Experimental Investigation of the Effect of Transverse Beams on the In-plane Behavior of Brick-Flat-Arch Roofs

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ABSTRACT

A number of historical and residential buildings were constructed with traditional brick-flat-arch roofs. The seismic behavior of this type of diaphragms has shown that they have a poor seismic performance. Several methods were suggested to retrofit this type of diaphragms. In this research, the in-plane seismic behavior of retrofitted brick flat arch diaphragms using transverse beams is investigated with experimental models. For this purpose, four full-scale experiments of roof diaphragm were conducted under cyclic loading. The results of the two first experiments showed that non-retrofitted traditional flat arch roofs have insufficient stiffness, shear capacity and integrity. In the retrofitted models however, the transverse beams within all the spans of roof can improve the in-plane behavior of this type of diaphragm to the extent that acceptable improvement in integrity and ductility of the diaphragm was observed in retrofitted roof, but the transverse beams could not properly improve the other seismic parameters of the diaphragm such as its shear capacity and stiffness. Therefore, this retrofitting method might not be an adequate method to secure the appropriate in-plane behavior of flat-arch roofs.

Keywords:
Brick Flat Arch; Diaphragm; Masonry Building; Seismic Performance; Retrofitting, Transverse Beams

1. Introduction

The flat arch roofs are one of the diaphragms used in different parts of the world and they are common in some countries now. These roofs consist of shallow jack arches supported by steel *I*-shaped beams. The steel beams are laid usually at a distance of 90 to 100*cm* apart, and shallow brick arches fill among them. Some of the existing buildings and historical structures are constructed with such roof systems, but there is a need to evaluate and retrofit these roofs.

The behavior of this floor system against gravity loads is almost appropriate, but their seismic behavior is relatively poor since they are usually unstable under lateral loads. The most important weaknesses and modes of failure of these diaphragms under seismic loadings are:

a) Sliding of the simply supported steel *I*-cross beams from their original position under earthquake shaking which usually causes the collapse of the brick arch;
b) Weakness of brickwork arch in transferring in-plane shear;
c) Inability to transfer in-plane axial loads;
d) Concentration of stresses in brick arch under out-of-plane bending;
e) Inability to act as an integrated diaphragm [1].

In traditional flat-arch roofs that are used in the existing buildings in Iran, the cross beams of the roof are not appropriately braced together. This problem can easily lead to dangerous dropping of the bricks between beams during the earthquake shaking as it has been observed in the past earthquakes (e.g. in Bam, Iran, 2003). Hence, this type of diaphragm has discontinuity and can not behave as an integrated diaphragm. In addition, the weak masonry arches between cross beams have low strength and are not able to transfer in-plane axial loadings. Therefore, adding other elements to overcome such weaknesses is necessary. Recently, new provision in some building codes such as *FEMA*-356, *FEMA*-547 and Iranian Seismic Design Code (*ISDC*) have proposed some improvements in the construction of these traditional diaphragms. A brief overview of these new propositions is:

i) *FEMA*-356 [2] has proposed the application of diagonal members to form a horizontal truss in order to strengthen the weak archaic diaphragm and the replacement of the fillers with a structural concrete-topping slab.

ii) *FEMA*-547 [3] proposed proper connection between the roof and the lateral resisting vertical elements, by using chord (collector), wall-to-diaphragm tension tie and shear tie. Diaphragm strengthening was also proposed through adding diagonal bracing or replacing filler with a topping concrete slab. In addition, providing tension tie across the beams and parallel to the wall was suggested in order to remove the interior tension in brick arch.

iii) According to *ISDC* [4], to improve the seismic behavior of flat arch slabs, the following provisions shall be satisfied:

   a) Steel beams shall be connected diagonally by means of steel bars or plates so that the length of a braced rectangle does not exceed 1.5 times its width and that its area does not exceed $25m^2$. In this context, The minimum cross sectional area of steel bars or plates for diagonal bracing of floor beams should not be less than $1.5cm^2$;

   b) The support for the last span of arches should be connected to the adjacent main beam of the floor by means of fully-stretched steel bars or plates.

