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Seismic investigation of un-reinforced masonry buildings rehabilitated by pipe bracing system

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Abstract

It is estimated that a large number of unreinforced masonry (URM) buildings, around the world, are seismic vulnerable. A wide range of techniques are applied for seismic rehabilitation as well as upgrading the unreinforced masonry buildings. The current paper introduces a new pipe bracing system for rehabilitating URM buildings. This system consists of using precast steel pipes positioned vertically and extending into the ground. This system transfers the lateral load from story level to the ground level during the occurrence of an earthquake. In other words, the pipe bracing system behaves like cantilever column. Some of the advantages of this system are limited disturbance of the original building in the case of rehabilitation, decreased construction time and a very economical process. In order to assess the performance of the proposed system, some models (short unreinforced masonry buildings) were selected and their seismic vulnerability was tested by the FEMA273 instruction. Applying nonlinear static pushover analysis, it took into account the system's stiffness, strength and ductility demands. The results indicated that this system not only helps strengthen the vulnerable short unreinforced masonry buildings rather increases ductility and stiffness capacity.

Keywords: Unreinforced Masonry Buildings,Rehabilitation, Pipe Bracing System, Seismic Evaluation

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1. Introduction

The past occurrences of earthquakes have showed seismic vulnerability of many unreinforced masonry buildings in the world. To understand this vulnerability, Mahmoudi (2005) evaluated some 125 URM buildings in the northern Iranian province of Mazandaran. They came to the conclusion that 69 percent of those buildings may collapse in a severe tremor. Hence they should be considered for retrofitting. Since codes for new construction cannot be used for existing buildings; a set of guidelines for seismic rehabilitation of buildings was developed by the Federal Emergency Management Agency (FEMA, 1997). In Iran, the instruction for seismic rehabilitation was first developed in 2005 (Report-360, 2005). In fact, this instruction is applicable for all kinds of structures such as, steel structures, concrete structures and unreinforced masonry buildings. A separate instruction was developed for unreinforced masonry buildings in 2007 (Report-376, 2007).

2. Existing Rehabilitation methods

Various retrofitting techniques are available to rehabilitate unreinforced masonry buildings with the aim to increase their strength, ductility and stiffness capacities. These include surface treatments such as ferrocement and shotcrete, grout and epoxy injection, application of external reinforcement, creation of confined masonry with tied column frames, addition of inner reinforced concrete shear walls, and addition of either moment resistant or braced external frames. However, despite the wide range of technical solutions to seismic retrofitting, little information or technical guidelines are available to judge the relative merits of those methods. In other words, there is lack of reliable analytical techniques to evaluate the seismic resistance of retrofitted masonry structures (ElGawady et al., 2004). As such, the present paper tries to do away with this shortcoming by introducing a pipe bracing system to rehabilitate the URM buildings and evaluate its performance during severe earthquakes.

3. Pipe bracing systems

The paper introduces a new pipe bracing system to rehabilitate URM. This system consists of using precast steel pipes (empty pipes with attachments) positioned vertically and extending into the ground about five meters. They are then connected to the floors at each level (Fig. 1) so that the lateral load due to earthquakes is transferred from the storey level to the ground level. Pipe bracing systems behave as cantilever columns. Some of the advantages of this system are limited disturbance of the original building in the case of rehabilitation, decreased construction time and a very economical process. It should be noted that the length of pipe buried beneath the building depends on the soil characteristics. The required length can be decreased by using a rigid floor or tie beams at the ground level (Saadatmehr et al, 2007).

