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Finite element analysis of unreinforced masonry walls with different bond patterns

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Abstract

Masonry is the oldest building material, yet it is also the least understood due to the non-linear and composite nature of masonry, which consists of brick units, mortar, and unit-mortar contact. In this paper, the response of a two-dimensional masonry wall with a window opening subjected to an in-plane lateral pushover loading is simulated by varying the interface properties of brick such as crushing, elastic, cracking, and shear properties. The simplified micro-modeling technique with the Engineering Masonry model for bricks and linear stiffness properties for the interfaces in the bed and head joints is employed to investigate the geometric nonlinear behavior of the masonry wall. The pushover curves obtained from the numerical simulations indicate that there is a significant influence on the lateral load response of the wall due to elastic, crushing, and shear parameters while the cracking parameters have less impact on the ductile capacity of the structure. Moreover, the study is also extended to examine the effect of bond patterns such as English, stretcher, Flemish, and header bonds with varied aspect ratios of 1, 1.5, and 0.75. In all four bond patterns, it was observed that the walls with lower aspect ratios exhibited higher strength. Further, in comparison to the other bond patterns, walls with the Flemish bond pattern demonstrated higher strengths at both lower and higher aspect ratios.

Keywords: Numerical modeling**,** Unreinforced masonry, Wall opening, Pushover curve**,** Interface properties, Parametric studies

1. Introduction

Masonry structures comprise a large part of the world's structures. Due to their simplicity of construction, high level of durability, attractive architecture, and minimal maintenance requirements, masonry materials, which are the oldest building materials, are widely employed in many nations around the world [1]. Unreinforced masonry (URM) is a structure made of clay bricks, concrete blocks, or stones that have been joined together without the use of reinforcing steel components using lime mortar or cement. Unreinforced masonry (URM) buildings continue to make up the majority of India's building stock. However, because of the non-linear and composite character of masonry, URM constructions are extremely susceptible to damage under the enormous lateral stresses generated by powerful earthquakes, and their performances need to be improved. [2-5]. The correlations between the mechanical properties of masonry at shear and compression differ greatly due to the non-homogeneity and anisotropy of masonry.

Numerous experimental studies have been conducted to examine the non-linear behavior of the brick wall under different loads and modeling techniques [6-9]. The two primary categories of numerical modeling for brick structures are macro and micro-modeling. The level of accuracy and precision required from the simulation determines the modeling technique to be employed in the analysis [10, 11]. Masonry is viewed as a homogenous continuum in macro modeling, with no differentiation made between the units, mortar, and unit-mortar contact. While in the micro-modeling approach for masonry, bricks, mortar, and the interaction between bricks and mortar are treated distinctly in detail using the relevant constitutive laws. Further micro-modeling is classified into two types i.e., extensive micro-modeling and simplified micro-modeling. The drawbacks of extensive micro-modeling were addressed by the development of simplified micro-modeling [12]. In this method, the masonry unit is modeled by expanding half of the thickness of the mortar in all directions, maintaining the brick wall's overall structural geometry. The nonlinear behavior of mortar joints and the interaction between the unit and mortar are incorporated using the discontinuous interface element while the masonry unit is represented by continuum components. To evaluate seismic behavior in masonry structures, numerous finite-element tools are available [13, 14]. Nonlinear finite-element modeling has been recognized as a general and effective technique for the analysis of the load-bearing and displacement capacity of unreinforced masonry systems. It can accurately describe the pre-peak and post-peak behaviors of masonry under various monotonic load combinations [12, 14]. However, only limited research is available on the effect of the various bond patterns on the lateral load response of unreinforced masonry walls. Similarly, limited research with no clear clarity or consensus is available on the effect of material and modeling properties on the lateral load behavior of unreinforced masonry walls.

The structure of the paper is organized as follows. Firstly, a detailed description of the numerical modeling of an unreinforced masonry wall with validation is provided. A simplified micro-modeling approach is employed to examine the non-linear static behavior of the wall. The general properties of Engineering Masonry models, as well as various masonry wall material characteristics, are tabulated. The software DIANA FEA is employed to develop the numerical model of masonry walls, and the software's standard case is used to validate the masonry wall [14]. Next, a parametric study is performed to examine the effect of various material properties of brick, such as the elastic parameters, the crushing parameters, the cracking parameters, and the shear properties. Finally, the effect of bond pattern on the lateral load response of the walls is examined for walls with various aspect ratios.

2. Numerical modeling of unreinforced masonry wall

Masonry has been used extensively in building construction for ages, largely because it is inexpensive and simple to use. Unreinforced masonry, exhibits anisotropy material property, with varying stiffness in the direction of the bed and head joints. The Engineering Masonry model based on the concept of smeared cracking is employed to simulate crushing, frictional slide, and fracture at material interfaces, at any joint in unreinforced brickwork. The mortar joints are modeled using nonlinear interface elements, whereas the brick elements are modeled as continuum elements. The model is based on multi-surface plasticity and consists of an elliptical compression cap, a tension cut-off, and a Coulomb friction model. Since the Engineering Masonry model assumes linear unloading for compressive stresses with initial elastic stiffness, the unloading behavior it describes is fairly realistic. The implementation of this model is recommended for static nonlinear cyclic or transient dynamic nonlinear evaluations of individual components and the entire structure [15, 16]. The general characteristic of the masonry wall is depicted in Figure 1.

A 2- dimensional wall with an opening in the center is modeled using a combined cracking-shearing-crushing model, both geometric and material nonlinear. The brick units in the finite element discretization were modeled using continuum elements. Eight-node continuum elements with plane stress were used to model each brick unit, and the composite interface is incorporated using the joints interface. The interface fracture element with large normal stiffness and shear stiffness is employed to model the vertical interface between the continuum elements within a brick unit that was modeled. The different material properties used to model the Engineering Masonry model such as the interface of bricks, and the properties of cracking, shearing, and crushing are listed in Table 1. The wall's bottom edge is constrained in both the x and y directions, whereas the top edge is constrained in the Y direction. Furthermore, for certain load deformation, the X-direction at the left top corner vertex is restricted. The mesh size of 0.05 mm has been employed to perform the non-linear static analysis of the masonry wall. The description of the masonry wall with boundary condition and mesh size is depicted in Figure 2. In this numerical model, iterations are carried out using the secant approach. Each step evaluates convergence after up to 30 iterations. The convergence is tested using the displacement and force norms. The numerical models were verified using Diana's FEA standard case. The peak load obtained in the numerical modeling was 51376.34 N with a difference in peak load of just 1-2 percent, the observed results were a perfect match with the baseline scenario (51466.1N) as shown in Figure 3. The load response curves matched the standard case as well, and the methodology was extended to further parametric studies discussed in this paper.

Table 1. Material properties for Engineering Masonry model

Property		**Value**	**Units**
Young's modulus (X direction)	E_x	$4 x 10^9$	N/m^2
Young's modulus (Y direction)	E_y	$6 x 10^9$	N/m^2
Shear modulus	G_{xy}	$2 x 10^9$	N/m^2
Mass density	ρ	1700	Kg/m^3
Cracking parameters			
Tensile strength head-joint defined by friction			
Bed-joint tensile strength	f_t	250000	N/m^2
Minimum tensile strength head-joints	$f_{t,min}$	250000	N/m^2
Fracture energy in tension	G_{F1}	18	N/m
Residual tensile strength	$f_{t,res}$	50000	N/m^2
Angle between stepped diagonal crack and bed-joint	α	0.436332	rad
Crushing parameters			
Compressive strength	f_c	$8.5 x 10^6$	N/m^2
Fracture energy in compression	G_c	15000	N/m
Factor to strain at compressive strength	n	2	
Unloading factor	L	1	
Shear failure parameters			
Friction Angle	Φ	0.642501	rad
Cohesion	c	350000	N/m^2
Fracture Energy in Shear	G_{sh}	250	N/m

Table 2. Interface properties used in the model

Property	**Value**	**Units**
Normal stiffness	$1 x 10^{12}$	N/m^3
Shear stiffness	$1 x 10^{12}$	N/m^3

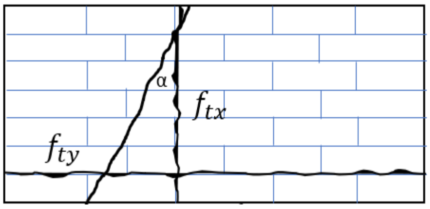


Figure 1. General characteristic of the Engineering Masonry model
α: angle between stepped diagonal crack and bed joints; f_{tx}: head-joint strength; f_{ty}: bed joint strength