According to *FEMA*-547, no specific research has been conducted on seismic rehabilitation of flat arch diaphragms. However, limited researches on the seismic rehabilitation of these diaphragms exist and a few authors have reported the performance of the existing flat-arch roofs during the past earthquakes. Himmelwrightin has reported some damages during the San Francisco Earthquake on flat arch roofs [5]. Reports of slab damage and collapse of flat arch roofs in recent earthquakes published by Razani and Lee [6], Maheri [7-8], and Zahrai and Heidarzadeh [9] reflect the weakness of the unanchored slab under seismic loads. To overcome this problem, Moinfar [10] has suggested that the slab beams must be joined together at their ends by transverse beams or steel tie bars. This form of anchored flat arch slab shows better seismic response because the relative movements of the slab beams are slightly prevented. An illustrative report of flat arch roof failures is presented by Alimordi [11]. He showed that a significant damage occurred in this type of floor while the tension ties did not exist.

More recently, Maheri and Rahmani [1] has proposed to use a number of transverse steel floor beams to span between the main cross beams to form a steel-grid, two-way flat arch system to overcome the shortcomings of the traditional one-way system. In this way, the unconnected parallel steel beams will become part of the interconnected steel grid allowing the vertical load and in-plane forces to be transferred in two directions. It provides a more homogeneous slab capable of transferring gravity and seismic loads. In this proposed system, the steel grid carries both the gravity and out-of-plane loads, mainly, and the low- strength brittle-brick arches will play a minor role in the system and act just as in-fill panels [1]. Based on this research, the Iranian National Building Code necessitates using transverse beams span between the cross beams [12].

Zahrai et al [13] experimentally investigated the behavior of a one-story, one-span steel frame structure with flat arch floor in three conditions consisting of non-retrofitted floor, retrofitted with transverse beams and retrofitted with diagonal bracings. The results revealed that the traditional flat arch roof in steel structure has a good behavior under cyclic lateral loading. Also in these experiments, the diagonal bracing could improve the stiffness and shear strength of the roof system but the transverse beams could not satisfy the required stiffness for flat-arch roof [13]. However, this study was focused on the assessment structural system and can not completely explain the behavior of flat arch roofs.

Shakib et al [14] investigated the seismic behavior of retrofitted roofs with diagonal bracing and tension tie. The results of the experiments showed that traditional jack arch roofs had insufficient shear capacity and unfavorable flexibility. In addition, diagonal bracing could considerably improve the seismic behavior of the flat arch diaphragm including its stiffness, shear capacity and ductility, so that about 108 and 88 percent improved the stiffness and shear capacity of the diaphragm, respectively. Finally, by adding tension ties within all the spans, the integrity of the diaphragm could be satisfied. Therefore, the study strongly proposed simultaneous use of diagonal bracing and tension tie to largely improve the seismic behavior of existing traditional brick flat arch diaphragms [14].

With the above background, there are three methods for retrofitting flat-arch roof diaphragms, which include diagonal bracing; topping concrete slab and transverse beams. Through these methods, the new added elements can transfer in-plane loadings and also prevent the beams displacement relative to each other. Therefore, they can overcome the existing weaknesses of this type of diaphragm. In this paper, the results of four experiments carried out on traditional and retrofitted flat arch diaphragms are presented and the effects of transverse beams on seismic performance (consisting of failure mode, integrity, shear capacity, stiffness and flexibility) of these floors are investigated.

2. Experimental Program

The experimental program in this study involved testing full-scale brick flat arch diaphragms under cyclic loading. For calculating the shear capacity and stiffness of diaphragms, in-plane loading is applied on the flat arch roofs, perpendicular and parallel to the steel cross beams (in *X* and *Y* directions, respectively). Figure (1) shows the set-up used for the tests in this study. The floor system should be isolated from the bearing frame of the roof. The roof frame was designed properly to transfer the entire applied shear load into masonry arch, so that the frame had no impact on the lateral bearing of the flat arch roof. To evaluate the behavior of the roof frame, at first, two experiments were conducted in the absence of masonry arch (*FX* and *FY* experiments). In the next stage, the traditional masonry arch roof was tested in experiments *TDX* and *TDY*. Finally, the retrofitted roofs with transverse beams were examined in experiments *RDX* and *RDY*. In total, the experimental program consisted of four experiments on flat arch roofs as well as two experiments on roof frames alone. Table (1) shows index for these experiments.

3. Description of Test Experiments

The set-up was built in full-scale dimension (3.6*m* x 3.6*m*). The roof frame included two supporting beams (2*IPE*20) and five *I*-cross beams (*IPE*160) as shown in Figure (2). All joints were flexible and the cross beams were connected to the supporting beams using pin connections. Experiments of *FX* and *FY* were designed to make sure that the lateral applied loads were completely transferred to masonry flat arches. In *FX* and *FY*, there were no arch slabs between cross beams and only the steel frame was

Table 1. Index for the experiments.