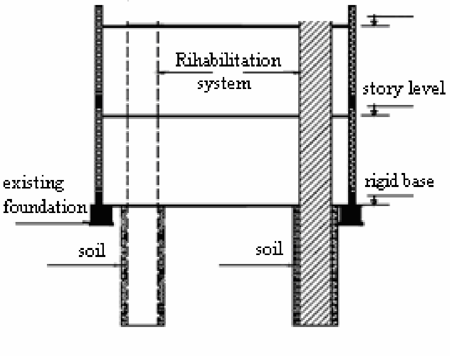


Figure 1. Pipe bracing system

3.1 The layout of pipes

With regard to the proposed system, at least two pipes are installed symmetrically in the plan (Fig. 2). It must be remembered that the number of pipes depends on the number of stories and the area of the building. It is much important to find the spaces of installing such pipes like that this system may sometimes be unusable because of space permitting.

3.2 Connections

The connections details are of utmost importance in the proposed pipe bracing system. The connections between pipe and floor actually make them able to transfer seismic load from the building. Figures 3 and 4 show the connection of pipes and floors by reinforced concrete members or steel sections, respectively.

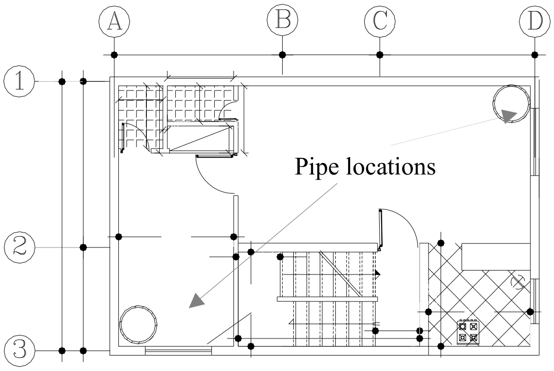


Figure 2. Layout of the pipes in the plan

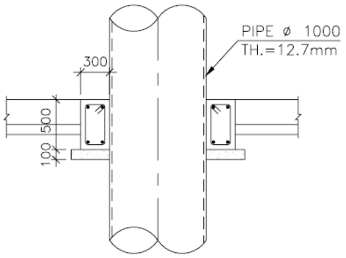


Figure 3. Connection of roof and pipes by reinforced concrete

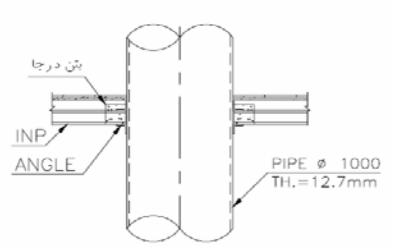


Figure 4. Connection of roof and pipes by steel sections

3.3 Floors

In this system, the floors must be rigid as they are required to transfer seismic load to the pipes without incurring any damage. The floors can be made rigid by installing bracing rods in the plane of the floor in an X-shape (Fig. 5) or by adding a layer of reinforced concrete.

4. Model buildings

In order to investigate the effectiveness of the proposed system, three URM buildings were selected and rehabilitated with the pipe bracing systems. Although their unreinforced nature makes them vulnerable, the walls are well spaced and the layouts are reasonably symmetric so that poor layout is not an additional factor in their vulnerability. All these buildings were two stories and used for educational purposes. The diaphragms are from joists connected to bearing walls with 35 cm thickness. The buildings have regular plan based on the FEMA 273 [2]. The buildings are located at region of relatively high seismic hazard with design base acceleration of 0.35g. The soil type is II. The area comprising the buildings are 792, 459 and 447 m^2 for number one, two and three, respectively. Figures 6, 7 and 8 show the plans and the number of building walls. In all cases, equivalent column elements (frame elements) were used to define nonlinear elements for masonry material. ETABS2000 software was used for nonlinear static analysis.

Figure 5. Increasing roof diaphragm rigidity using bracing rods or reinforced concrete

5. Seismic Vulnerability Assessments of Original Buildings

Each of the buildings was seismically evaluated based on FEMA 273 (FEMA, 1997) provisions as well as using the nonlinear static analysis (pushover analysis). The pushover analysis is more reliable for the seismic assessment of the buildings (FEMA, 1997).

