildings. Low maintenance costs, better thermal and sound insulation, high fire resistance and compressive strength are some advantages of masonry construction. However, the tensile resistance of masonry, when unreinforced, is weak due to the weak bond that exists between mortar and concrete blocks. In fact, the compressive strength of the concrete blocks cannot be fully developed since the cracks formed do not allow the wall assemblage to work as a fully functional composite [1].

Fully or partially grouted reinforced concrete walls can effectively resist in-plane as well as out-of-plane loads [2]. However, the grout used for the construction of these walls increases their self-weight [3] and carbon footprint and involves an additional trade on-site [4]. The grouting process for fully or partially grouted reinforced masonry walls can be more time-consuming [5, 6], labour-intensive and expensive [7]. The time required for placing grout and the two-four-hour wait time between lifts slows down the project speed [7-9]. Workplace injuries may also result due to the need for masonry workers to thread blocks up and over-reinforcement that has already been grouted in place [7, 8].

Currently, masonry construction companies acknowledge the need to accelerate their construction processes [3]. Many researchers have been trying to develop innovative reinforcement strategies for masonry walls for the past couple of years [3]. One such technique is un-grouted masonry which is considered to perform favourably under lateral loads, particularly when designed with specific geometries that enhance their structural integrity [4, 10]. The use of unbonded reinforcement allows for relative movement between the reinforcement and surrounding masonry, which enhances the wall's ability to undergo higher displacements and then return to its mean position during seismic events [11, 12]. This phenomenon, also termed as self-centring, is particularly beneficial in seismically active regions [12], where maintaining structural integrity under lateral loads is critical. Due to the tensile action of the unbonded reinforcement, these walls exhibit improved lateral stability compared to conventionally bonded systems [7].

Research on un-grouted unbonded reinforced masonry walls is very limited [4], with only a few studies highlighting their structural performance and behaviour under different loading conditions. Most of the existing literature mainly focuses on other configurations of masonry walls, such as fully grouted, partially grouted or mortarless interlocking systems, which dominate the field of masonry research [13-15]. On the contrary, the performance of un-grouted unbonded reinforced masonry systems remains the least investigated. Past research indicates that the interaction between grouted and un-grouted elements significantly influences the overall performance of masonry structures [16-20]. It has been underexplored how the absence of grout would affect the lateral load resistance and overall stability of unbonded reinforced concrete masonry walls.

This gap in research needs to be explored, to evaluate the potential benefits of un-grouted unbonded reinforced masonry walls, such as less construction time and reduced project costs. Consequently, there is a fundamental need for comprehensive studies that specifically focus on the behaviour, failure pattern, and overall performance of un-grouted unbonded reinforced masonry walls. One of the primary areas of research could be the structural behavior of un-grouted unbonded reinforced concrete masonry walls with different wall dimensions. This question aligns with findings from studies that highlight the complexities of un-grouted sections in partially grouted masonry systems [16, 17, 20].

This study demonstrates the potential of unbonded reinforced masonry walls using numerical modelling in ABAQUS. Numerical simulations provide an acceptable alternative method for experimental research on the performance of masonry walls [21], which can simulate the linear and nonlinear behaviours of masonry. Considering different wall configurations, this research provides a thorough comparison among various grouted and un-grouted concrete masonry wall configurations subjected to in-plane loads. It also compares the predominant failure mechanisms of unbonded reinforced concrete masonry walls with those of conventional grouted masonry walls. Lastly, it highlights the potential benefits and challenges of using unbonded reinforcement in un-grouted masonry walls under in-plane lateral loads.

FINITE ELEMENT MODEL DETAILS

In this study, a simplified micro-modelling approach was used to model masonry walls using ABAQUS software. The concrete masonry units, foundation beam and bond beam were modelled using solid hexahedral-shaped eight-node linear brick elements with reduced integration (C3D8R), with hourglass control enabled to mitigate spurious zero-energy modes. Each C3D8R element is explained by 8 nodes, each node possessing three translational degrees of freedom in the x, y, and z directions. However, the vertical and horizontal steel reinforcements were modelled using wire features associated with two-node three-dimensional truss elements (T3D2).