No.	Index	Description of Specimens
1	FX	Frame System under X-Direction Loading
2	FY	Frame System under Y-Direction Loading
3	TDX	Traditional Flat Arch Diaphragm under X-Direction Loading
4	TDY	Traditional Flat Arch Diaphragm under Y-Direction Loading
5	RDX	Retrofitted Flat Arch Diaphragm with Transverse Beams under X-Direction Loading
6	RDY	Retrofitted Flat Arch Diaphragm with Transverse Beams under Y-Direction Loading

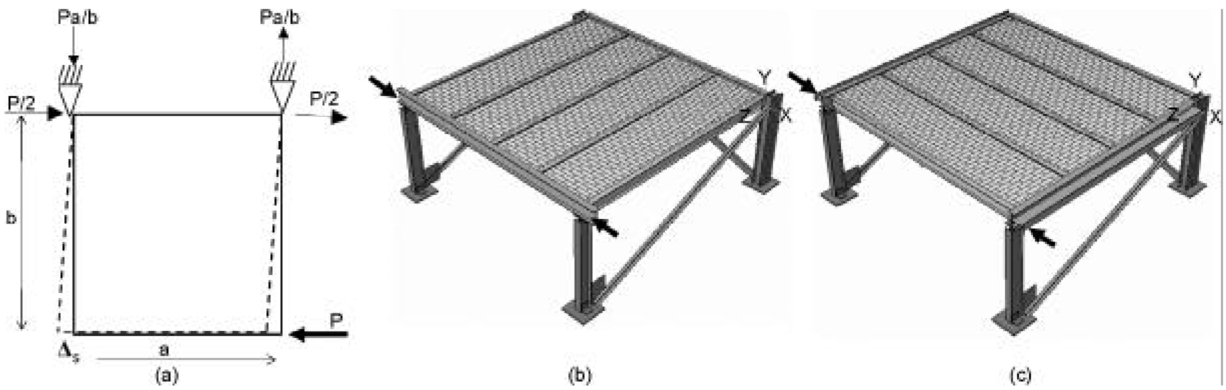

Figure 1. General set-up of the experiments: a) the plan of the experiments; b) shear-loading perpendicular to cross beams; c) shear loading parallel to the cross beams.

tested.

The masonry arch between steel beams was made of gypsum mortar and pressed brick, with average 3 cm as the rise. The mortar mix had a gypsum/clay ratio of 1:1 as well as a sufficient amount of water. For reducing the effect of gravity load on the relative displacement and torsion of two end cross beams, it is common to use a transverse tie in two end bays. Therefore, a steel plate $40mm \times 5mm$ was installed in the middle of two end bays and was welded to the cross beams as shown in Figure (2).

Experiments of *TDX* and *TDY* were planned to study the seismic behavior of the non-retrofitted traditional slabs in two directions. A typical retrofitting method for existing flat arches is adding transverse beams between main beams as shown in Figure (3). The section of transverse beams is usually less of *I*-cross beam section [12]. Hence, *IPE*140 was selected for transverse beams in the retrofitted roofs. The transverse beams were welded to the web of cross beams with flexible connection. The samples of *RDX* and *RDY* show lateral behavior of a retrofitted roof with transverse beams perpendicular and parallel to the steel cross beams, respectively.

