Comparison of Efficiency of Shotcrete and FRP System for Strengthening of Masonry Structures by ABAQUS Software

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Abstract

A high percentage of buildings made worldwide are buildings made of masonry materials, which are often built before the development of the latest seismic design criteria and have weak shear strength inside plane and bend outside. In this paper, by understanding the necessity of strengthening masonry structures against earthquakes and comparing the system of repair and seismic strengthening of buildings with masonry materials, the ability of both shotcrete and FRP system has been evaluated and simulated. The results of finite element analysis of a sample of brick buildings modeled in ABAQUS software have been compared with the results of tests performed on unreinforced and masonry buildings and reinforced brick buildings with reinforced concrete coating. Also, in order to investigate the effect of strengthening with FRP layers on the seismic performance of unreinforced masonry walls, several masonry walls reinforced with FRP layers were modeled at the same time and with the same behavior as damaged concrete with plastic properties in compressive and tensile loading. The effect of each of these characteristics has been investigated by comparing the hysteresis and energy-time curves. The results show that the shotcrete reinforcement method, improves the final strength and ductility of the masonry wall, has weaknesses such as imposing additional mass on the foundation and the need for manpower and special equipment, which leads to exorbitant costs. FRP plate due to features such as high strength and low weight, immunity against corrosion, and easy and fast installation; it has become a suitable alternative to traditional methods for seismic retrofitting.

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1. Introduction

The importance of repairing, improving and strengthening structures in is not hidden from anyone. The most important thing is that they comply with the relevant criteria and standards such as EN1504 and ACI 440. Obviously, the design, calculation, preparation of executive details and implementation of restoration projects requires sufficient knowledge and special expertise. With regard to this point and considering the shortcomings such as poor workmanship that exist in the field of construction of structures and their repair and improvement and strengthening in construction industry and considering the large amount of capital that is spent on such projects and the importance of this matter, this research is compiled. This research aims to model the seismic behavior of shotcrete and FRP reinforced masonry structures with Abaqus software. Many reinforced concrete structures in the world have suffered major damage due to contact with corrosive agents. This has resulted in high costs for repairing, rebuilding or replacing damaged structures around the world. This issue and its consequences are sometimes considered not only as an engineering issue, but also as a serious social issue Hamada, et al. (1992). Repairing and replacing damaged concrete structures has resulted in millions of dollars in damage worldwide. In the United States, more than 40 percent of highway bridges need to be replaced or rebuilt Ehsani (1993) and Bedard (1992). For each building and its structure, a suitable safety margin is considered at the time of design, i.e. the design level is above the duty level and the building and structure are designed so that in emergencies they can perform slightly heavier tasks without damage and or do so with minimal damage. The technical useful life of a building may be due to wear and tear or gradual corrosion of the materials used in it or due to accidents and incidents such as earthquakes that lead to a significant reduction or loss of safety margin and its destruction and reconstruction is necessary. Or the economic useful life of the building may be terminated due to changes in the biological needs of its operation or due to changes in environmental conditions and require its demolition and replacement. In general, considering the consequences of demolition and reconstruction of buildings, it can be accepted as a general principle that this solution should be considered as the last solution and when it is considered that other solutions do not work and meet the needs. The main points in the reconstruction of structures damaged by the seismic loads are: 1- Complete demolition and reconstruction requires more time than rehabilitation. 2- Demolition of every small part of the building requires collecting, transporting and storing materials from the demolition and reconstruction of the building.

Various methods have been developed to strengthen masonry structures in the past, including: 1- Restoration and reinforcement using sprayed reinforced concrete (shotcrete) or sprayed mortar (Gunite). 2- External pre-stressing to increase bearing capacity. 3- Using steel to reinforce the wall by providing and drilling holes (about 2 inches) and inserting reinforced bars in the walls.

In civil engineering, strengthening means increasing the resistance of a structure against the forces applied. All buildings that have not been constructed according to the current principles and rules of building design regulations need strengthening, which are in two categories: 1- Those prior to the compilation of the relevant by-laws, they were designed and constructed, and at the time of their construction the suitable building regulations were not existed 2 - Those that have been built in recent years, but unfortunately due to the negligence of employers and their lack of knowledge of the principles of construction, the structures were not efficiently constructed. From a practical point of view, it is not possible to rehabilitate all buildings in terms of time, cost, durability and implementation strategy. Therefore, we divide the buildings into two categories: 1- Vital buildings that due to the variety of uses and the use of them, it is not possible to transfer equipment and on the other hand must maintain their function after the earthquake. Such as security centers, telecommunication and television stations. 2- Buildings that do not have special conditions at the moment but are needed as relief centers after the earthquake. Like some sheds and mosques Jalili (2006). The most common method of strengthening masonry buildings is to use shotcrete on the walls. This layer, in addition to creating proper coherence in the masonry walls, also increases the strength and ductility inside and outside the walls. In this method, first a rebar mesh is placed on the wall, which must be fastened to the wall with epoxy and bolts. Then, concrete or mortar is sprayed on this rebar mesh. The rebar network with the sprayed concrete acts like a layer of reinforced concrete and improves the seismic behavior of the wall.

Composites are materials that are made up of more than two parts: microscopic components and insoluble in each other. In the past, civil engineers have worked with a variety of composites. In a general classification, composites can be divided into two categories: natural composites and polymer composites Mostofinejad et al. (2004).

The small filaments called microfiber are joined together in different ways so that they are fully engaged so that when tensile force is applied, if some of them are torn, they can transfer the force to other fibers. These strings, called strands, are then woven together in different ways Qods, A (2003). The fibers in the composite are mainly elastic and brittle and are the main load-bearing member. Therefore, it is the fibers that form the mechanical properties of FRP such as strength, modulus of elasticity, etc. and have high resistance and tensile strength Darya Beygi (2005). The diameter of these fibers is between 5 and 25 microns depending on the material. Fibers are available today in various shapes, sizes and materials Mostofinejad et al. (2005).

2. Materials and Methods

In this research, studies and analyzes have been performed on FRP-reinforced masonry walls in order to calculate their shear capacity and also modeling and strengthening brick masonry structures with reinforced concrete (shotcrete) to evaluate the torsional performance of the building. Abaqus software and finite element method have been used for modeling and analysis of structures. In the finite element method, the structure in question is divided into discrete shapes called elements. These elements are connected at specific points called nodes. The finite element method is a numerical instruction for solving physical problems that are described by the differential equation. This method has two features that distinguish it from other numerical methods: 1- In this method, an integral formulation is used to create a system of algebraic equations. 2- In this method, smooth functions are used in continuous pieces to approximate unknown quantities.

2.1. Finite Element Method and ABAQUS Software

The finite element method can be divided into five main steps: 1. Dividing the area in question into a large number of sub-small areas, called elements. 2- Determining the initial approximation for solving as a function with unknown constant coefficients that is always either linear or second order. After determining the order of the initial approximation, the governing equation is written in each node. 3- Extraction of algebraic equations system: The weight function for each node is specified and then the residual weight integral is formed. By integrating, an algebraic equation is created for each node, which after extracting the equations of all nodes, the system of equations is created. 4- Solve the system of created equations. 5- Calculation of other quantities from node values Hoffman (2001).

Among the many softwares based on finite element method, one of the most reliable and powerful softwares that engineers and researchers use as a useful tool to meet their needs is ABAQUS. From version 6.3 onwards, this software does not need to write commands to create, meshing and solve the model, and with the features of the ABAQUS / CAE environment, the model can be fully created and analyzed. The evaluation of the results can be done after the completion of the processing stage, i.e. when the stresses, displacement and other basic variables have been calculated. Evaluation is usually done using visual modules or other post-processors. The visual module reads the data of the binary output file and has various options such as color contours, animation, modified form or graphical data to display the results. ABAQUS includes an extensive library of elements that can model any type of geometry virtually. The program also includes an extensive list of material behavior models that can simulate the behavior of most engineering materials such as metals, rubber, polymers, composites, reinforced concrete, brittle foams, and even geotechnical materials such as soil and rock Hoffman (2001).