The materials used in the masonry walls included: an elastic concrete bond beam with the elastic modulus E_c = 30,000 MPa and Poisson's ratio = 0.2, 25-mm diameter vertical steel reinforcement and 10-mm diameter horizontal steel bars. Mesh discretization was performed with a 50-mm element size for the masonry units, 25-mm for the reinforcement, and 100-mm for the foundation and bond beams.

The simplified micro-modelling approach used in this study does not treat the mortar layer and the interface between mortar and blocks separately but simulates them as an assumed interface [22]. While modelling the mortar, the mortar joint thickness is halved. Each half is attached to the adjacent masonry unit (expanded masonry unit) from one side and interacts with the other half of the mortar joint and its adjoining masonry unit through the interface. The mortar interfaces at the bed and head joints were modelled using cohesive surface-based elements. "Hard" contact was assumed in the normal direction of contact while in the tangential direction, penalty friction was used. After maximum degradation, the cohesive contribution to the shear stresses is zero, and the only contribution comes from the friction model. All the parameters used for modelling the mortar joint in ABAQUS are shown in Table 1.

Table 1: Cohesive surface-based contact parameters

Interface Parameter	Wall-foundation	Other joints
Normal behaviour	Hard contact	Hard contact
Coefficient of friction, μ	1.5	0.75
Tensile strength (MPa)	1.5	1.38
Shear strength (MPa)	2.3	1.9
Normal fracture energy (N/mm)	0.0	0.07
G^{I}_{f} (N/mm)	0.7	0.7
G^{II}_{f} (N/mm)	0.7	0.7
Joint stiffness parameters K_{nn}, K_{ss}, K_{tt} (MPa)	441, 192, 192	441, 192, 192

Constitutive material model

To simulate the concrete masonry elements, the concrete damage plasticity (CDP) model in ABAQUS was used. Tension cracks and crushing in compression are the main failure modes of this model. The CDP model is designed to model the behaviour of quasi-brittle materials like concrete and masonry. Although the input parameters for CDP need different types of experimental tests, in the absence of such data, common values suggested in the literature were used. The parameters used for the CDP model in this study are listed in Table 2.

Table 2: Mechanical properties of materials used in the parametric investigation

Masonry Units		**Parameters for the CDP model**	
Density (tonne/mm^3)	1.8×10^{-9}	Dilation angle	30º
Compressive strength f'_{uc} (MPa)	24.8	Flow potential eccentricity	0.1
Tensile strength f_{ut} (MPa)	2.54	σ_{b0}/σ_{c0}	1.16
Elastic modulus E_u (GPa)	21168	Ratio of second stress variant	0.667
Poisson's ratio, ν	0.15	Viscosity factor	0.002
Reinforcement Properties		**Horizontal Steel**	**Vertical Steel**
Density (tonne/mm^3)		7.8×10^{-9}	7.8×10^{-9}
Nominal yield strength (MPa)		491	502
Ultimate tensile strength (MPa)		635	650
Modulus of Elasticity (GPa)		200	200
Poisson's ratio ν		0.3	0.3
Diameter (mm)		10	25

The Kent and Park material model of concrete [23] under compression without confinement was used for the compression behaviour of masonry units as shown in Fig. 1(a). The tensile response of concrete was modelled, as shown in Fig. 1(b). A generic elastic-perfectly plastic model was used to simulate the uniaxial response of horizontal and vertical steel bars.