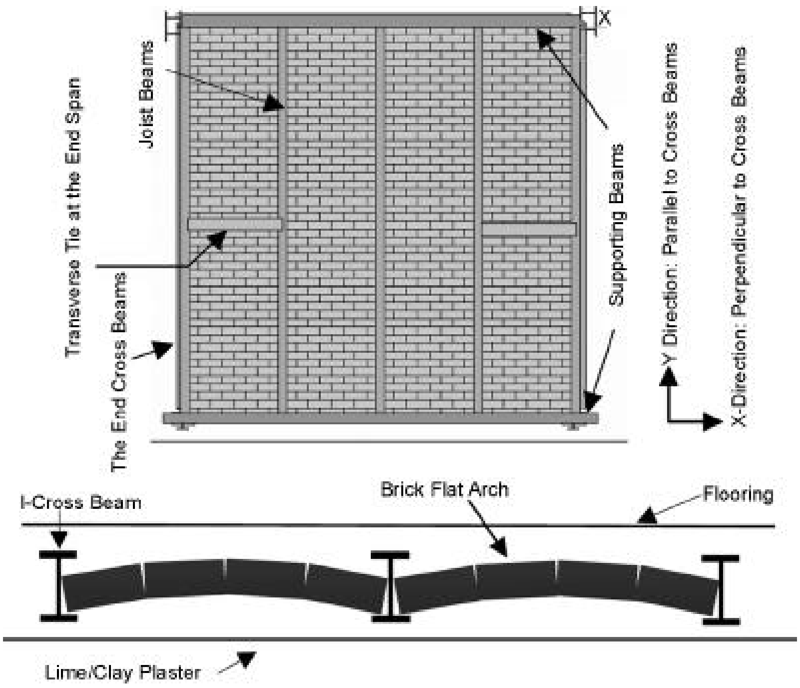

Figure 2. Geometry of the roof and its elements: the X direction is parallel to the supporting beams and perpendicular to the I-cross beams.

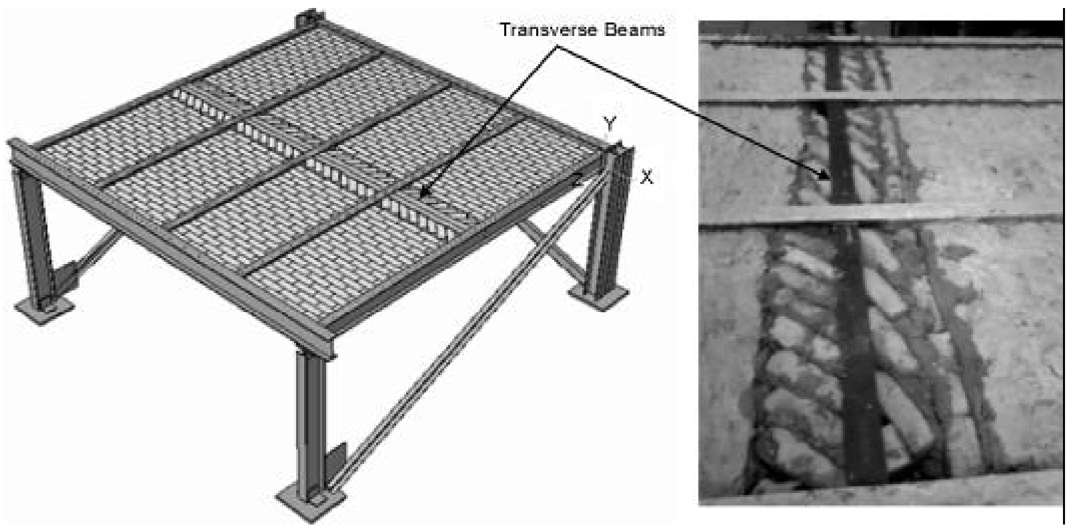

Figure 3. View of the retrofitted roof with transverse beams.

4. Material Properties

Quality control samples were obtained during the experiments for the compressed brick units and the masonry prisms, see Figure (4). The average compressive strength obtained from ten compression tests of bricks was 11.5*MPa*. According to the *ASTM C* 1314-02*a*, the compressive strength of ten 4-course masonry panel prisms (couplet specimens) was measured. The average prism compressive strength was 4.24*MPa*.

As no *ASTM* testing procedures exist for shear strength determination, the modified triplet specimen for pure shear was used to obtain the mortar shear strength and friction coefficient [15]. This specimen represents the actual shear loading case of masonry arches along the mortar bed-joints. The value of brick-mortar interface bond strength (shear bond strength of the mortar) was 0.18*Mpa* and the average coefficient of friction of mortar joint was 0.53.

To evaluate the flexural bond strength of prisms, 5-course masonry units were tested according to the *ASTM C* 1072-*a*. The average flexural bond strength was determined 0.11*MPa*.

5. Loading Arrangement

The test set-up included a roof frame, two reaction frames, two load cells, two hydraulic jacks and a data-logger as illustrated in Figure (5). The in-plane shear loads were applied with two hydraulic jacks aligned in two directions. The capacity of each hydraulic jack was 200*KN* for compression. The load measurement was carried out by installing two load cells placed in line with the general axes of the loading beam connected to a data-logger system.

In order to apply distributed load to the roof, a steel beam made of *IPE*200, which was properly stiffened with *PL*200×200×20*mm* in the end, was used as the supporting beam.

