Modeling of FRP Strengthened Masonry Wall under In-plane Lateral Loading

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Abstract— **Masonry is an old and commonly used building material in the world. However, due to its brittle nature, it is vulnerable to earthquake loads. Strengthening of masonry walls with fiber reinforced polymer (FRP) sheets is one of the techniques used to strengthen masonry walls. Numerical analysis is crucial to study the behavior of structures under various boundary conditions. This paper aims to numerically study and analyze the effect of fiber reinforced polymer sheets. In particular, various geometrical configurations of the FRP sheets on masonry walls are analyzed using the finite element modeling (FEM) approach. ABAQUS software is used for the finite element modeling. A macro-modeling approach is adopted for modeling masonry, in which masonry is considered as homogenous and isotropic continuum. Carbon fiber reinforced polymer (CFRP) sheets with different patterns are applied on masonry walls. Different configurations include: single diagonal, vertical, horizontal and FRP lamina on the whole wall. Cohesive interaction is used for the bond between masonry and FRP sheets. The analysis is performed under in-plane loading condition. The numerical results indicate that tensile stresses from the masonry are taken by the FRP sheets which significantly increased the strength of the wall. Numerical results also revealed that among different patterns of FRP sheets on masonry wall, single diagonal FRP pattern was efficient and more economical.**

Keywords—; Unreinforced masonry (URM), Fiber reinforced polymer (FRP), Macro-modeling, strengthening of masonry.

Introduction

Masonry is an old and commonly used building material in the world. Masonry is a body in which bricks or blocks are linked with one another using mortar. It has a composite behavior [1]and is used for structural and nonstructural walls. Although masonry has its stiffness but unfortunately due to its brittleness, it is most vulnerable against earthquake loads [2]. Humans have been victims of casualties in earthquakes due to structural damage in masonry structures. To reduce damage in masonry structures they must be strengthened. Additionally, for preserving the beauty of historical masonry structures, we need a smart and easy way to strengthen these structures is needed. Strengthening of such historical structures is one of the ways for maintaining these structures. There are numerous methods adopted for strengthening of masonry such as application of steel stripes on masonry wall [3], injecting epoxy and grouting [4], and using Ferro-cementing technique [5], etc. Furthermore, several other conventional methods for strengthening are adopted in which steel is used as strengthening material such as, shotcrete in which rods are embedded in cement mortar [6]. Strengthening of masonry is achieved by embedding FRP rods in the masonry wall [7 ,8].

Now a days fiber reinforced polymers, which has high elastic modulus, ductility, corrosion resistance, and low weight, is getting greater attention in the area of strengthening and retrofitting. FRP composite consists of high strength fibers which are enclosed in resin. The tension is resisted by fibers and the load is transmitted among the fibers by resin [9]. In the last decade, investigations have been performed to determine the usefulness of the FRP application [10,11] on masonry buildings for improving their seismic performance. Researchers used different approaches for improving the resistance of masonry to shear. FRP composite has largely been utilized for enhancing the lateral strength of masonry elements. Masonry retrofitted with FRP laminates and subjected to monotonic loading indicated that near surface and externally bonded FRP laminates on masonry walls enhance the shear capacity of masonry walls [12]. Studies have shown that the lateral load carrying capacity of unreinforced masonry (URM) increases using FRP composites [13, 14]. For enhancing the lateral load carrying capacity and resistance to deformability in URM walls, the FRP retrofitting technique also showed great effectiveness [15, 16]. [17] Performed experimental tests on masonry walls to investigate the influence of FRP on the lateral load capacity of masonry walls. It was observed that the lateral load taking capacity has significantly increased. [18] Applied Polyurea on masonry for increasing its resistance to in-plane loading. [19] Performed experimental tests on full scale six masonry walls, consisting of a control wall specimen and another wall which was used to study the repair techniques. For the remaining walls unidirectional E-glass /epoxy or carbon/epoxy FRP layers on one or two sides were used. Axial loads as well as incremental in-plane horizontal cyclic loads were applied on the walls. The experimental results showed a remarkable increase in strength, ductility, and stiffness using FRP on the masonry wall. Masonry elements strengthened with FRP composite have also given good response when subjected to loadings produced by earthquakes, wind storms, etc. [20]. Experimental study conducted by [21] for increasing the shear strength of URM wall using FRP on both faces of masonry wall, confirmed the effectiveness of FRP application in enhancing the ductility, stiffness and shear strength. A study performed by [22] on masonry wall retrofitted with vertical FRP bars has shown seismic improvement of the wall.