2.2. Analytical Modeling of Masonry Wall and Reinforcement with FRP

Two unreinforced masonry walls and four GFRP-reinforced masonry walls loaded with cycling loading inside the plane have been examined (for a school building). To strengthen the walls, two types of horizontal and diagonal arrangement of FRP layers have been used. The walls are made of real scale and made of hollow clay bricks. The FRP strips used are made of carbon woven fibers. Dimensions and mechanical characteristics of fibers, building units and concrete used are presented in Table 1.

Table 1. Properties of the Material Used in this Research

Compressive strength of bricks	11MPa	Thickness of FRP	0.13 mm
Mean shear strength obtained from diagonal pressure test	0.85MPa	Tensile strength	35000 MPa
Mortar compressive strength	25MPa	Modulus of tensile elasticity	230000MPa

28- day compressive strength of - concrete beams above and below the sample	35MPa	Final tensile strain (%)	0.5
28-day compressive strength of concrete beams above and below the sample	13MPa	Dimensions of bricks clay	112x240x140mm

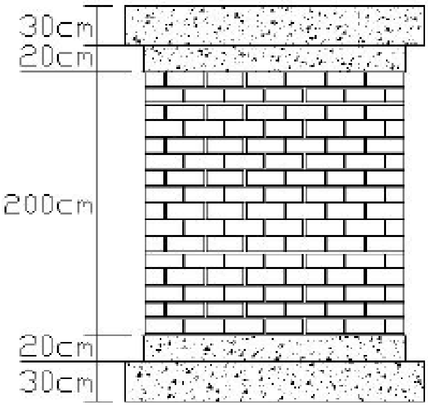


Figure 1; Dimensions of the Wall [11]

Six examples of masonry walls consist of two concrete beams at the top (150× 200 mm and 400 × 330 mm) and at the bottom's dimensions (150× 200mm and 400 × 300mm) for load transmission and wall support according to Fig. 1 were considered. The dimensions of the masonry wall are also (1975× 2000 × 140 mm) and the wall is reinforced horizontally (HRM) which has three horizontal CFRP strips with widths of 100 and 150 mm on each side of the wall and the other two walls are reinforced diagonally (DRM). They have two diameter strips with widths of 200 and 300 mm on each side of the wall and the other two walls are without reinforcement.

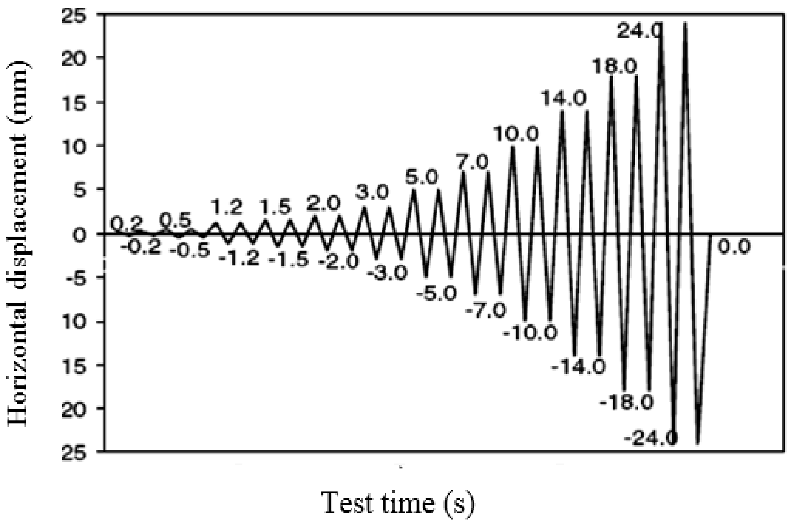


Figure 2; Lateral Loading Method in Cyclic Shear Test [11]

In this experiment, the walls were subjected to periodic shear force while simultaneously being subjected to a constant vertical force exerted by a hydraulic jack. The behavior of the experimental samples was controlled by deformation. Horizontal loading consists of two cycles per shift and starts from 0.2 mm and continues up to 24 mm; These amounts of displacement was provided that no rupture appeared in the specimen before the 24 mm displacement (Fig. 2). The amount of vertical force (98KN) is also considered. The walls were attached to the floor and had rotational freedom at the top. The amount of horizontal displacement above the transmission beam is calculated. In this experiment, the URM wall has a wide diameter crack, the DRM wall has several cracks, and the HRM wall has the highest crack distribution (Fig.3). DRM wall strength increased between 63% -84% and HRM wall strength increased between 57% -61%. In both cases, the increase in resistance was accompanied by an increase in the amount of reinforcing FRP. Failure also began in reinforced diagonal examples from the bottom of the wall with FRP layer delamination (Fig. 4).

a) URM Wall **b) DRM Wall** **c) HRM Wall**

Figure 3; Cracking of the Wall Samples [11]

Figure 4; Failure in Diagonal Bracing Reinforced Specimens Starts from the Bottom of the Wall [11]

2.3. Analytical Modeling of Masonry Walls

In this model, it is assumed that the response to uniaxial tension and pressure is controlled by the plastic failure criterion, as shown in Fig. 5. Due to uniaxial tensile stress, the tensile stress changes linearly to the point of failure, which coincides with the onset and expansion of fine cracks in concrete. After passing this point, the failures become visible cracks, which are displayed as a "softening" curve in the stress-strain region. Under uniaxial pressure, the response will be elastic until it reaches the yield point, and in the plastic region the behavior is generally expressed by the "hardening" curve, which eventually becomes a softening curve when it reaches the final stress point. This introduced model, despite its relative simplicity, satisfies the main properties of concrete ABAQUS (2003).

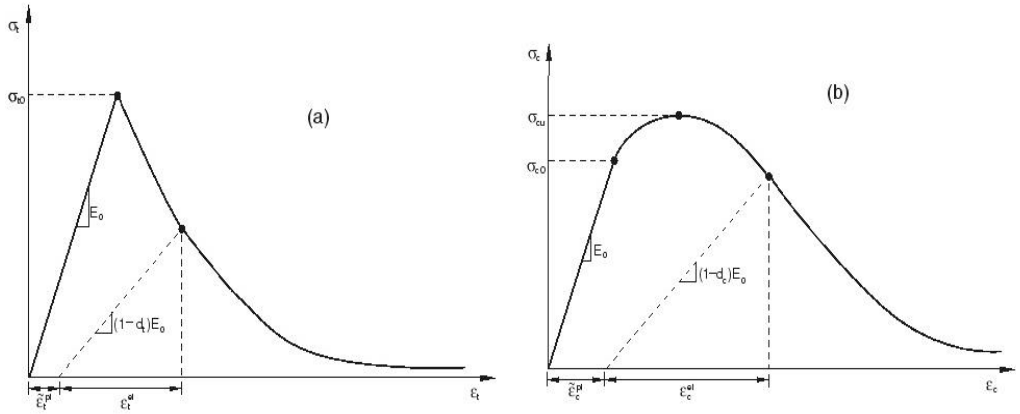


Figure 5; Response of Concrete to Uniaxial Loading in Tensile (a) and High Pressure (b) [12]

In periodic loading, decrement behaviors become much more complex. It has been experimentally observed that by changing the direction of loading, a certain amount of elastic stiffness is increased, which is known as the "one-way effect", which causes the cracks to close and the pressure hardness to be restored. This model uses a reduced modulus of elasticity.