Gravity loading of a real structure is sum of its dead and live loads. Dead load consists of floor weight as well as overload. It was assumed that only

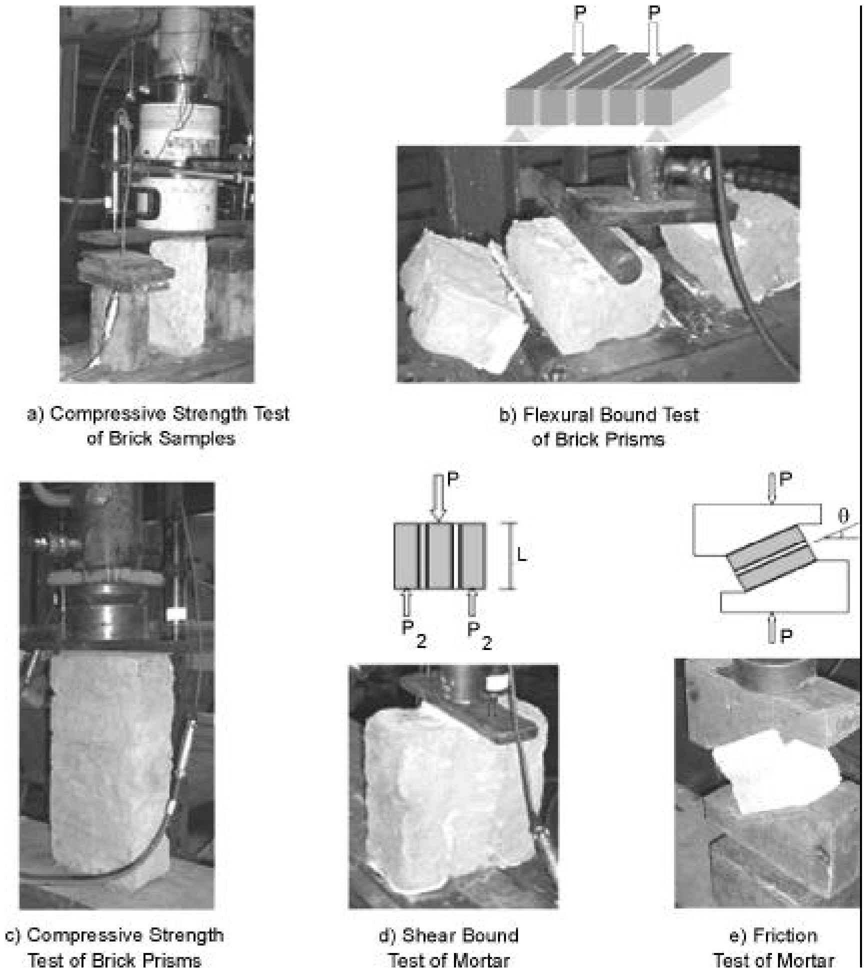

Figure 4. Material test specimens.

20 percent of live load would be contributed under the lateral loads. Therefore, a uniform load (6.4*N/m*^{2}) was considered as gravity loads and was applied with overburden loads as shown in Figure (5). In addition, Lateral load was applied horizontally and in a quasi-static cyclic manner on the diaphragms.

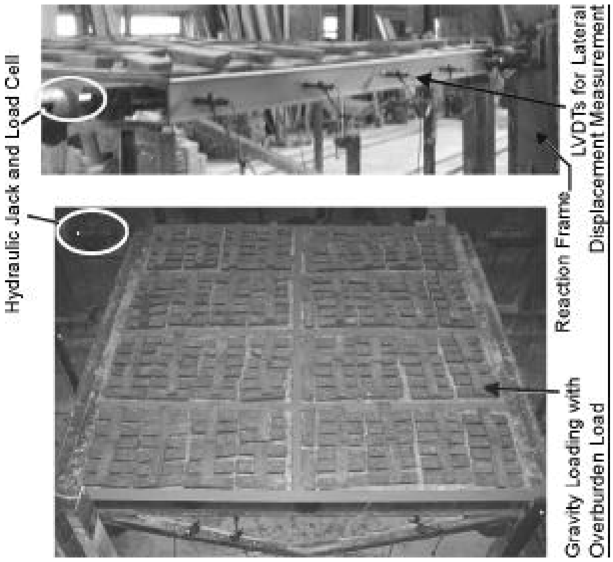

Figure 5. Simultaneous gravity and lateral loading on the specimens.

6. Instrumentation

The flat arch diaphragms were instrumented with *LVDTs* (Linearly Variable Displacement Transducer) aligned in different regions of slabs. The *LVDTs* were installed to measure the axial, lateral and diagonal displacements over different points. Ten strain gauges (*YFLA*-5 type) were installed on the tension ties and transverse beams. Two load cells recorded the amount of load in the hydraulic jacks. A data-logger system was used to display monitor and record the load and displacement measurements in real time during the test.