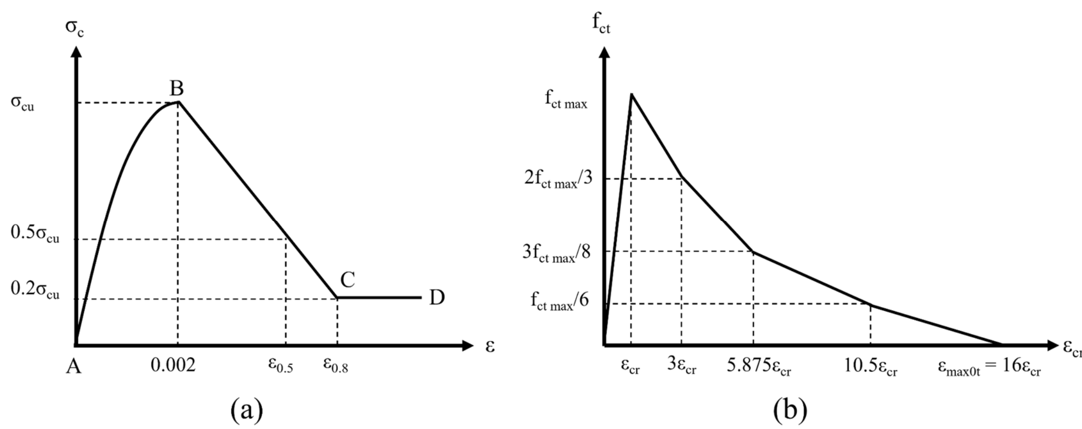

Figure 1: Stress-strain model specified in CDP Model: (a) compressive (b) tensile

Interactions and constraints

Interactions between the masonry unit and the unbonded vertical reinforcement were modelled by using the surface-to-surface contact approach. In the normal direction, a "hard contact" formulation was applied, which prevents penetration between the contact surfaces while allowing separation when tensile stresses develop. For tangential behaviour, a frictional contact model with a coefficient of friction of 0.5 was used to simulate the sliding resistance between surfaces. In cases where full bonding between the reinforcement and masonry was required (e.g., in fully grouted walls), embedded region constraints were employed to simulate perfect bond behavior between the reinforcement bars and the surrounding concrete.

FINITE ELEMENT MODEL VALIDATION

In the absence of experimental research on the in-plane behaviour of the un-grouted unbonded (UGUB) reinforced masonry walls, the authors have considered an experimentally tested fully-grouted wall from Shedid et al. [24] for validation. Although the wall chosen for numerical validation is not the true representation of a UGUB wall, it serves the purpose of building confidence in the model validation process. Furthermore, the modeling strategy used is able to model masonry wall behaviors. Due to the lack of published research on un-grouted masonry, a full grouted wall was chosen for model validation as a starting point. The selected wall was constructed using standard 400×200×190 mm hollow concrete masonry blocks and had length l_w = 1.8m, and height h_w = 3.6m as shown in Fig. 2. No pre-compression was applied on the wall tested. Vertical reinforcement consisted of 9 #25 (9×500 mm^2) mild steel bars resulting in a vertical reinforcement ratio ρ_v = 1.31%, while #10 (100 mm^2) bars were used with 200 mm spacing as horizontal reinforcement making a horizontal reinforcement ratio ρ_h = 0.26%. A rigid connection was adopted between the foundation and the main masonry wall. Moreover, the bottom of the wall was completely fixed, and the top was cantilevered with no out-of-plane translation (u_z = 0).

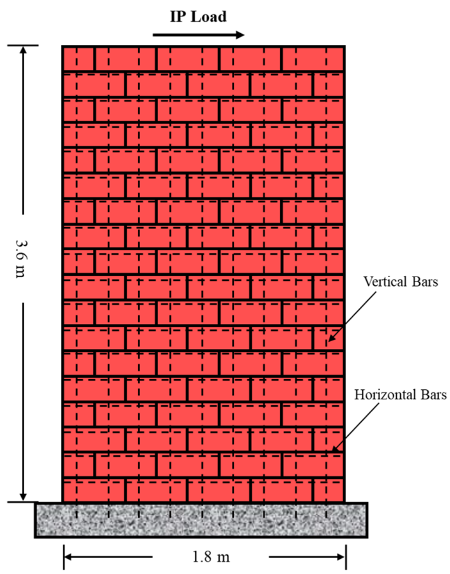

Figure 2: Masonry wall configuration used for model validation [24]

The model used a single loading step with an Implicit Solver to apply the required in-plane cyclic at the top of the wall. The force-displacement comparison of the curves obtained from the test [24] and numerical simulation is shown in Fig. 3. In general, similar shapes of the force-displacement curves were observed through comparative analysis. Both curves showed obvious linear growth characteristics before 10 mm in-plane displacement; during the displacement of 10-35 mm, the curves still exhibited a gradual increasing trend. When the displacement reached 40 mm, the wall strength started decreasing which was more gradual in the case of the experimental curve. Overall, there was observed acceptable agreement between the experimental and simulation results.

