



NUMERICAL INVESTIGATION OF THE TIE BEAM EFFECT IN BRICK WALLS

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Highlights

- The control wall exhibited highly monolithic behavior.
- A single horizontal tie beam produced the highest peak load (46 kN).
- More horizontal tie beams reduced capacity by up to 15.38%.
- Vertical tie beams caused significant strength and performance losses.
- Window openings reduced wall strength by approximately 11%.

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ABSTRACT: Brick walls are load-bearing elements commonly found in historical and traditional structures. The behaviour and capacity of these structures under seismic effects must be investigated from various perspectives. Numerous studies exist in the literature to determine the in-plane behaviour of brick walls under different conditions. However, there has been insufficient research on timber tie beams, which are frequently used in wall construction and form part of the load-bearing structure. In this context, a numerical study was conducted to determine the effect of different tie beam configurations on the structural behaviour of brick walls and to address this gap in the literature. In this regard, the effects of horizontal and vertical timber tie beams were investigated in solid walls and wall models with openings. Ten different wall configurations were examined in the study. The wall models were constructed using brick material and mortar mixed with lime. A simplified micro-modelling approach was used in ABAQUS to define the cohesive interface between the brick units and represent the mortar. The walls were analysed using displacement control in the in-plane direction. Sensitivity analyses were performed to obtain a realistic representation of the tie beam-wall behaviour. Load-displacement curves, compression and shear stress distributions, elastic and plastic deformation changes, and failure mechanisms were evaluated in wall models. According to the results, the horizontal resistance of walls with timber tie beam elements decreased. Increasing the number of horizontal and vertical tie beams reduced the performance of the walls. It has been determined that the tie beam arrangement significantly changes the crack distribution and failure mechanism. These results indicate that the use of tie beams in lime-mortar brick walls does not improve horizontal load performance.

Keywords: Brick wall, Horizontal load capacity, Micro-modelling, Tie beam

1. INTRODUCTION

Masonry structures constitute a large part of today's rural and historical buildings. In these structures, the walls that form the load-bearing system are constructed by assembling masonry units and mortar in a specific order. Because they are formed by assembling multiple materials, they exhibit highly variable and complex behaviour. It is essential to understand the behaviour and capacity of masonry structures, especially in Türkiye, where seismic effects are significant. In this regard, new experimental, numerical, and analytical studies are emerging with the development of research methods and resources [1], [2], [3]. While natural stone, brick, and adobe are commonly used in historical structures, materials such as pumice and aerated concrete are also commonly used today. Masonry structures are affected by many parameters. These can be listed as masonry unit and geometry, material, workmanship quality, dimensional irregularities, horizontal/vertical tie beams, door and window openings, and position in or out of plane [4], [5]. The impact of these parameters on masonry structures during recent earthquakes has been evaluated in various studies [6], [7], [8], [9]. Following the earthquakes with magnitudes of Mw 7.7 and Mw 7.6 that occurred in the Maraş-Pazarcık and Elbistan regions on February 6, 2023, investigations reported serious damage to masonry structures in the

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affected region. It has been reported that tie beams in masonry structures can reduce damage during earthquakes and improve structural seismic performance. Various studies have indicated that tie beams affect seismic behaviour and reduce damage [7], [10], [11], [12]. Considering that there are limited studies in the literature evaluating the tie beam effect and that tie beams affect structural performance, this research is found to be necessary. Brick walls using lime-mixed mortar exhibit brittle behaviour during earthquakes due to their low compressive strength and weak mortar-to-brick adhesion. Consequently, fractures occur, and part or all of the structure collapses [5], [13]. The low adhesion between the unit and the mortar, the presence of large numbers of geometric irregularities, weak areas caused by openings, and weakened support conditions cause masonry structures to collapse at an early stage. In addition, under seismic effects, the resistance of walls is lost at an early stage due to tensile stresses. In post-earthquake assessments, the effect of tie beams has been emphasized. According to various studies, tie beam elements have been determined to play an important role in limiting brittle failure. They have been found to affect the failure mechanism, but there are differing opinions regarding their effect on wall integrity [3], [7], [14], [15]. There are many studies in the literature explaining masonry wall behaviour. These include studies on seismic strengthening, ring beams, and tie beam systems. However, there are limited studies examining the adhesion behaviour of lime-based mortar and brick walls using a nonlinear modelling approach. Because brick is widely used in Türkiye, the study focuses on brick masonry structures. Since lime-mixed mortar is used in some of these structures, it was considered in the present study. Support conditions are another parameter that directly affects structural behaviour. In masonry structures, fixed foundations and fixed supports are often preferred [4], [5]. In this context, the effects of sliding and overturning on foundations are often related to wall resistance. Another parameter, the arrangement of bricks, is an important factor that determines load transfer and stress distribution within the structure. Experimental and numerical studies have shown that different brick arrangements change the strength, structure, and failure mode of masonry elements such as walls, domes, and vaults [16]. Szabó et al. [17] reported that the wall construction arrangement directly affected the results of the pushover analysis. Wall thickness, length, height, and number of wythes are also parameters that affect structural behaviour. As wall thickness, length, and number of wythes increase, slenderness decreases [5], [18], [19]. This increases the lateral load capacity. In this context, structures that are more resistant to earthquake effects are designed taking these parameters into account. Multi-wythe walls are being constructed relatively more commonly. In most cases, the wythes are interlocked using tie bars or tie bricks. Openings left for structural or aesthetic purposes also affect wall behaviour. In various studies, openings have been found to cause stress discontinuities, affect the failure mechanism, and reduce wall capacities [20], [21], [22], [23]. Fractures occur around the openings due to load transfer discontinuity, and this has been observed to cause the wall to collapse prematurely. The tie beams around the openings are expected to direct and limit these fractures [24]. In structures affected by seismic forces, the presence and configuration of openings become important. Therefore, the location and size of openings must be carefully designed. Wall position behaviour directly changes in response to seismic forces. Walls are often designed to work in the plane direction where their resistance is high [25], [26]. In this way, the safety of walls moving out of plane (OOP) is attempted to be ensured through the roof diaphragm. Walls located in the in-plane direction efficiently transfer loads to the ground and limit the displacement of the structure. Therefore, the strength of the wall affects the safety of the structure. Although relatively few in number, capacity studies in the OOP direction have increased in recent years [19], [27], [28]. In masonry structures, vertical loads and roof diaphragm effects often improve structural performance and increase horizontal load resistance [21], [29]. The roof diaphragm on the wall ensures the integrity of the structure and joins the walls in the plane and out of the plane together. The roof load affecting the wall is carried by the units and mortar and transmitted to the foundation. This increases the shear capacity of the walls under vertical load.

In most experimental studies conducted on masonry structures, load capacity, displacement, and deformations are measured [4], [30], [31], [32]. In small-scale precision studies, stress levels are also

determined by measuring strain gauges. However, in this case, the cost of the experiment increases, and it is often not possible to take measurements from every point on the wall. When it is not possible to conduct experimental studies, numerical and analytical studies are carried out. Various numerical and analytical methods exist to predict the actual behaviour and capacities of walls. The use of more than one material in masonry structures increases structural uncertainties. In this case, the appropriate method must be used for the study. In particular, the interaction between units guides the numerical and numerical method. Numerical modelling techniques to capture the interaction behaviour are developing with increasing studies [33], [34], [35], [36]. Numerical modelling is fundamentally divided into three categories. These are macro modelling, detailed and simplified micro-modelling techniques [4], [37], [38]. Macro modelling is used when the wall size is relatively large or when a portion or the entire structure needs to be modelled. On the other hand, micro-modelling techniques are preferred when the wall size is small or in small-scale structures. In detailed micro-modelling, mortar and units are modelled as separate solid elements, and a contact representing the adhesion/separation properties at the interface is defined. However, due to the number of elements and the mesh density, the analysis time and cost increase. In this case, a simplified micro-modelling technique is used by adding the mortar unit thickness to the brick height. Analysis results are obtained in a relatively shorter time.

This study focuses on the effect of vertical/horizontal timber tie beams on wall behaviour. The study examines the configuration and mechanical effects of tie beams. The material commonly known as mixed brick or fired clay brick, widely used in Türkiye, has been considered. This material is summarized as “brick” in the following sections. Brick, used as a masonry unit and the primary carrying material in wall, directly affects wall behaviour [6], [32]. Lime mortar exhibits different mechanical properties in different references [18], [39]. Compared to cement-based mortars, lime mortar has a much lower modulus of elasticity and adhesion strength. Mortar is one of the main parameters determining wall integrity. In this context, its effect should be carefully evaluated in the analysis of masonry walls. The lime mortar used by Kıpçak et al. [18] has been considered in this study. ABAQUS has been used in various studies to ensure that the analysis procedures for masonry systems are representative of actual conditions and to accurately predict the interaction between units. In this context, ABAQUS software was used for numerical calculations. A dynamic analysis was performed using small time increments. A micro-modelling technique was selected to accurately represent the interaction behaviour while reducing the analysis time and computational cost. Sensitivity analyses were performed for mesh size and shear resistance to assess the reliability of the numerical model. The support conditions in the study were fixed, and all models shared the same characteristics. A double-wythe model was used, and the wythe pattern and size were kept constant for all models. The first row of masonry was laid to provide interlocking, while the second row was placed perpendicular to the first to connect the two wythes. The wall models were loaded and analysed in the in-plane direction. A steel solid beam was placed on top of the wall to provide the roof diaphragm, and the vertical load was applied through this beam. This allowed the load capacities, failure mechanisms, brick displacements, and top displacements of the wall models to be examined. The measurements were compared with capacity curves and damage mechanisms. As a result, curves, evaluations, and tables were added to the study to address the gaps in the existing literature based on the findings obtained.



