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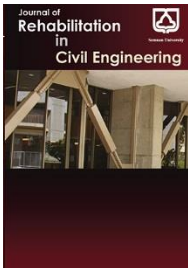

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Investigating Efficiency of Shotcrete for Retrofitting Masonry Buildings

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ABSTRACT

One of a feasible and efficient method to retrofit structures is spraying shotcrete which is widely applied around the world. Shotcrete is concrete with fine aggregates which are sprayed through a hose and by air pressure coat at high velocity onto a surface. In the current research, three masonry schools from different regions of Iran are selected. The retrofitted wall surfaces have been prepared and became flatted, and Schmidt hammer and Ultrasonic tests are performed for each point. The results from the experimental investigation are compared with each other, and some experimental results are compared with theoretical results. To investigate the seismic behavior of structures, one of the schools is chosen and then finite element method is used to do time history analysis regarding four ground motions record. Finally, there was an agreement between experimental and theoretically dynamic modules. In retrofitted conditions, the obtained frequencies are more than the un-retrofitted condition and dynamic time- history analyses have shown that in retrofitted condition, the displacements will decrease and the seismic performance of structure will increase considerably.

1. Introduction

Masonry buildings are the most general type of structures which applying for constructing buildings around the world. In some countries masonry buildings are used in the rural, urban and hilly zone up to its optimum, since these structures are compatible with environmental conditions [1]. Masonry buildings have historically been constructed with little or no considering for the seismic loadings or high speed winds and other destructive loads. Furthermore, many of masonry buildings are needed to repair due to natural defectiveness or lack of maintenance [2]. Masonry buildings can be divided into three general groups: adobe, brick and stone masonry. Each of these has specific and construction technique that is relying on its geographic zone and degree of local proficiency [3].

Iran is one of the countries which is in danger of earthquake. It necessitates the structural safety as a high priority. Many of kids study in schools every day and these students are in danger of earthquake [4]. There are many methods for retrofitting of masonry buildings which have been investigated in the last years. These are including using of reinforced concrete elements for masonry walls or improving strength of the wall by shotcrete or gunite, applying FRP and so on. Many usual methods such as grout spraying, shotcrete and reinforcing are available for retrofitting. Also many methods are suggested to develop the seismic behavior of masonry buildings, such as: post-tensioning using steel reinforcing bars or strands; Near Surface Mounted (NSM) reinforcement using steel reinforcing bars or Fiber Reinforced Polymer (FRP) strips; and surface bonded reinforcement such as shotcreting or FRP sheets. More researches are investigated by [5 to 16].

Elgawady et al. [17] considered disadvantages and advantages of these methods. The disadvantages of these methods include: time consuming to use, reduce available space, disruption the occupancy and affect the aesthetics of the available masonry wall. Also, it can cause to increase the mass of wall, so the earthquake induced inertia forces will be increased and it require to strengthening of the foundations. In the vulnerable masonry buildings, the shotcrete is ideally method for strengthening masonry buildings. By using a layer of shotcrete on the surface of the wall, load bearing of masonry walls would considerably increase across the seismic movement [1]. Shotcrete is concrete with fine aggregates which sprayed through a hose and by air pressure projected at high velocity onto a surface, as a structural method this method is investigated by [18: 22]. The shotcrete method is generally used with a mesh of welded wire for controlling of crack. Tomazevic [19] and Kahn [21] suggested wetting the masonry surface prior to spraying shotcrete. Kahn [21] resulted that brick surface treatment does not affect significantly the cracking or ultimate load and only affects the limited extend in the inelastic deformations. Teymur et al [22] investigated the behavior of reinforced concrete frames retrofitted with Shotcrete panels connected to the beams. The results of the experiments presented that the lateral load carrying capacities of the retrofitted frames were 60 % higher than that of the bare one and 30 % less than the concrete wall. Helal et al [23] investigated the reinforced concrete beams retrofitted with post-tensioned metal straps. Redmond et al [24] used finite element to study on the reinforced concrete frames with masonry infill and mesh reinforced mortar subjected to earthquake loading. They concluded that there are diminishing returns in increasing the dowel area and that the connections must be present on both the top and bottom of the infill walls to be effective. Shakib et al [25] evaluated the behavior of retrofitted confined unreinforced masonry walls using carbon fiber–reinforced polymer (CFRP) strips and mesh-reinforced shotcrete. They concluded that the strength of the mesh-reinforced shotcrete retrofitted wall increased up to 55%. Vandoros and Stephanos [26] investigated the interface treatment in shotcrete jacketing of reinforced concrete columns to examine the seismic performance of retrofitted structures. They concluded that disparate methods of interface treatment could influence the failure mechanism and the crack patterns of the specimens.

Many researches have been done on retrofitting using shotcrete and the seismic behavior of masonry walls. However, there is inadequate research about the comparing of experimental and theoretical results of this subject. Current research focuses on the in-plane behavior of walls before and after retrofitting using shotcrete. In this research, three schools from different regions of Iran country are selected. In various regions Schmidt hammer and Ultrasonic test are performed. The experimental investigation results are compared with each other and some experimental results are compared with theoretically results for retrofitted and un-retrofitted walls. To investigate the seismic performance of the structures, one of the schools is modeled using finite element method. Afterward time history analyses are carried out with the aid of four ground motions on both retrofitted and un-retrofitted conditions. Finally, the results are compared with each other.