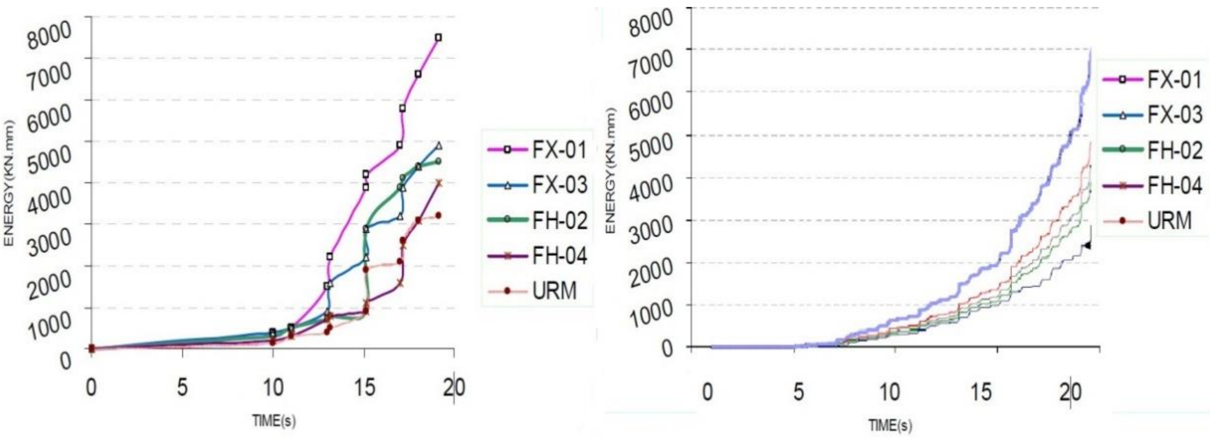
2.3.1. Interaction Properties, Loading and Application of Boundary Conditions of Masonry Wall Model

To determine the interaction properties between the model components (concrete base, wall body and FRP layer), two hypothetical constraints are defined. One constraint to introduce the type of contact surface between the edges of the wall and the concrete layer and another to determine the contact surface of the wall body and the FRP layer. Since the modulus of elasticity of the wall is less than the modulus of elasticity of the concrete base and FRP layer, so the wall is selected as the follower level and the concrete base and the FRP layer of the base level. Depending on the type of loading in the experiment, two steps are considered. One step is to apply a concentrated load and the other step is to load periodically.

2.4. Checking the Accuracy of Modeling

The accuracy of the modeling is checked by comparing the hysteresis curves and the energy-time curve obtained from finite element analysis and similar curves obtained from the experiment. The hysteresis loops show the relationship between the calculated lateral load and the displacement, so the lateral resistance can be obtained from the hysteresis curve Tamazevic (1997).

To evaluate the accuracy of the modeling, a comparison between the hysteresis and energy-time curves obtained from the FEM test and analysis was performed. Figure 6 shows the comparison between the energy-time curve obtained from the experiment and the analysis.



A) FEA Analysis **B) The Experiment**

Figure 6; Comparison between Energy-time Curves of Masonry Walls

2.5. Numerical Study

In order to study the effect of geometric characteristics and arrangement of FRP layer, in addition to the masonry walls in the experiment, it is necessary to model other masonry walls with different thickness and number of FRP layers and compare them with each other from different perspectives. Table 2 shows the specifications of all masonry walls modeled by ABAQUS software:

Table 2. Specifications of all Masonry Walls Modeled by ABAQUS Software

Number of FRP layers	FRP strip thickness (mm)	FRP strip width (mm)	Type of reinforcement	Sample name
Three rows on both sides	0.13	100	Horizontal	H100-13
Three rows on both sides	0.26	100	Horizontal	H100-26
Three rows on both sides	0.39	100	Horizontal	H100-39
A row on both sides	0.13	150	Horizontal	H150-1S
Two rows on both sides	0.13	150	Horizontal	H150-2S
Three rows on both sides	0.13	150	Horizontal	H150-3S
Four rows on both sides	0.13	150	Horizontal	H150-4S

Diagonal on both sides	0.13	100	diagonal	X-100
Diagonal on both sides	0.13	150	diagonal	X-150
Diagonal on both sides	0.13	200	diagonal	X-200
Diagonal on both sides	0.13	300	diagonal	X-300
Full coverage on one side	0.13	1975*2000	coating	1 Laminate
Full coverage on both sides	0.13	1975*2000	coating	2 Laminate

2.6. Modeling a Structure with Reinforced Concrete Coating (Shotcrete)

In this study, in order to investigate the effect of wall-to-wall connections on the torsional performance of a brick building, first two laboratory samples, the first of which was a not reinforced brick building and the second of which was reinforced with a reinforced concrete cover, were modeled in ABAQUS finite element software. Then the effect of wall to wall connections on the torsional performance of the brick building was investigated. The modeling of these samples in finite element software was of micro-model type. Also, for the accuracy of the modeling, the results of finite element analysis of the modeled samples were compared with the results of experiments. By comparing the two, there was almost a good agreement between the experimental results and numerical modeling of the samples.

2.7. Modeling of Laboratory Samples

Experimental samples selected to evaluate torsional performance and modeling accuracy include two one-story brick buildings that were tested by Tasnimi et al. (2007). The first example is an unreinforced brick building that was used as a base example. The second example is a brick building quite similar to the base example, whose walls are reinforced from the outside by a steel grid and a concrete cover. This sample was studied to investigate the effect of reinforcement on the torsional behavior of unarmed masonry. The two specimens were placed under a uniform torsional load. To simulate this torsional behavior, two concentrated forces were used at the corners of the brick building as shown in Fig. 7 Reza Zadeh et al. (2010).

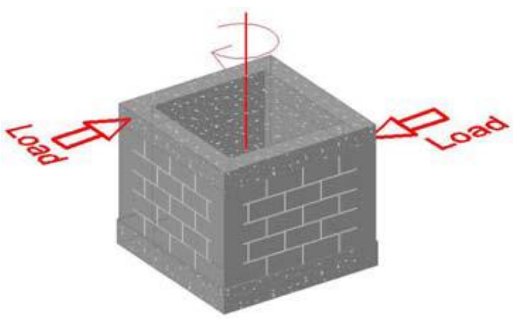


Figure 7; Location of Lateral Forces [15]

2.7.1 Modeling the Base Brick Building

In order to reduce the volume of calculations in micro-modeling, the mortar element was removed and its properties were considered as bricks element, in which case the thickness of the mortar is included in the thickness of the brick element. Behavioral models used for numerical modeling of laboratory samples in ABAQUS software are adhesive (mortar) element behavioral model, contact element behavioral model and concrete plastic damage (CDP) behavioral model, each of which is directly used in numerical modeling. Based on the standard tests of consumables in the base sample, the specifications of the materials used in the modeling are in accordance with Table 3:

Table 3. Engineering Specifications of Brick Building Materials [14]

Contact element specifications	Rate	Specifications of the adhesive element	Rate	Brick specifications	Rate
Contact friction coefficient	0.53 tgφ=	Elastic properties	Knn=240, Kss=96, Ktt=96 N/mm^2	Elastic properties	E=8080 N/mm^2
-	-	Density	ρ=0/0000023 N/mm^2	Density	ρ=0.0000021N/mm^2
-	-	Plastic properties	fn=0/058, fs=0/14, ft=0/14 N/mm^2	-	-

The mentioned building has dimensions of 202 x 202 cm, height of 150 cm and wall thickness of 22 cm. The thickness of mortars is considered as an average of 1 cm. It should be noted that in this model, due to the fact that in the experimental model, the vertical straps of the wall are filled with mortar, the same specifications are considered for the vertical and horizontal straps. Also, the gravity load of 8 tons and the weight of the concrete slab were widely applied to the upper surface of the concrete above the building, the value of this load is 0.07 MPa, which was entered statically. It should be noted that the loading of the wall is considered as explicit dynamics (Dynamic / Explicit). The ceiling of laboratory samples, which are of concrete slab type, was selected on both sides with a thickness of 15 cm. The analysis time for this model is 10 seconds, The weight of gravity from the second 0 to the second 5 has an increasingly linear effect on the structure and remains constant from the second 5 to the second 10. Also, the lateral load on the building increases linearly from 5 to 10 seconds to the wall. Fig. 8 shows the unformed modeling of the base brick building.