(a) Use of tie beams in a stone masonry structure

(b) Closer view of the tie beam

Figure 1. Example of a structure using timber tie beams (The image was taken by the author)

2. NUMERICAL INVESTIGATION

2.1. Wall models

The study modelled 10 different wall configurations to investigate the effect of tie beams. All walls were constructed using two wythes. The walls were constructed so that the bricks interlocked with each other. This ensured that the brick joints were not aligned vertically. A lime-based mortar was used to create horizontal and vertical adhesion between the brick units. The study aimed to investigate only the effects of horizontal and vertical tie beams in solid walls and walls with openings. Therefore, brick, which is commonly used in Türkiye, was selected as the masonry unit. Table 1 shows the wall models, codes, and definitions investigated in the study. Figure 2 shows the views and dimensions of the walls investigated. The wall arrangement is shown in Figure 3. All wall models were 1500 mm long, 200 mm wide, and 1500 mm high. Steel beams were used at the top and bottom of the walls to ensure the even distribution of the load. The steel beams were 1500 mm long, 200 mm wide, and 200 mm high. To evaluate the timber tie beam effect, a reference solid wall without a tie beam (REF) was considered. One, two, and three horizontal tie beams were used in the H1, H2, and H3 walls, respectively. The effect of using horizontal tie beams in these walls was evaluated. The spacing between the tie beams decreased from H1 to H3. Although the tie beam application in the H3 and V3 models is not common, the effect of low-interval tie beams was evaluated in these walls. Similar tie beam spacing has been observed in “Bagdadi” and “Himis” structures [40]. One, two, and three vertical tie beams were used in walls V1, V2, and V3, respectively. The effect of vertical tie beams was evaluated in these walls. The OWB wall with a window opening and no tie beam was used as a reference to see the effect of tie beam use in walls with openings. A lintel was required for this wall. The lintel was 700 mm long, 200 mm wide, and 50 mm high. The window opening measured $500 \times 500 \times 200$ mm. In walls OH2 and OV2, two tie beams were used horizontally and vertically in the wall with openings, respectively. In this context, the effect of tie beams in walls with openings was evaluated, and the effectiveness of tie beams around the opening was investigated.

Table 1. Wall models and definitions

Wall Code	Description
REF	Reference model without a tie beam
H1	Model with one horizontal tie beam
H2	Model with two horizontal tie beams
H3	Model with three horizontal tie beams
V1	Model with one vertical tie beam
V2	Model with two vertical tie beams
V3	Model with three vertical tie beams
OWB	Model with an opening and without a tie beam
OH2	Model with an opening and two horizontal tie beams
OV2	Model with an opening and two vertical tie beams

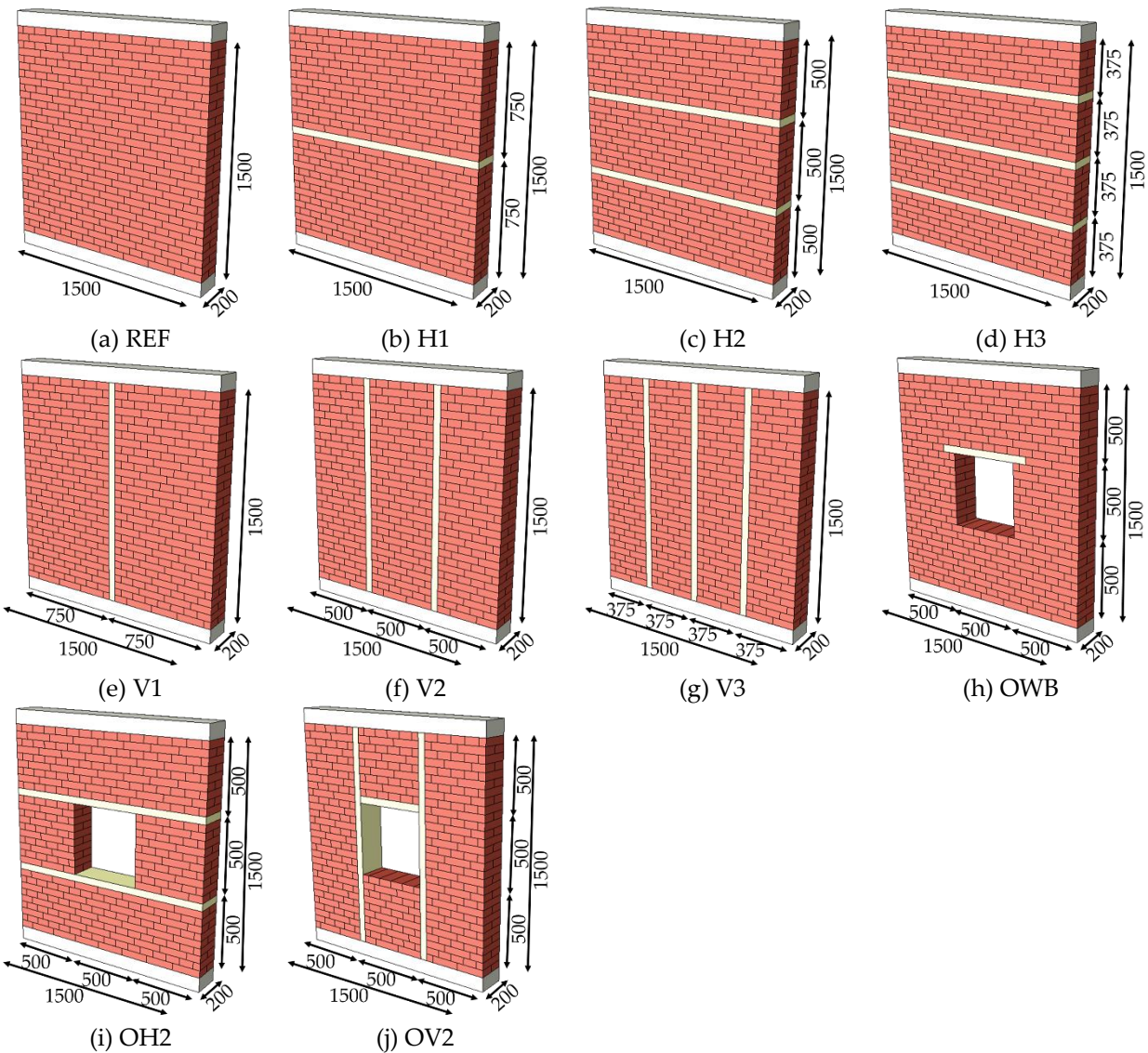


Figure 2. Views and dimensions of the wall models investigated (dimensions are in mm)

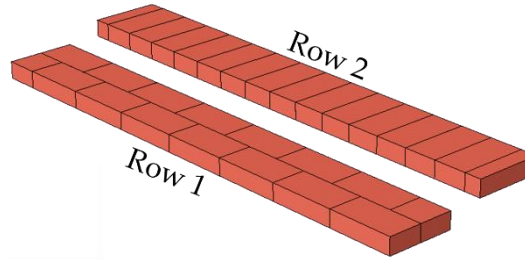


Figure 3. Wall arrangement

2.2. Material, Modelling, and Loading Conditions

In this study, finite element analyses (FEA) were performed using the ABAQUS/Explicit Dynamic Analysis (EDA) approach. The wall models were modelled in three dimensions (3D). During the modelling process, the brick units, interfaces, and boundary conditions were defined to represent actual construction conditions. Geometric properties were carefully considered to determine behaviour, and both linear and nonlinear material properties were taken into account. The analysis process consisted of two stages. The stability of the model and the continuity of contact behaviour were continuously monitored throughout the analysis. The first stage consisted of a 2-second analysis step. In this step, the effects of gravity and vertical pressure were applied to the models. A vertical roof pressure equal to half the mortar pressure resistance, $\sigma = fm/2 = 0.54/2 = 0.27 \text{ N/mm}^2$, was applied. The initial contact stresses were intended to remain within elastic limits. Gravitational acceleration was defined as a smooth ramp to prevent inertial effects associated with sudden loading. It was defined to reach a value of 9806 mm/s^2 at the end of 2 s. The pressure of 0.27 N/mm^2 was defined to increase linearly from 0 to 2 s. This allowed the wall to settle realistically under its own weight. The formation of pressure force between the bricks and the locking of the contact surfaces were ensured. In the second stage, a 10-second dynamic analysis was performed. In this stage, the horizontal displacement movement applied to the wall was defined. The steel beam placed on top of the wall was assigned a linearly increasing displacement, reaching 110 mm at the end of the 10 s analysis step. This two-stage approach allowed the initial conditions to be formed appropriately, as they are in reality, and enabled the detailed investigation of mechanisms such as damping, friction, interface damage, and crack propagation while moving horizontally. The short time steps of the explicit solution enabled detailed tracking of contact and separation movements. This ensured the accurate determination of discontinuity and damage formation processes in the interfaces defined at the horizontal-vertical joints. This analysis setup was considered appropriate for obtaining the dynamic behaviour of the wall models.