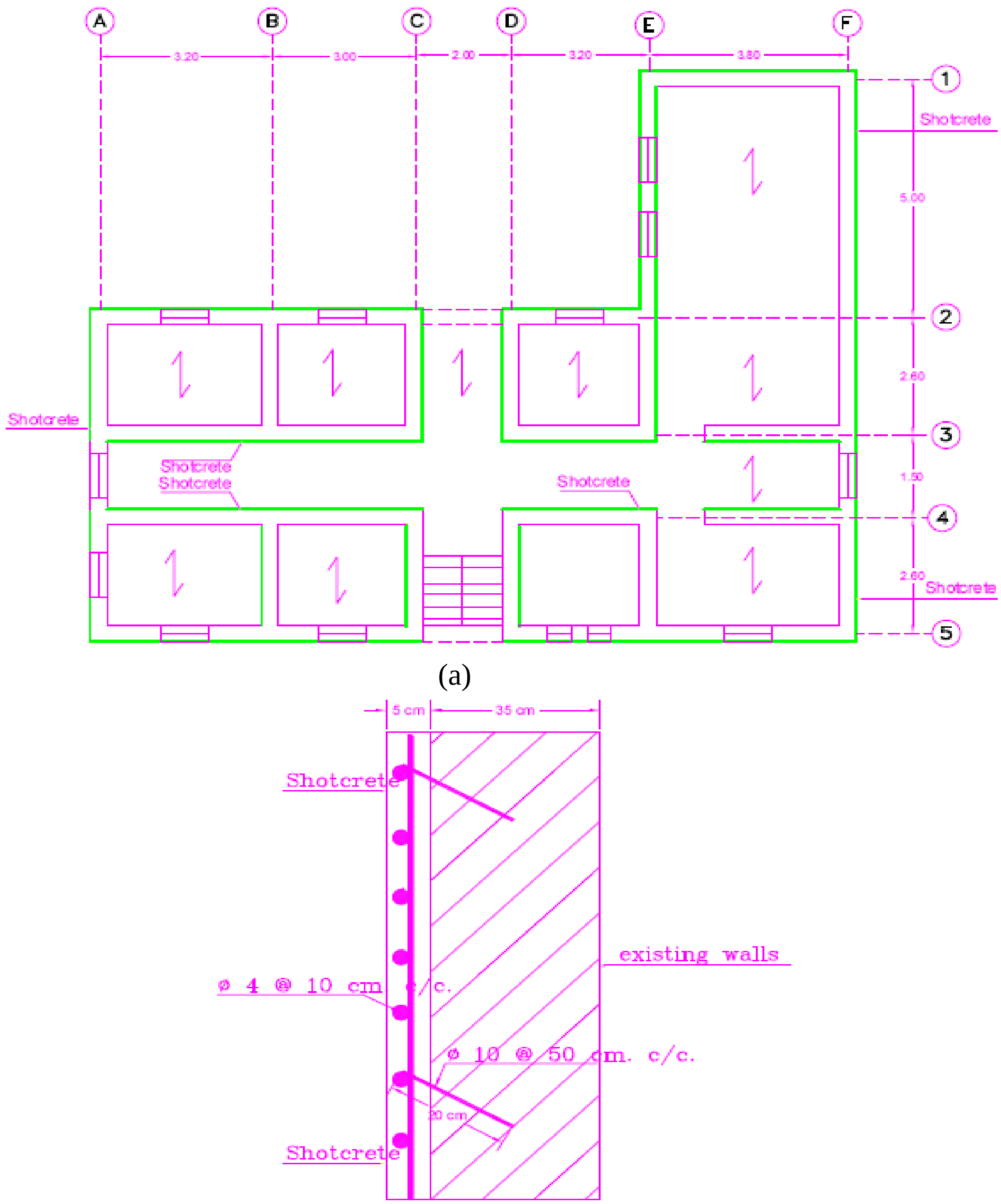
2. METHOD OF RETROFITTING

In table 1, selected schools are shown. These schools are selected from different seismological zones and city of Iran country. All these schools are masonry buildings.

Table 1: Name, type and properties of retrofitted schools

Name of school	Number of Class / Number of Story	Type of structure	Type of retrofit	Danger of earthquake
Enghelab	21 / 2	Masonry	Shotcrete of walls and roof bracing	intermediate
Sherafat	18 / 2	Masonry	Shotcrete of walls and roof bracing	intermediate
Bordbar	12 / 1	Masonry	Shotcrete of walls	high

The walls are covered with one layer of steel rebar mesh. Then shotcrete shouted out on surface. In figure 1(a) plan of Bordbar School and position of shotcreted walls are illustrated. Also, in figure 1(b) the section of retrofitted walls is showed. To summaraize, plan and section of Bordbar school is illustrated as follow.



(b)

Figure 1: (a): plan of Bordbar School (b): section of Bordbar School

Nine points of Enghelab school walls, 6 points of Sherafat School, 6 points of Bordbar school walls are selected for the experimental investigation. These regions are smoothed for experiment. After the surfaces have been arranged and became ready, Schmidt hammer test to measure compressive strength of shotcrete is performed at every point. Schmidt hammer device is famous as a Swiss hammer or a rebound hammer. This device is shown in figure 3. It's a device for measuring the elastic properties or strength of concrete or rock, mainly surface hardness and penetration resistance. Schmidt Hammer test is used specially for determining the hardness of the concrete surface; harder concrete surface is a symbol for better quality of concrete surface [27]. For correlating the Schmidt hammers results, Ultrasonic device is used. The Ultrasonic method is for investigating of surface and under of the surface vulnerability. This device is shown in figure 2. For use of this device ASTM C597 [28], BS 1881-203 [29] codes are used. These standards depict the standard test techniques for determination of pulse velocity through concrete. According to this standard the average of Schmidt hammer rebound is given to Ultrasonic device indirectly and the space between Transducer and Receiver is 200 mm. Also Ultrasonic device is used for achieving dynamic and elasticity module of wall elements. Efficiency of the walls can be observed by using this device and seismic performance of the wall can be observed.