2.7.2. Modeling of Reinforced Brick Building

For numerical modeling of the reinforced sample, in addition to the specifications of the mentioned materials, for the modeling of the base sample, the specifications of concrete and steel mesh based on the standard tests performed in the laboratory according to Table 4 have been considered. Also, in the reinforced brick building, a 40 mm thick concrete cover has been applied on the outer surface of the brick building. To reinforce this concrete coating, according to the recommendation of publication 376, a mesh of plane Φ4 bars with 100 mm spacing distances has been used. This mesh of rebars is connected to the reinforced brick wall of the reinforced specimen by Φ6 restraint rods with maximum distances of 300 mm [16].

Table 4. Engineering Specifications of Reinforced Concrete Coating Materials for Reinforced Sample

Rebar reinforcement specifications		Concrete coating specifications	
Elastic properties	E=190000 (MPa), /ν=0.2	Elastic properties	/E=25000 N/mm^2 , ν=0.2
Density	ρ=0.00000785 (MPa)	Density	ρ=0.0000024N/mm
Poisson's ratio	Yield Stress =300(MPa), Plastic Strain=0, ν=0.3	Properties of plastic (concrete damage)	Dilation Angle=25, Eccentricity=0.1 f_{bo}/f_{bc}=1.16 K=0.67, , Viscosity Parameter=0

According to the above explanations, the modeling of the amplified sample was performed in the software, which is shown in Fig. 9.

It is noteworthy that in the base wall as well as the modeled reinforced walls, the initial cracks filled with epoxy and cementitious adhesive are considered.

Figure 8; Un-deformed Model of the Base Sample

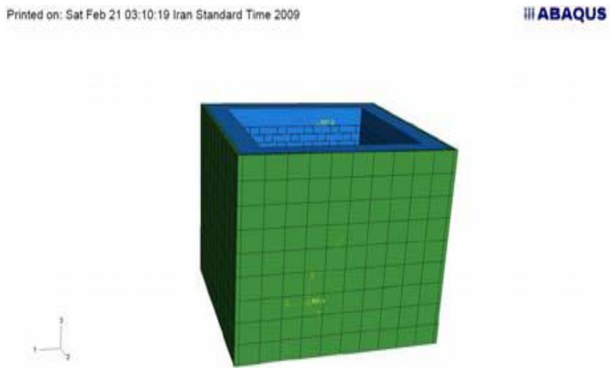


Figure 9; Un-deformed Model of the Reinforced Specimen

3. Result and Discussion

3.1. Analysis of Modeling and Reinforcement Results of Masonry Structures with Reinforced Concrete (Shotcrete)

The results of the torsional anchor curve of the laboratory test for the base sample are compared with the results of the torsional anchor curve of this sample, which was calculated using finite element software, in Fig. 10. This study shows that the results with the percentage of error difference are less desirable. Also, the comparison between the experimental results of the torsion-rotation curve of the reinforced specimen with the torsion-rotation curve obtained from the numerical modeling of the reinforced specimen is given in Fig.11. Also, by observing this study, the results are relatively in good agreement in the elastic part and are less desirable in the plastic part with a percentage of error difference.

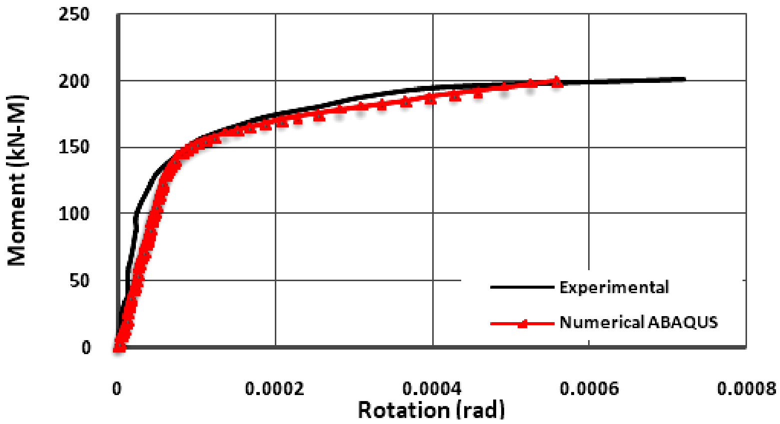


Figure 10; Torsion Anchor Diagrams - Rotation in Numerical and Experimental Modes for the Base Mode

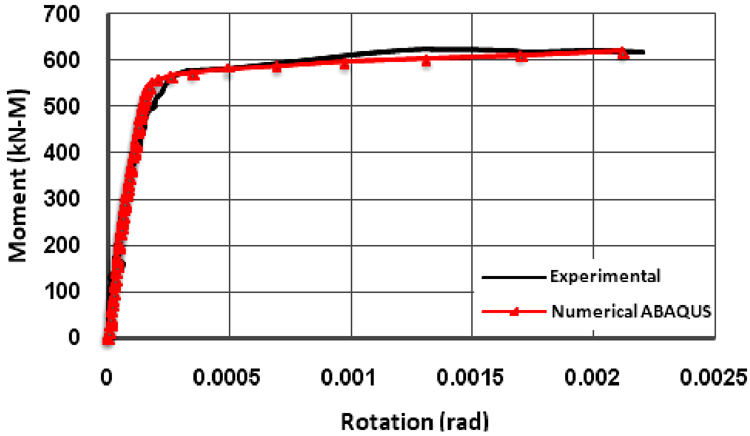


Figure 11; Torsion Anchor-rotation Diagrams in Numerical and Laboratory Modes for Reinforced Specimen

3.2. Investigating the Effect of Connection on the Torsional Performance of a Brick Building

In this section, the effect of wall-to-brick wall connection on the torsional behavior of the building is investigated. According to Standard 2800 regarding the connection of the partition to the wall, if it is installed simultaneously or in a lattice or in the form of a hashtag, this connection is considered sufficient Iranian code (2015). This building was modeled in ABAQUS software by weakening the connection area in the base sample. In addition, the roof of this building is considered rigid in modeling. Fig. 12 shows a comparison between the behavior of a brick building with a vulnerable connection and a base brick building under a torsional anchor.