As far as the failure pattern is concerned, both the walls exhibited a similar failure pattern with the crushing of the masonry units at the toe on both ends of the walls showing a flexural rocking behaviour. The damage started with the opening of a crack at the wall-foundation interface which then caused the toe crushing at the opposite end of the wall when the flexural stresses increased. The wall was pushed to a maximum drift ratio of 2%. Near the end of the analysis, diagonal tension cracks started forming in the bottom courses of the wall.

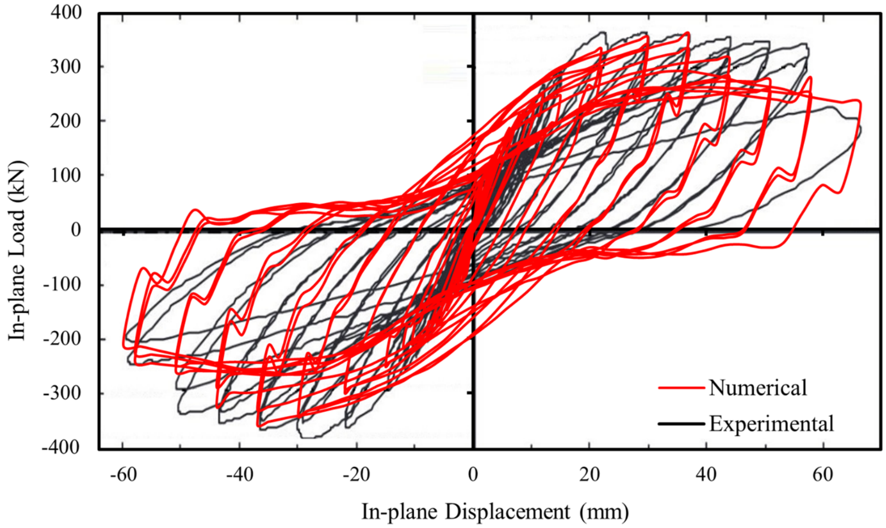

Figure 3: Comparison of the results of experimental testing and simulation

MODELLING PROGRAM

Model Design

Four masonry wall models with aspect ratios of 2, 1.44, 1 and 0.86 were designed. In total, 20 walls were numerically analysed as shown in Table 3. In order to demonstrate the effectiveness of UGUB walls, their behaviour needs to be compared with other types of walls with similar configurations. There were 5 groups of walls (1) grouted unreinforced masonry walls (URM), (2) un-grouted unreinforced masonry walls (UG-URM), (3) full grouted reinforced masonry walls (FG), (4) un-grouted unbonded reinforced masonry walls (UGUB), and (5) grouted unbonded reinforced masonry walls (GUB). Each group consisted of 4 walls, 1 wall for each aspect ratio.

Table 3: Summary of the walls analyzed

Sr. No.	Wall Type	Walls Count
1	Unreinforced masonry malls (grouted)	4
2	Unreinforced masonry malls (un-grouted)	4
3	Fully grouted reinforced masonry walls	4
4	Un-grouted unbonded reinforced masonry walls	4
5	Grouted unbonded masonry walls	4
	Total	20

The prime focus of this study is to evaluate the potential of using un-grouted masonry walls. The configuration of the reinforced masonry walls under consideration is given in Table 4. A range of aspect ratios was considered to evaluate both the shear and flexural behavior of UGUB walls. Typically, masonry walls with an aspect ratio of up to 1 tend to exhibit shear-dominated failure, while those with aspect ratios greater than 1 are more prone to flexural failure. The selection of aspect ratios in this study was informed by previously published research on masonry wall behaviour [8, 25-27]. For vertical reinforcement, every reinforced wall contained 9 #25 vertical reinforcing bars (ρ_v = 1.31%) and #10 bars with a spacing of 200 mm as horizontal reinforcement (ρ_h = 0.26%). There was no vertical reinforcement in the unreinforced groups of the walls. Furthermore, to simplify the analysis, no pre-compression force was applied at the top of the walls.

Loading actions

The in-plane monotonic load was applied at the top of the wall using displacement boundary conditions. Each wall was displaced to a maximum of 70 mm lateral in-plane displacement. The walls with higher aspect ratios were expected to sustain the maximum applied displacement, however, the shorter shear walls were expected to fail before reaching this displacement due to their limited drift capacity.