Figure 2: Ultrasonic device and Schmidt hammer

Figure 3: Schmidt hammers testing.

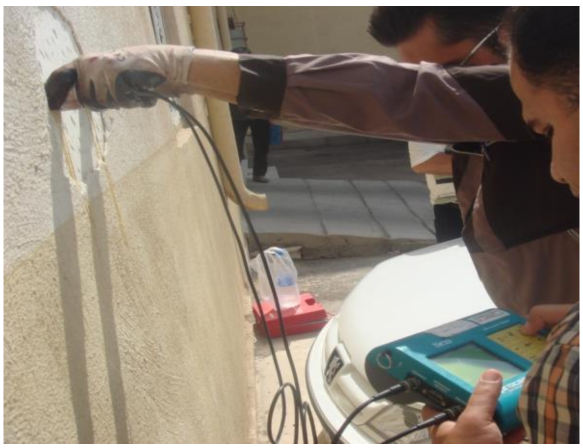


Figure 4: Ultrasonic testing in one side of the wall.

3- RESULTS

3-1- EXPERIMENTAL RESULTS

In table 2, 3, 4 the experimental results are shown. In the Schmidt hammer column the compressive strength of wall is resulted. These compressive strengths have been achieved from the average of 10 tests in every piece of Enghelab, Sherafat and Bordbar Schools. The parameter of velocity is achieved in Ultrasonic test. Also Poisson's ratio and density are different in retrofitted and un-retrofitted walls. The parameter of dynamic module E_d is achieved from Eq. 1. The value of results from Schmidt hammer may be not accurate and the results affected by shape, surface hardness, age of concrete, type of cement which is used in concrete and humidity condition. The value of results like as velocity and hardness of elements and dynamic module in retrofitted condition are more than the results in un-retrofitted condition. In research, it's resulted that the Enghelab and Bordbar schools have achieved similar velocity but less than Sherafat school. The performance of Sherafat School across shotcrete is better than two other schools.

Dynamic modulus using transmission velocity would be calculated as ASTM C597 and BS 1881-203 [29]. These Equations is presented as follow.

$$E_d = k = \frac{[\rho V^2(1+\nu)(1-2\nu)]}{(1-\nu)} \qquad (1$$

In which ρ is density, ν is Poisson's ratio, k is dynamic modulus and V is wave velocity. Wave velocity is measured using ultrasonic instrument (figure 2). By using follow Eqn, natural frequency is obtained.

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (2$$

In this equation f is natural frequency of the structure, k is stiffness and m is the mass of the structure.

Table 2: Ultrasonic and Schmidt hammer test results in different part of Enghelab school

Number of piece	Condition type	Schmidt hammer	Ultrasonic		Parameters			
		Average of results (Mpa)	Test 1	Test2	$\bar{V}(m/s)$	ν	ρ	$E_d = k$
			V(m/s)	V(m/s)				
1	retrofitted	31	2600	2640	2620	0.11	2150	14.36
2	Un-retrofitted	18	650	560	605	0.11	1850	0.66
3	retrofitted	29	1710	1770	1740	0.11	2150	6.33
4	retrofitted	29	1710	1770	1740	0.11	2150	6.33
5	Un-retrofitted	22.2	530	530	530	0.11	1850	0.51
6	retrofitted	33	1720	2430	2075	0.11	2150	9.01
7	Un-retrofitted	19	800	610	705	0.11	1850	0.89
8	retrofitted	19.4	1060	1030	1045	0.11	2150	2.28
9	retrofitted	25	1630	2480	2055	0.11	2150	8.83

Table 3: Ultrasonic and Schmidt hammer test results in different part of Sherafat school

Number of piece	Condition type	Schmidt hammer	Ultrasonic		Parameters			
		Average of results (Mpa)	Test 1	Test2	$\bar{V}(m/s)$	ν	ρ	$E_d = k$
			V(m/s)	V(m/s)				
1	retrofitted	23	3160	3190	3175	0.11	2150	21.08
2	retrofitted	26	1600	1600	1600	0.11	2150	5.35
3	retrofitted	25	2830	2920	2875	0.11	2150	17.29
4	retrofitted	25	1370	1410	1390	0.11	2150	4.04
5	retrofitted	30	20302	2540	2285	0.11	2150	10.92
6	Un-retrofitted	25	1990	2300	2145	0.11	1850	8.28

Table 4: Ultrasonic and Schmidt hammer test results in different part of Bordbar school

Number of piece	Condition type	Schmidt hammer	Ultrasonic		Parameters			
		Average of results (Mpa)	Test 1 V(m/s)	Test2 V(m/s)	$\bar{V}(m/s)$		ρ	$E_d = k$
1	retrofitted	24	2010	1890	1950	0.11	2150	7.95
2	retrofitted	29	780	780	780	0.11	2150	1.27
3	retrofitted	27.5	1360	1350	1355	0.11	2150	3.84
4	retrofitted	29	2000	2050	2025	0.11	2150	8.58
5	Un-retrofitted	32	2140	2525	2332.5	0.11	2150	11.38
6	Un-retrofitted	33	1490	1500	1495	0.11	2150	4.64