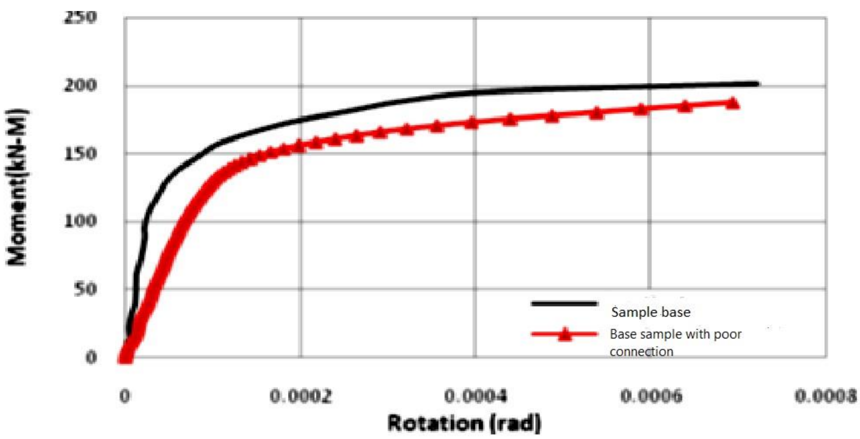


Figure 12; The base Building is Compared to a Brick Building with a Wall-to-wall Connection of a Vulnerable Wall

Then, to investigate the effect of reinforced concrete coating on improving the torsional performance of the base brick building with wall-to-wall vulnerabilities of the outer surface, this sample was reinforced with concrete coating and steel mesh. The characteristics of this reinforced concrete coating are the same as a reinforced brick building. Fig. 13 shows the effect of reinforced concrete reinforcement on the torsional behavior of a brick building with a vulnerable joint:

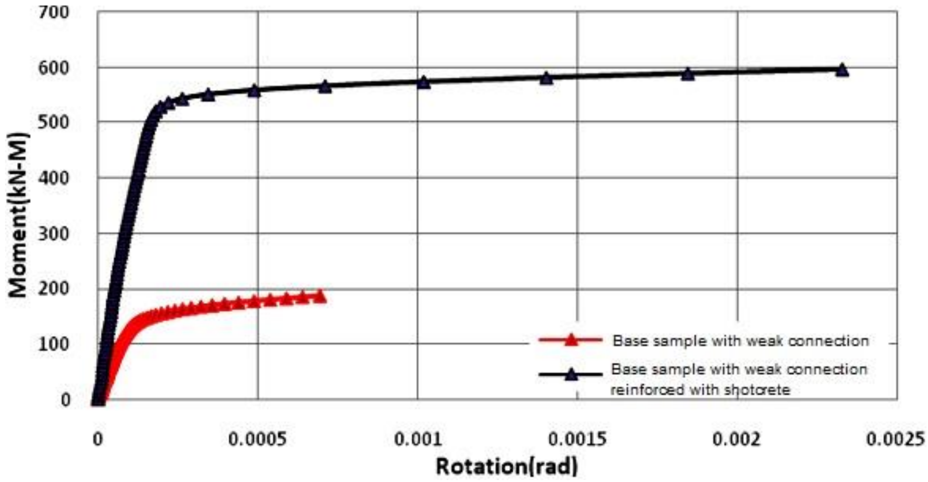


Figure 13; Effect of Shotcrete Reinforcement on the Torsional Behavior of a Brick Building with Wall-to-wall Vulnerability

Fig. 14 can also be used to investigate the effect of reinforcement with a reinforced concrete cover on the torsional stiffness of a brick building with vulnerable wall-to-wall connections.

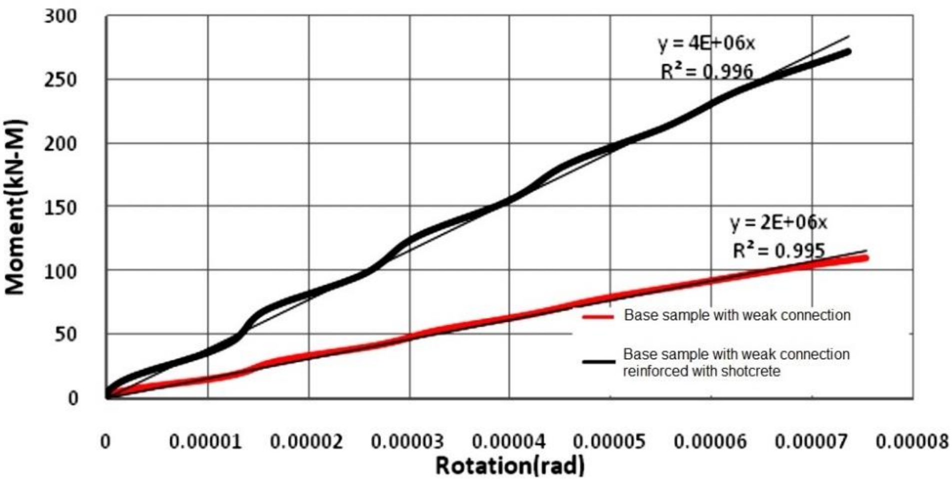


Figure 14. Torsional Stiffness of the base Sample with Weak and Reinforced Connection

According to the above curves, the behavioral characteristics of laboratory samples and constructed models are summarized in Table 5:

Table 5. Behavioral Characteristics of Samples

Sample	Initial torsional stiffness (kN-m / rad)	Maximum torsional resistance (kN-m)	Plasticity
Base sample	3960000	201.1	17
Base sample with vulnerable connection	1540000	187.88	8

Base sample reinforced with vulnerable connection	3860000	596.45	15

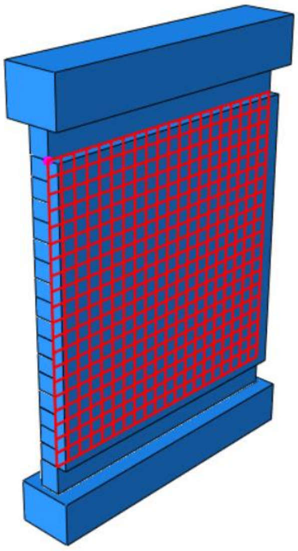


Figure 15; Connection of Shotcrete Concrete and a Rebars Mesh inside the Concrete

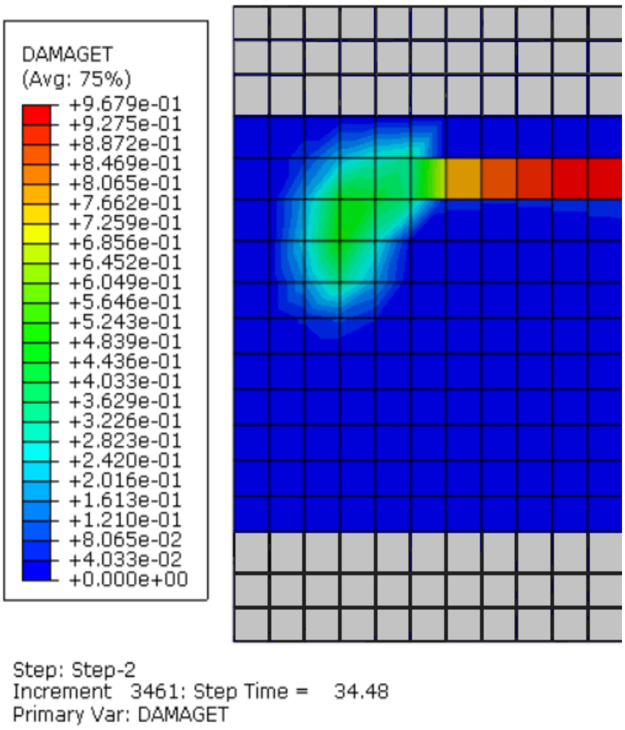


Figure 16; Strain Stress Distribution Plate in the Masonry Wall (Shotcrete)

3.3. Analyzing the Results of Masonry Wall Modeling and FRP Reinforcement

The "hysteresis" and "energy-time" curves obtained from the analysis of masonry walls reinforced by ABAQUS software are shown in Fig. 15 to 21, 24 and 25. The area below the hysteresis curve represents the amount of energy lost in the form of heat, and the thicker the hysteresis curve, the greater the energy lost [6]. Due to the application of shotcrete, the hardness of the wall increases significantly (about 6 times. The brick wall loses its stiffness without immediate reinforcement after cracking and plastic deformation (the curve falls with a steep slope). However, in the reinforced specimen, the slope of the curve is smoother and the stiffness decreases with a slower trend. According to these curves, the effect of FRP layers can be understood, which is discussed below.