Table 4: Dimensions of the walls under consideration

Wall	Height (m)	Length (m)	Aspect Ratio	Thickness (mm)
Wall-1	3.6	1.8	2	190
Wall-2	2.6	1.8	1.44	
Wall-3	2.6	2.6	1	
Wall-4	2.6	3	0.86	

RESULTS AND DISCUSSION

Force-displacement behaviour of un-grouted reinforced masonry wall

Fig. 4 shows the in-plane load-displacement behaviour for three types of concrete block masonry walls: FG-URM (fully grouted unreinforced masonry), UG-URM (un-grouted unreinforced masonry), and UGUB (un-grouted unbonded reinforced masonry) for wall-1 having an aspect ratio of 2. There is a considerable difference in load-carrying capacity, ductility, initial stiffness, and overall failure modes of these walls.

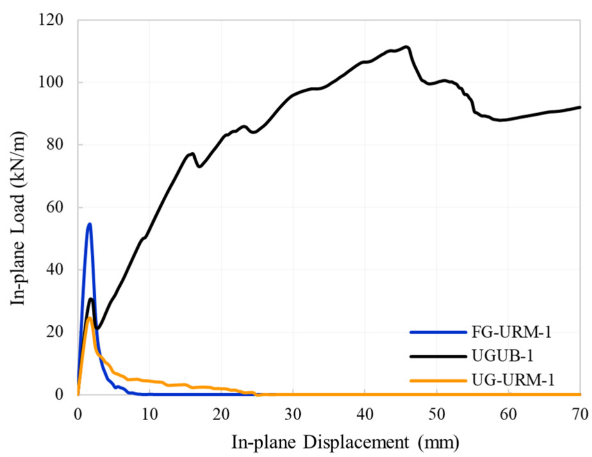

Figure 4: Load-displacement response of UGUB wall under in-plane load

The initial stiffness is highest for the FG-URM-1 wall. The UGUB-1 wall, although having lower initial stiffness compared to FG-URM-1, surpasses both FG-URM-1 and UG-URM-1 in load-carrying capacity, achieving a peak load of approximately 110 kN/m length of the wall. Experimental research by Hassanli et al. [12] also concludes that the absence of effective bonding in grouted unbonded masonry walls leads to a reduction in the overall stiffness of the wall. The UG-URM-1 wall shows the lowest initial stiffness and peak load (25 kN/m), suggesting limited resistance under initial loading conditions.

Furthermore, it can also be seen that the UGUB-1 wall tends to undergo large displacements without losing significant load capacity. Such ductility is very critical for seismic applications, where structures must withstand a large drift ratio. Ghorbani et al. [28] also reported that unbonded reinforced masonry infill walls typically exhibit a more flexible response under in-plane loading due to the lack of continuous bonding between the masonry units and the reinforcement. In comparison, the FG-URM-1 and UG-URM-1 walls demonstrate a sudden drop after the peak load, showing a brittle failure. So, the unreinforced masonry walls quickly lose their ability to absorb energy post-peak due to their brittle nature. As far as the failure is concerned, all the walls exhibited a flexural rocking failure with toe crushing due to higher aspect ratio of 2.

Overall, the UGUB-1 wall seems a better option for low-rise masonry construction against unreinforced masonry walls in terms of ductility. This preliminary comparison suggests that the un-grouted unbonded reinforced walls have some potential to be used in the current masonry construction practices.

Effect of grout and bonding on masonry walls

Grout plays an important role in bonding the masonry units which increases the initial stiffness and ultimate strength of a wall. It also helps mitigate shear failure by providing a more uniform distribution of stresses across the wall, thus reducing the possibility of localized failure. This effect has also been noticed in partially grouted masonry walls, where the interaction between grouted and un-grouted sections can lead to complex failure mechanisms [16, 17].

The main objective of comparison in this section was twofold: first, to examine the effect of bar-to-masonry bonding by comparing FGRM and GUB walls, and second, to evaluate the influence of grout removal by comparing the load-displacement responses of FGRM and UGUB walls. The GUB walls contain PVC ducts in the centre of the masonry cells, placed before the pouring of grout. After grouting, the vertical steel bars are placed in the ducts and anchored at wall ends.