The brick material used in the study was red clay brick, commonly referred to as “Harman brick” in Anatolia. The brick was obtained by forming and firing a mixture of sand, clay, and water. It has a structure that exhibits surface roughness and geometric irregularities. On average, it measures $191 \times 93 \times 47 \text{ mm}$ and weighs approximately 1.556 kg [4], [13], [18]. A rectangular recess is provided on the upper surface of the brick to enhance mortar adhesion. No recesses were modelled in the brick units in this study. Modelling the recesses would increase the computational cost and analysis time. In the study by Kıpçak et al. [18], the average compressive strength of bricks with surface roughness was determined to be 23.46 MPa. In the same study, the unit weight was determined to be 19.53 kN/m^3 . Assuming that the recesses are filled and recalculating the unit weight based on the brick dimensions given in Figure 4 using the equal-mass principle, the unit weight of the brick was determined to be 15.267 kN/m^3 . The calculated unit weight of 15.267 kN/m^3 was defined for the brick material in the model. The elastic modulus of the material was taken as 16,700 MPa,

the Poisson's ratio as 0.15, and the friction coefficient under vertical load as $\mu = 0.82$. The high friction coefficient indicates that the units can provide sufficient interlocking under vertical load. In this mortar-based wall system, lime-mixed mortar was considered. The mortar compressive strength was 0.5 MPa, and its elastic modulus was calculated as 85.32 MPa using $E_m = 0.54 \times 158$ given in the study by Costigan et al [39]. As the number of units increases in multi-layered or high walls, the number of horizontal joints and the amount of mortar also increase. Different studies have reported a significant decrease in compressive strength due to irregular load transfer and an increase in mortar planes [18].

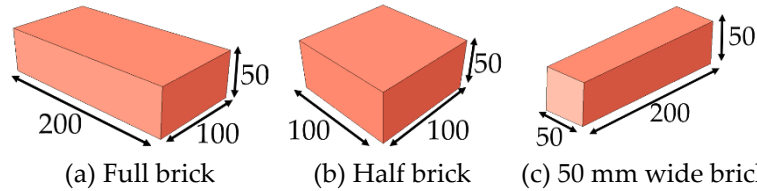


Figure 4. Bricks used and their dimensions (dimensions are in mm)

Figure 5 shows the loading and support conditions considered for the analysis of the walls. All walls were initially subjected to a pressure of 0.27 N/mm^2 to account for the roof effect. Steel beams were placed at the bottom and top of the walls to provide a rigid diaphragm effect. As shown in the figure, a displacement-controlled loading was defined in the horizontal direction. A horizontal displacement of 110 mm was applied at reference point RP-1. The lower steel beam forming the foundation was fixed at point RP-2. Since masonry walls are mostly loaded in the plane direction, the wall models also move in this direction [25], [26]. The tie beams and lintels were made of timber. They were defined as linear elastic materials, and the mechanical properties reported by Bolmsvik et al. [41] were assigned as shown in Table 2. The purpose of this study is to investigate the in-plane behaviour and failure mechanism of masonry walls. The analysis results indicate that the nonlinear behaviour is primarily associated with the behaviour of the brick elements and the mortar interfaces. Stress evaluations revealed that the stresses occurring in the wood material remained below the characteristic yield limits. This condition is thought to be due to the load applied to the wall being as low as 0.27 N/mm^2 . In this case, plastic deformation or local crushing behaviour in the wood material is not expected to be active. In this context, the linear elastic definition of the wood material is considered sufficient for determining the global behaviour of the system and the failure mechanism.

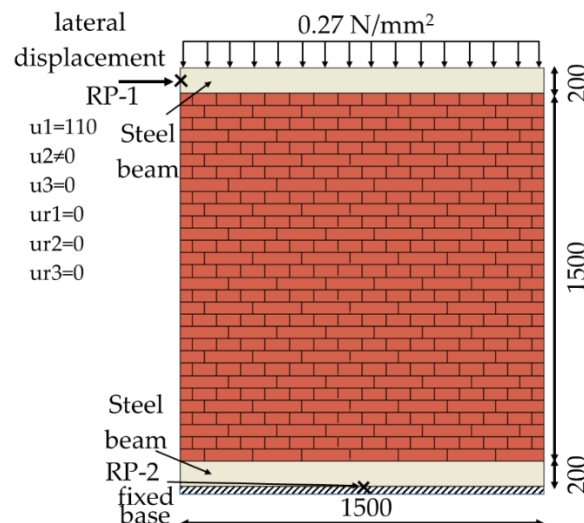


Figure 5. Load and support conditions on walls (dimensions are in mm)

In various studies, Drucker–Prager (DP) and Concrete Damage Plasticity (CDP) models have been defined for brick materials [42], [43], [44], [45]. The elastic capacity of bricks can be exceeded in different wall types. Masonry walls exhibit brittle behaviour. However, providing only the elastic parameters was considered to limit the scope of the study. The stresses in the bricks may vary for different structural configurations and can be investigated in future studies. In this regard, the CDP parameters were calculated and taken into consideration. The elastic modulus and Poisson’s ratio were used to define the elastic material properties in the numerical study, while the CDP model was used to define the plastic properties. When only elastic properties were used, no significant change was observed in the analysis results. This is because the stresses are low, as mentioned. The CDP model was adopted for walls in which high stress levels were observed within the brick units. Accordingly, CDP parameters were provided. The CDP model was used to account for the different damage behaviours of brittle and quasi-brittle materials, such as concrete, under tension and compression. The CDP model is a continuum material model that determines plastic damage. The model is widely used in the characterization of masonry-type materials. In recent years, various studies have been published on the suitability of CDP for masonry structures, parameter sensitivity and modelling principles [46]. In CDP, two separate damage parameters (tension and compression) are important variables. The flow rule is defined by a Drucker–Prager-type non-associated potential. Crack propagation under tension and crushing under compression are represented by separate damage parameters. The calculation principle of the CDP material model in ABAQUS is based on the formulations of Lubliner et al. [47] and Lee–Fenves et al. [48]. The dilation angle (ψ) is an important parameter, and values higher than 35° are not recommended [49]. In this study, a dilation angle of 30° was adopted for the brick material with a compressive strength of 23 MPa [50]. The second parameter, the eccentricity, was taken as 0.1, as recommended in the ABAQUS documentation. The third parameter, $F=f_{t0}/f_{c0}$, was taken as 1.16, as recommended in the ABAQUS documentation. The fourth parameter, K_c , was defined as 2/3. Viscosity is an analysis parameter that affects the analysis time and final stress values. It was set to zero to avoid deviations in the stress response. As in Guo et al. [51] and simulia guide books [52], eccentricity, $F=f_{t0}/f_{c0}$, K_c , and viscosity values were defined [53]. The elastic and plastic parameters of the brick material are given in Table 2. The contact interface modelling parameters are given in Table 3.

Table 2. Brick material properties [54]

Brick				
Unit weight, kN/m³	Compressive strength, MPa	Tensile strength MPa	Elastic modulus, MPa	Poisson’s ratio
19.53	23.49	2.00	16700	0.15
Mortar				
15.72	0.54	0.31	85.32	0.2
Timber tie beam/Lintel				
4.32	-		12000	0.25

Stress–strain curves were required to determine the damage occurring in the brick units. No stress–strain equations specifically developed for brick materials were found in the literature or relevant regulations. Due to its brittle structure and low tensile strength, brick exhibits mechanical properties similar to concrete. Accordingly, the stress–strain equations defined for concrete in the Chinese Code GB50010 [55] were adapted for the brick material. The equations provided in the regulation were found to be adequate for accurately representing the mechanical behaviour of the walls. Various studies indicate that the Chinese Code equations

recommended for concrete in the literature accurately model the nonlinear behaviour of brittle materials under compression and tension [53], [56], [57]. Within this framework, the equations provided in the regulation were calculated based on the maximum compressive strength (23.49 MPa) and tensile strength (2.00 MPa) of the brick material. The curves obtained from the values are shown in Figure 6. First, stress-strain curves were generated for the brick. The yield strength and strain were determined by taking 40% of the ultimate strength defined according to the secant method [58]. The inelastic strain was calculated by subtracting the total strain from the strain at the yield point. In the FEA model, stress-inelastic strain and damage parameter-inelastic strain curves were defined for the brick. Total strain was not defined in the model. Thus, the nonlinear behaviour of the brick material was defined using widely accepted analytical equations.