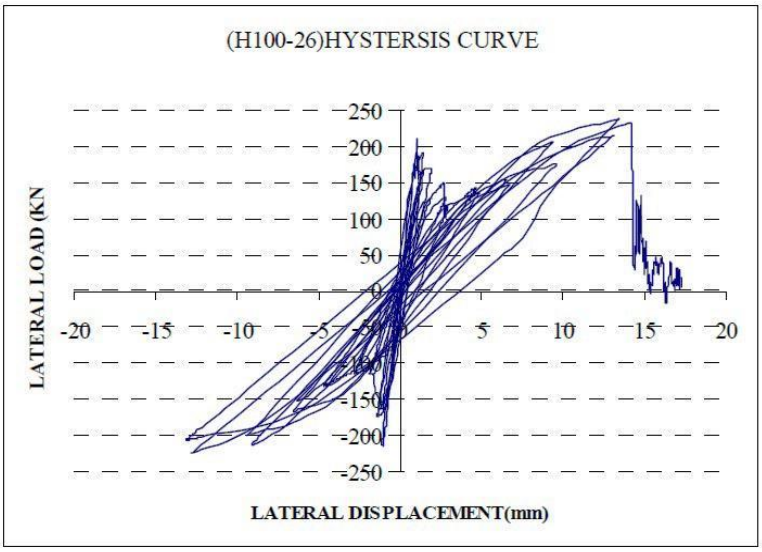


Figure 17; Reinforced Masonry wall Hysteresis Diagram (H100-26)

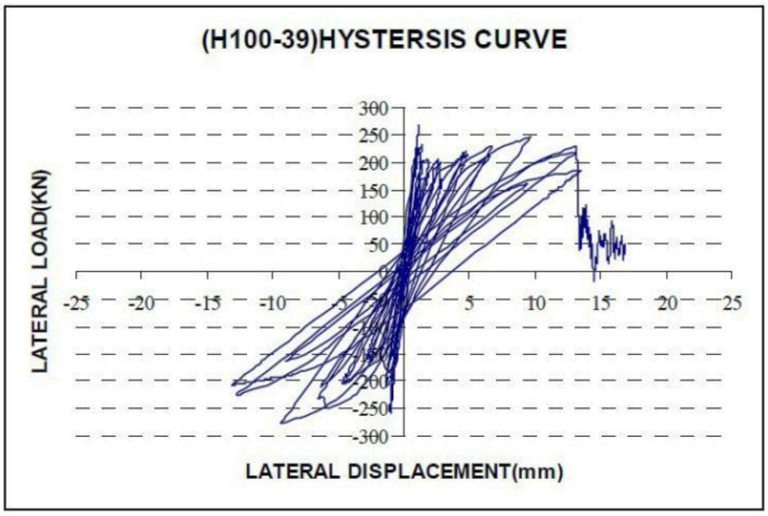


Figure 18; Diagram of Reinforced Masonry Wall Hysteresis (H100-39)

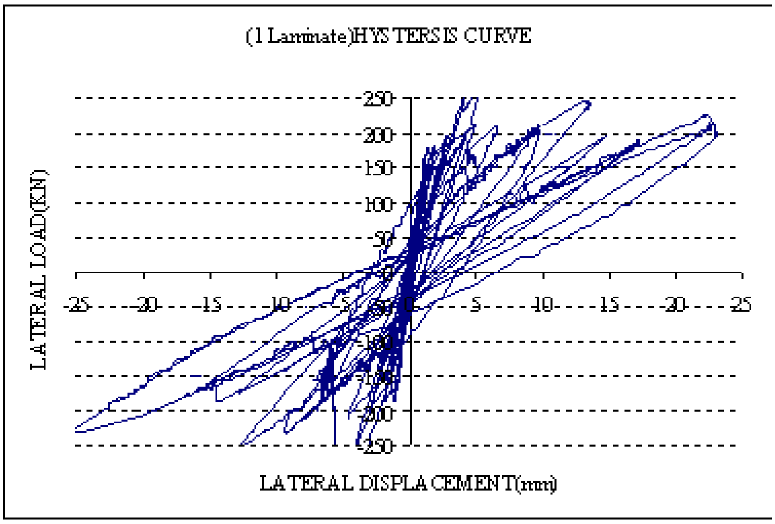


Figure 19; Diagram of Hysteria of Reinforced Masonry Wall (1 Laminate)

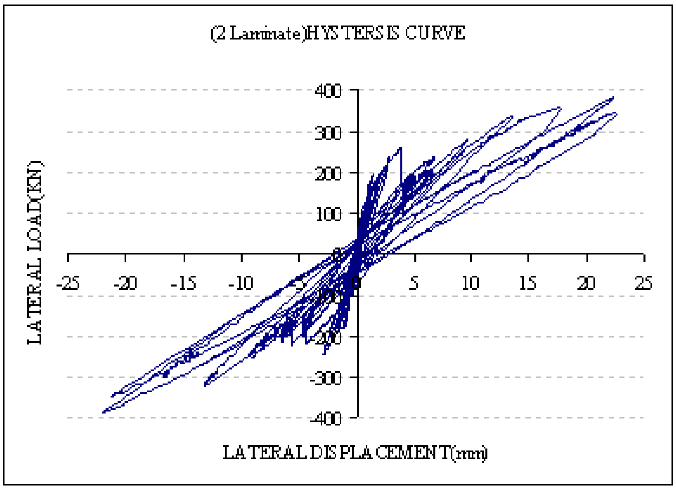


Figure 20; Hysteria Diagram of Reinforced Masonry Wall (2 Laminates)

The 2Laminate sample, which has a FRP plate on each side of the wall, has the same crack pattern as the Laminate sample, but this crack has a slower rate. According to the hysteresis curves of the two samples, the role of FRP plates in improving the performance of the masonry wall can be understood. The amount of horizontal force that the 2Laminate sample was able to withstand was F = 380KN, which had a growth of 1.52 compared to the 1Laminate sample and was also in a better position in terms of energy loss.

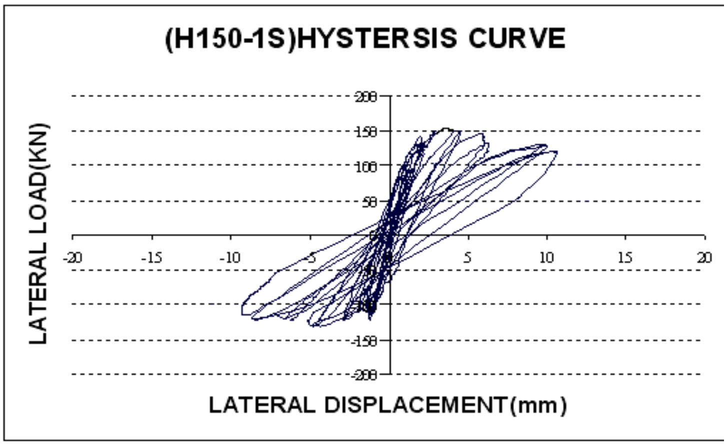


Figure 21; Diagram of Reinforced Masonry Wall Hysteresis (H150-1s)

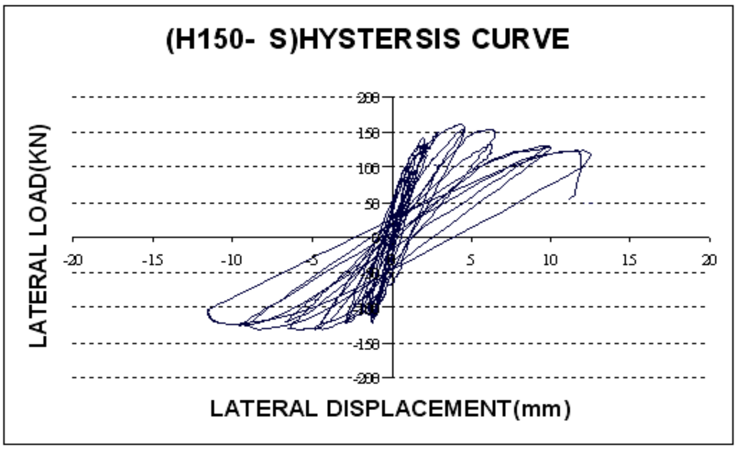


Figure 22; Diagram of Reinforced Masonry Wall Hysteresis (H150-2s)