In terms of peak-load capacity, when compared with FGRM walls, the GUB walls show different responses based on the aspect ratio as shown in Fig. 5. For higher aspect ratios (Wall 1 and Wall 2), the FGRM walls typically outperform GUB in terms of peak load capacity and initial stiffness due to the continuous bonding of the vertical reinforcement. As stiffness is of greater importance in slender walls, therefore, the presence of bonded steel helps improve their load-displacement behaviour. However, for shorter walls (Wall 3 and Wall 4), the GUB walls begin to exhibit better performance because the vertical reinforcement initially doesn't contribute much to the wall strength. Therefore, the bonded reinforcement in FGRM walls may have a negative effect by limiting relative displacement between the steel and masonry, which can reduce the peak lateral load capacity. It needs to be noted here that GUB walls experienced some numerical issues while modelling the contact between unbonded rebars and the PVC ducts and were not exhausted to their maximum displacement.

In terms of displacement capacities, it was observed that UGUB masonry have almost similar displacement capacity as fully grouted masonry. This is because all the in-plane lateral load is initially carried by the masonry units themselves, with limited contribution from the vertical reinforcement. However, in the post-peak phase, the unbonded vertical reinforcement starts to contribute effectively to the wall's ductility by accommodating relative movement until progressive failure occurs in the masonry. The removal of grout significantly reduces the initial stiffness and peak load capacity of the UGUB walls when compared with FGMR walls. It implies that grout plays an important role in ensuring a composite action in the grouted walls [8, 12]. Fig. 5 also suggests that adding unbonded grout improves the structural response of masonry walls compared to UGUB walls. The presence of grout in every cell, provides better load transfer, resulting in higher initial stiffness and peak loads. The unbonded reinforcement in GUB walls contributes to ductility while benefiting from the added strength provided by grouting. This dual advantage ensures a more controlled failure mechanism. Like UGUB walls, a sudden drop in stiffness and load capacity was also observed in slender GUB walls when the wall-foundation interface cracks and unbonded reinforcement starts to resist flexural stresses.