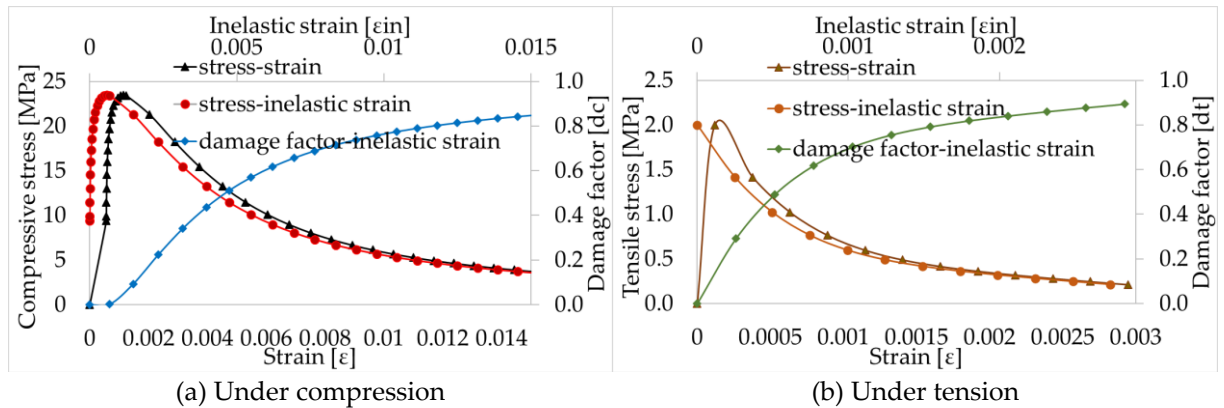


Figure 6. Stress-strain/inelastic strain curves for the brick material defined in the model

2.3. Contact definition

The cohesive interface model defined between the brick units is presented in Table 3. The interaction between brick units is represented by a cohesive interface model on all horizontal and vertical unit interfaces. The interaction in the normal direction was defined using normal behaviour with separation allowed after contact. This definition ensured contact between brick surfaces under compression and allows the surfaces to separate when tension occurs. This definition represents the actual adhesion–separation behaviour of the interface. Shear interaction was defined using tangential behaviour with a friction coefficient. Horizontal stiffness coefficients and shear stresses were defined. This definition ensured that the shear stress along the interface is limited by the friction coefficient. When this limit was exceeded, relative movement between the bricks occurred. The friction coefficient is an important parameter in masonry structures. The value of 0.82 used in this study was based on the friction coefficient obtained from the experimental studies of Kıpçak et al. and Erdil et al. [13], [54]. Defining mechanical interaction in walls where mortar is used only through friction contact is insufficient. To accurately represent fracture behaviour and obtain capacities consistent with experimental results, a cohesive behaviour/traction–separation model was also defined. The parameters K_{nn} (normal direction stiffness), K_{ss} (first shear direction stiffness), and K_{tt} (second shear direction stiffness), which define the linear elastic region of the interface, were used. These stiffnesses control the elastic behaviour of the interface before crack formation under loading. They also determine the magnitude of the displacements between the units. Crack initiation at the interface was defined using the “damage initiation” feature. In this context, limit values were defined for the normal tensile stress and the stress components in the two shear directions. When these limit values were exceeded, fracture occurred. Fracture propagation was defined using the “damage evolution” feature. Energy damping and the reduction in load capacity after ultimate capacity were modelled at this stage. The normal stress component represents the tensile effect that causes the separation of bricks. The shear I and shear II components represent the shear stresses on the shear plane

perpendicular to the normal direction. All of these parameters were determined based on experimental measurements conducted by Kıpçak et al [54] on brick material. This detailed interface model was used to realistically capture contact, separation, sliding, and crack propagation between the brick units. In this context, wall behaviour, capacity, and failure mechanisms were investigated.

In this study, no mechanical connection (steel anchor, bolt, or dowel-type connection element) was defined between the wooden tie beams and the brick units or supports. The tie beam-brick and beam-support interaction was modelled according to the cohesive surface model. In this case, a rigid bond assumption was not made. Therefore, a fully monolithic behaviour between the beam and the wall was not forced.

Table 3. Cohesive interface model defined between bricks [54] (defined in all vertical and horizontal joints)

Tangential behaviour-Friction coefficient		0.82
Normal behaviour/Allow separation after contact		Hard contact
Cohesive behaviour/ Traction- (K_{nn}), N/mm ³		15.88
separation behaviour (K_{ss}), N/mm ³		6.61
Stiffness coefficients (K_{tt}), N/mm ³		6.61
	Normal, (f_m) MPa (mortar compressive strength)	0.54
Damage/	Shear I, MPa	0.046
initiation	Shear II, MPa	0.046
Damage/evolution	Plastic displacement, mm	1.21

2.4. Analysis Validation and Mesh Arrangement

In this study, the validation process was carried out by examining changes related to mesh size and shear stress to assess the reliability of the analyses. The aim was to realistically represent the cohesive behaviour defined at the interfaces. Changes in mesh size were considered necessary in this study, as in similar numerical analyses [33], [44]. In this regard, brick units were divided into 15 mm, 20 mm, 25 mm, 50 mm, and 100 mm grids for analysis. Mesh sensitivity analyses were performed under shear loading. For this purpose, a displacement of 110 mm was applied to cause shear movement between two bricks. A vertical force of 100 N was applied to the brick. The mesh sensitivity results shown in Figures 8a and 8c were obtained by correlating the resulting horizontal stress with displacement. As the element size decreased, the shear, separation, and stress distributions at the interface were observed to be more stable and consistent. Due to the significant increase in computational cost associated with finer meshes, a mesh size of 25 mm was selected for the study. In this respect, an appropriate mesh size that correctly represents the behaviour of the wall models was determined. The selected mesh density was found to be consistent with the shear stresses of 0.046 MPa given in Table 3. Sensitivity analyses were also performed to assess the consistency of the contact stresses between two bricks. The study evaluated the change in contact stress and analysed the adhesion effect created by the lime-mixed mortar. The stress variations are shown in Figures 8b and 8d. The stress increase was found to be directly proportional to the applied load. A uniform increase in stress was observed under five different axial loads. The contact solution was found to be stable, with no excessive element distortion. Thus, both the validation and mesh convergence processes were completed. To minimize inertia effects, the loading was applied over an extended time period. Kinetic energy (ALLKE) and internal energy (ALLIE) values were obtained using ABAQUS software to verify that the analyses proceeded under quasi-static conditions. The ratio was calculated as given in Equation (1), ALLKE/ALLIE. The energy values were obtained from the ODB file using the total value for the whole model. The total analysis time was 12 s, and the load was increased linearly throughout this period. According to the analysis results, the kinetic energy/internal energy ratio for wall models remained below 5% until the end of the analysis. This ratio was found to be 3.7%, 3.9%, 3.95%,

4.2%, 4.0%, 4.3%, 4.1%, 3.6%, 3.9%, and 4.2% for the REF, H1, H2, H3, V1, V2, V3, OWB, OH2, and OV2 walls, respectively. These values indicate that the solution proceeded under quasi-static conditions and that the results were not significantly affected by artificial inertial effects. The change in the ALLKE/ALLIE ratio over the 12s process for the REF model was presented in Figure 7.

$$KE/IE \text{ ratio} = \frac{\text{Total Kinetic Energy (ALLKE)}}{\text{Total Internal Energy (ALLIE)}} \quad (1)$$

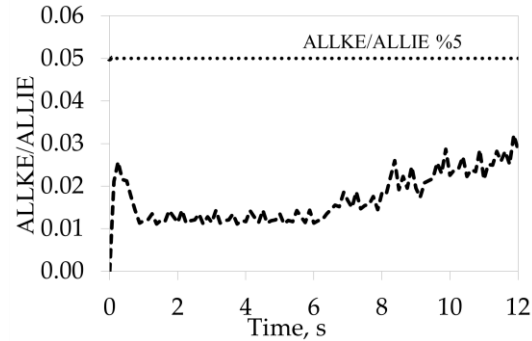


Figure 7. ALLKE/ALLIE ratio curve for 12 s on REF wall.