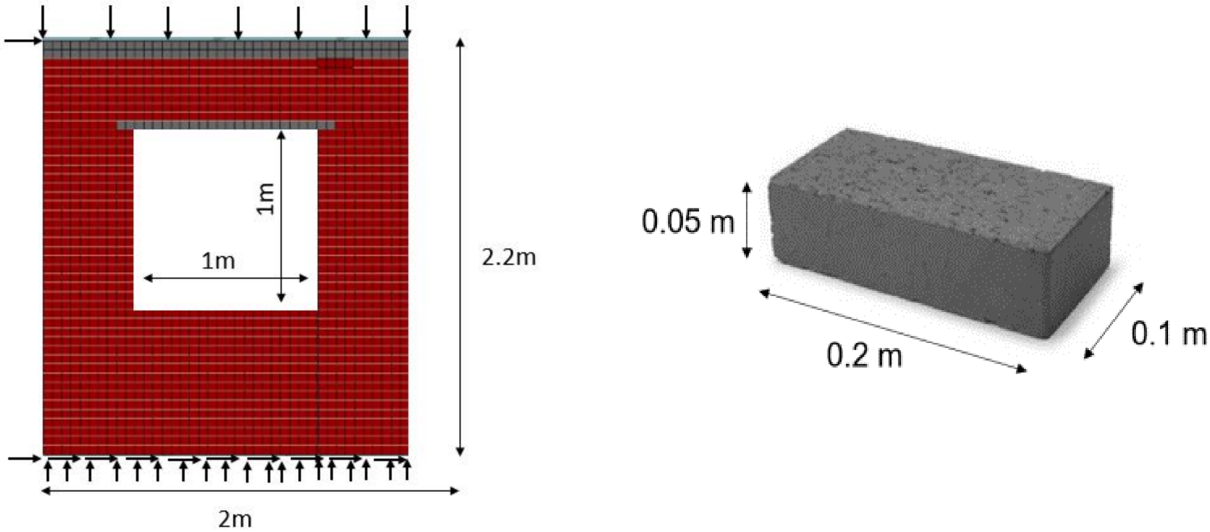


Figure 2. Description of the masonry wall with boundary condition and mesh size of 0.05mm; Details of the brick used in the current study

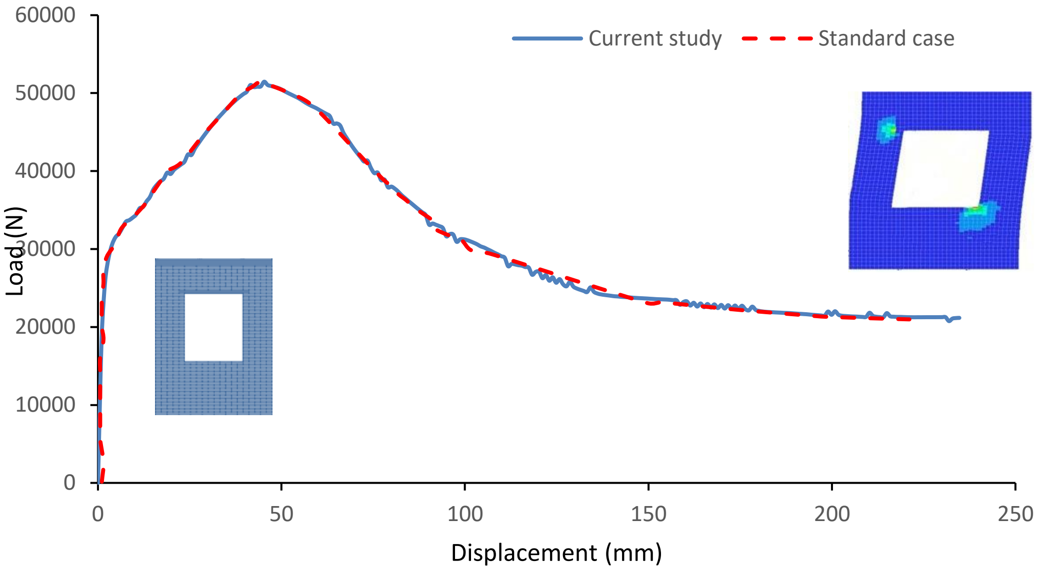


Figure 3. Validation of load-displacement curves for the current study and the standard case in DIANA FEA

3. Results and discussion

Studies on the strength of masonry are expensive and difficult to carry out because of the size of the specimens used in the experiments. Because of this, a parametric study has been conducted to examine the influence of different material properties on the response of masonry walls to the prescribed load. The variation in elastic parameter, crushing parameter, cracking parameter, and shear failure is described in this section.

3.1 Elasticity parameters

The elastic parameter investigated in this section is Young's Modulus. It is defined as the intrinsic property of material which can be evaluated using the 15 to 85% elastic stress values using a quasi-static test process on an untested sample [17]. In this study, Young's modulus is varied by increasing and decreasing it to 5% of the original case in both x and y-directions (Ex, Ey) as shown in Figure 4. The Young's modulus is increased in the range of $4x10^9$ to $6x10^9$ N/m^2 and $6x10^9$ to $9x10^9$ N/m^2 in y- direction and reduced in the range of $4x10^9$ to $2x10^9$ N/m^2 and $6x10^9$ to $3x10^9$ N/m^2 in the x-direction, respectively. It has been found that increasing Young's modulus enhances the brick wall's load capacity; the peak load point grew as Young's modulus increased to 50%, and vice versa as shown in Figure 4.

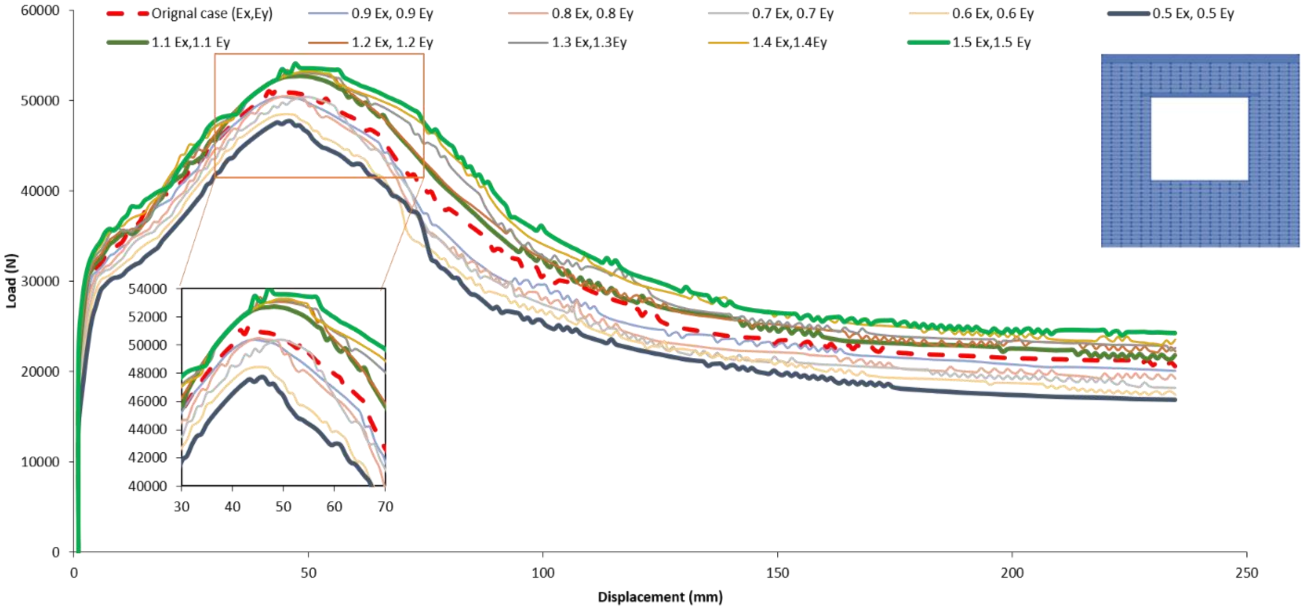


Figure 4. Influence of varied Young's modulus for Engineering Masonry model on load-response curves**.** The solid blue color depicts a 50% reduction, the solid green color shows a 50% increase, and the dashed red line represents the original case for the rest of the paper

3.2 Crushing parameters

The different crushing parameters investigated in this section are compressive strength and fracture energy in compression**.** The compressive strength is directly proportional to the strength of the wall. It is observed that as we increase compressive strength to 9% of the original case, the ductile capacity of the wall also increased and vice versa as shown in Figure 5. The compressive strength varied in the range of 8.5×10^9 to 17×10^9 N/m2 and decreased from 8.5×10^9 to 0.85×10^9 N/m2. Similarly, fracture energy is defined as the energy needed for a one-unit area of crack to spread. The fracture energy in compression is varied as 5% of the original case i.e. increased to 15000 to 22500 N/m and reduced from 15000 to 7500 N/m, which is an important statistic for examining fracture mechanisms. It is also observed from Figure 6 that the load-bearing capacity of the wall increases as fracture energy increases and vice versa.