Rigidity of retrofitted wall with shotcrete is modeled with increase thickness of wall from 35 to 40 centimeter and increase in stiffness lead to an increase in E (elasticity modulus of wall shells) according follow equations. The values of new elasticity module for retrofitted walls are obtained as follow:

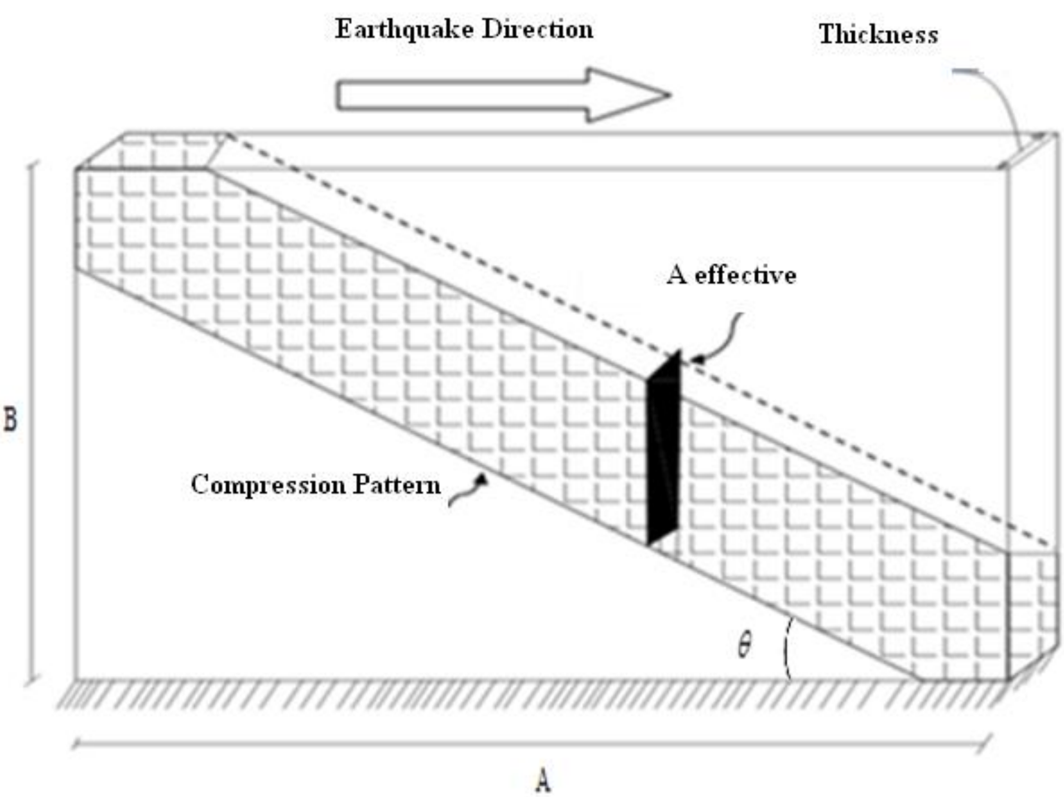


Figure 5: Characteristics of element of the wall

$$L = \sqrt{A^2 + B^2} \quad (3$$

$$A_b = \alpha \times t_b \quad (4$$

$$A_s = \alpha \times t_s \quad (5$$

Where, A_b is effective area of the masonry wall element; A_s is effective area of the shotcrete wall element; α is the width of compression pattern; t_b is thickness of the masonry wall element and t_s is the thickness of the shotcrete element. Elasticity module of brick is equal to 20000 kg/cm^2 and elasticity module of concrete is equal to 250000 kg/cm^2. Stiffness of masonry wall and shotcrete are presented in Eqns. 6 and 7.

$$k_b = \frac{E_b A_e}{L} \times \cos(\theta)^2 \quad (6$$

$$k_s = \frac{E_s A_e}{L} \times \cos(\theta)^2 \quad (7$$

Where, L is length; k_b is stiffness of the masonry wall; k_s is stiffness of the shotcrete wall and θ is the angle of masonry wall length to horizontal line as it shown in the figure 5. Also β is defined as Eq. 8.:

$$\beta = (\alpha \times \cos(\theta)^2) \quad (8$$

$$E_s = \frac{1}{(k_b \times t_b) + (k_s \times t_s)} \times [(k_b \times t_b \times E_b) + (k_s \times t_s \times E_s)]$$

(9

So, E_s is equal as follow for a wall which thickness is 35 cm and has a 5 cm shotcrete. Parameter of β is omitted in Equation (8) due to it’s in both numerator and denominator. Finally, elasticity module of wall in un- retrofitted condition is equal to 20000Kg/cm^2 also it is equal to 66747kg/cm^2 in retrofitted condition. In table 5 the theoretical and experimental elastic modulus of walls are compared with each other. According to table 5, agreement between results is observed. However, there is a difference in some of them. The values of experimental Es are obtained from E_d and the value of E_d are presented in table 2, 3, 4.