5.1 Target displacement

Using pushover analysis, the buildings with the pipe bracing system is pushed to an expected target displacement, δ_t , as given in the following equation:

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi^2} g \tag{1}$$

where C_0 relates the roof displacement to the spectral displacement, C_1 relates the inelastic displacement to the elastic displacement for short period buildings, C_2 accounts for a pinching of the hysteresis loop, C_3 accounts for P-Δ effects for negative post-yield stiffness and S_a is the spectral acceleration at the fundamental period of the building, T_e .

5.2 Lateral load patterns

So far as the two- and three-dimensional analyses are concerned, both would consider at least two vertical distributions of lateral loads. The first pattern, often termed as a uniform distribution, is based on lateral forces proportional to the total mass at each floor level. The second, as a modal pattern, depends on the modal shapes. The current paper has selected the uniform and triangular patterns in which the forces will be imposed at each floor level (FEMA, 1997).

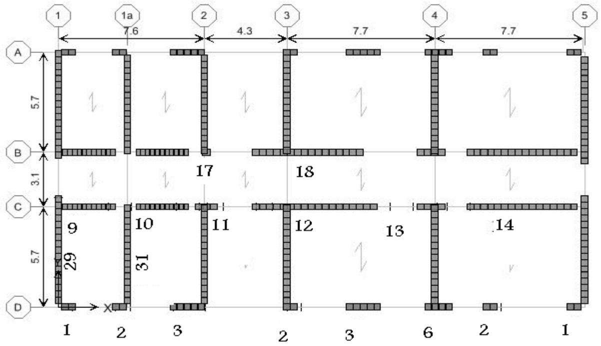


Figure 6. Building number 1

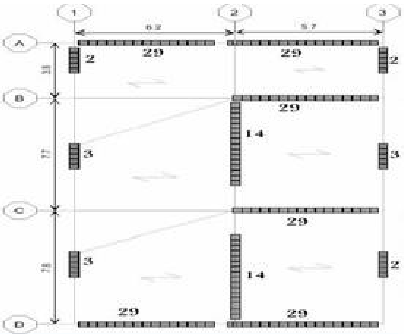


Figure 7. Building number 2

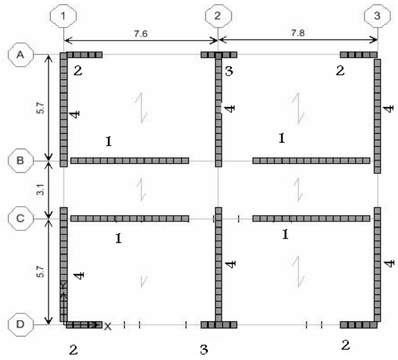


Figure 8. Building number 3

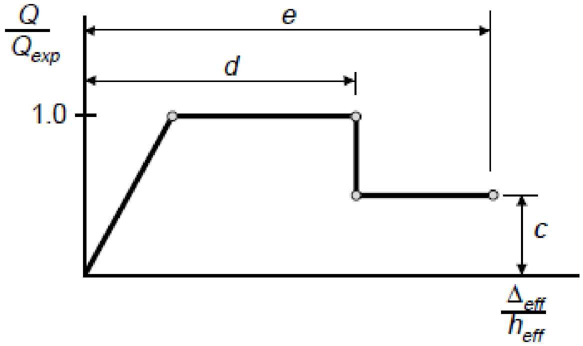


Figure 9. Load-deflection curve for wall and pier components

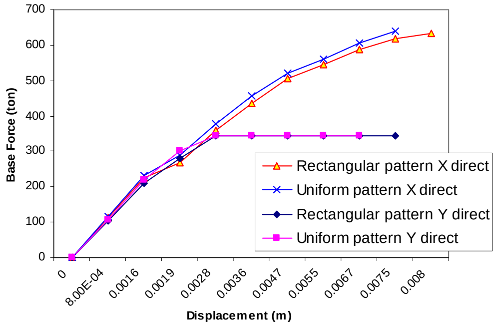


Figure 10. Capacity curve for original building number 1

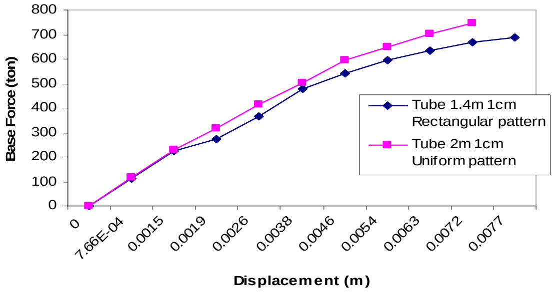


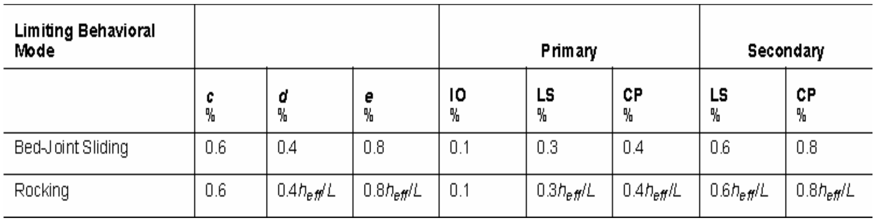
Figure 11. Capacity curve for rehabilitated building no. 1

5.3 Plastic hinges definition and strength acceptance criteria

The lateral stiffness of masonry walls and piers subjected to lateral inplane forces shall be determined considering both flexural and shear deformations. For nonlinear procedures, the in-plane stiffness of URM walls or piers shall be based on the extent of cracking. In the nonlinear static analysis, deformation-controlled wall and pier components are assumed to deflect to nonlinear lateral drifts as shown in Fig. 9. Wall and pier components shall be assumed to deflect to nonlinear lateral drifts as