7. Results and Discussion

In the *FX* and *FY* experiments, the frame had about 100*mm* shear displacement under 4*KN* lateral load. The supporting frame of floor had little stiffness. This implies that the most of the lateral load can be transferred to masonry arches. In Figures (6) and (7), the hysteresis behavior and failure mode in different experiments are presented. According to Figures (6a) and (6d), the *TDX* and *TDY* experiments had 28*KN* and 42*KN* shear capacity respectively and the traditional floor lacked

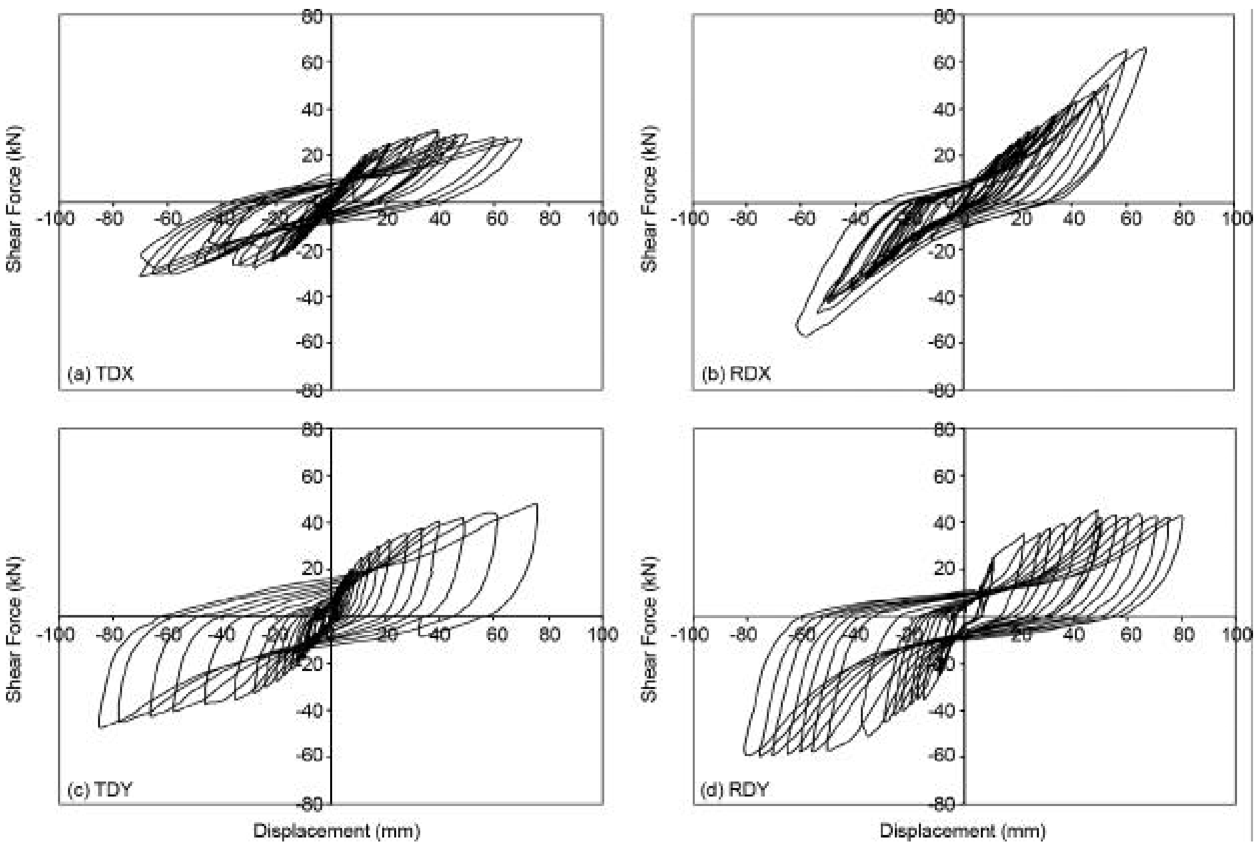

Figure 6. Lateral load vs. displacement (hysteresis loop) for all specimens.