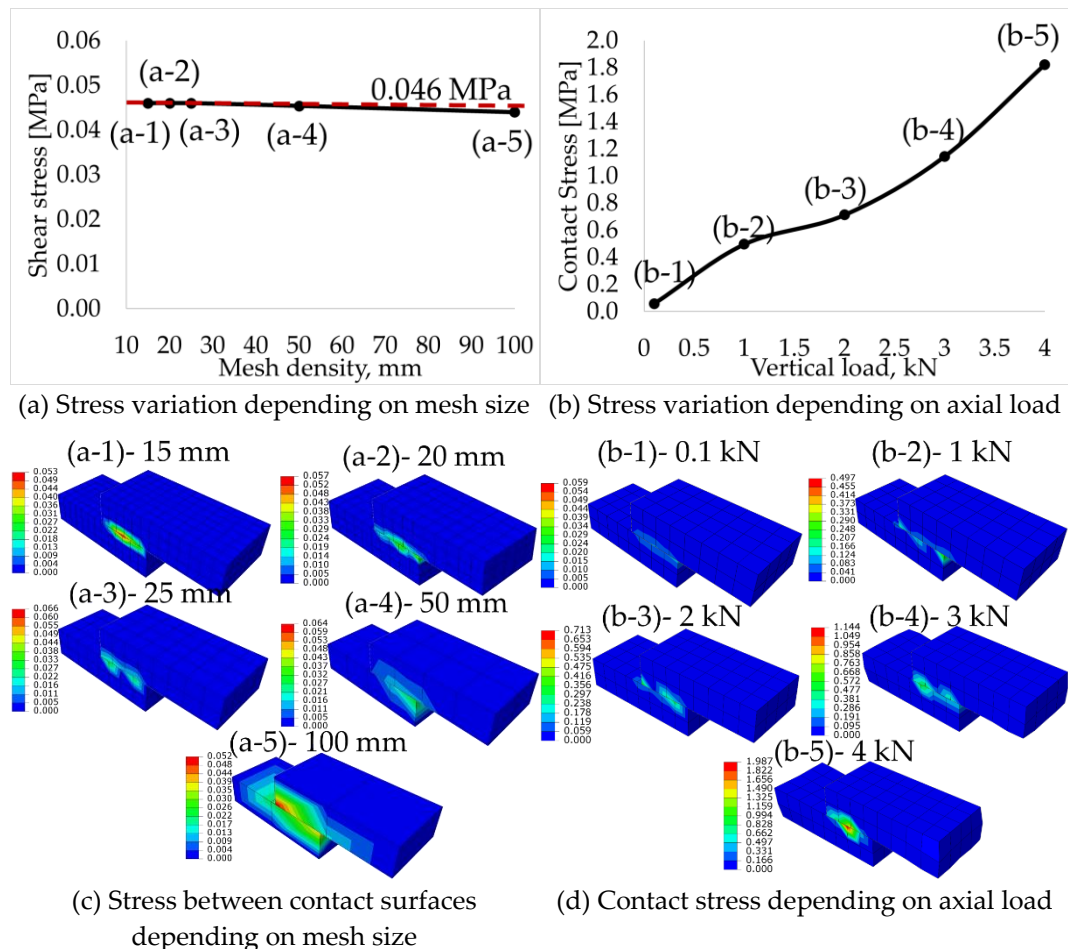


Figure 8. Sensitivity analysis

The numerical model developed in the 2025 study by Kıpçak et al. was used as a reference [54]. An experimentally validated study was considered to verify the present numerical model. The BM-U-2-NO-Numeric wall model reported in the reference study was selected for validation [54]. The BM-U-2-NO-Numeric wall is made of clay brick units and the lime-based mortar used in this study. The material used in this wall has the same compressive strength, elastic modulus, and density as those reported in the reference study. In this regard, the materials in this study were defined in accordance with the materials used in the reference experimental study. In addition to the experimental results for the BM-U-2-NO wall, ABAQUS/dynamic explicit analysis was performed. The curve comparing the numerical and experimental results is presented in Figure 9. The curves showed good agreement between the numerical and experimental results. This verification demonstrated that the selected material properties and solution approach could reliably represent the physical behaviour. In this article, the same numerical solution method (ABAQUS/Explicit), the same energy control approach, and a suitable analysis time for the walls under investigation were used. For the wall given in the reference study, $W=18.04$ kN was calculated. The horizontal capacity in kN and top displacement in mm, consistent with this study, were given in Figure 9. BM-U-2-NO-1, -2, and -3 represent three separate repeated experiments. -Numeric represents the numerical results [54].

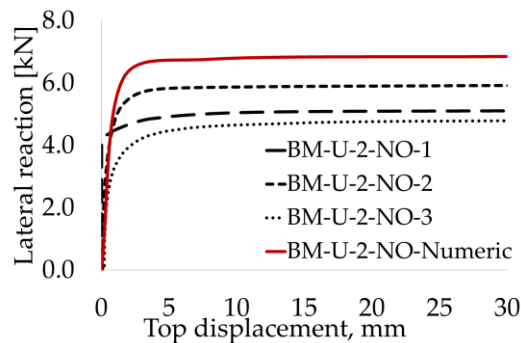


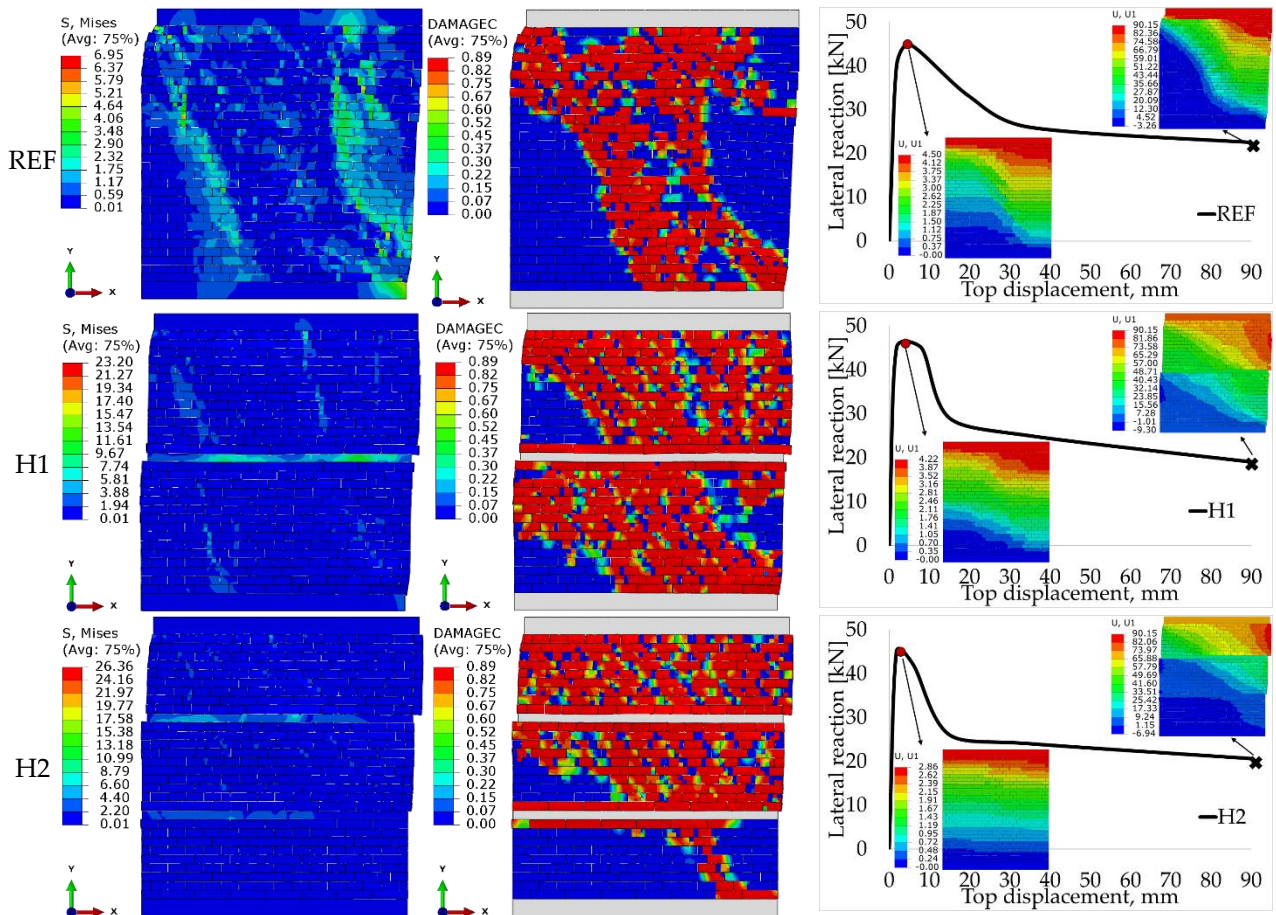
Figure 9. Verification of experimental and numerical results