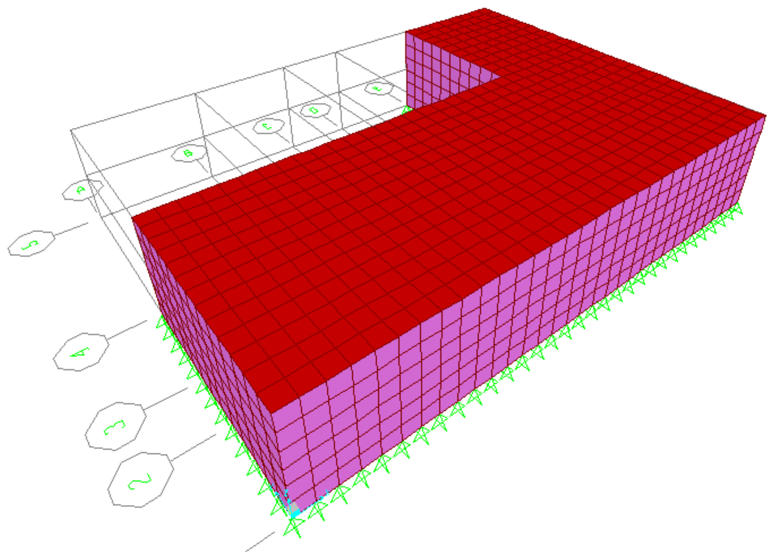
Table 5: Comparing of the theoretical and experimental elasticity modulus of walls.

School Name	Piece No	Type	Experimental		Theoretically
			$E_d\,(Gpa)$	$Es = 0.7E_d\,(Gpa)$	$Es(Gpa)$
Enghelab	1	retrofitted	14.36	10.052	6.67
	2	Un-retrofitted	0.66	0.462	2
	3	retrofitted	6.33	4.431	6.67
	4	retrofitted	6.33	4.431	6.67
	5	Un-retrofitted	0.51	0.357	2
	6	retrofitted	9.01	6.307	6.67
	7	Un-retrofitted	0.89	0.623	2
	8	retrofitted	2.28	1.596	6.67
	9	retrofitted	8.83	6.181	6.67
Sherafat	1	retrofitted	21.08	14.756	6.67
	2	retrofitted	5.35	3.745	6.67
	3	retrofitted	17.29	12.103	6.67
	4	retrofitted	4.04	2.828	6.67
	5	retrofitted	10.93	7.644	6.67
	6	Un-retrofitted	8.28	5.796	2
Bordbar	1	retrofitted	7.95	5.565	6.67
	2	retrofitted	1.27	0.889	6.67
	3	retrofitted	3.84	2.688	6.67
	4	retrofitted	8.58	6.006	6.67
	5	Un-retrofitted	11.38	7.966	6.67
	6	Un-retrofitted	4.64	3.248	2

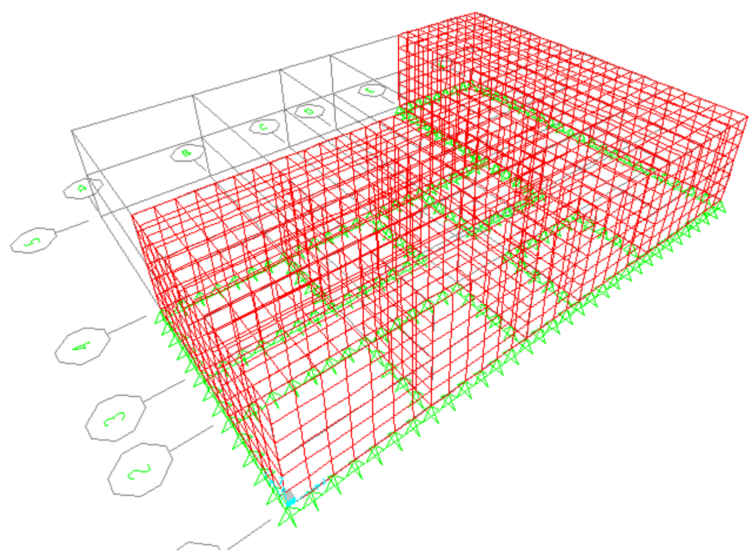
3-2- Finite element Modeling

For finite element modeling, nonlinear finite element software, SAP2000, V.12 [30] is used. Modeling is carried out only for Bordbar School. Walls and roof modeled as figure 6. Retrofitting of roofs is not modeled here. All structural elements modeled using with rectangular 4 node shell elements. All of the elements assumed to be homogeneous and break mortars don't modeled as discrete elements. Cracking of masonry wall don't regarded in finite element modeling. Also rigidity of retrofitted wall with shotcrete is modeled with increase thickness of wall from 35 to 40 centimeter and an increase in E_s

(elasticity modulus of wall shells) leads to an increase in stiffness. Elasticity modulus of retrofitted walls is achieved according Eq. 9. These calculations are presented in Eqns. 3 to 9. The value of theoretically E_s is presented in table 5. In the figure 6 the finite element model of the building is presented. In loading combination, the dead load of 550 kg/m^2 and the live load of 250 kg/m^2 values is considered for the roof.