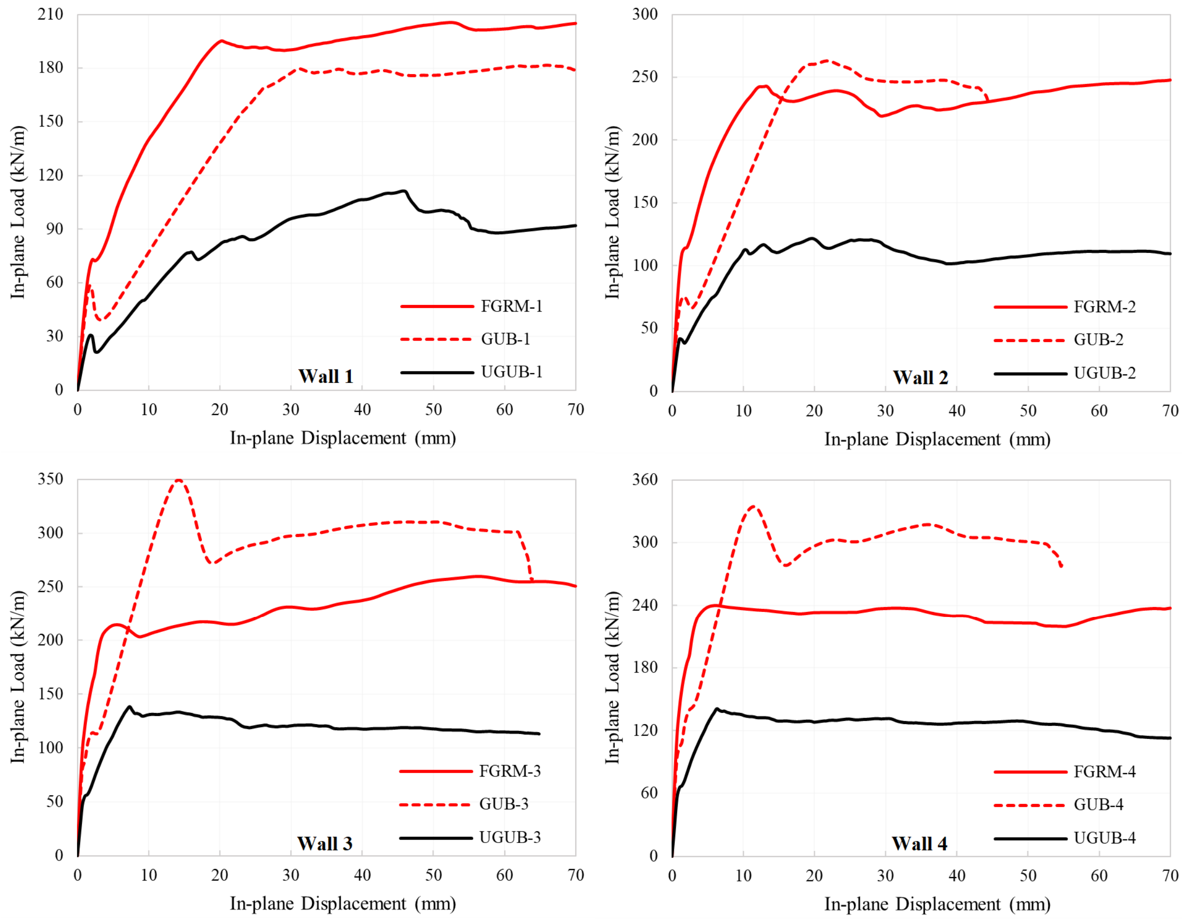

Figure 5: Effect of grouting and bonding on the behaviour of unbonded masonry walls

From the above comparison, it is evident that grout plays a very important role in flexural walls to ensure the composite action of vertical reinforcement. However, for shorter walls, bonding of steel may be selectively avoided in favour of unbonded reinforcement to improve overall behaviour while maintaining flexibility and resilience. Additionally, the UGUB walls should be encouraged only in low-rise construction.

Damage pattern and failure mode of UGUB walls

The un-grouted reinforced masonry walls are more likely to exhibit a relatively brittle failure pattern due to the absence of grout [8]. At a smaller drift ratio of 1%, UGUB walls exhibit localized damage zones near the base, with UGUB-2 showing some vertical crack propagation. In contrast, the shorter UGUB-3 and UGUB-4 walls reveal a broader spread of damage with evidence of complex vertical and horizontal crack dominance, aligning with their reduced slenderness. As the drift increases to 2%, damage in UGUB-1 and UGUB-2 progresses vertically, suggesting sustained flexural failure with minimal diagonal crack development as shown in Walls 1 and 2 in Fig. 6.

The UGUB walls rely solely on vertical reinforcement to carry flexural loads, leading to flexural cracking that can propagate quickly once the tensile capacity of the masonry is exceeded. The cracks take a more direct path through the concrete masonry units, as can be seen in Walls 2 and 3 in Fig. 6. This failure mode is anticipated in UGUB shear walls because the relatively high steel content would develop significant flexural overstrength [8, 29], thus causing crushing of the masonry units. However, in UGUB-3 and UGUB-4, the damage propagates significantly across the wall width, indicating a transition to more distributed failure mechanisms. Shear failure occurs in these shorter walls, characterized by diagonal cracking and possible separation at mortar joints. This observation was consistent with the damage pattern of un-grouted cells in partially grouted walls [8, 16-18]. The un-grouted portions contribute to localized cracking and reduced load capacity, resulting in less uniform load distribution and potential abrupt failure after initial cracking [8].