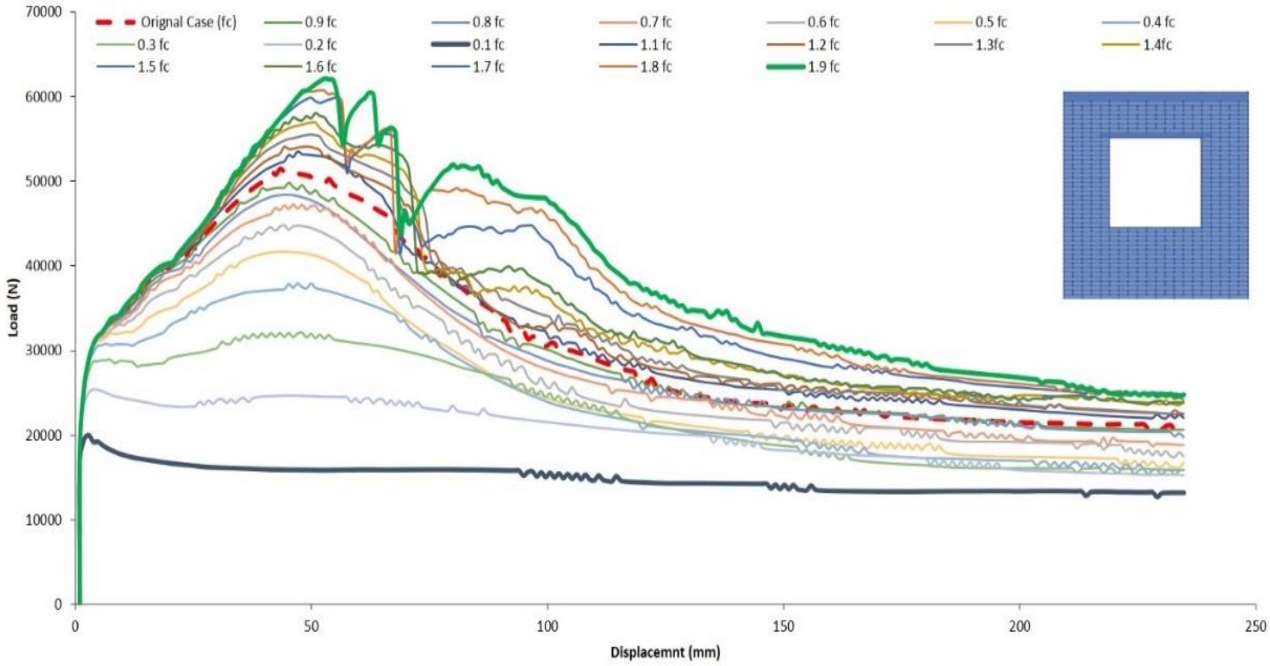


Figure 5. Influence of varied compressive strength for Engineering Masonry model on load-response curves

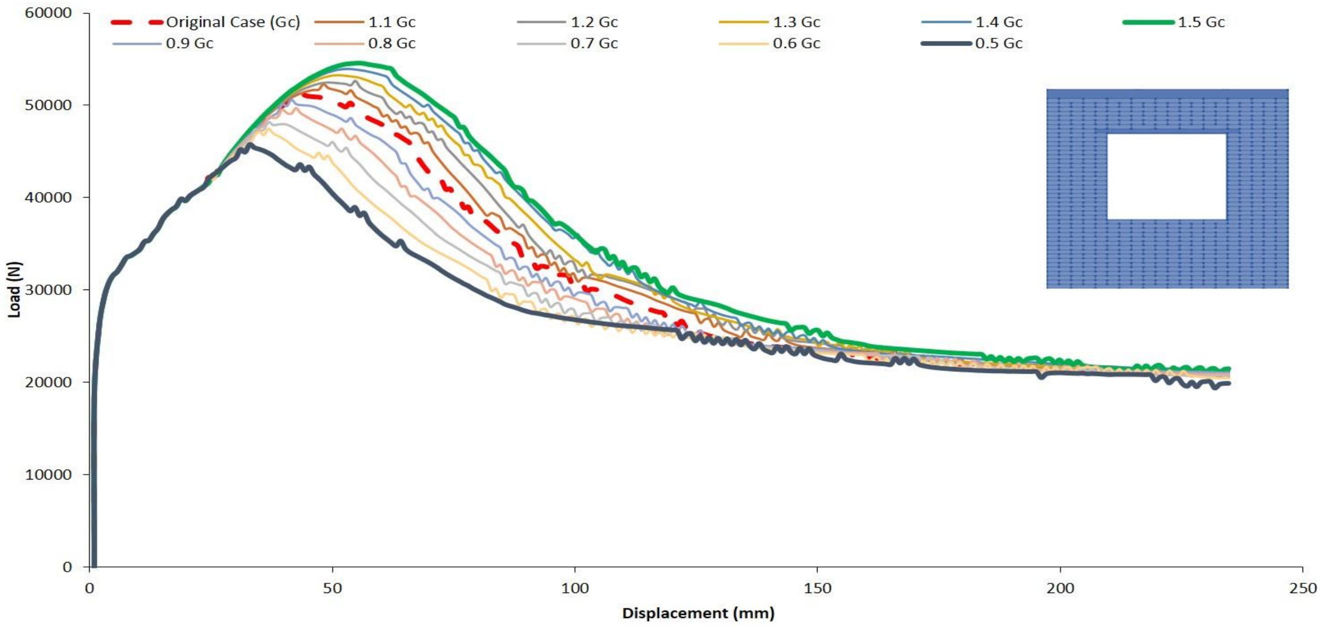


Figure 6. Influence of varied fracture energy in compression for Engineering Masonry model on load-response curves

3.3 Cracking parameters

In this section, different cracking parameters such as bed-joint strength, head-joint strength fracture energy in tension, residual tensile strength, and angle between stepped diagonal crack and bed-joints are evaluated to investigate the response of the masonry wall. In all the cases, the cracking parameters are increased and reduced to 5% of the original case. Bed joint (f_{tx}) and head joint (f_{ty}) are signified as horizontal and vertical spaces in the brick as shown in Figure 1. The bed joint and head joint strength is varied in the range $25x10^4$ to $37.5x10^4$ N/m^2 and reduced to $25x10^4$ to $17x12.5^4$ N/m^2 respectively as shown in Figure 7 and Figure 8. Friction-based head joint friction is utilized to examine its effect on the response of the wall. The cracking and crushing in the direction normal to the head joint are taken into consideration in addition to the failure in the direction normal to the bed joint and the shear failure. The fracture energy in tension and residual tensile strength is increased from 18 to 27 N/m and $5x10^4$ to $75x10^3$ N/$m^{2,}$ and reduced from 18 to 9 N/m, $5x10^4$ to $25x10^3$ N/m^2 as shown in Figure 9 and Figure 10. The angle between the crack and bed joint (α) as shown in Figure 11 is varied from 0.21 to 0.654 rad. It is observed that the variation of cracking parameters is significantly less on the load-response curve of the wall as shown in Figure 7-11.

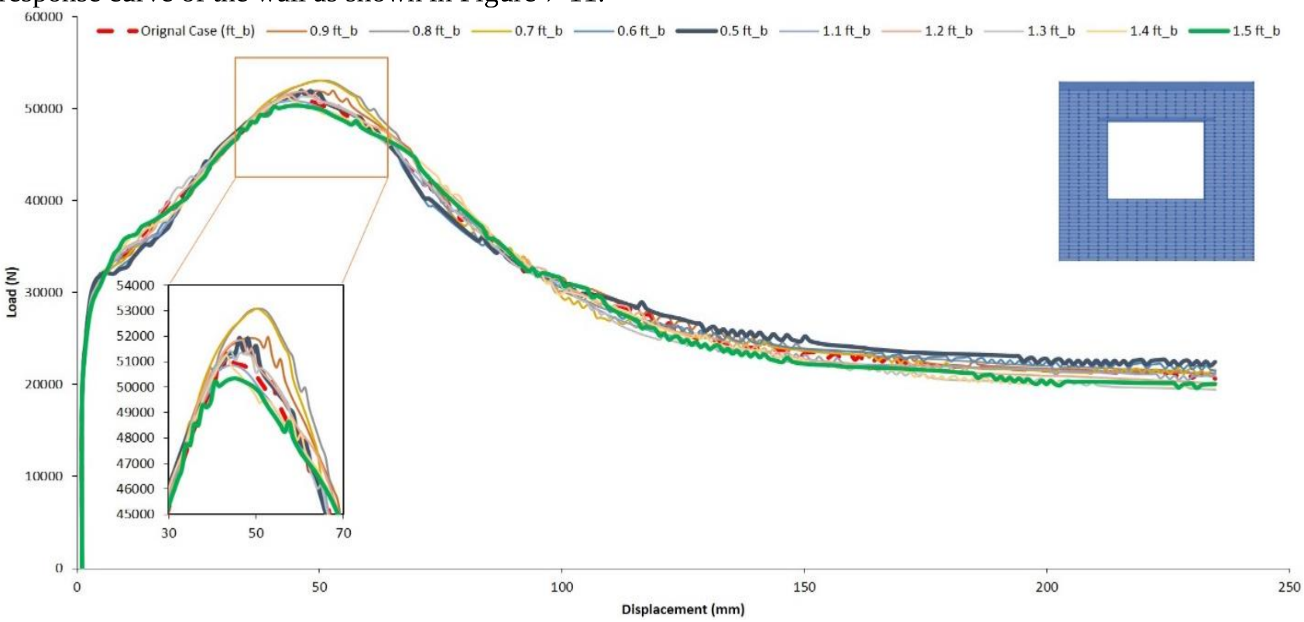


Figure 7. Influence of varied bed-joint strength for Engineering Masonry model on load-response curves