(a)

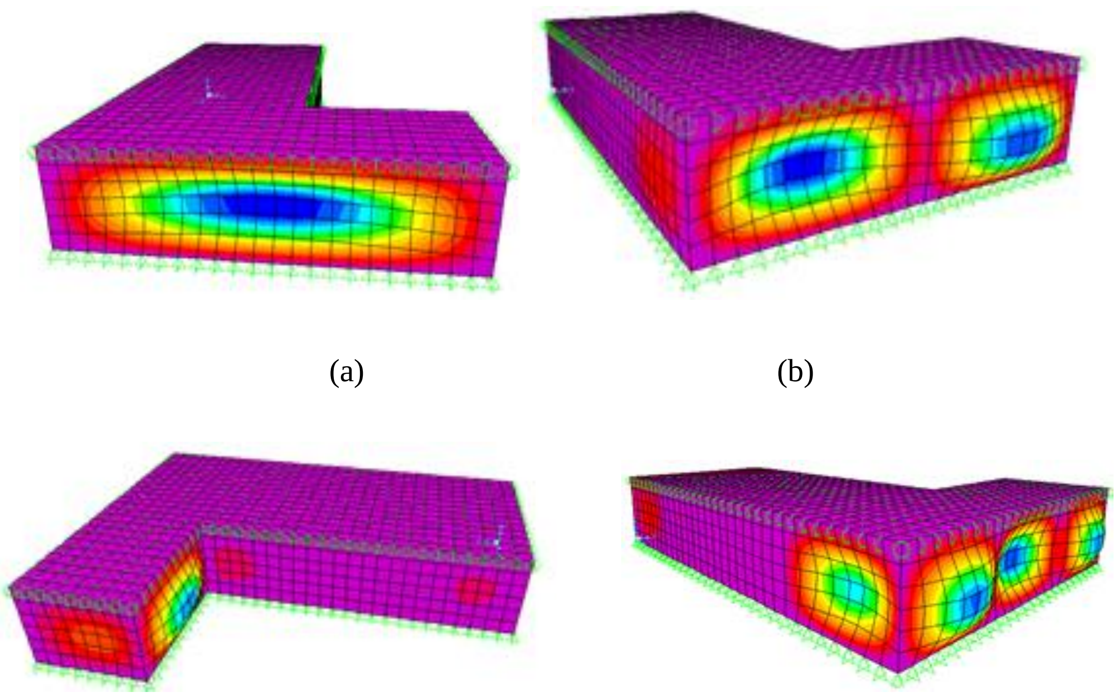


(b)

Figure 6: Schematic view of the finite element model (a) fill walls, (b) internal and surrounding walls.

3-3- Modal analysis

Modal analysis is carried out for Bordbar School. The modal analysis is performed for both retrofitted and Un-retrofitted condition. The purpose of modal analysis is to find the natural mode shapes and frequencies of a structure during free vibration. Finite element method is applied for determining the modes. First four mode shapes are shown in Figure (7) for Bordbar School.



(a) (b)

(b) (d)

Figure 7: First four modes of Bordbar School.

In table 6 the frequencies of the walls are illustrated. It is observed that in retrofitted condition the frequency is more than Un- retrofitted condition. The value of increasing in retrofitted condition is more than 2 times than un-retrofitted condition and this value is constant in all the Mode numbers. So, it can be concluded that retrofitting walls would cause to increase frequencies.

Table 6: comparing the Un-retrofitted and retrofitted walls frequency

Mode number	Un-retrofitted	Retrofitted	Ratio
1	19.786	36.492	1.84
2	21.913	40.518	1.85
3	22.669	42.913	1.89
4	23.848	45.884	1.92
5	25.519	47.904	1.88
6	26.09	50.878	1.95
7	27.917	54.016	1.93
8	29.338	54.811	1.87
9	29.418	55.397	1.88
10	29.746	58.768	1.98
11	30.149	60.145	1.99
12	30.799	61.956	2.01

3-4- Time history analysis

Time history analysis is used to estimate the amount of structural response across the earthquakes. For time history analysis, four ground motions are selected. The properties of these ground motions is illustrated in follow table. These ground motions as Table C-3 of FEMA 440 [31] Appendix C for site class “D” are chosen.

A point which is shown in figure 9 is selected for comparing results. Two parameters include base shear and displacement are chosen for comparison. The results for these two parameters are compared with each other in both retrofitted and un- retrofitted conditions in horizontally (X) and vertically (Y) directions.

Table 7: Characteristics of earthquake ground motion

Number	Earthquake Name	Station Name
1	Landers	Palm Springs, Airport
2	Loma Prieta	Gilroy 2, Hwy 101 Bolsa Road Motel
3	Morgan Hill	Gilroy #3 Sewage Treatment Plant
4	Imperial Valley	El Centro #13, Strobel Residence