given in Table 1. Variables d and e, representing nonlinear deformation capacities for primary and secondary components, are expressed in terms of story drift ratio percentages, as defined in Figure 9. For components of primary lateral-force-resisting elements, collapse shall be considered at lateral drift percentages exceeding values of d in the table, and the Life Safety Performance Level shall be considered at approximately 75% of the d value. For components of secondary elements, collapse shall be considered at lateral drift percentages exceeding the values of *e* in the table, and the Life Safety Performance Level shall be considered at approximately 75% of the *e* value in the table. Drift percentages based on these criteria are given in Table 1.

Unreinforced masonry walls and piers shall be considered as deformation-controlled components if their expected lateral strength limited by bed-joint sliding shear stress or rocking is less than the lower bound lateral strength limited by diagonal tension or toe compressive stress. Otherwise, these components shall be considered as force-controlled components. Table 1 shows the acceptance criteria for each performance levels. IO means Immediate Occupancy; LS represents Life Safety and CP means Collapse Prevention (FEMA, 1997).

Table 1
Simplified Force-Deflection Relations for URM Walls and Piers



Limiting Behavioral Mode				**Primary**			**Secondary**	
	c %	***d*** %	***e*** %	**IO** %	**LS** %	**CP** %	**LS** %	**CP** %
Bed-Joint Sliding	0.6	0.4	0.8	0.1	0.3	0.4	0.6	0.8
Rocking	0.6	$0.4h_{eff}/L$	$0.8h_{eff}/L$	0.1	$0.3h_{eff}/L$	$0.4h_{eff}/L$	$0.6h_{eff}/L$	$0.8h_{eff}/L$

5.4 Vulnerability assessment results

Table 2 shows the target displacement for each sample buildings. The Tables 3, 4 and 5 show the results of pushover analysis for buildings nos.1, 2 & 3, respectively for all performance levels. It is observed that the first plastic hinge is formed at displacements equal to 0.0067, 0.0063 and .006 m, respectively, for life safety level in the buildings. The analysis indicates that all the selected buildings are vulnerable to life safety (LS) performance. For example, wall types 3 and 6 in building 1 do not have enough strength to remain safe during the tremor.