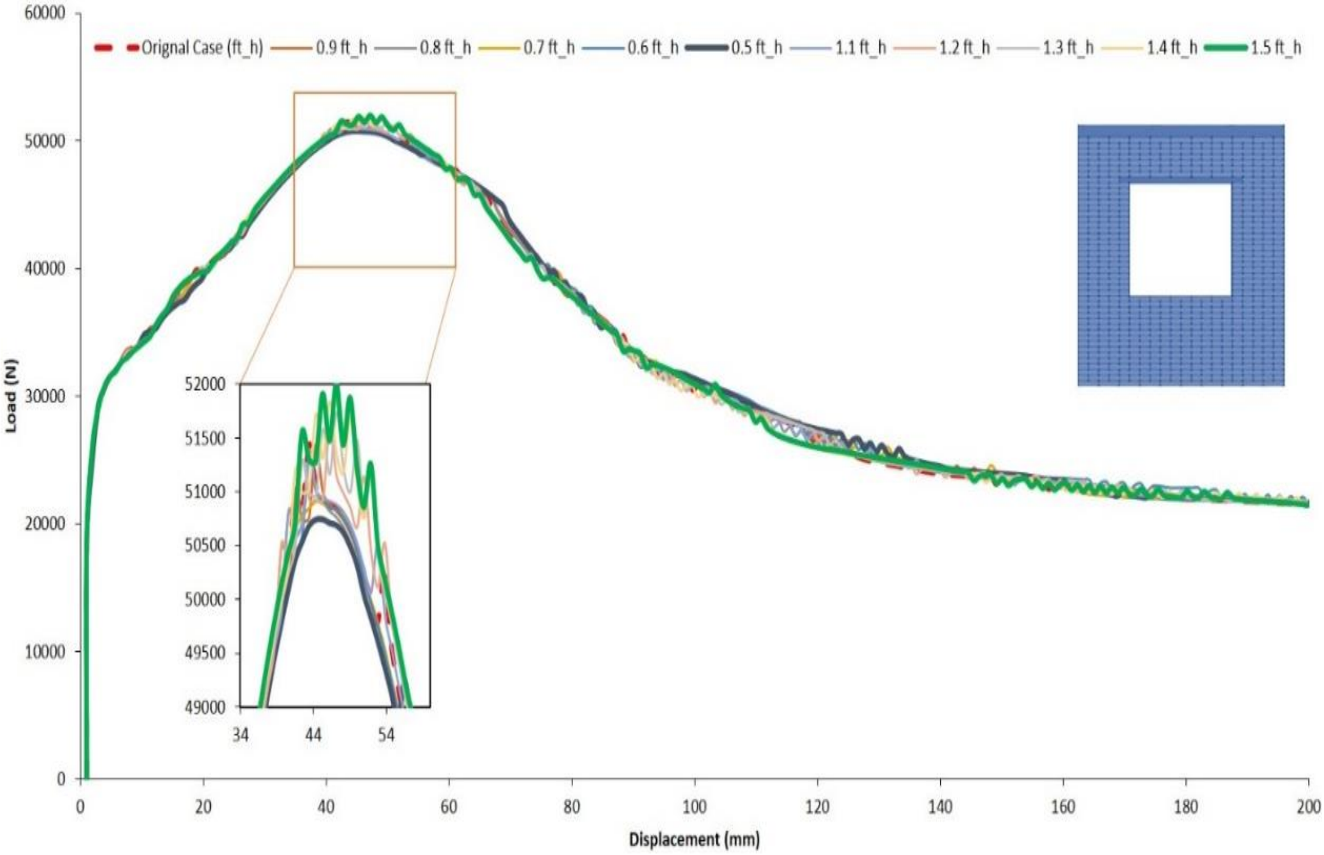


Figure 8. Influence of varied head-joint strength for Engineering Masonry model on load-response curves

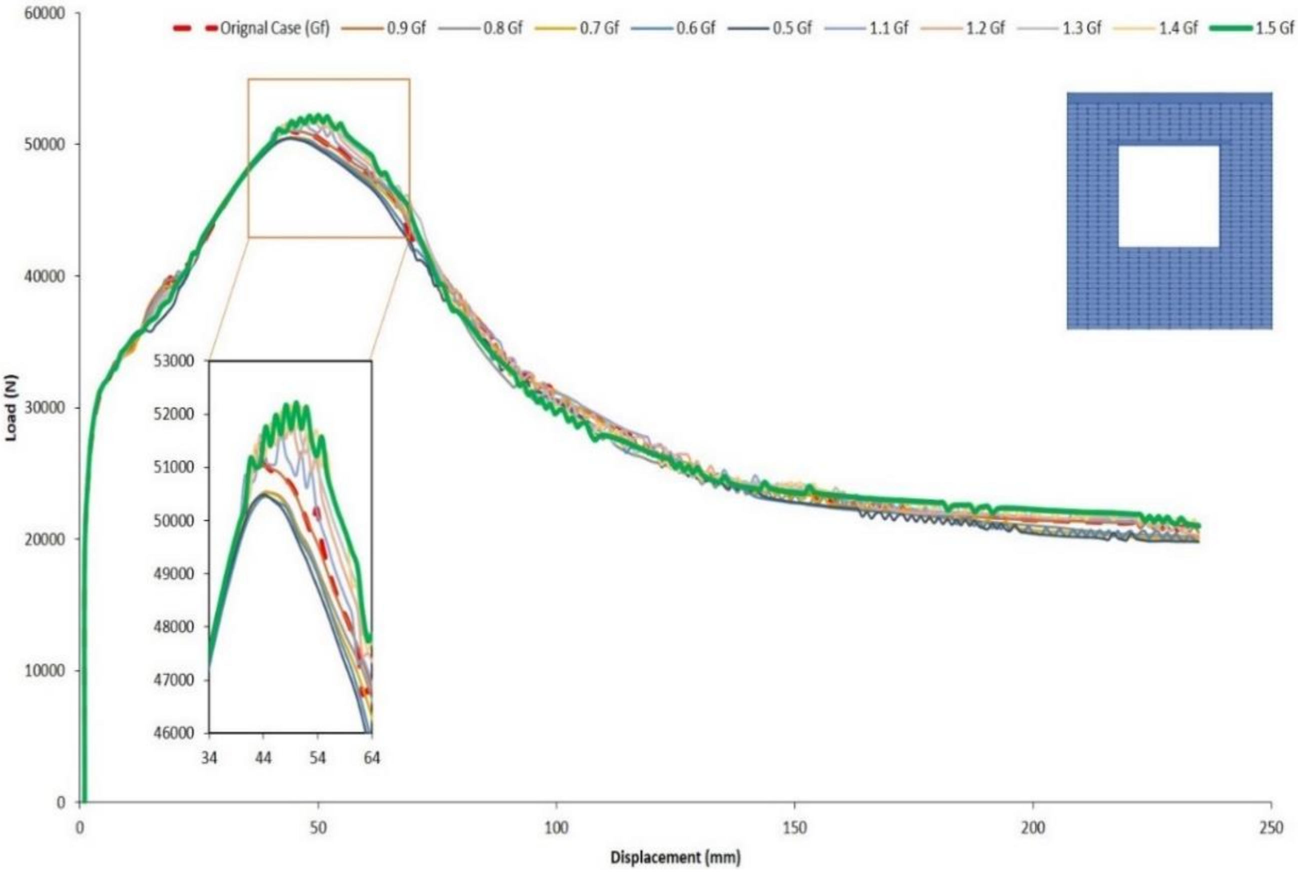


Figure 9. Influence of varied fracture energy in tension for Engineering Masonry model on load-response curves

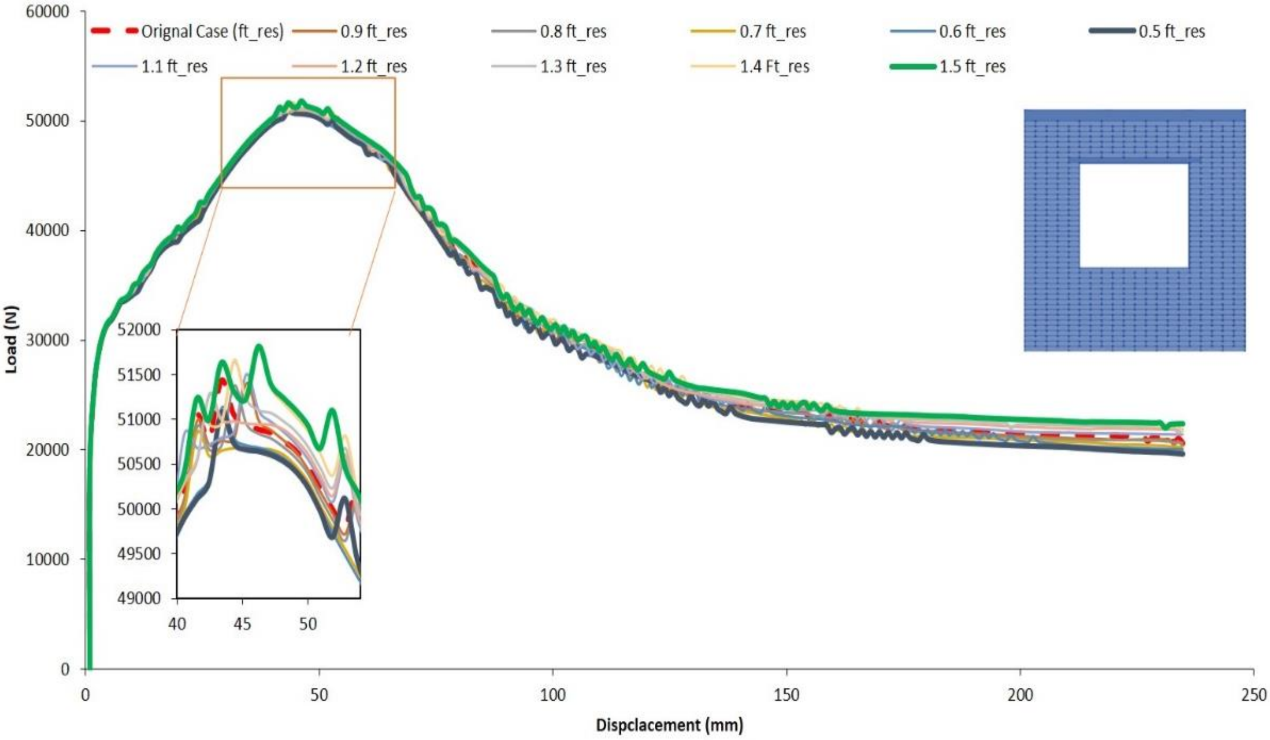


Figure 10. Influence of varied residual tensile strength for Engineering Masonry model on load-response curves