On the other hand, limited studies have been performed on numerical simulation of FRP strengthened masonry. Although, studies have been performed by researchers on the finite element modeling of other different elements such as, [23] numerically studied the response of FRP strengthened concrete beams and columns and found that the finite element model is successful in the prediction of a column and beam failure load. Similarly, in order to numerically study the response of masonry structures, a finite element analysis is performed by different researchers. Two methods; Macro modeling and Micro modeling techniques are commonly applied, and both are proven appropriate for masonry [24]. Similarly, for simulating the non-linear behavior of masonry under in-plane loading [30] has used macro modelling approach, which has shown good agreement with experimental results. Numerical modeling of curved masonry structure retrofitted with FRP has shown that the Seismic capacity of curved masonry has increased in terms of their ductility and strength [25]. A recent study performed by [26] , in which numerical analysis of Masonry Arch bridge strengthen with FRP, showed an increase in the strength.

It can be concluded from the literature review, that there is a need of a finite element model to simulate FRP strengthened masonry under various boundary conditions. Such a model will be helpful to study not only the behavior/effectiveness of FRP strengthened masonry but also to determine the optimum configuration of FRP lamina. The objective of this manuscript is twofold. First to develop a computational scheme to model and analyze the effectiveness of FRP strengthened masonry using ABAQS software. Secondly, to find out which configuration of FRP sheets/strips is more effective when applied on the masonry wall to get the required strength. This study presents, three-dimensional macro modeling approach for brick masonry strengthened with CFRP sheets. Moreover, a numerical study is performed to study the effect of different configurations of FRP strips on masonry walls.

The paper is organized as follows. In the 2nd section Geometry, material model, and finite element model of strengthened as well as unstrengthen masonry wall is discussed. Section 3 presents the numerical results of the analysis. Validation of the numerical model and analysis results of FRP strengthened masonry wall are discussed. Section 4 briefly summarizes the main conclusions from the numerical study.

I. MACRO-MODELING OF MASONRY WALL REINFORCED WITH FRP

This section briefly presents the three-dimensional finite element model of masonry shear walls. First, a numerical analysis of URM walls having lateral loading is carried out. The numerical results are then validated against the experimental results of the unreinforced masonry wall. After that, the analysis of different configurations of FRP strip applied on the wall is performed for checking the influence of FRP strip on the lateral load-carrying capacity of masonry.

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A. Finite element model and Geometry of masonry wall

Numerical analysis is carried out on masonry shear walls, experimentally tested by [27]. The wall consists of 18 courses of clay bricks (210 x 53 x 100 mm3). The thickness of the mortar is around 10 mm. Boundary conditions include a compressive load (uniformly distributed) of 0.30 N/mm2 applied at the upper surface. A horizontal displacement of 20 mm is applied at the upper surface. Similarly, the bottom surface of the wall is given fixed support. A static analysis was selected. Figure 1a illustrates the dimensions and boundary conditions of the wall.

The macro-modeling approach was adopted for masonry modeling. Macro-modelling technique was used for understanding the overall resisting mechanism of walls. In addition, macro modelling is simple, and does not require a high processor computer. On the other hand, micro-modelling needs high processor computer and more computational time. Nevertheless, for more accurate modeling micro-modelling approach is preferred. The geometry of the wall was discretized using C3D4 elements, which is a standard three-dimensional solid deformable element in ABAQUS software with four nodes. The element type is tetrahedron. The finite element mesh consists of 1684 number of nodes and 6995 number of finite elements. Mesh convergence defines how many elements are needed in a model to ensure that increasing the mesh size has little impact on the output results. The mesh sizes for this analysis range from 10mm to 100mm. With reducing element size, the system output (stress, deformation) converges to a repeatable solution. Then approximate global size of the mesh was kept 50mm for the masonry wall. To avoid interlocking of the reduced integration was used in the finite element model. While setting the element type, reduced integration was selected. The finite element model with boundary conditions of the masonry wall is presented in figure 1b.

