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Experimental study of typical and retrofitted jack arch slabs in a single story 3D steel building

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Abstract

Seismic retrofit of masonry slabs in existing steel or masonry buildings has found special significance in current codes as failure of unstable jack arch slabs has been reported as a major reason for collapsing structures in Middle East deadly earthquakes. In this paper, three retrofit schemes are investigated and compared. The proposed rehabilitation techniques consist of a single X strapping, SXS, a double X strapping, DXS, and a two-way jack arch slab supported by a steel grid. Using experimental studies, advantages and disadvantages of each scheme are evaluated. In-plane stiffness and capacity of the diaphragm are adopted as the seismic performance index of each rehabilitation scheme.

According to the obtained results, the jack arch slab systems designed and constructed based on proposed retrofit methods provide an appropriate alternative to other forms of flooring in seismic zones. DXS can greatly improve diaphragm performance in terms of in-plane stiffness, capacity and even energy dissipation of the diaphragm compared with the other two techniques. The second place belongs to SXS while the steel grid scheme has a minor effect on the in-plane stiffness of the diaphragm.

Keywords: *Jack arch masonry slab, Retrofitting methods, Seismic behavior, In-plane stiffness, Diaphragm, Cyclic testing.*

1. Introduction

Jack arch slabs widely used in existing structures, basically consist of shallow brick arches spanning between steel floor beams (joists) with the arches packed tightly between the beams to provide necessary resistance to thrust forces as introduced in FEMA 356, (2000) [1] and Iran No. 2800 code, (2005) [2]. Jack arch flooring system was developed in Britain in the end of 19^{th} century. Due to its technical simplicity, construction speed, chance for modifying the constructed slabs and overall low-cost, this slab is still popular in the Middle East. This type of floor has been used in both masonry and steel framed buildings. For example, in Iran, there are many old steel frame buildings with jack arch slabs.

The behavior of this traditional floor system against the gravity loads is appropriate, but the seismic behavior of jack arch slabs in strong earthquakes has shown an instable and poor performance. The potential vulnerability of unreinforced masonry buildings, designed with little or no consideration for seismic design requirements, is well documented. Recent earthquakes have greatly contributed to raising awareness of the seismic hazard of unreinforced masonry buildings.

The performance of the traditional jack arch slabs in a number of recent earthquakes in Eastern Europe and the Middle East, particularly in Iran, has generally been unacceptable. The Bam terrible earthquake (southern Iran - December 2003) also has caused death of more than 40000 people [3]. Despite the wide use of the jack arch floor slabs and their shortcomings, there has been almost no distinctive research process for their engineered design and no mention of reliable guidelines in codes of practice. According to Bruneau (1994) [4], while there is evidence that unreinforced masonry buildings can survive major earthquakes, the conditions required for satisfactory performance are not fully understood and the usual modern analytical tools are often unable to discriminate approximately. A search of the literature discloses no reference to any extensive particular scientific research directed to study masonry slab except a small group of research projects. Some codes, such as the 1991 edition of the Uniform Code for Building Conservation (UCBC) (ICBO 1991)[5], is a notable case which specifically addresses the seismic strengthening of unreinforced masonry buildings, and includes a special procedure that is based on empirical evidence that can be applied to many unreinforced masonry buildings. In the recent decade, FEMA 547, 2006 [6] has devoted a subsection about jack arch slabs supported by masonry bearing walls and suggested some retrofitting techniques to enhance their seismic performance.

According to the witnesses and observations in recent

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earthquakes of Iran and on the basis of Maheri and Rahimi (2003) [7], typical weaknesses and modes of failure of the traditional jack arch slabs include: 1- Movement of simply supported steel beams from their position due to earthquake. 2- Weakness of brick arches to transfer in-plane loads perpendicular to the steel beams and in-plane shear as well as disability of the slab to show diaphragm performance required for good seismic behavior. 3- Concentration of stresses in the stiff brick arches due to out-of-plane vibration of the slabs. 4- Dynamic interaction between the stiff brick arches and flexible steel beams under vertical vibration.

There are two classes of jack arch slab, the first kind is traditional or typical one (non-engineered), mostly used in Iran; the second class is engineered one, proposed by some building standard codes such as FEMA 356 [1] and FEMA 547 [6], and Iranian standard seismic codes standard No. 2800, 2005 [2]. FEMA 356 has proposed the following methods for rehabilitations [1]: 1. Adding diagonal members to create a single X bracing as a horizontal truss to strengthen weak diaphragm. 2. Strengthening existing steel members by adding shear connectors to enhance composite action. 3. Removing weak filler and replacing it with a structural concrete slab after verifying the effects of the added weight of concrete fill. While the proposed scheme in FEMA 547 [6] is more general, it suggests tension ties for exterior and interior joists, shear ties for exterior joists to act as collector, additional elements to improve chord performance of the diaphragm, diagonal bracing to enhance in-plane strength and stiffness of the diaphragm, and finally replacing topping fillers with reinforced concrete according to vertical capacity of the floor and bearing system.