3. RESULTS AND DISCUSSION

3.1. Walls investigated for the effect of horizontal tie beams

The effect of horizontal tie beams was investigated using walls H1, H2, and H3. Figure 10 shows the stress distributions, compression damage, and horizontal load–top displacement curves for these walls. A reference wall was used to evaluate the changes observed in these and the other models. The reference model wall was considered to evaluate the load-displacement relationship, the failure mechanism, and the overall behaviour in the absence of tie beams. The peak horizontal load on this wall was measured as 45 kN, with a displacement of 4.5 mm at peak load. As shown in Figure 10a, the stress distribution occurred diagonally from the bottom right support edge to the top left support edge. The stress distribution increased along two separate diagonal lines. When the compression damage at a horizontal displacement of 90 mm was examined in Figure 10b, almost all brick units can be seen to have experienced compression damage. The H1 wall was divided into two parts by a timber tie beam located at mid-height. Compared with the reference model, the peak load increased by only 1 kN, reaching 46 kN. As shown in Figure 10a, an increase in stress was observed above and below the horizontal tie beam. Different diagonals developed in two separate wall parts. Due to the short diagonal length, compressive damage spread to a wider part of the wall, as shown in Figure 10b. All bricks in the row in contact with the top and bottom of the horizontal tie beam were crushed. In wall H2, the wall height

was divided into three parts by two horizontal tie beams. This arrangement caused the peak load to decrease to 44 kN. This indicates a reduction in the interaction between the separated wall segments. The stress magnitude in the tie beams of the H2 wall was higher than that in the brick units. This situation ensured that the stress was lower because the bricks separated from each other due to movement. Because each tie beam acted as a single component, it was subjected to relatively high shear and tensile stresses at different locations. As shown in Figure 10b, the compression damage was higher in the middle and top parts, and it was observed that these parts had relatively more horizontal displacement. The H3 wall was divided into four parts with three horizontal tie beams. In this wall, the peak load was determined to be reduced to 39 kN. Increasing the number of horizontal tie beams resulted in peak loads being reached at smaller displacements. The monolithic behaviour was replaced by the behaviour of smaller parts. These results generally indicate that increasing the number of tie beams weakens the monolithic behaviour of the wall. The results show that both the peak load and displacement capacity decrease with an increase in the number of parts. In this wall, the stress gradually decreased from the upper part to the lower parts. Diagonal stress occurred in the middle portion of each part. As seen in Figure 10b, more intense compression damage occurred in the upper part. In the middle and lower parts, the bricks in contact with the tie beams, whose diagonal distance remained short, were crushed. In figures showing contour levels, gray areas do not indicate damage levels because damage parameters were not defined.



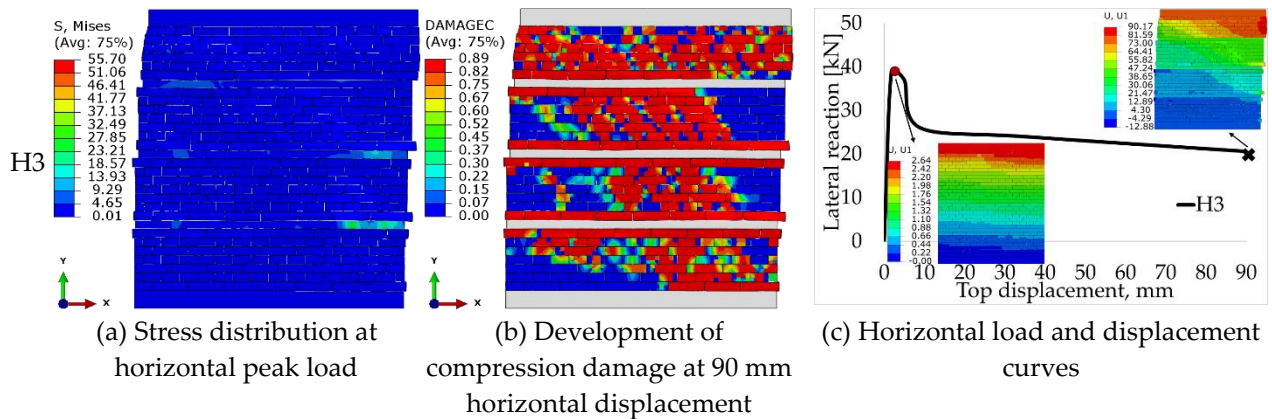
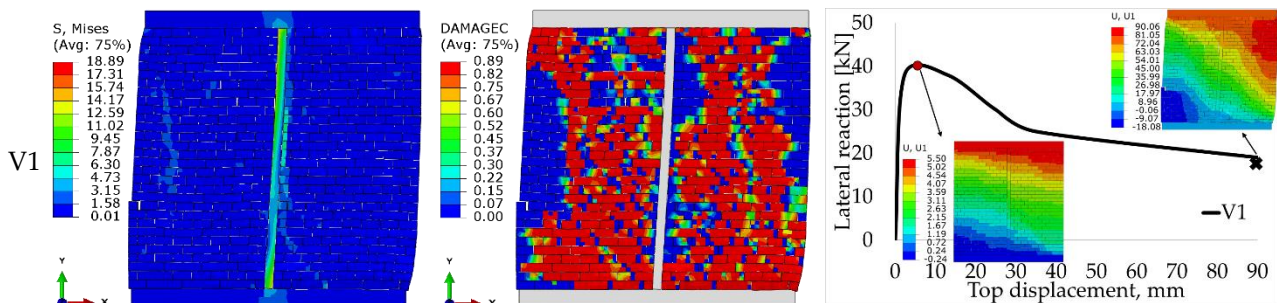


Figure 10. Walls investigated for the effect of horizontal tie beams

3.2. Walls investigated for the effect of vertical tie beams

To investigate the effect of vertical tie beams, walls V1, V2, and V3 were considered, and their stress distributions, compression damage, and capacity curves are shown in Figure 11. In wall V1, which has a single vertical tie beam, the wall was divided vertically into two parts, each moving independently. The addition of the tie beam to the V1 wall resulted in a reduction of the peak load to 40.2 kN. The stress distribution shown in Figure 11a indicates that a high stress level developed in the vertical tie beam. The two wall parts moved independently, and the diagonal damage direction was inclined towards the vertical direction. Figure 11b clearly shows the diagonal damage distribution. The damage was found to increase towards the lower part of the wall. In V2, which contained two vertical tie beams, the wall was divided into three vertical parts. The peak load decreased to 35 kN. The vertical tie beams were observed to reduce the interlocking between the units along the wall. Therefore, the peak reaction load decreased. As given in Figure 11b, separation occurred in the left and right parts of the wall. In the middle part, compression damage was observed to be relatively widespread. Four vertical parts were formed in the V3 wall, which contained three vertical tie beams. The peak load on the V3 wall decreased to 33 kN. The increase in the number of vertical tie beams was observed to relatively reduce the interlocking between the bricks. In this case, the horizontal reaction load decreased, and the sections moved separately. The monolithic behaviour of the wall was found to be negatively affected. When the walls reached a top displacement of 90 mm, the smaller number of tie beams resulted in greater damage to the brick units. However, this led to a decrease in capacity. Although the lower level of brick damage can be considered a positive outcome, the separation of the wall into individual parts weakened its resistance. The use of tie beams with more systematic connections can be evaluated in future studies. In general, vertical tie beams reduced the interlocking between brick units in the wall and caused discontinuity. Increasing the number of vertical tie beams reduced the shear and bending capacities of the wall.