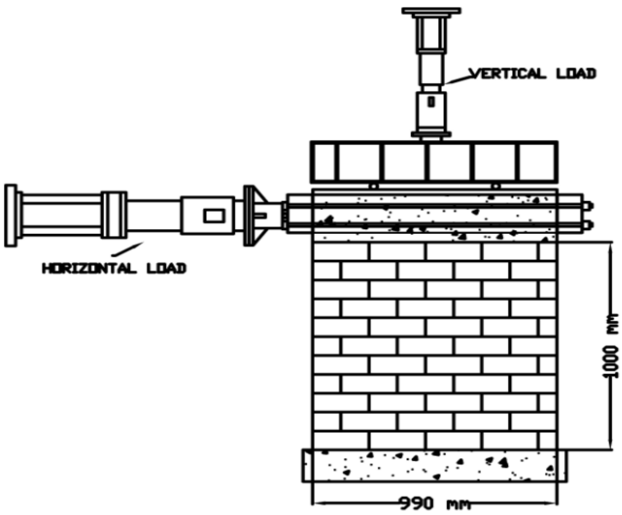


Fig.1 (a) Dimensions of the wall [adapted from 33]

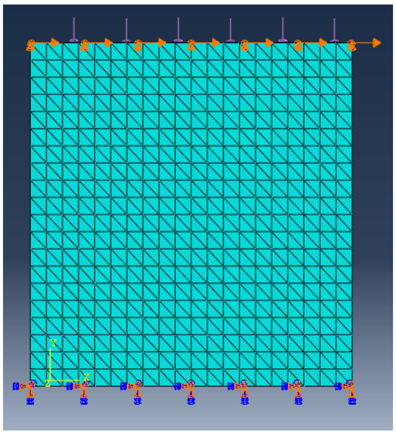


Fig.1 (b) Meshed wall with boundary conditions

B. Finite element model of FRP and its connection with masonry wall

The FRP lamina is modeled using a 3D shell element (S4R) available in ABAQUS/CAE. The thickness of FRP is taken as 2 mm, due to its easy availability in the market and width 200 mm. Although thickness is a variable. The load carrying capacity of lamina can be increased if the thickness is increased. The FRP was applied on both sides of the wall. The linear mesh of global size 40 was adopted for the FRP strip. Similarly, a surface-to-surface standard interaction was created between masonry wall and FRP strip, in which the surface of masonry is selected slave surface and surface of FRP is selected as master surface.

C. Material models

1) Material model for masonry

Masonry's constitutive behavior is modeled using a concrete damage plasticity model (CDPM) in Abaqus 6.1.4 software. Continuum damage plasticity model can simulate cracking and crushing (in tension and compression respectively). The model can simulate hardening behavior in compression as well as softening behavior when tension occurs [34]. The total strain tensor (ε) consists of an elastic portion (ε^{el}) and a plastic portion (ε^{pl}).

$$\dot{\varepsilon} = \dot{\varepsilon}^{el} + \dot{\varepsilon}^{pl} \qquad (1)$$

Whereas, the relationship between stress and strain is given as;

$$\sigma = (1 - d)\ D_0^{el} : (\varepsilon - \varepsilon^{pl}) = D^{el} : (\varepsilon - \varepsilon^{pl}) \qquad (2)$$

D_0^{el} Indicates the initial elastic stiffness of the material, D^{el} is the degraded elastic stiffness of the material; and d is the scalar damage variable. Due to cracking and crushing, a loss of stiffness occurs which is considered by the damage variable. The damage variable is related to the energy dissipated during fracture. For an undamaged material d = 0 and for fully damaged material d = 1. Properties used for macro-modeling of masonry wall are taken from [35] and are presented in table 1.

Table 1 Material properties

Table 1: Material Properties

2) Material model for FRP

Modulus of Elasticity	Tensile Strength	Compressive Strength	Fracture Energy	Dilation Angle	Poisson's Ratio
E	f_t	f_c	GFI	ψ °	ν
(N/mm2)			(N/mm)		
3000	0.35	7	0.1	20	0.15

The constitutive behavior of FRP is considered linear elastic in this research. The properties of the FRP lamina used for modeling are taken from [28] and which are presented in Table 2.