Adding diagonal rebars results in more in-plane stiffness of the diaphragm and this guarantees the less lateral deflection for the slab. In other words, X bracing system, i.e. diagonal strapping, enhances integrity of the diaphragm. A number of transverse steel beams spanning between the main I-beams, joists, forming a steel grid to overcome the imperfections of the one-way jack arch slabs have been proposed by Maheri and Rahimi (2003) [7] as shown in Fig. 1. In this way the unconnected parallel steel beams will become part of an inter-connected steel grid, allowing the vertical load to be transferred in two directions also enabling better transfer of in-plane forces.

To improve the performance of jack arch slabs, Kim and White (2004) [8] investigated using shear walls to transfer in-plane shear force and to increase lateral stiffness. They proposed this technique for important masonry buildings with jack arch slabs.

Shakib and Mirjalili (2010) [9] conducted 4 full-scale tests of roof diaphragm under cyclic loading to investigate in-plane seismic behavior of retrofitted brick flat arch diaphragms using transverse beams. Although the transverse beams could improve the in-plane behavior to provide integrity and ductility of the retrofitted diaphragm, they could not properly upgrade the shear capacity and stiffness. Then, the retrofitting method might not be enough to secure the proper in-plane behavior of flat-arch roofs.

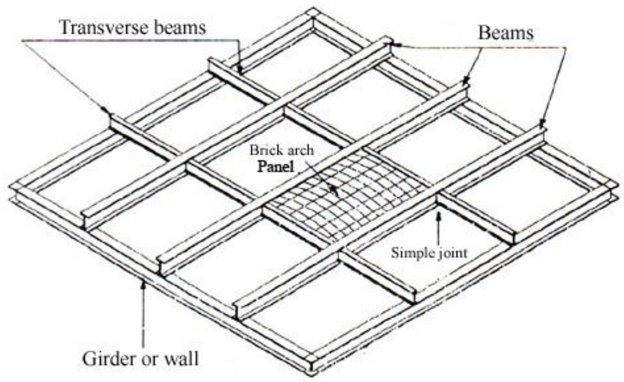

Fig. 1 Two-way jack arch slab using steel grid (Maheri and Rahimi 2003)

Maheri et al. (2012) [10] conducted out-of-plane pushover tests on a number of full-scale ordinary and retrofitted jack arch slabs, to compare the strength capacity and other seismic performance parameters of the slabs including; ductility and the behavior factor. It was found that the steel grid method of retrofitting provides all the strength and performance requirements of the slab, whereas, the concrete layer method, though effective in increasing the strength, considerably increases the weight of the slab as well, that in turn, may increase strength demand on other structural elements.

Due to hazardous interaction between stiffer bricks and steel beams, perhaps division of the panels between the steel cross beams surrounded by added transverse beams may be seen as a solution to decrease the dynamic interaction between two different kinds of materials. These added beams, if correctly used, might improve the structural performance by declining the stiffness differences between materials and assigning the role of filler to bricks. However, this technique is appropriate for new construction and cannot be simply used for under operation existing slabs.

In this paper, using five experimental specimens, the FEMA 356[1] retrofitting method which is a single X strapping, SXS, two-way jack arch slab, and double X strapping, DSX, are compared with non-retrofitted traditional slabs. The objectives of this paper are to evaluate the effectiveness of such rehabilitation methods. It is clear from Fig. 2 that one can expect a higher value for in-plane stiffness of the DSX system compared with the SXS and two-way slab. Moreover, unlike SXS and two-way slab, DSX system would improve the chord action of the exterior joists. It should be clarified that SXS is a method considered according to techniques proposed by FEMA 356 [1] and DSX is adopted according to FEMA 547 [6].