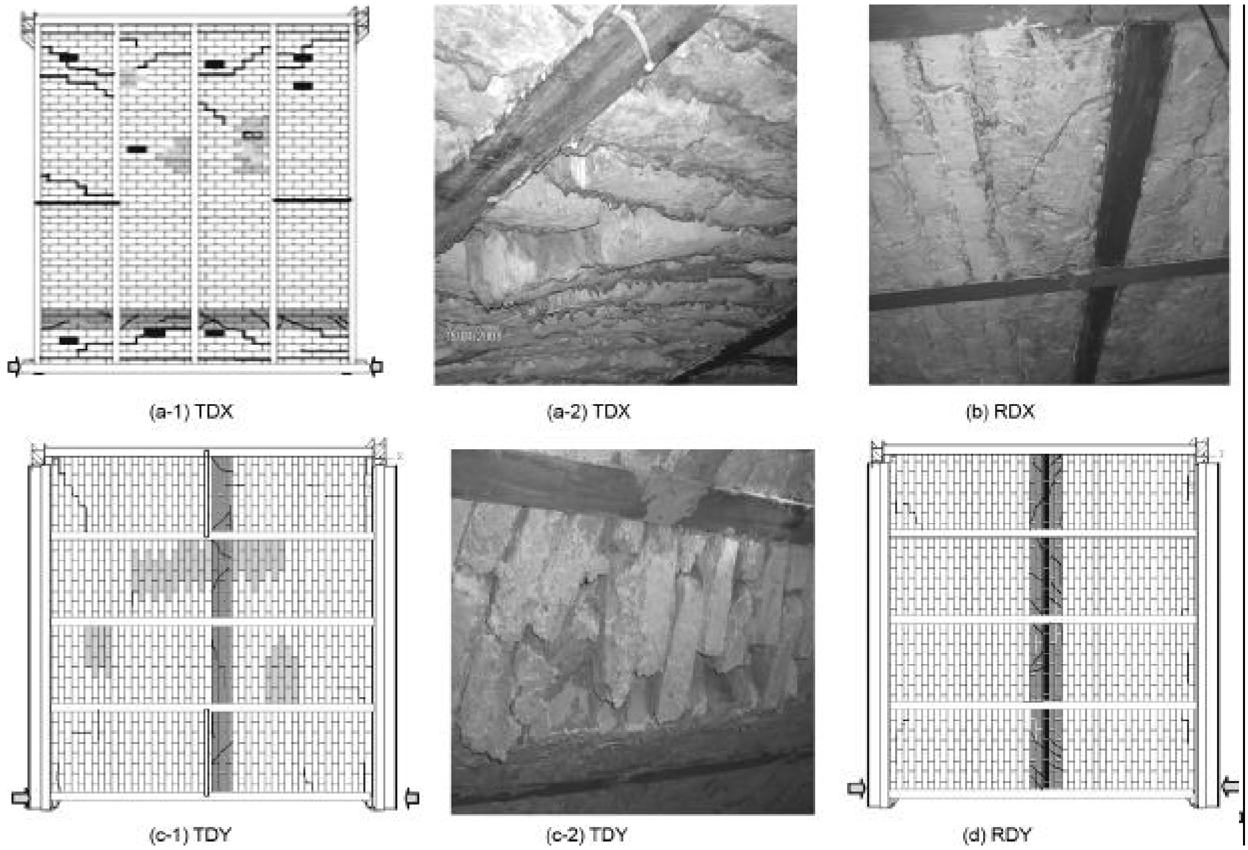

Figure 7. Failure mode of brick-flat-arch roof for all specimens: Inserted borderlines represent the crack patterns; Detached bricks from the roof indicated in light color; Cracked bricks indicated by black color.

continuity in large displacement. Therefore, the bricks in the middle of inner spans of the roof were detached from the masonry arch, see Figures (6a-1) and (6c-1). As a result, the traditional roof was unable to act as a roof diaphragm which is required for good seismic performance.

The amount of strain in the transverse beams were monitored under loading. The maximum amount of strain in the transverse beams was recorded about 180μ. It was shown that the strain in the steel beams is very low and these beams were not yielded. Therefore the failure only occurred in masonry-flat-arch elements.