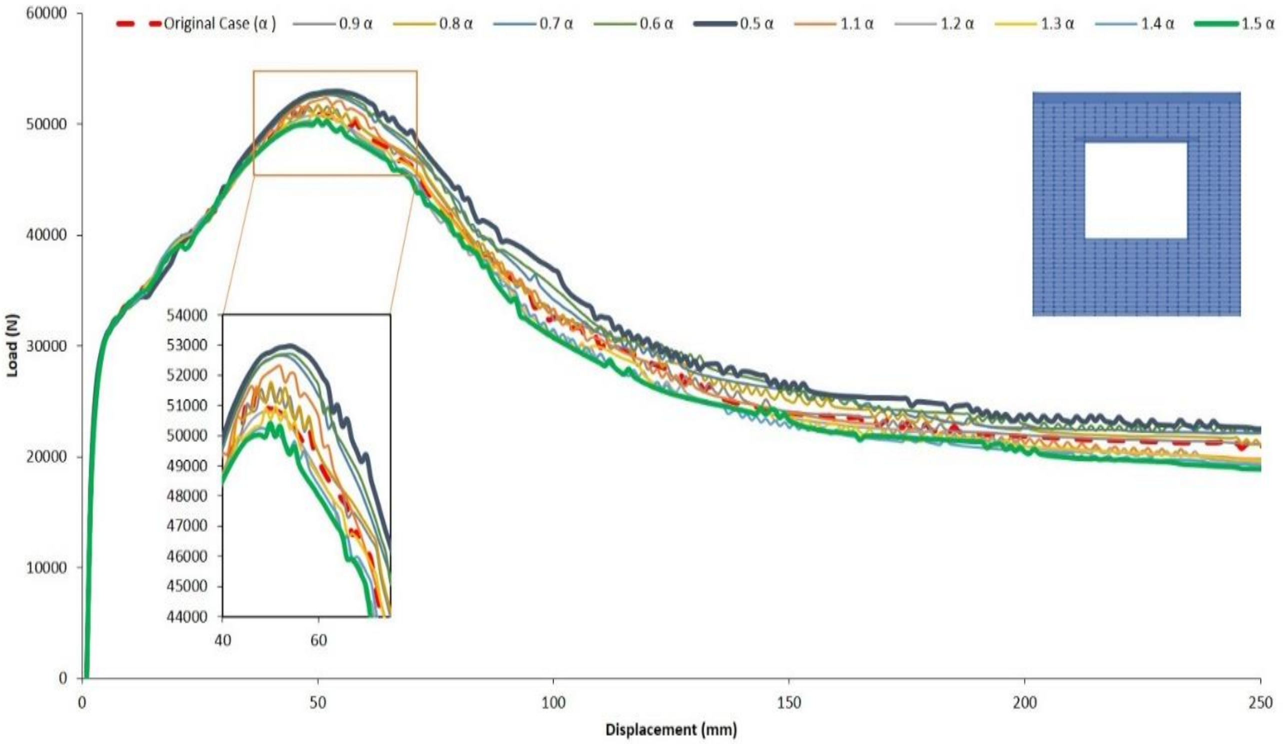


Figure 11. Influence of varied angle between stepped diagonal crack and bed joints for Engineering Masonry model on load-response curves

3.4 Shear failure parameters

In this section, different shear failure parameters such as friction angle, cohesion, and fracture energy were examined to study their effect on the load-response curve. The Engineering Masonry model incorporates the shear failure mechanism based on the typical Coulomb friction failure criterion [14]. The friction angle and cohesion are varied in the range from 0.312 to 0.963 rad and 17.5×10^3 to 52.5×10^3 respectively. The fracture energy in shear is varied from 125 to 375 N/m. The effect of variation in shear failure parameters is considerably noticed when it is changed to 5% of the original case for friction angle and cohesion as shown in Figure 12 and Figure 13. The variation of fracture energy is significantly less as compared to other shear parameters as shown in Figure 14.

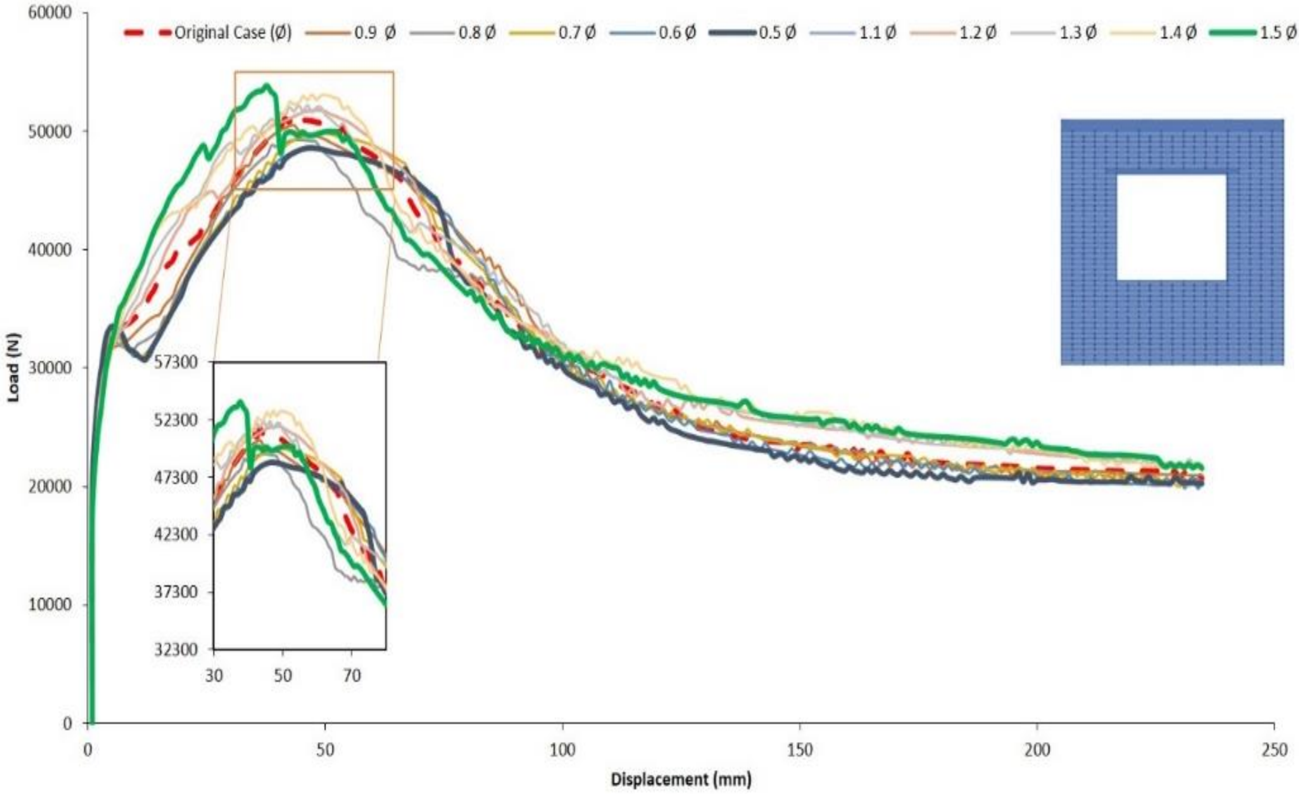


Figure 12. Influence of varied friction angle for Engineering Masonry model on load-response curves