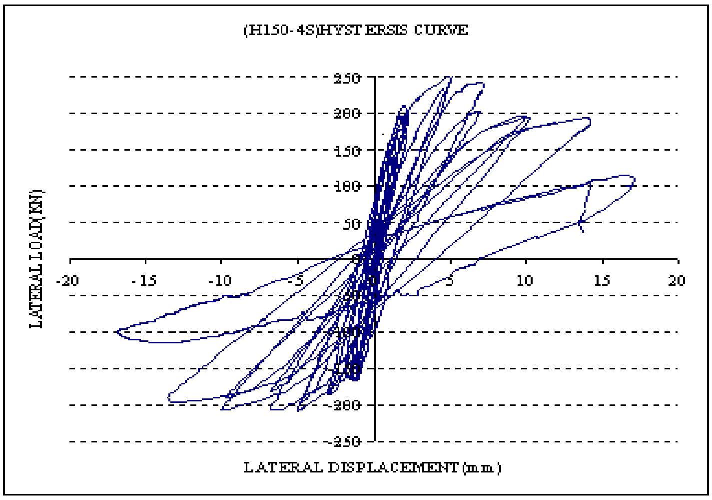


Figure 23; Reinforced Masonry Wall Hysteresis Diagram (H150-4s)

3.4. The Effect of FRP Layer Thickness on the Seismic Performance of the Masonry Wall

To investigate the effect of FRP laminate thickness on improving the seismic performance of masonry wall, three walls that have been reinforced with different layers t_f = 0.13 mm, t_f =

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0.26 mm, t_f = 0.39 mm were compared using hysteresis and energy-time curves of stress contours. . The results of this comparison include a significant improvement in flexibility and the amount of maximum lateral force due to the doubling of the thickness of the FRP layer; So that the maximum lateral force has increased from F = 200 KN to F = 240 KN and the horizontal displacement has increased from d = 13mm to d = 15 mm. This sample extends from the center of the wall and the last laminate of FRP is stretched. Minor cracks are seen in the middle of the wall.

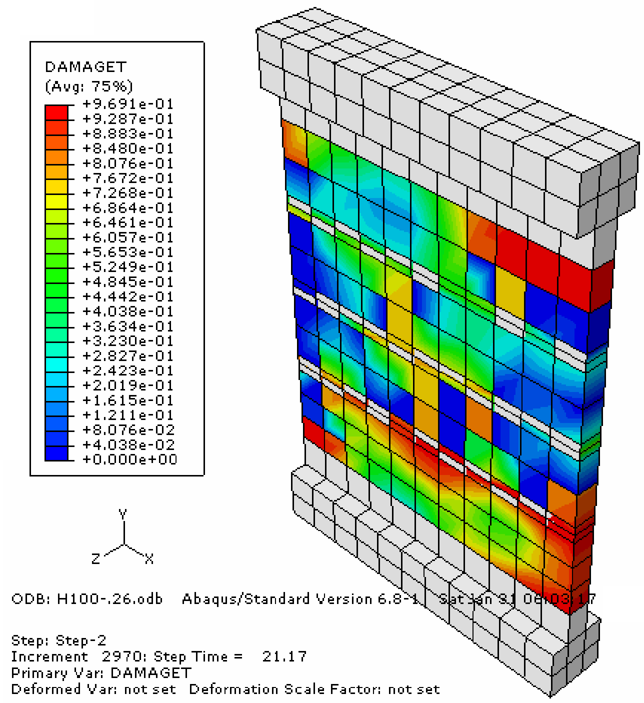

Figure 24; Strain- stress Distribution Plane in Masonry Wall (H100-26)

In a sample with t_f = 0.39 mm, almost the same trend is observed. The hysteresis curve is wider than the curve with t_f = 0.26 mm and the residual loops are thicker, indicating better energy dissipation. However, the values of the maximum displacement force and displacement did not change much compared to the case where the thickness was t_f = 0.26 mm; therefore, it seems that the H100-26 model is economically the best option compared to the two models H100-13 and H100-39. Another study to investigate the effect of FRP laminate thickness on the improvement of seismic performance of masonry wall is the comparison of masonry wall with t_f = 0.26 mm with two masonry walls reinforced by a FRP plate on one and both sides of the wall. In Laminate 1, which uses a FRP plate on one side to reinforce the masonry wall, tensile damage begins at the top and bottom corners of the wall. However, this amount is low until the fourteenth second and after that it causes the building units to be failed. The cracks then spread rapidly from the bottom to the center of the wall and open from that point upwards. At the end of the loading period, the sides of the wall remain intact (Fig. 25).

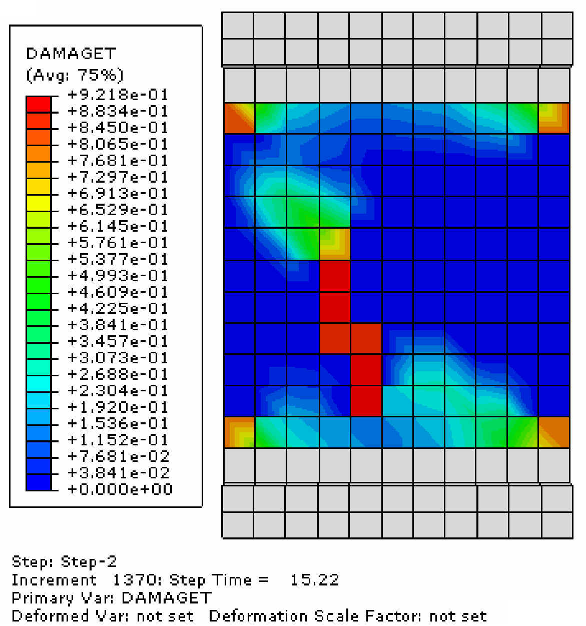

Figure 25; Strain- stress Distribution Plate in Masonry Wall (1 Laminate)

Comparing the energy curves of the two samples (H100-13 and H100-39) and the sample H100-26, it can be seen that the amount of energy dissipated energy is higher in sample H100-26. This could be due to the presence of more cracks in the sample, which also waste some energy when cracks opening and closing. Also, by doubling the thickness, the amount of energy wasted by the masonry wall increased even compared to when both sides of the wall were strengthened with FRP plate. Fig. 26 compares the energy-time curves of masonry walls reinforced by strips of different FRP thicknesses as well as FRP sheets.

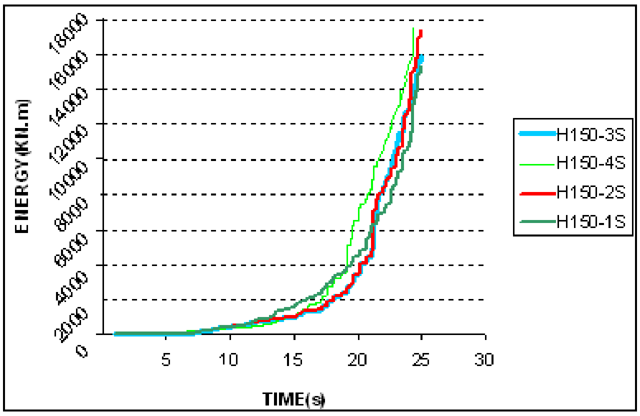

Figure 26; Effect of the Number of FRP Strips on the Energy-time Curve

3.5. Investigating the Effect of the Number of Strips on the Performance of the Masonry Wall

To investigate the effect of FRP strips on improving the performance of masonry wall, four samples with different number of strips were modeled and compared with each other. Lateral force has been increased from F = 150KN for a sample with one row of FRP laminate to F = 250KN in the sample with four rows of FRP laminate. Also, the amount of lateral displacement has increased from d = 10mm to d = 17mm. Due to the limited distance between FRP strips, all these walls were compared and evaluated with a sample with a FRP plate on one side of the wall and it was observed that in this sample the values of force and lateral displacement are equal, d = 23mm F = 250KN, respectively. Laminate has more strength and flexibility than wall (H150-4s). Therefore, due to the preparation of the surface before attaching the FRP laminate, 1Laminate sample is considered as an optimal design in terms of economy and higher speed. Also, since the amount of maximum force, lateral displacement and the amount of energy wasted by the wall (H150-3s) is close to the same values as the wall (H1500-4s), it has the most suitable arrangement among four reinforced masonry walls with different number of strips. Fig. 27 compares the energy dissipated in walls with different FRP strips.