According to the cyclic behavior of *RDX* and *RDY* shown in Figures (7b) and (7d), strengthening of the diaphragm by transverse beams could not suitably improve the seismic behavior of the traditional roof. The integrity, shear capacity and stiffness of the experimented structures are described in more details as follows:

7.1. Integrity

Regarding the integrity of the roofs, it has been observed that in traditional flat arch slabs, the steel cross beams of the roofs was not appropriately braced together. This could lead to dropping of the bricks between them during an earthquake. The results shown in Figures (7a-1), (7a-2), (7c-1) and (7c-2) show that the traditional roofs can not keep their integrity in large displacements so that the bricks in the middle of inner span of the roof would be detached from the masonry arch at about 60*mm* of shear displacement. Figures (7b) and (7d) show that the roof with a transverse tie has a relatively safe behavior and can maintain its integrity in larger shear displacements. In this application, the transverse ties work as tension ties to prevent cross beams' displacement and consequently the bricks between them will be safe from dangerous dropping. Therefore, we may conclude that application of transverse beams within all the spans of a roof can greatly improve the integrity of the roof and their effect is relatively similar to that of tension ties.

7.2. Shear Capacity

For evaluation of vulnerability of structures, it is required to measure the shear capacity parameter of the floor [16-17]. The value of shear capacity of flat-arch diaphragm is often not the same in different directions. Table (2) shows the amount of the shear capacity and stiffness obtained from the experiments. The transverse beams applied in the samples *RDX* and *RDY* were able to increase shear capacity from 7.8 to 16.7*kN/m* in the direction perpendicular to the cross beams, but they could not increase the shear capacity in other direction.

7.3. Stiffness

In order to limit the displacement of the floor, flexibility of diaphragms should be controlled and a sufficient amount of stiffness should be provided. The amount of initial tangential stiffnesses of the experimental results are determined in Table (2). It shows that the stiffness of traditional slab is low. According to this table, transverse beams could improve the stiffness of the diaphragm up to 135 and 37 percent compared to traditional roofs in perpendicular and parallel to the cross beams, respectively.

Figure (8) summarizes the results of the experiments and shows the pattern of degradation of stiffness with increasing of the loads.

8. Conclusions

This study describes a series of experiments on full-scale traditional and retrofitted brick-flat-arch roofs using transverse beams. The result of the two first experiments proved that the non-retrofitted traditional slabs have insufficient shear capacity and unfavorable flexibility. The experimental results of the second series of experiments revealed that the retrofitting method (i.e. using transverse beams) can partly improve the in-plane seismic behavior of the flat arch diaphragms. By adding transverse beams within all the spans, only the integrity of the diaphragm could be satisfied, however the stiffness and shear capacity of the retrofitted diaphragm were insufficiently improved. Therefore, this retrofitting method is insufficient and the diaphragm is not safely retrofitted. However, the diagonal bracing method is comparatively more efficient than transverse beam method for strengthening the flat-arch roof diaphragms [14].

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Table 2. The stiffness and shear capacity values of the masonry flat arch diaphragm in the experiment.

Floor System	Shear/Stiffness of Roof Diaphragm			
	Perpendicular to Cross Beams		Parallel to Cross Beams	
	Stiffness (N/mm)	Shear Capacity (kN/m)	Stiffness (N/mm)	Shear Capacity (kN/m)
Traditional Roof	620	7.8	1270	11.8
Roof with Transverse Beams	1460	16.7	1740	12

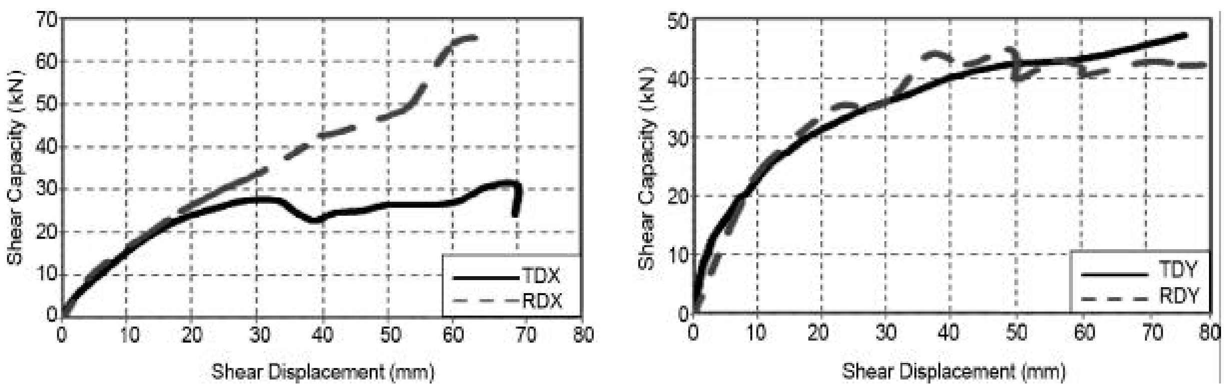

Figure 8. Capacity curves obtained experimentally.

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