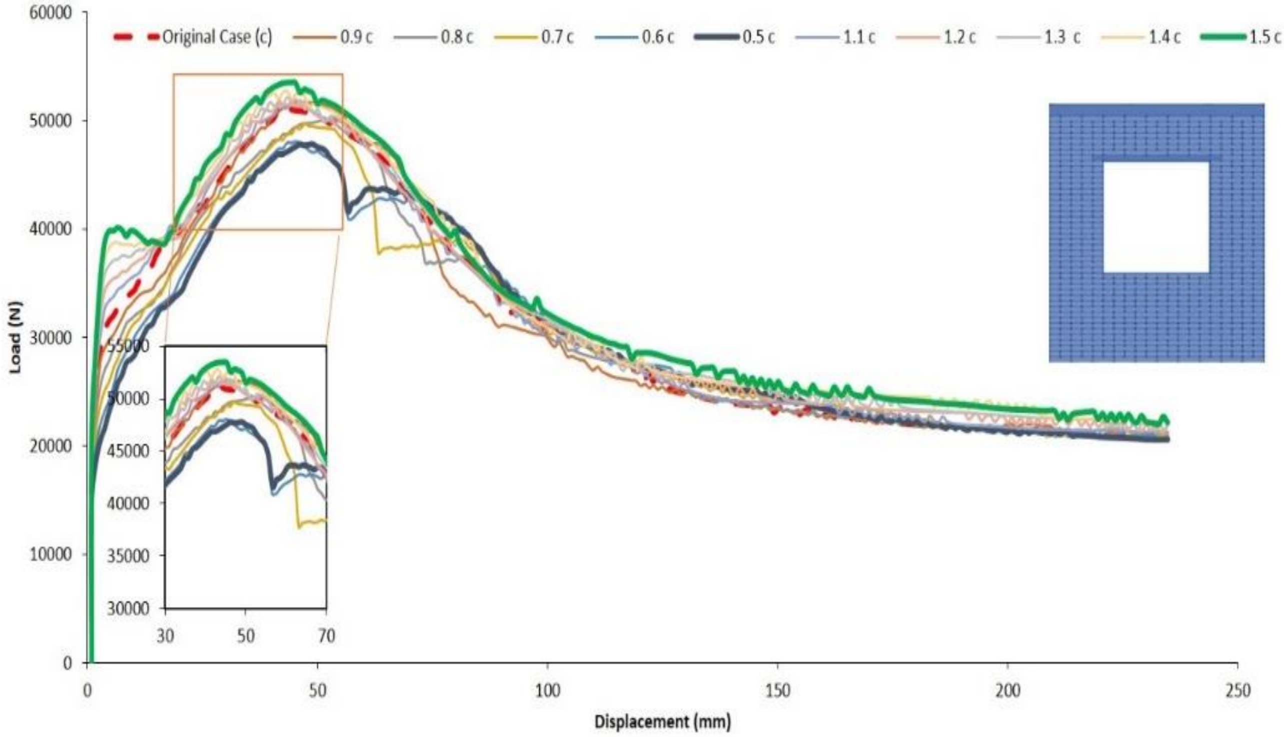


Figure 13. Influence of varied cohesion in shear for Engineering Masonry model on load-response curves

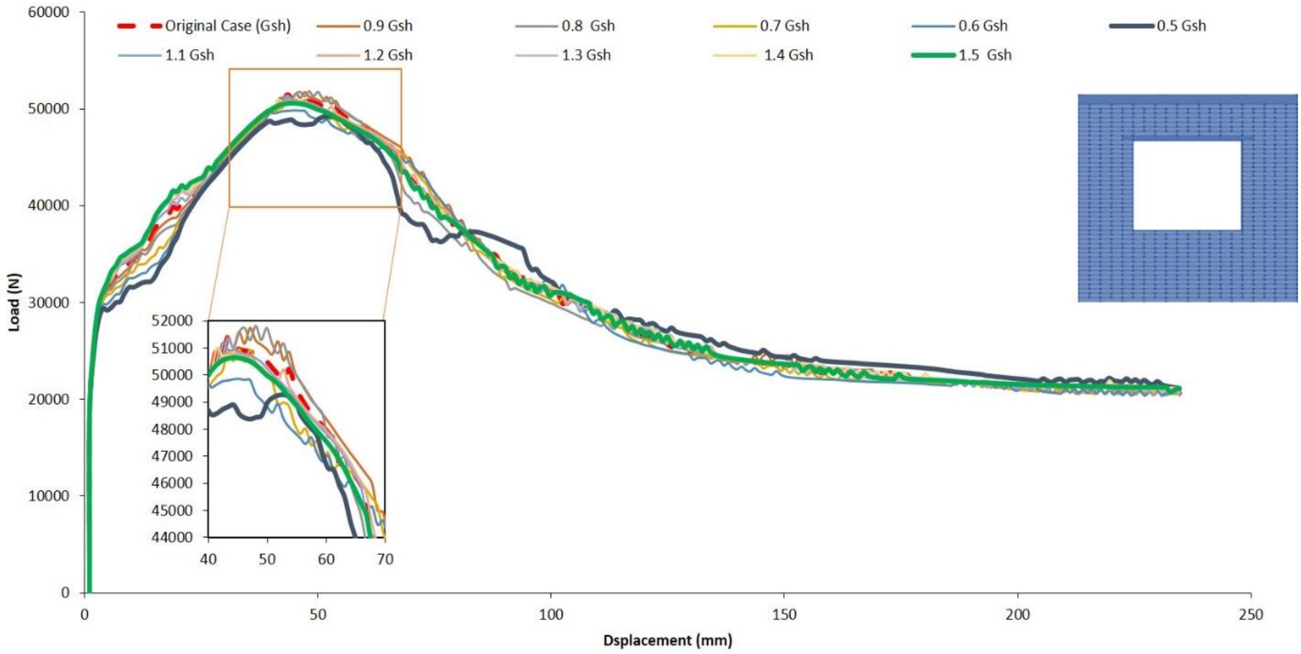
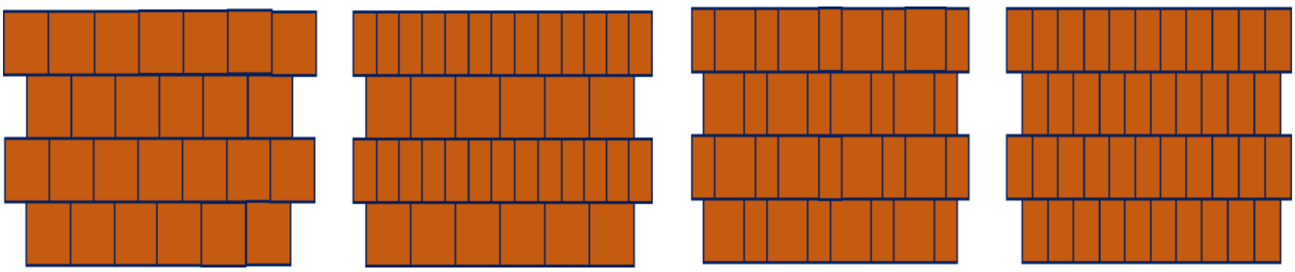


Figure 14. Influence of varied fracture energy in shears for Engineering Masonry model on load-response curves

3.6 Effects of different bond patterns

In this section, load response curves of numerical models with different bond patterns such as English header, stretcher, Flemish, and header as shown in Figure 15 were investigated to examine the load response curve with varied aspect ratios. Figure 16 shows the load response curves for models with an aspect ratio of one. The influence of bond type is not seen in this situation since the load response curves show no substantial change in peak load. Figure 17 depicts the models with an aspect ratio of 1.5. When compared to the load response curves of the remaining bond types, the Flemish bond has a larger peak load. However, the increase in peak load is not significant. Figure 18 illustrates all models having a 0.75 aspect ratio. When compared to other bond types, the Flemish bond has a larger peak load. The rise in peak load, like the load response curve in Figure 16, is not very substantial.

Figures 19, 20, 21, and 22 depict the influence of aspect ratio on the load response curves of various bond types. A similar pattern was seen for the four bond types investigated in this study. In all cases, models with an aspect ratio of 0.75 had a very high peak load, whereas models with an aspect ratio of 1.5 had a very low peak load. Damage contours for the stretcher bond for all the aspect ratios can be observed in Figure 23. The contours indicate that large compressive stresses were developing on the top left and bottom right sides of the walls. Significant stresses were being developed near the window openings. From the damage contours, it is observed that the model with an aspect ratio of 0.75 was under higher compressive stress at failure when compared to other models. The model with an aspect ratio of 1.5 has failed under lower compressive stress.