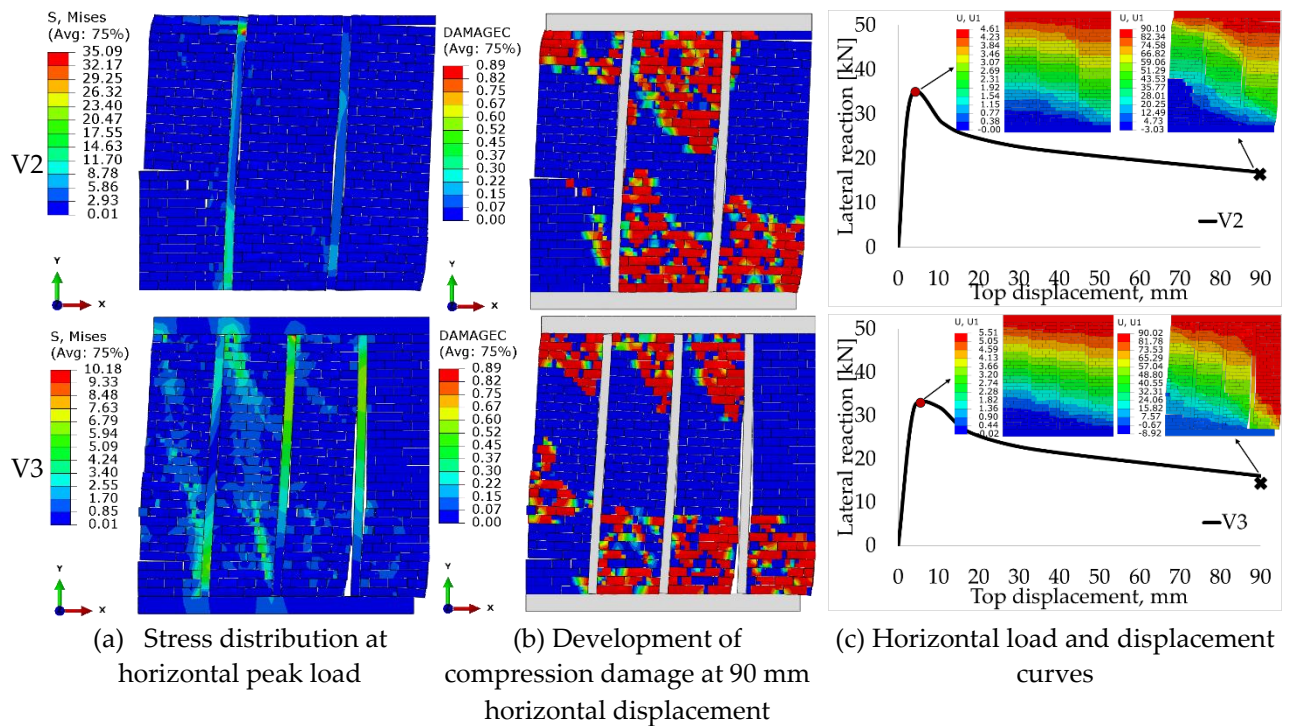


Figure 11. Walls investigated for the effect of vertical tie beams

3.3. Walls with openings investigated for the effects of vertical and horizontal tie beams

In walls with window openings, the horizontal reaction load decreased because the openings weakened the integrity of the wall. Window openings were considered in the OWB, OH2, and OV2 walls. The capacity and failure patterns of these walls are shown in Figure 12. There is no tie beam in the OWB wall, and the peak load was measured as 40.5 kN. The peak loads of the OH2 wall, which contained a horizontal tie beam, and the OV2 wall, which contained a vertical tie beam, were 40.5 kN and 34 kN, respectively. The horizontal tie beam placed at window level did not make a significant contribution, as the peak load and displacement values were identical to those of the OWB wall. In this context, the horizontal timber tie beam was found to be insufficient in compensating for the stress discontinuity caused by the window opening. As shown in Figure 12a, the stress in the OWB wall was distributed over a wide area. The diagonal stress distribution was observed to accumulate at the support corners as it progressed around the opening. On the OWB wall, intense compression damage was observed on the upper right and lower left edges of the window, as shown in Figure 12b. The damage was concentrated in the upper section of the wall. The tie beams located above and below the opening in the OH2 wall carried a significant portion of the stress. When displaced by 90 mm, compression damage was observed in almost all bricks in the middle part of this wall. A large portion of the lower part and almost half of the upper part were damaged. Unlike the other walls, compression damage spread towards the lower left corner in the lower part of this wall. The window opening and vertical tie beams in the OV2 wall divided the wall into three vertical parts. The tie beam did not adequately compensate for the discontinuity formed at the edge of the opening. On the contrary, it was observed that it reduced the interlocking between the bricks and negatively affected both the stiffness and monolithic behaviour. No damage was observed in the right section of the wall. This was found to be due to the low shear and tensile strength between the units. As a result, the units did not experience significant damage during horizontal displacement. Damage occurred at the top and bottom of the left part of the wall, while the absence of damage in the middle section was due to the opening. In this section, increased displacement towards the opening prevented serious damage. These

findings showed that horizontal tie beams did not have a significant effect on walls with window openings, whereas vertical tie beams reduced the horizontal reaction force by dividing the wall into separate parts.

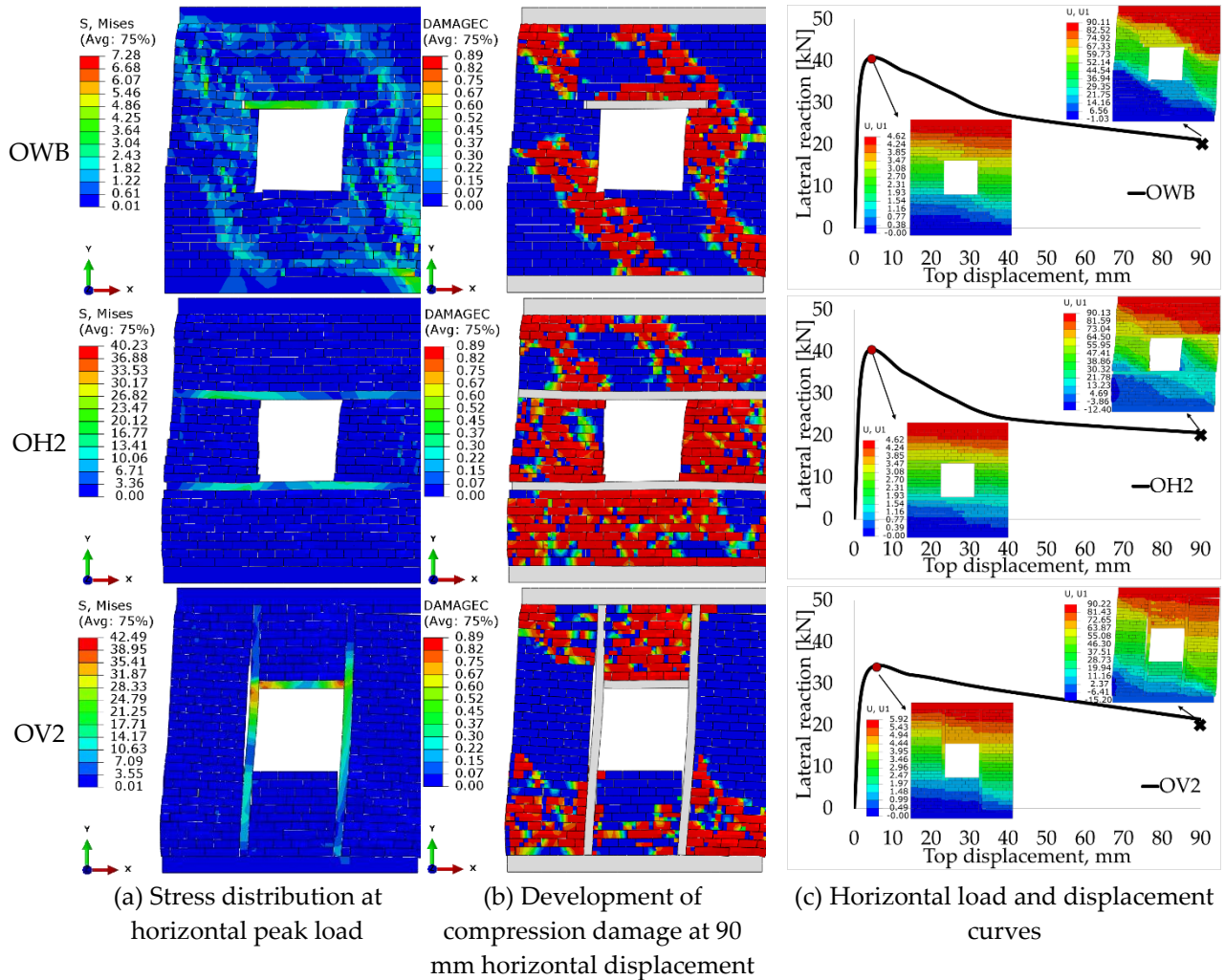


Figure 12. Walls with openings investigated for the effects of vertical and horizontal tie beams

Figure 13 compares the capacity curves of all wall models, and Table 4 provides a summary of the results. The table shows the horizontal peak load and displacement at that point, as well as the absolute and relative differences in horizontal load. According to the results, the highest horizontal load was obtained for the H1 wall. This was followed by the reference wall and the H2 wall, respectively. Compared to the reference wall, lower horizontal loads were measured in all walls with vertical tie beams and openings. Displacement capacities decreased as the number of horizontal tie beams increased. All walls experienced a sudden loss of strength after reaching the peak load. This was attributed to the brittle nature of the wall and its low shear resistance. The displacement at the highest horizontal peak load was observed on the OV2 wall. The displacement was high in this wall because of the weak connection between the separated parts. In general, the monolithic wall structure weakened and its behaviour was negatively affected by the increase in vertical tie beams and the presence of openings. The lowest change was observed on the H1 wall, with an absolute difference of 1 kN and a relative difference of 2.22%. The 4 mm displacement in this wall, as shown in Table 4, indicates that the tie beam provided only a limited increase in stiffness. The absolute difference of 1 kN and

the relative difference of 2.12% for wall H2 indicate that there was no significant change in the ultimate capacity. The displacement of 2.8 mm indicates that the stiffness was relatively high. However, after reaching peak load, sudden strength loss was also observed in this wall. An absolute difference of up to 6 kN was found in wall H3. Although the difference increased, the displacement decreased. In wall V1, the absolute and relative differences were 4.8 kN and 10.67%, respectively. This indicates that the capacity loss was associated with a reduction in interlocking. The sudden drop after the peak horizontal load was similar to the reference wall, as seen in Figure 13b. The use of two vertical tie beams in the V2 wall further reduced the capacity, with absolute and relative differences of 10 kN and 22.22%, respectively. The sudden loss after peak load occurred relatively faster on the V2 wall. The capacity on the V3 wall was found to be the lowest among all walls. The absolute and relative differences were 12 kN and 26.67%, respectively. The use of three vertical tie beams did not have a positive effect on the wall; on the contrary, it reduced the capacities by dividing the wall into more parts. In the OWB wall, the presence of the opening alone caused a 4.5 kN decrease in horizontal force and an 10.00% relative decrease. The loss of resistance after the peak load occurred more gradually. Although placing lintels above and below the opening affected the collapse mechanism, it did not change the capacities compared to OWB. The loss of resistance after horizontal peak load on the OH2 wall occurred relatively earlier compared to OWB. On the OV2 wall, vertical tie beams were recorded to reduce wall capacity, and the capacity curve is shown in Figure 13c. An absolute loss of 11 kN and a relative loss of 24.44% were measured. In this case, the positive effect of vertical tie beams is to reduce the number of damaged bricks, while the negative effect is a decrease in capacity. Except for wall H1, increasing the number of tie beams concentrated deformation in specific areas and consequently had a negative effect on the monolithic behaviour of the wall.