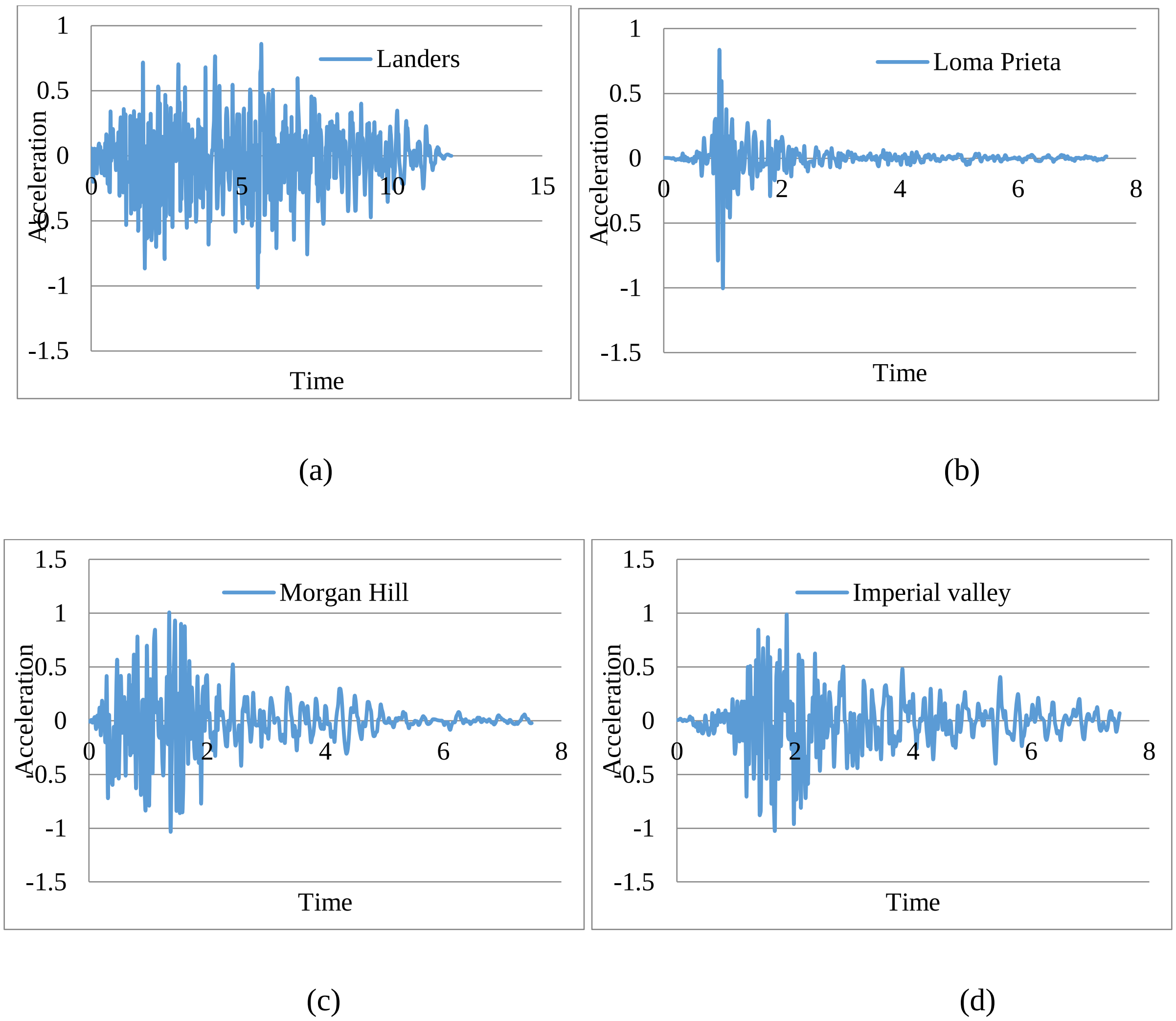


Figure 8: Time history acceleration in X direction of (a): Landers, (b): Loma Prieta, (c): Morgan Hill, (d): Imperial Valley

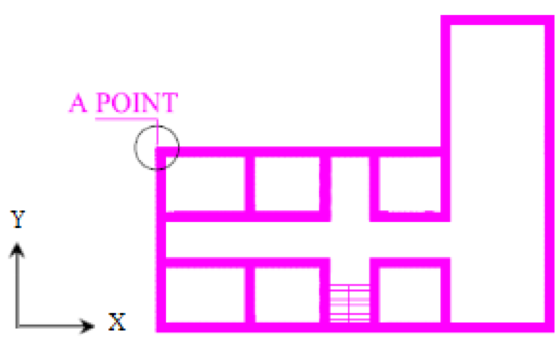


Figure 9: Marked point A for out puts.

Table 8: Comparison of the results in the retrofitted and Un- retrofitted condition in X direction

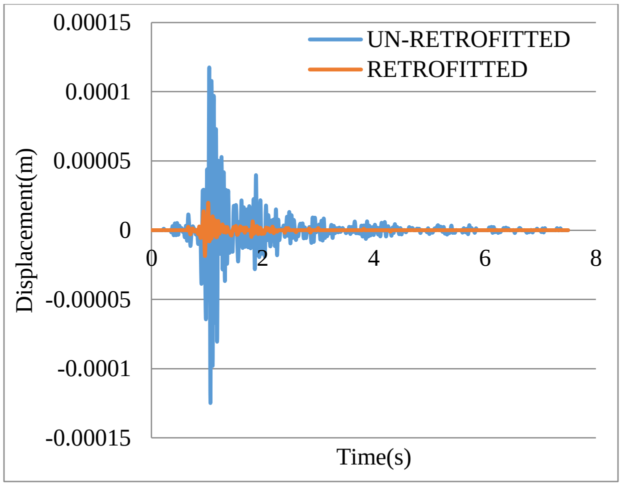
Earthquake name	Un- retrofitted		retrofitted	
	displacement (mm)	Base shear (KN)	displacement (mm)	Base shear (KN)
Loma prieta	0.03935	24.11337	0.01008	32.33131
Morgan Hill	0.04286	26.99438	0.01086	37.99512
Imperial Valley	0.04182	38.40046	0.04182	38.40046
Landers	0.03362	25.94	0.01077	29.67226

Table 9: Comparison of the results in the retrofitted and Un- retrofitted condition in Y direction