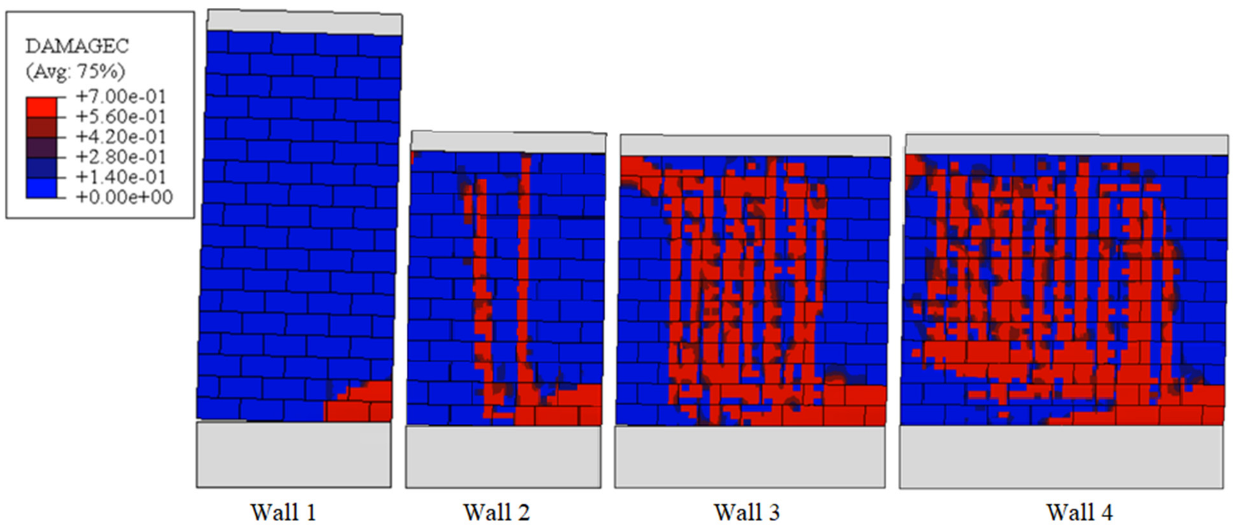

Figure 6: Compression damage in UGUB walls at 2% drift

On the other hand, the fully grouted walls exhibited more gradual and concentrated damage propagation, especially for higher aspect ratios, due to the composite action of grout and vertical reinforcement. The differences in failure mechanisms, particularly the reduced resistance to compressive and flexural forces in UGUB walls, highlight the essential role of grouting and reinforcement bonding in slender walls.

PRACTICAL USE OF UGUB MASONRY WALLS

Based on the above comparison of the four wall configurations with varying aspect ratios, it is evident that UGUB walls are not the preferred choice for slender masonry wall construction. However, shorter shear-dominated UGUB walls exhibit higher peak load capacities, and better ductility, which are indicative of a more stable response. The lower aspect ratios allow for a broader base and more efficient redistribution of lateral forces, which aligns with the strengths of UGUB shear walls and enhances their performance. Given these observations, slender masonry wall construction should not be constructed with un-grouted unbonded reinforced wall configurations. Fully grouted and reinforced configurations would likely offer superior performance in these cases. Instead, UGUB walls are more effective for low-rise buildings, retrofitting projects, and structures in seismic-prone areas that require a balance of strength and deformability.

CONCLUSIONS

This study has been conducted to evaluate the potential of constructing un-grouted unbonded (UGUB) reinforced masonry walls and compare their behaviour with the existing conventional masonry construction. The comparison across different wall aspect ratios withing the scope of this study has provided insights into the load-carrying capacity, ductility, and failure modes associated with each wall configuration. The results indicate that UGUB walls, while being cost-effective and offering certain construction advantages, exhibit varied performance depending on aspect ratio and reinforcement configuration. Nonetheless, they demonstrate promising potential for adoption in masonry construction.

The analysis suggests that UGUB walls demonstrate a reasonable degree of ductility, especially in shorter walls where bonding of vertical reinforcement plays a negative role. However, their peak load-carrying capacity is generally lower (roughly one-half) compared to conventional fully grouted walls. UGUB walls are more prone to crushing of un-grouted masonry units as the absence of grout makes their failure complex in nature. This type of failure could be streamlined by a balanced selection of reinforcement. Furthermore, shorter UGUB walls could be reasonably accepted in the low seismic activity areas or where a retrofitting of the existing unreinforced masonry is under consideration. Overall, UGUB walls have almost double load-carrying capacity and much better ductility than that of the URM wall. From a practical standpoint, UGUB walls can be considered for applications in low-rise or non-critical buildings where construction speed, reduced material costs, and moderate lateral load resistance are prioritized.

It is important to note that this study was based on the numerical validation of a fully grouted reinforced masonry wall, owing to the absence of published experimental research on UGUB walls. Therefore, further experimental validation is essential before these walls can be confidently recommended for broader structural application.

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