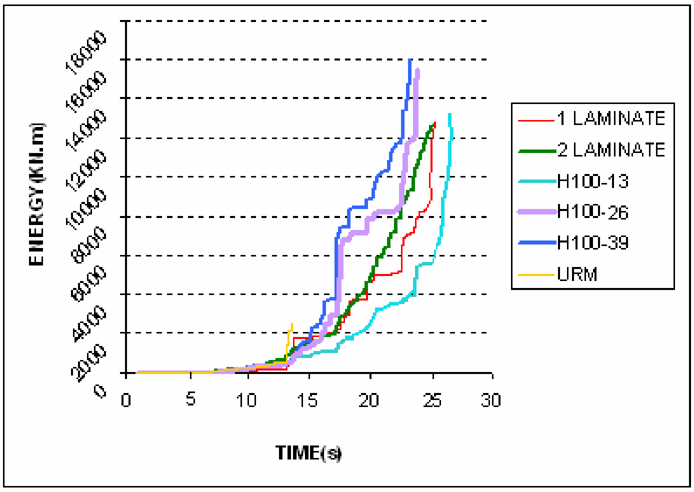

Figure 27; The Effect of FRP Layer Thickness on the Energy-time Curve

3.6. Investigating the Effect of Strip Assembly Method on Masonry Wall Performance

Damage to the X-300 masonry wall due to tensile stresses is also shown in Figure 28. Cracks in reinforced diameter walls along FRP strips are fewer in number but deeper than reinforced horizontal walls. These walls have been able to withstand a larger amount of lateral force than reinforced horizontal walls, so that the amount of horizontal force has improved from F = 170KN in the sample (H150-2s) to F = 230KN in the sample (X-200). All diametrically reinforced walls have brittle fractures with several cracks and the compressive stress at the lower end of the wall due to in-plane bending that caused damage to the elements in these areas.

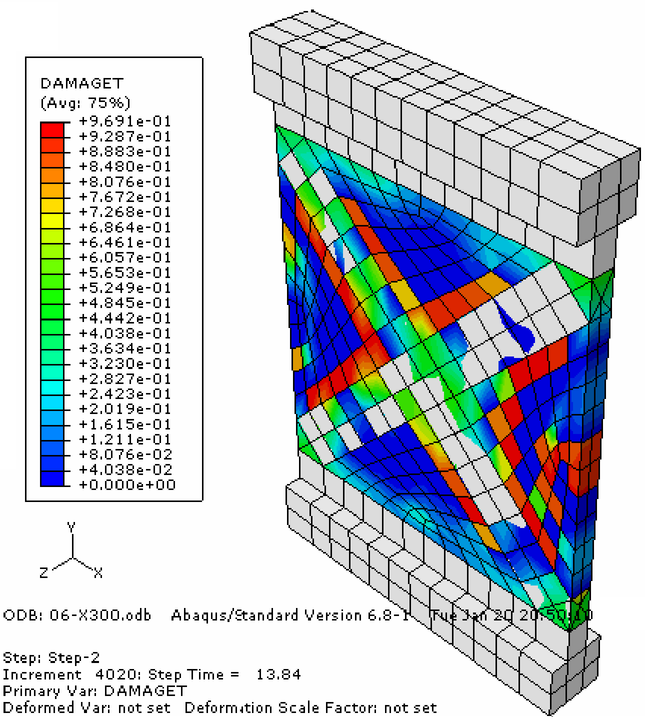

Figure 28; Strain- stress Distribution Plate in Masonry Wall (X-300)

Taking into account the results of the analysis and comparing the models analyzed, Table 6 is obtained. As can be observed from this table the maximum resistance is achieved by shotcrete i.e. 596 kN about 3.2 times greater than base model with displacement 5.6mm with higher resistance to lateral load i.e. 34.48sec. Higher seismic resistance by FRP system is 21.17sec.

Table 6. Summary of Comparison Results in the Properties of the Samples

Sample name	Maximum resistance (kN)	yield displacement (mm)	Duration of tensile damage at the point of yielding (sec.)
Base model	188	3.12	7.8
Shotcrete	596	5.60	34.48
1 Laminate	250	23	15.22
H100-26	240	15	21.17
X-300	235	17	13.84

4. Conclusion

In the present study, by comparing the experimental results and numerical modeling, calculations and analytical results and drawn reinforcement curves with shotcrete method, the following results are inferred:

a. By comparing the numerical modeling and the experimental results of brick buildings, it is observed that with the development of this modeling, it is possible to better study the unreinforced and reinforced specimens by reinforced concrete coating.

b. Weakening of wall-to-wall connections in a brick building without vertical layer has a significant effect on torsional stiffness, so that the torsional stiffness of a brick building with a vulnerable joint is reduced to approximately 0.4 torsional stiffness of the base brick building.

c. The use of reinforced concrete cover in reinforcing brick buildings with vulnerable joints improves the ductility almost twice.
d. Vulnerable wall-to-wall connections in a brick building reduce the maximum torsional strength to approximately 0.9 by the maximum torsional strength of the base brick building.
e. Also, connecting the wall to the vulnerable wall reduces the ductility of the brick building to 0.47.
f. Reinforcing a brick building with a vulnerable joint by reinforcing concrete increases the torsional stiffness by 2.5 times.
g. Reinforced concrete coating increases 3.17 times the maximum torsional strength in a brick building with vulnerable joints.

The following are the results of reinforcement with FRP layers.

a. By comparing the hysteresis and energy curves obtained from FEA analysis and experiments and also comparing the crack level in laboratory and modeled samples, it can be said that homogeneity of masonry wall as a suitable solution for rapid modeling of laboratory samples and walls with real scale can be raised.
b. Due to the possibility of brittle failure in the case of sheet FRP, the value of the reinforcement coefficient should be limited.
c. In reinforced horizontal walls, a row of FRP tape, which is thicker and wider, can be used at the bottom of the wall to prevent the heel from breaking and damaging the last FRP strip.
d. Increasing the thickness from a certain limit, in addition to increasing the possibility of scaling of the FRP layer, does not have a significant effect on the strength and flexibility of the masonry wall.
e. Due to the higher strength and flexibility of the reinforced masonry wall with full coverage of FRP plate on one side compared to the reinforced masonry wall with four rows of FRP on both sides of the wall and also preparing the substrate before adhering the FRP laminates, the sample reinforced with one plate. FRP on one side of the wall is the optimal design in terms of higher speed.
f. Horizontal arrangement of FRP strips has a greater effect on improving the flexibility and diagonal arrangement of the mentioned strips has a greater effect on increasing the strength of masonry walls.
g. Since small cracks can be used as a precaution and prevent brittle failure, and to achieve higher strength, a combination of horizontal and diagonal arrangements can be used.
h. To use the diagonal method, high-thickness sheets should be avoided due to the increased probability of scaling and brittle failure.

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