The interface model used for both brick-to-brick and brick-to-beam connections had the same characteristics. In other words, the mortar material itself is the interface. The significant loss of strength observed in the V2 and V3 models was attributed to the vertical separation of the wall into multiple parts and the increase in these separations as the number of tie beams increased. This resulted in continuous joints forming from the top to the bottom along the left and right edges of the tie beams. This weakened the interlocking between the bricks, causing a decrease in strength. The findings partially differ from those reported in the literature, which generally indicate that ring beams and tie rods increase capacity. However, a significant proportion of these studies showed that tie beams were connected to the wall using mechanical connection elements (anchors, bolts, or dowel systems) and are effectively integrated. In this study, the wooden tie beams and lintels were not mechanically connected to the bricks or supports. Consequently, the system could not exhibit monolithic behaviour. In particular, vertical beams and openings in walls did not contribute to the structure. On the contrary, they were found to weaken its integrity. These findings can be explained as follows. When sufficient mechanical interlocking is not provided, tie beams may have a negative rather than a positive effect on the horizontal load capacity of the wall. The wall was not observed to effectively limit crack propagation. Therefore, the main reason for the reduction in load capacity in this study was considered to be the insufficient level of connection rather than the presence of tie beams. Thus, monolithic behaviour could not be achieved. As a final assessment, these results indicate that the behaviour of the wall may change when tie beams are connected differently. The results may differ in studies in which the tie beams are connected differently.

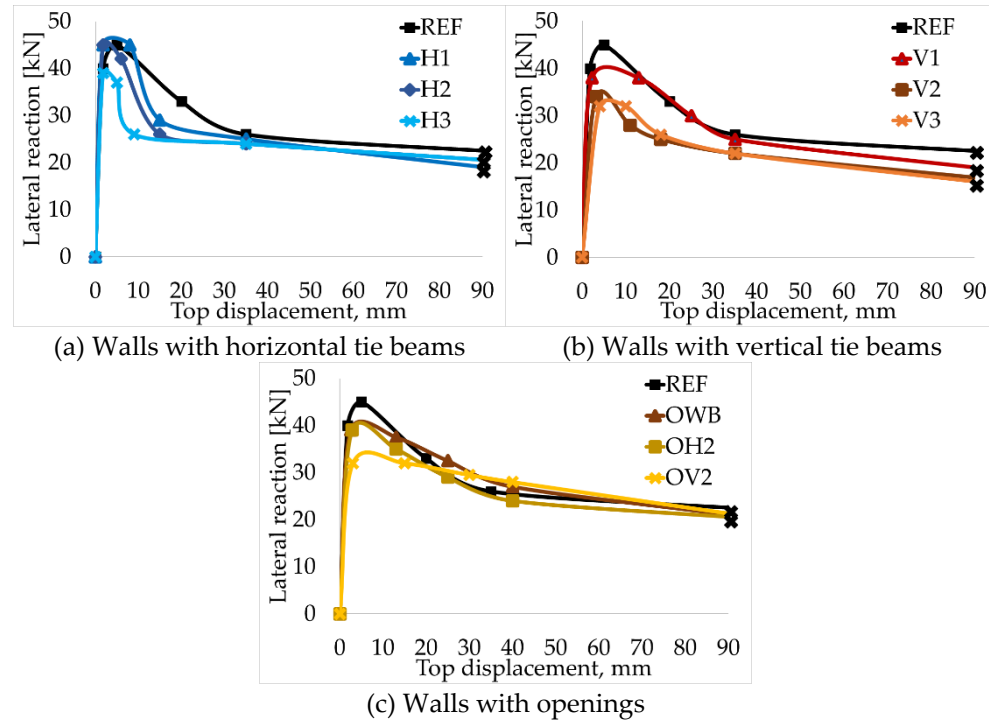


Figure 13. Comparison of capacity curves for all wall models

Table 4. Summary table of numerical analysis results

Wall Code	Horizontal peak load, kN	Displacement occurring at horizontal peak load, mm	Absolute difference in horizontal load, kN	Relative difference in horizontal load, %
REF	45.00	4.50	0.00	0.00
H1	46.00	4.00	1.00	2.22
H2	44.00	2.80	1.00	2.22
H3	39.00	2.60	6.00	13.33
V1	40.20	5.50	4.80	10.67
V2	35.00	4.50	10.00	22.22
V3	33.00	5.50	12.00	26.67
OWB	40.50	4.50	4.50	10.00
OH2	40.50	4.50	4.50	10.00
OV2	34.00	5.80	11.00	24.44

4. CONCLUSIONS

The study investigated the effects of tie beams in masonry walls. For this purpose, models with horizontal and vertical tie beams were investigated in walls with and without openings. Unlike experimental studies, which are costly and time-consuming, the study was conducted numerically, and capacity curves, wall failure mechanisms, and stress distributions were evaluated. The results are presented below.

- The monolithic behaviour of the wall without a tie beam, which was used as the reference model, was found to be superior. The wall with a single horizontal tie beam had the highest peak load of 46 kN.

- The increase in horizontal tie beams caused a decrease in capacity of between 2.22% and 13.33%. Bricks above and below the horizontal tie beams exhibited compression damage. Contrary to the initial assumption, increasing the number of tie beams decreased the wall capacity.
- Increasing the number of horizontal tie beams divided the wall into separate parts. Performance improved in the wall with a single horizontal tie beam but decreased as the number of horizontal tie beams increased further.
- In walls with vertical tie beams, significant reductions in peak load were observed as the number of tie beams increased. In the model with three vertical tie beams, the relative decrease reached 26%. The reduction in ultimate horizontal load was more pronounced than that observed for the horizontal tie beam configurations.
- Models with vertical tie beams may exhibit increased local deformation and an irregular failure mechanism. This behaviour can be attributed to excessive local separation near the foundation.
- Window openings reduced the wall strength by approximately 10%. The presence of the window opening reduced the ultimate load. The addition of a horizontal tie beam did not compensate for this reduction.
- The window opening and vertical tie beam combination had the most negative effect on performance. The peak load decreased by 24%.

Overall, the addition of tie beams reduced damage to the brick units but did not improve the wall capacity. Increasing the number of horizontal and vertical tie beams negatively affected the monolithic behaviour because the wall was divided into separate parts. A sudden decrease in capacity was observed in all walls after the peak load. Vertical tie beams further reduced the interlocking between the brick units, resulting in greater capacity losses. Among the investigated configurations, these arrangements had the most negative effects on peak load and deformation behaviour. The presence of a window opening weakened the wall performance. Future studies may investigate alternative methods for connecting vertical tie beams to the supports. Increasing the interlocking between brick units through appropriately connected vertical and horizontal tie beams may be effective in maintaining monolithic behaviour. Different types of tie beams and interlocking configurations are recommended for future studies.

Declaration of Ethical Standards

I declare that the study was conducted in accordance with all ethical guidelines regarding authorship, citation, data reporting, and originality. Since the research did not involve human participants, animals, or sensitive data, no specific ethical approval was required.

CRedit Authorship Contribution Statement

As the sole author, I am fully responsible for all contributions to the conception, methodology, analysis, writing, and finalization of the manuscript in accordance with the CRedit (Contributor Roles Taxonomy) framework.

Declaration of Competing Interest

I declare that I have no competing financial or non-financial interests.

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Data Availability

No external datasets were generated or used in this study. Therefore, data sharing is not applicable.

Use of Artificial Intelligence

No generative artificial intelligence (AI) tools were used in the preparation of this manuscript. All research data, methods, analyses, interpretations, and references are based on the author own research and published scientific literature. No AI-generated content or references were used or cited in any part of the manuscript. The author takes full responsibility for the accuracy, originality, integrity and scientific content of the manuscript.

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