a) Stretcher Bond b) English Bond c) Flemish Bond d) Header Bond

Figure 15. Different bond types used in this study

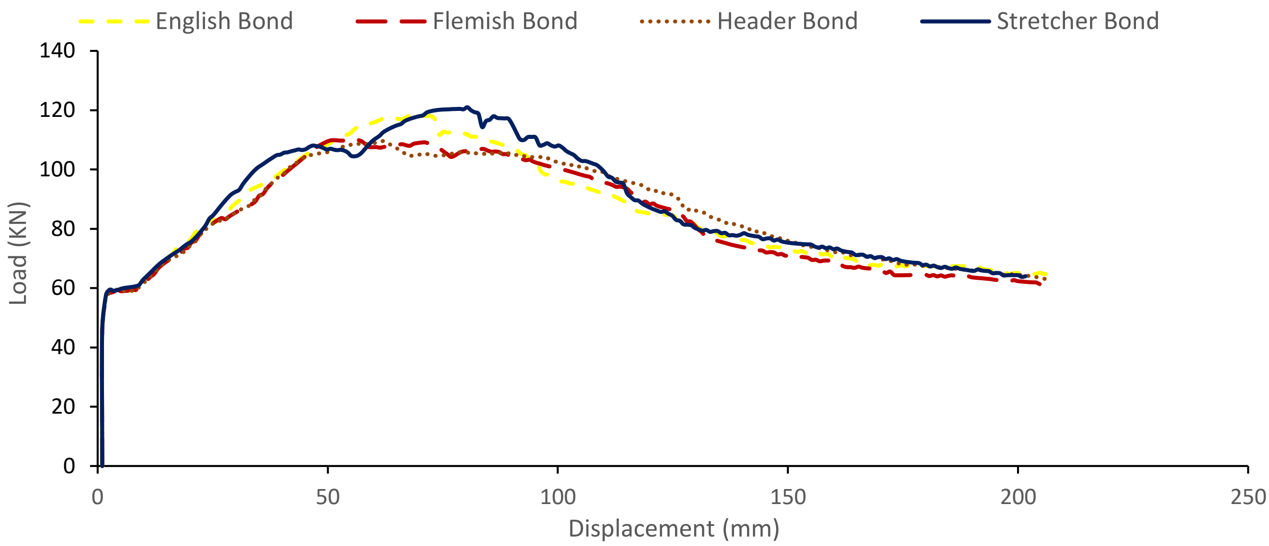


Figure 16. Load response curves of all the bond types with aspect ratio (H/L=1)

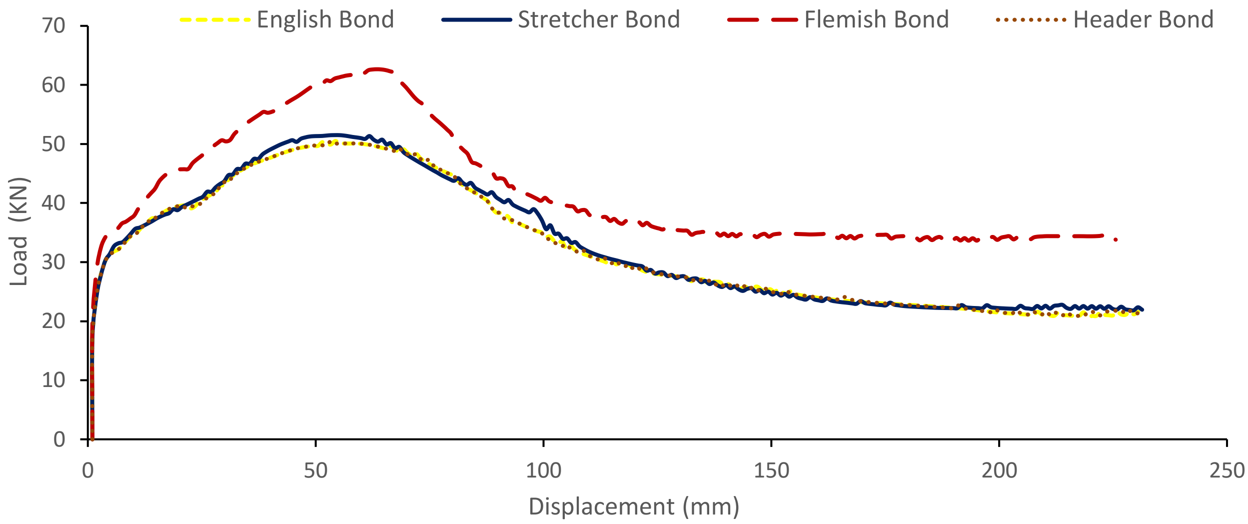


Figure 17. Load response curves obtained with an aspect ratio (H/L=1.5)

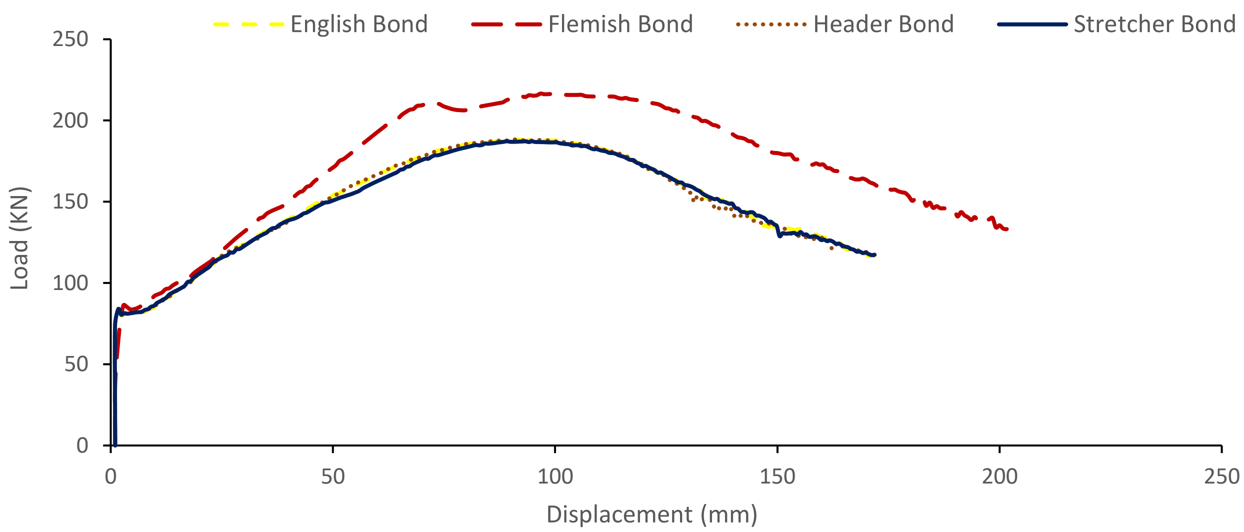


Figure 18. Load response curves obtained with an aspect ratio (H/L=0.75)

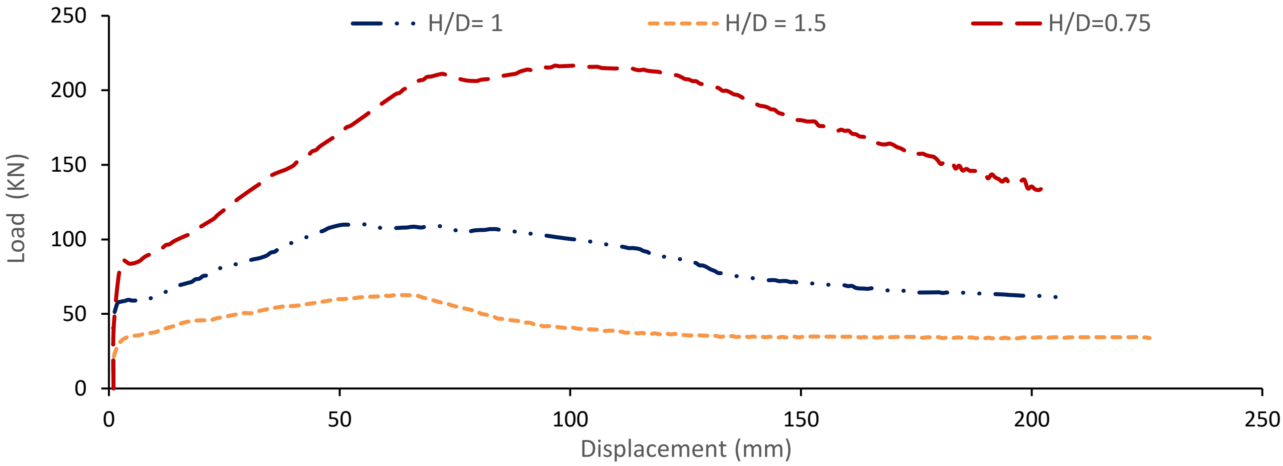


Figure 19. Load response curves obtained from the Flemish bond models with varying aspect ratios

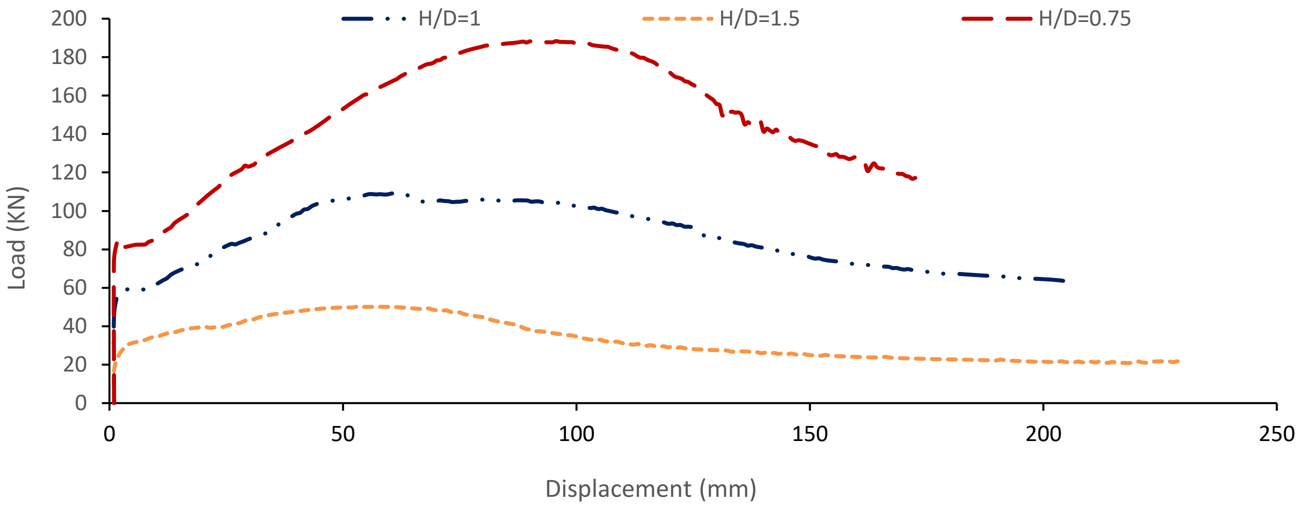


Figure 20. Load response curves of numerical models using header bond type with varying aspect ratios