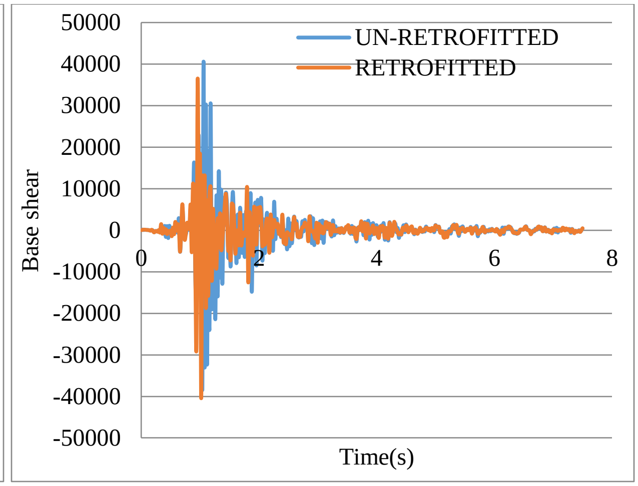
Earthquake name	Un-retrofitted		retrofitted	
	Displacement (mm)	Base shear (KN)	Displacement (mm)	Base shear (KN)
Loma prieta	0.1166	40.57464	0.01986	36.16389
Morgan Hill	0.1511	55.53127	0.01999	38.28527
Imperial Valley	0.1705	49.38301	0.01799	37.37533
Landers	0.1126	51.93011	0.01806	29.21992

In Tables 8 and 9 the results of the time history analyses are shown. It can be observed that in retrofitted case, the displacements are decreased and the performance of structure is improved. From comparing results of Tables 8 and 9 it can be observed that the value of base shear in X direction is less than the value of base shear in y direction. Displacements and base shears in Gillory ground motion are higher than the others.

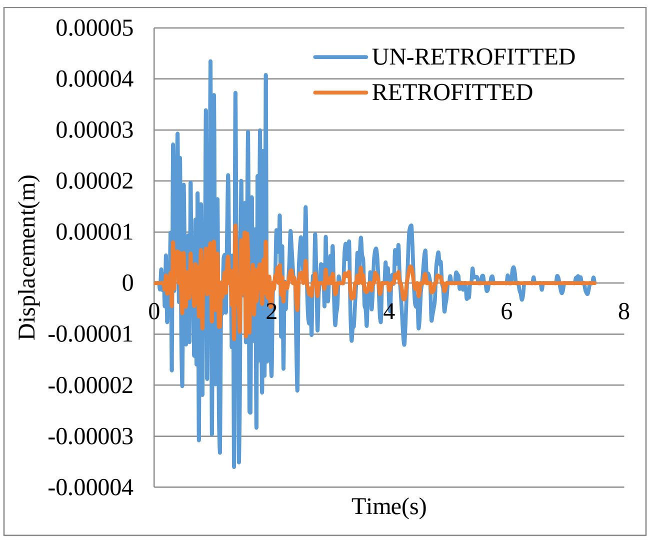
Time history response of Bordbar School is shown as figures 10. It can be observed that two parameters include base shears and displacements in Loma Prieta and Morgan Hill earthquakes are achieved in both un-retrofitted and retrofitted conditions. It can be observed that, the values of displacements are decreased in retrofitted condition in both Morgan Hill and Loma Prieta Earthquakes.



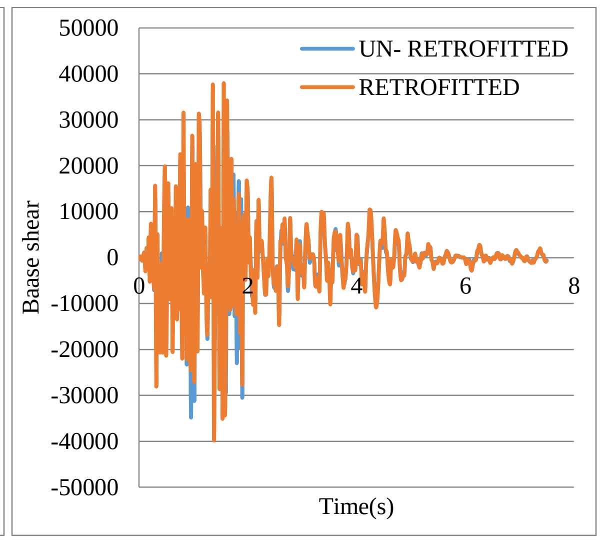
a) Displacement in Y direction (Loma Prieta)



b) Base shear in Y direction (Loma Prieta)



c) Displacement in X direction (Morgan Hill)



d) Base shear in X direction (Morgan Hill)

Figure 10: time history response of Bordbar School

4- CONCLUSION

In current research an improvement in structural performance of masonry buildings using reinforced shotcrete is investigated. Case study is carried out for three retrofitted masonry schools in Iran country and schools are selected from different seismological zones. The results from experimental investigations are compared with each other in retrofitted and un- retrofitted cases. To investigate the seismic performance of schools, finite element software is used. To compare the frequencies in retrofitted and un- retrofitted cases, modal analysis is performed and also, four ground motions are selected for nonlinear dynamic time history analyses and nonlinearity of homogenous materials was regarded in modeling. The results have shown that retrofitting using reinforced shotcrete would increase stiffness of masonry buildings considerably. Also, modal and dynamic analyses were shown that shotcrete would increase seismic performance of masonry buildings. This have to be considered that appropriate joint between roof, foundation and walls for working together during earthquakes is significant. Although modal analysis was shown a considerable increase in natural periods of buildings after retrofitting. However, this point should be mentioned that improving seismic performance is significantly dependent on the intelligently arrangement of shotcreted walls to prevent torsion.

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