Table 2 Mechanical Properties of CFRP lamina

E_1	E_2	Nu_{12}	G_{12}	G_{13}	G_{23}
(MPa)					
124000	124000	0.3	5000	5000	3800

Where E= Elastic Modulus, Nu12= Poisson's ratio, G= Modulus of rigidity

3) Material model for the bond between masonry and FRP

The interaction between the masonry wall and FRP is modeled using a cohesive interaction feature available in the ABAQUS/CAE. Cohesive interaction behaves like a zero-thickness cohesive element [29]. In a cohesive interaction model, surface interaction between two surfaces is defined using the surface-based cohesive constitutive law. A bi-linear traction separation law is used to characterize the interaction between FRP and masonry wall. The traction-separation law represents the constitutive behavior of adhesive material. Material properties of the adhesive used in the simulation are taken from [30] and given in table 3.

Table 3 Adhesive Properties

Adhesive's Young `Modulus (Psi)	Shear Modulus of adhesive (GPa)	Stiffness Coefficients (N/mm3)		Maximum Shear Strength (MPa)		Fracture Energy (N/mm)	Thickness of adhesive (mm)
E	G	K_{nn}	K_{ss}	K_{tt}	τ	G	t
2.5×106	0.665	172369	6650	6650	2.84	0.9	0.1

D. Numerical examples

This section presents different numerical examples. First, a numerical analysis of the URM wall, on which in-plane lateral load is applied, is presented and the numerical results are validated against experimental results. After this, a series of numerical analyses are performed on masonry shear walls reinforced with FRP sheets which are attached to the wall in different patterns.

E. Numerical analysis of unreinforced masonry wall

Numerical analysis of URM wall under lateral load performed using ABAQUS. Figure 2 shows the contours of principal stress and strain on the deformed shape It is observed from the figure 2a that maximum stresses occur at the bottom left corner, top right corner, and in the middle. Tensile stress at the bottom left corner increases and moves up, with an increase in the load. At the remaining corners, compression has been observed. Furthermore, the strain contour shows maximum strain at the diagonal, thus a diagonal tension crack in the masonry wall can be expected.

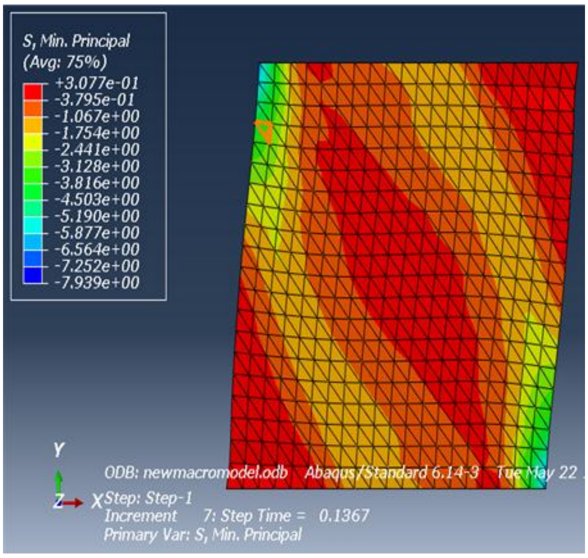
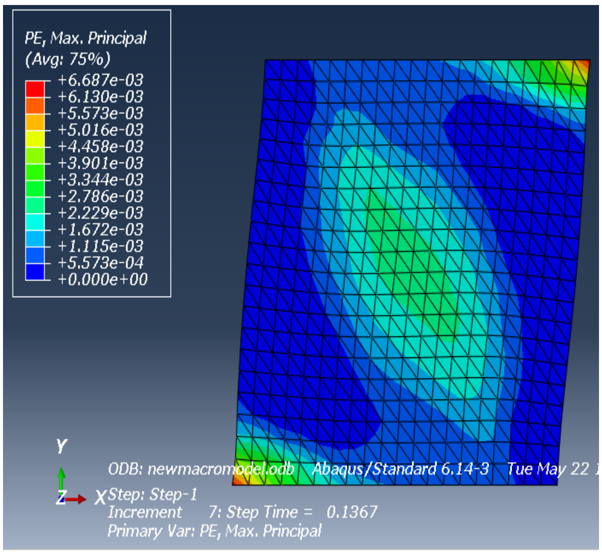