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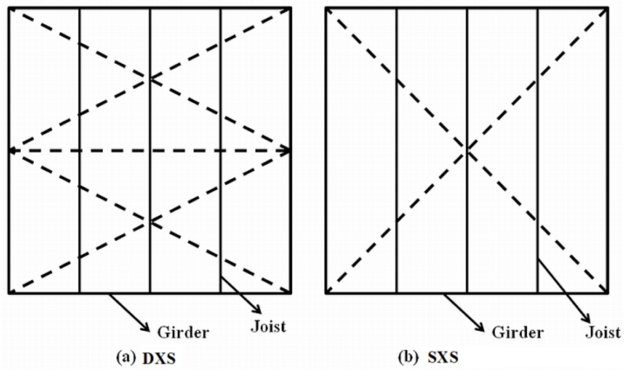

Fig. 2 (a) Double X strapping system, (b) single X strap. Dotted lines represent strap elements

2. Failure of Jack Arch Slabs

The jack-arch floor slabs constructed using the steel I-beam jack arch system as illustrated in Fig. 3 are essentially stable under normal static conditions as the brick arches transfer the gravity loads mainly in compression and along the arch to the supporting beams. The load is then transferred along the parallel steel beams to the supporting walls or girders. The geometric form of steel I-beam jack arch system and the load transfer to the steel beams, make the slab act in one-way system [7].

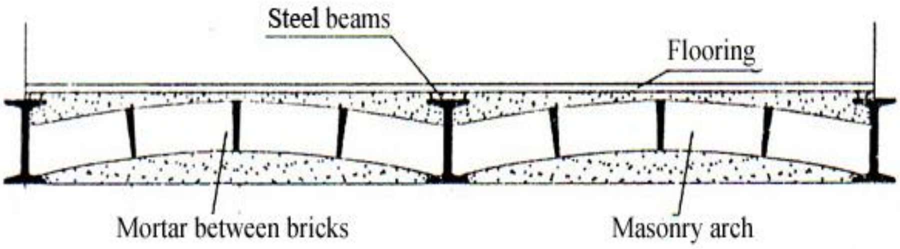

Fig. 3 A typical form of jack arch slab and its details

While these slabs perform well under gravity downward loads their seismic behavior is questionable. For instance, many steel buildings with jack arch slabs were destructed in the 2003 Bam earthquake [3]. A major part included buildings with steel internal columns, load-bearing external brick walls, and roofs, often made of shallow Jack arches with steel **I**–beams. The performance of this type of construction as a sort of unreinforced masonry structure was poor. The flexible steel columns tended to displace much more than the rigid external walls resulting in inclining of the steel columns and mostly the collapse of the whole structure (Fig. 4). This earthquake clearly demonstrated that the combination of relatively rigid load-bearing external brick walls and flexible internal steel columns is hazardous.

Fig. 4 Damaged buildings, combination of steel internal columns and load-bearing external brick-walls

3. Experimental Program

Five experimental specimens corresponding to approved failure reasons described above were built to verify the effectiveness of different rehabilitations strategies. Two overall strategies were considered in this research. First, diagonal rebars were used to induce the diaphragm rigidity, i.e. SXS and DXS as single and double diagonal rebar bracing, respectively. Second, the transverse steel beams were used to modify the dynamic interaction between the stiff brick arches and the flexible steel beams and also to enhance the behavior of slab in transferring in-plane shear.

3.1. Test specimens and set-up

The specimens had identical geometry and material as well as equal gravity loading on the floor with general specifications of single-story, single-span 3D steel frame (4.2*4.2m in plan view). Some common specifications in all 5 tests were: 1- To create slipless connection between frame and laboratory precast strong floor, 2IPE180 with 6 bearing stiffeners as well as 4 bolts were used for each of 4 connections between the specimens and strong floor. 2- Steel frames included, columns of double IPE140 (with 2m height), 2 girders (IPE270), 6 joists (IPE180), 2 X-bracing (each 2L100x100x10) such that all joints were simply connected. 3- Jack Arch brick slab was made of gypsum mortar and pressed bricks with average 3cm rise in the middle. However, these models were varied in terms of retrofitting methods and direction of lateral loading.

It should be noted that the steel frame was designed such that it would elastically resist against the progressive

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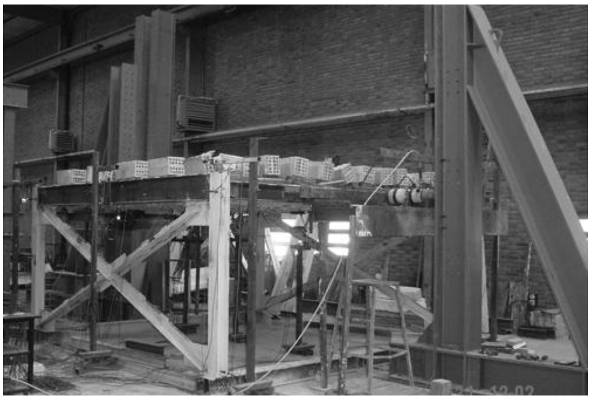
lateral loads during the tests. The instrumentation framing for one of the non-retrofitted specimens is shown in Fig. 5(a). For realistically modeling of seismic lateral loads and reducing the negative effect of web crippling due to direct loading on two side beams, as depicted in Fig. 5(b), two additional beam segments were placed in both sides of slab panels between the hydraulic jacks and the side beams.