The non-linear analysis results are also shown by capacity curve, in which the horizontal axis shows the roof displacement in the building and the vertical axis represents base shear ratio. For example Fig. 10 shows the structural capacity curves up to the target displacement for building no.1. It can be seen the results about two directions of building subjected to two load patterns in this figure.

Table 2
Buildings target displacements

Buildings	Rectangular pattern X direct (m)	Uniform pattern X direct (m)	Rectangular pattern Y direct (m)	Uniform pattern Y direct (m)
Building 1	0.008	0.0077	0.0073	0.007
Building 2	0.0091	0.0087	0.0079	0.0076
Building 3	0.0065	0.0062	0.0081	0.0078

6. Seismic vulnerability assessments of rehabilitated buildings

All the previous vulnerable buildings were rehabilitated by proposed pipe bracing system. Various layouts were applied in pipe bracing systems to evaluate the effectiveness of rehabilitation. Table 6 shows the number of pipes, their diameters and thicknesses for the proposed systems. The rehabilitated buildings were evaluated by the pushover analysis in the same way as the original buildings for life safety (LS) performance. The pipes and soil were modeled according to FEMA 273 provisions (FEMA, 1997). Soil-structure interaction (SSI) may modify the seismic demand on a building. A rational method of modeling SSI was used in this research. The values of target displacements of X direction (vulnerable direction) for rehabilitated building no.1 are shown in Table 7.

Table 3
Pushover analysis results for building number one in X direction

Displacement (m)	Base Force (ton)	A-B	B-IO	IO-LS	LS-E	TOTAL
0	0	676	0	0	0	676
8.00E-04	111.8525	676	0	0	0	676
0.0016	223.705	675	1	0	0	676
0.0019	267.024	632	44	0	0	676
0.0028	357.6629	614	32	30	0	676
0.0036	436.6852	552	68	56	0	676
0.0047	505.0049	499	121	56	0	676
0.0055	545.3499	489	59	128	0	676
0.0067	588.2928	447	63	138	28	676
0.0075	617.1457	443	67	138	28	676
0.008	633.5947	443	67	138	28	676

Table 4
Pushover analysis results for building number two in Y direction

Displacement (m)	Base Force (ton)	A-B	B-IO	IO-LS	LS-E	TOTAL
0	0	320	0	0	0	320
7.90E-04	61.3692	320	0	0	0	320
0.0016	122.7383	310	10	0	0	320
0.002	152.6365	275	45	0	0	320
0.0028	199	260	60	0	0	320
0.0028	199.9602	260	28	32	0	320
0.0036	218.0869	260	0	60	0	320
0.0044	236.2135	260	0	60	0	320
0.0051	254.3401	228	32	60	0	320
0.0055	263.2057	228	32	60	0	320
0.0063	263.2048	228	0	62	30	320
0.0071	263.2039	228	0	62	30	320
0.0079	263.203	228	0	62	30	320

Table 5
Pushover analysis results for building number three in X direction

Displacement (m)	Base Force (ton)	A-B	B-IO	IO-LS	LS-E	TOTAL
0	0	436	0	0	0	436
6.50E-04	64.6948	436	0	0	0	436
0.0013	129.3896	434	2	0	0	436
0.0015	154.1556	396	40	0	0	436
0.0017	165.1195	376	60	0	0	436
0.0026	220.7819	376	54	6	0	436
0.0033	249.4399	376	0	60	0	436
0.0039	278.098	312	64	60	0	436
0.0041	284.2778	312	64	60	0	436
0.0047	284.2779	312	64	60	0	436
0.0054	284.2781	312	0	124	0	436
0.006	284.2782	312	0	94	30	436
0.0065	284.2783	312	0	94	30	436

Table 6
The number and characteristics of pipes

Case number	Tube number	Tube diameter (m)	Tube thickness (cm)
1	Two	2	2
2	Four	1.2	1.5
3	Four	1.4	1
4	Four	2	1