Fig2. (a) Stress contour of URM wall



(b) Plastic strain contour URM wall

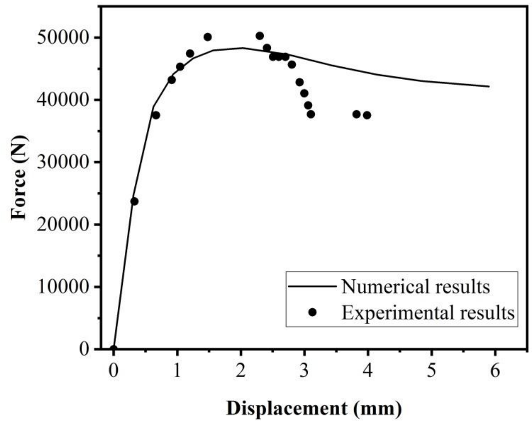
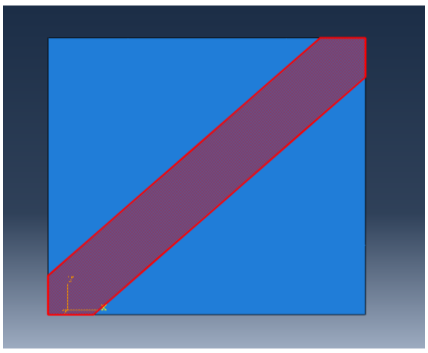


Figure. 3 Force versus displacement curve of URM wall

Figure 3 shows a comparison between numerical and experimental results. Experimental load-displacement data is taken from [31]. The peak value (maximum load carrying capacity) of the masonry wall is about 50 kN, which occurs at 2 mm displacement. The curve shows that the masonry wall fails after 2 mm displacement. The stress distribution and predicted the collapse mechanism of the wall matches the typical failure of brittle materials under lateral loads. Similarly, both the experimental force-displacement curve and numerical curve indicates that they are in good match with each other.

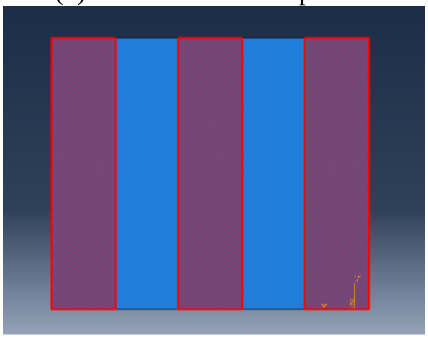
F. Analysis of FRP strengthened masonry wall

To examine the effect of FRP sheet strengthening and pattern of FRP application on masonry wall, numerical analyses with different patterns of FRP sheets on masonry wall are carried out. The different cases studied are single diagonal, horizontal, vertical, and FRP lamina on the whole wall. FRP sheets were applied on both front and back side of the wall.

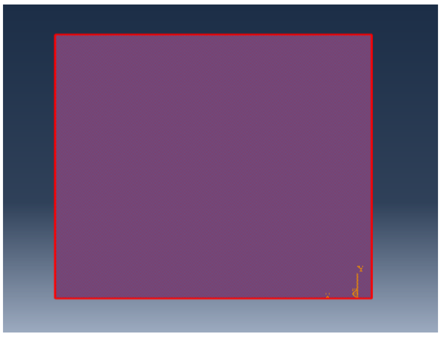


(a) Case 1: Single diagonal pattern

(b) Case 2: Horizontal pattern



(c) Case3: Vertical pattern of FRP



(d) Case 4: FRP on the whole wall

Figure 4. Different patterns of FRP application on masonry wall

1) Case1: Single diagonal pattern

It is observed from Figure 5a, that application of a diagonal FRP on masonry wall reduced the stresses compared to the case of unreinforced masonry, Figure 2a. Since the FRP lamina can take large loads when loaded in the fiber direction therefore in case of reinforced masonry wall the stresses are taken by the FRP lamina. From Figure 2a, it is clear that in an unreinforced masonry wall, the tensile stresses are maximum at the bottom left corner, at the top right corner and the center of the wall, but in case of FRP strengthened masonry wall having a diagonal pattern of FRP lamina, maximum stresses are reduced at the corners and the center of the wall. Moreover, the area of maximum stresses is also reduced i.e. stress distribution has occurred. Similarly, from the strain contour in Figure 2b, the plastic strain is maximum in the areas including bottom left corner, top right corner, and at the center of the simple masonry wall. While in the case of FRP strengthened masonry wall plastic strain has reduced. Furthermore, the diagonal tension failure, which was predicted in simple masonry, is resisted by this pattern of FRP application.