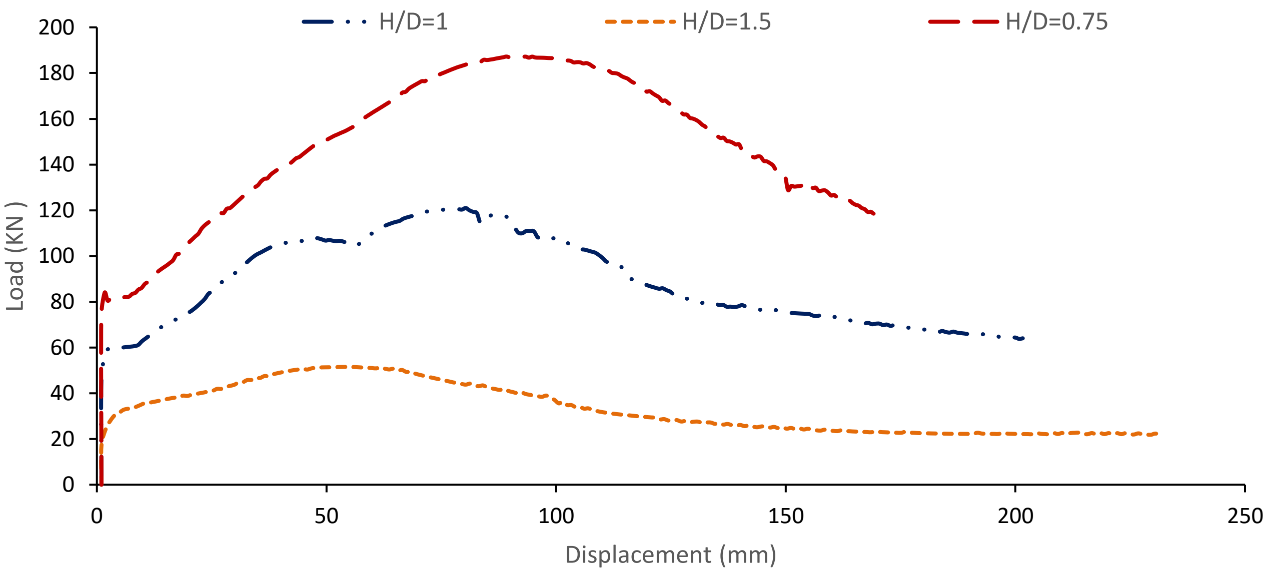


Figure 21. Load response curves of numerical models using stretcher bond type with varying aspect ratios

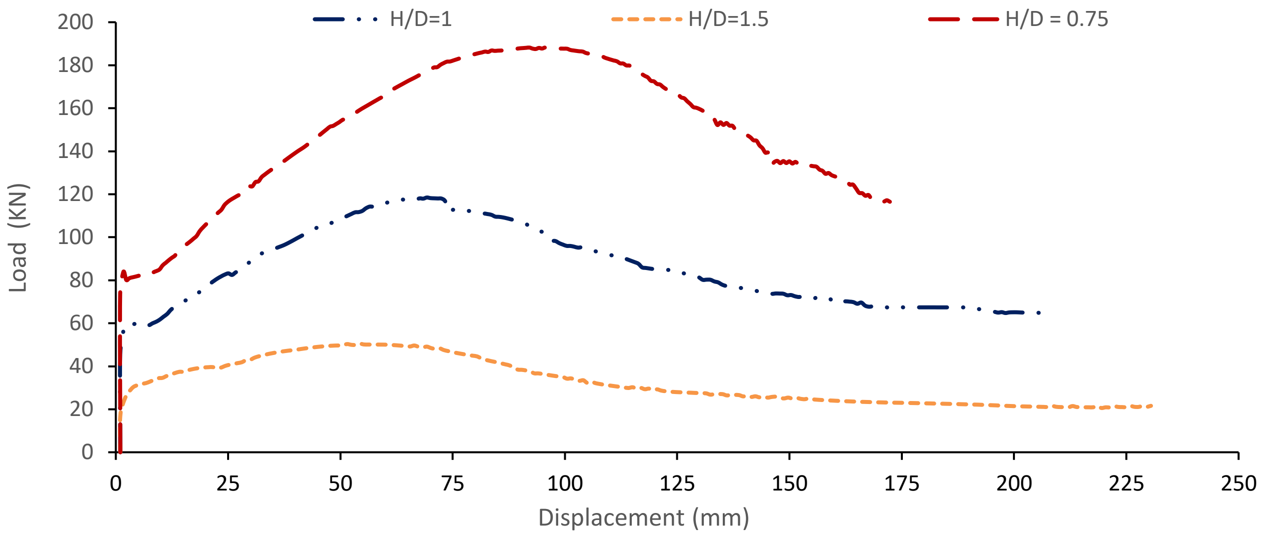


Figure 22. Load response curves of numerical models using English bond type with varying aspect ratio

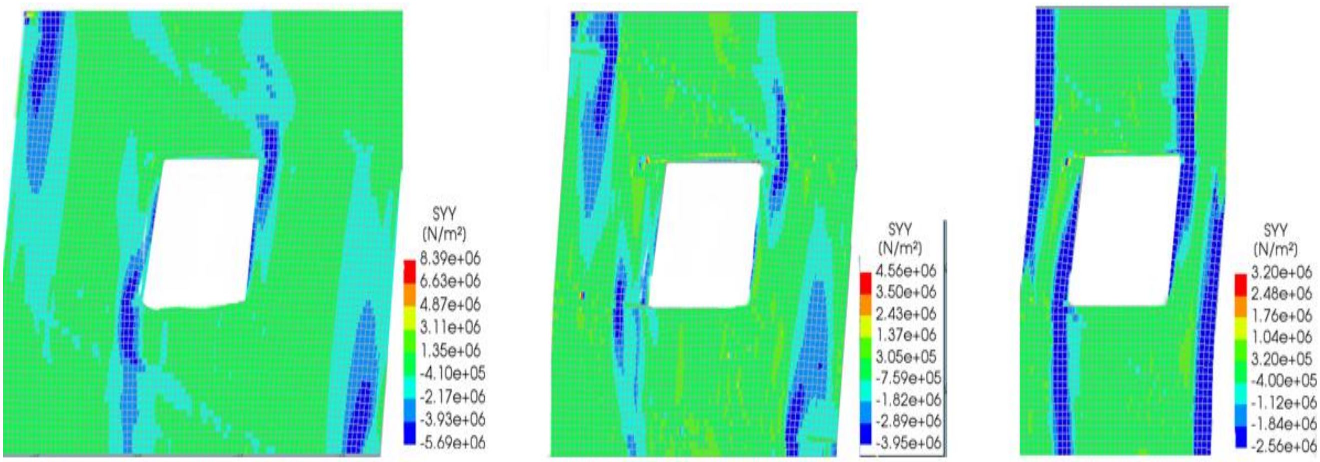


Figure 23. Damaged contours of stretcher bond models at failure for different aspect ratios

Conclusions

Seismic assessment of URM structures requires response predictions, which are inherently uncertain and associated with estimations of properties of the materials, the geometry, and the construction details. The absence of a standardized production process for bricks and construction practices for masonry across the world contributes to the uncertainty in building quality. Similarly, lack of access to structural designs and drawings of existing buildings, inadequate knowledge of material strength statistics, etc. can affect the knowledge of structural uncertainty. Finally, in current seismic codes, objective limit states are absent for individual masonry piers and masonry infill, thus presenting a challenge to the performance measurement process. Overall, these uncertainties present a challenge to the accurate evaluation of the seismic fragility of an unreinforced masonry structure. The current study evaluated, the response of a two-dimensional masonry wall with a central opening was simulated using the Engineering masonry model. The load response curve of the masonry wall was validated with the typical DIANA FEA example using static non-linear analysis four parametric studies, elasticity, crushing, cracking, and shear parameters were studied by varying the masonry properties by 5 % of the original case in increasing and decreasing order. The results reveal there is a significant influence on the lateral load response of the wall due to elastic, crushing, and shear parameters while other parameters such as cracking have less impact on the ductile capacity of the structure. Additionally, the results of bond patterns with different aspect ratios showed that as the aspect ratio rises, the strength of the walls significantly decreases and vice versa. In comparison to the other three bond types, the Flemish bond type has demonstrated notable strength at both lower and higher aspect ratios. Additionally, the damaged contours indicate regions near the wall opening are prone to cracking as those regions have shown higher compressive stresses when compared to the other regions of the wall.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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