Table 7.
Target displacements of rehabilitated Buildings for building no. 1

Case number	Target Displacement (m)
1	0.0076
2	0.0077
3	0.0077
4	0.0071

Tables 8, 9 and 10 show the outcome of the pushover analysis for rehabilitated buildings number 1, 2 and 3 respectively for all performance levels. It is observed that, for life safety, there is no plastic hinge in the buildings up to target displacements. Fig. 11 shows the global response curve (capacity curve) up to target displacements for the building no. 1, for example. Therefore, the pipe bracing system can promote the strength of the unreinforced masonry buildings. Although, the analysis indicates that all rehabilitated buildings are not vulnerable for life safety (LS) performance.

Table 8
Pushover analysis results for rehabilitated building no. 1 with two pipes 2m*1cm

Displacement (m)	Base Force (ton)	A-B	B-IO	IO-LS	LS-E	TOTAL
0	0	676	0	0	0	676
7.20E-04	115.8498	676	0	0	0	676
0.0014	231.6995	655	21	0	0	676
0.0019	312.0723	631	45	0	0	676
0.0027	412.4743	618	29	29	0	676
0.0035	494.8427	553	67	56	0	676
0.0046	586.5977	516	104	56	0	676
0.0054	641.9344	489	116	71	0	676
0.0062	689.3523	448	94	134	0	676
0.007	731.9772	442	91	143	0	676
0.0072	743.5245	442	91	143	0	676

Table 9
Pushover analysis results for rehabilitated building no. 2 with two pipes 1.6m*1cm

Displacement (m)	Base Force (ton)	A-B	B-IO	IO-LS	LS-E	TOTAL
0	0	320	0	0	0	320
7.10E-04	60.1421	320	0	0	0	320
0.0014	120.2842	315	5	0	0	320
0.0019	163.4478	288	32	0	0	320
0.0027	217.9036	260	23	37	0	320
0.0038	254.5947	260	0	60	0	320
0.0046	274.6642	260	0	60	0	320
0.0053	294.7338	230	30	60	0	320
0.0056	304.7712	228	32	60	0	320
0.0064	313.6433	228	32	60	0	320
0.0071	322.0704	228	32	60	0	320
0.0071	322.3182	228	32	60	0	320

The result shows that the third case (Four pipes with 2m in diameter and 1cm in thickness) is the most optimum ones for building no. 1. For building nos. 2 & 3, the optimum designs of two pipes have 1cm thickness, 1.6m and 1.4m in diameter, respectively.

Table 10
Pushover analysis results for rehabilitated building no. 3 with two pipes 1.2m*1cm

Displacement (m)	Base Force (ton)	A-B	B-IO	IO-LS	LS-E	TOTAL
0	0	436	0	0	0	436
6.00E-04	67.1533	436	0	0	0	436
0.0012	134.3065	416	20	0	0	436
0.0016	177.3484	391	45	0	0	436
0.0022	226.4902	376	60	0	0	436
0.0031	273.0382	355	29	52	0	436
0.0037	304.0792	313	69	54	0	436
0.0037	305.5461	312	66	58	0	436
0.0043	311.6389	312	66	58	0	436
0.0049	317.5363	312	21	103	0	436
0.0055	323.4337	312	2	122	0	436
0.006	328.0722	436	0	0	0	436

7. Conclusion

Based on the above discussion and analysis, it found that the proposed pipe bracing system is an important technique for seismic rehabilitation of URM buildings. For this purpose, three seismic vulnerable buildings were selected and rehabilitated using the proposed system. Applying nonlinear static analysis (pushover analysis) as well as seismic rehabilitation instructions, the behavior of rehabilitated buildings (system’s strength and ductility demand) was evaluated. The results show that this system ably increases rehabilitation performances. It is also found that increasing pipes' diameter is more efficient than its number or thickness in structural performances.

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