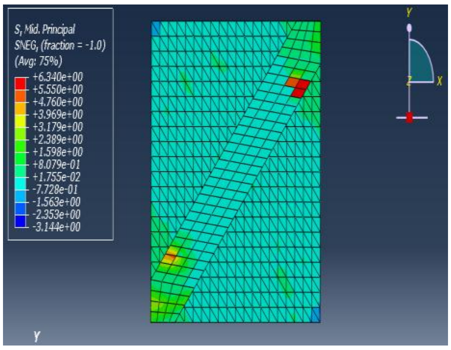


Figure 5. (a) Principal stress contours

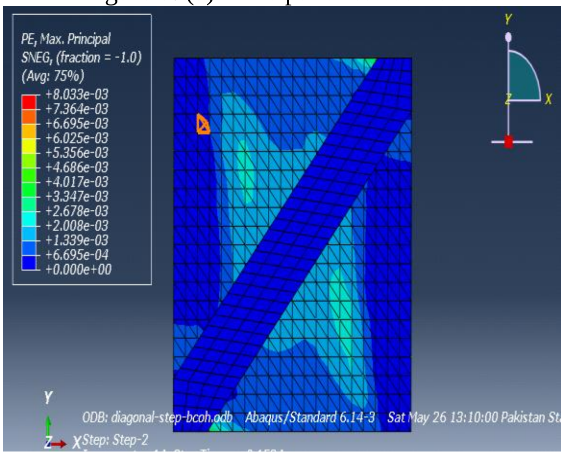


Figure 6. (b) Plastic strain contours on the wall strengthened by applying diagonal FRP lamina and subjected to lateral

2) Case2: Horizontal pattern

In this case, a horizontal pattern of FRP lamina has been applied to the masonry wall. The stress contours in Figure 6a shows that the stresses have transferred from masonry to FRP lamina. It can also be seen that the stresses are reduced in comparison to that of unreinforced masonry, Figure 2a. However, in the horizontal pattern, the masonry wall has larger stresses compared to the masonry wall strengthened with diagonal FRP pattern. In the case of the diagonal pattern, the stresses are distributed, and the stresses are large only at the corners. The strain contour (Figure 6b) indicates that strain is maximum just below and above the FRP sheet. It can also be predicted that in this case shear failure will occur just above the FRP sheet at the bottom left corner and just below the FRP sheet at the top right corner.

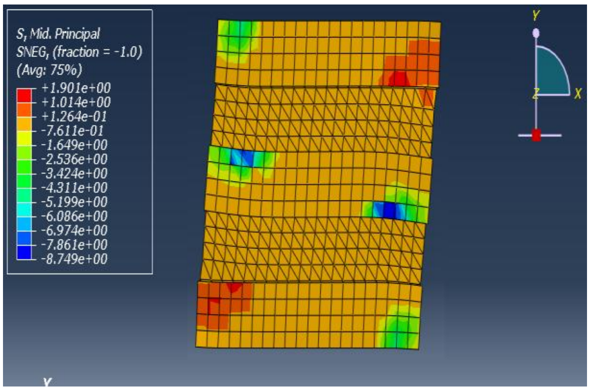


Fig 6. (a) Stress contours

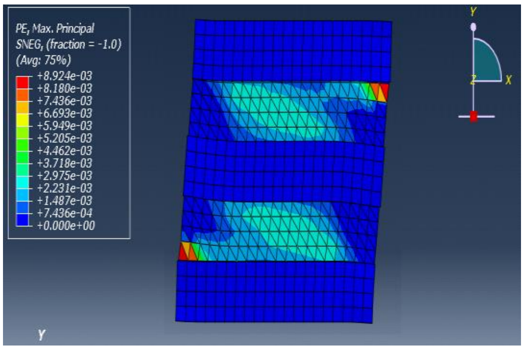


Fig. (b) Plastic strain contours on the wall strengthened by applying horizontal FRP lamina and subjected to lateral load

3) Case3: Vertical pattern

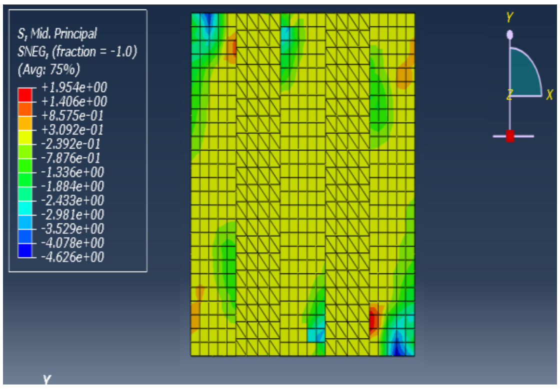


Figure 7. (a) Stress contours

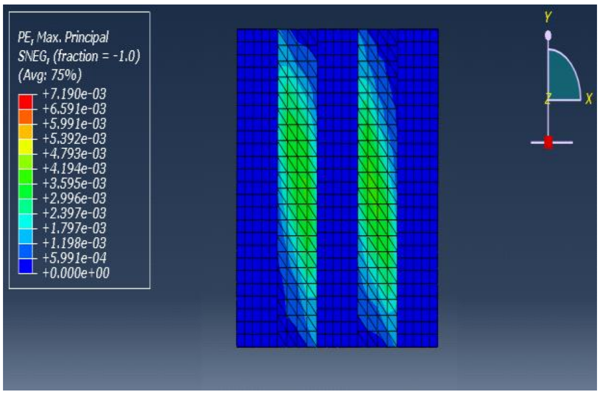


Fig. 7 (b) Plastic strain contours on the wall strengthen by applying vertical FRP lamina and subjected to lateral load

In this case, a vertical pattern of FRP lamina has been applied to the masonry wall. The stress contour is shown in Figure 7a. It is observed from the figure that the stresses have reduced in comparison to the stresses in case of an unreinforced masonry wall and the wall having the horizontal pattern of FRP sheets. However, in comparison to the wall having a diagonal pattern of FRP sheets, the stresses and strains are larger. Moreover, the results show that shear failure, which was predicted in the horizontal pattern, is not seen in this case.

4) Case3: FRP sheet on whole wall

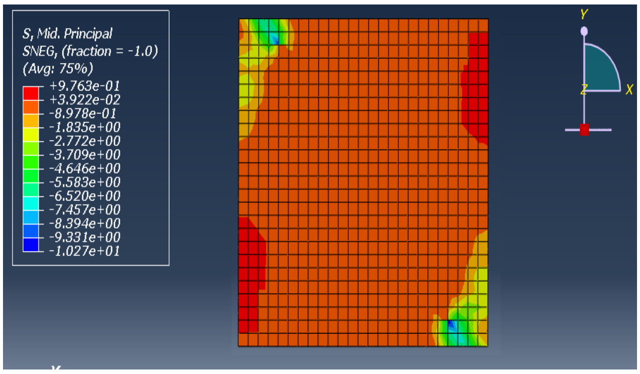


Fig. 8 (a) Stress contours

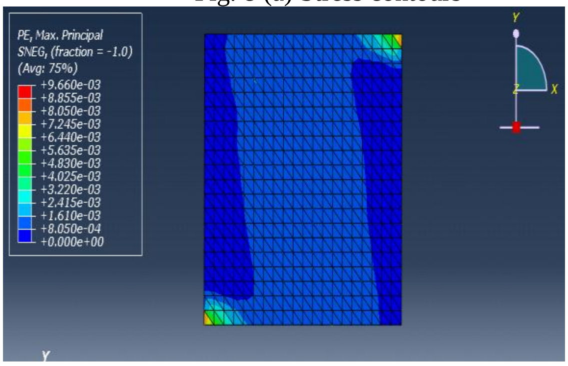


Fig8. (b) Plastic strain contours on masonry wall strengthened by applying FRP lamina on the whole wall and subjected to shear load

In this case, FRP lamina has been applied on the whole wall and the resulting stress contour is presented in Figure 8a. It is shown in the above figure that, FRP has taken a greater magnitude of stresses from the masonry wall. The stresses are more distributed in the middle portion of the wall, whereas maximum stresses are observed at the corners of the wall. Furthermore, in the case of FRP applied over the whole wall, the strains are significantly reduced due to FRP lamina in comparison to the strains in the case of an unreinforced masonry wall. Moreover, the strains in the middle portion are very small. In comparison to the diagonal, vertical, and horizontal FRP patterns, the area of maximum stress in the Case 4 (FRP on whole wall surface) is greatly reduced. This pattern gives the best results but the only problem with this pattern is that applying the FRP sheet on the whole wall is quite expensive.

Figure 9 compares the force-displacement response of masonry walls strengthened with different patterns of FRP sheets. It is observed from figure 9 that the application of FRP lamina on an unreinforced masonry wall improves the in-plane horizontal load carrying capacity of the wall. Figure 10 shows percent increase in strength of masonry wall after application of different patterns of FRP sheets. It can be observed from figure 10 that load carrying capacity has almost doubled using FRP on the whole wall. Similarly, the diagonal pattern, which needed only one sheet and is economical, has shown an increase of 55% in the lateral strength. However, vertical and horizontal patterns have shown less increase in the lateral strength. Moreover, it is clear from figure 9 that no failure occurred in the FRP strengthen wall at the horizontal displacement of 2mm as was observed in the case of the unreinforced masonry wall. Application of FRP sheets on masonry wall not only increased the strength but also increased the ductility.

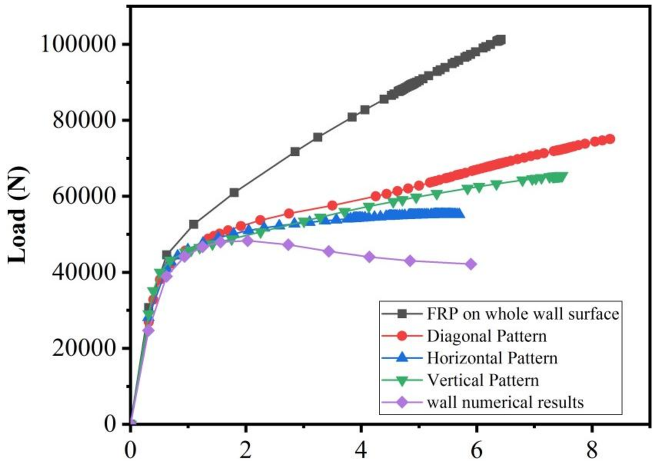


Fig 9. Force displacement curve of the simple masonry wall and masonry wall having different patterns of FRP sheet

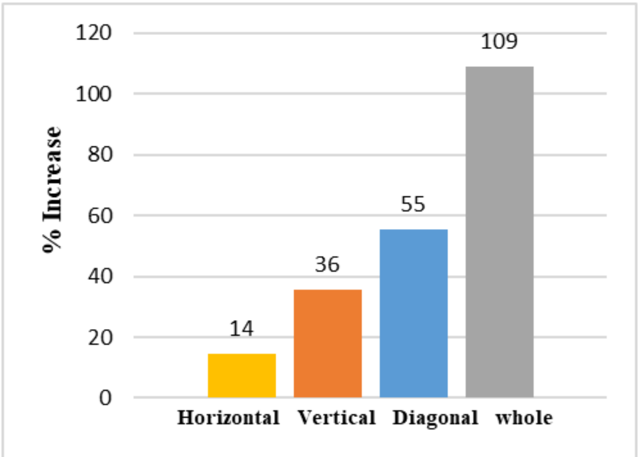


Fig. 10 Lateral strength increases in masonry wall after application of FRP sheets

G. Conclusions

This study presented modeling and analysis of Carbon fiber reinforced polymer strengthened masonry wall using the finite element method. The analysis is performed using ABAQUS software. Different patterns of FRP lamina were investigated for strengthening the masonry wall.

Overall, each pattern of FRP on the masonry wall showed an increase in the lateral strength of the masonry wall and demonstrated that the application of FRP was efficient. The results indicated that stresses from masonry were taken by the FRP sheets. FRP on the whole wall has almost doubled the strength of the masonry wall. Similarly, the diagonal pattern has shown an increase of about 55% in the lateral strength. The vertical and horizontal pattern has shown an increase of 36% and 14% respectively.

However, using the FRP sheet on the whole wall surface is relatively more expensive compared to other patterns of FRP application. On the other hand, applying diagonal pattern is observed to be economical among all the patterns investigated in this paper, because only one strip of FRP is used diagonally on the wall surface which significantly enhanced the lateral strength and ductility of the masonry wall.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Author contributions

Tahir Ahmad: Investigation, writing original draft, formal analysis. Zeeshan ullah: Writing, review and editing. Awais Ahmed: Conceptualization, Methodology, Project administration.

Availability of data and material

Not applicable

Compliance with ethical standards

All the accepted principles of ethical and professional conduct have been followed in this manuscript, in order to ensure the objectivity and transparency in research.

Consent to participate

Not applicable

Consent for Publication

Not applicable

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