(a) Test set-up and instrumentation framing

(b) Lateral loading

Fig. 5 Test set-up, lateral loading and instrumentation framing.

To simplify definitions of experimental specimens, following abbreviations are used in this paper: N-G, N-GL, and N-L, representing, N: number of specimen, G: gravity loading only (floor weight and overburden), L: lateral loading without gravity loads, GL: Gravity and lateral loading simultaneously.

3.2. Gravity and lateral loading

Gravity loading in real structures is sum of dead and live loads. Dead load consists of floor weight as well as overload. In this research, according to standard codes it was assumed that only 20 percent of live load was applied to the test samples. In all specimens, a uniform gravity overburden load (7.4 kN/m^2) was applied; moreover, lateral cyclic loading was applied by hydraulic jacks from both sides of specimens until slab failure occurred. Two lateral loading approaches, force control and displacement control method are usually used in testing. Because of almost linear behavior of the framing system and practical limitations, in the current study, only the force control approach was used as illustrated in Fig. 6.

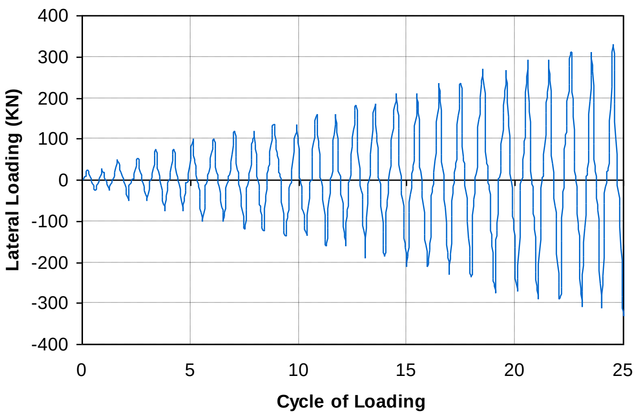


Fig. 6 Lateral loading cycles, applying each step of loading twice

For each specimen, first the gravity load was applied and structural responses were captured by data logger. Then, these masonry specimens were subjected to a series of tests under lateral loading of progressively increasing intensity. Cyclic lateral load was applied using two hydraulic jacks in a special procedure assuming that ground motion was directly transmitted to the floor using two side distributing peripheral beams perpendicular to earthquake direction.

3.3. Instrumentation

Displacements, strains, and girders rotations were measured independently on each side of the models to determine the important structural behavior parameters. Two kinds of LVDT were used for displacement measurement in all specimens, DP-C (Long Measurement Displacement) was used to measure overall lateral displacement of slabs and CDP (Compact Displacement Transducer) was applied for other small displacements such as vertical movements of beams and slabs. These LVDTs were placed at the center of the diaphragm as shown in Fig. 7. Numerous strain gages were also installed on various locations of each specimen to monitor the behavior of steel frames.

Fig. 7 LVDTs for capturing displacements of the diaphragm in different directions

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Specimen 1 (test codes: 1-G, 1-GL)

This non-retrofitted specimen was used to study the performance of the typical Jack arch slabs. This model was influenced by gravity and cyclic loads to study the behavior of the existing sample with lateral loading in direction parallel to joists and perpendicular toward two main girders. For this model, two tests were considered: 1-G (only gravity loading) and 1-GL (gravity-lateral loading simultaneously). Fig. 8 shows gravity loading by lead blocks and bricks in the 1st specimen, i.e. 1-G test.

Fig. 8 Gravity loading by lead blocks and additional bricks in the 1st specimen

Specimen 2 (Test codes: 2-G, 2-GL, 2-L)

This specimen was used to study gravity and gravity-lateral behavior of another non-retrofitted slab. Especially in this model, structural seismic behavior was studied without gravity overburden loading (2-L, only lateral loading). However, contrary to the previous case, lateral loading direction was parallel to girder and perpendicular to joists. The main objective of preparing this specimen was to evaluate probable changes in structural behavior due to different lateral load directions.

Specimen 3 (Test codes: 3-G, 3-GL)

The retrofit strategy of SXS examined in the sample, followed the philosophy of improved rigid jack arch slab having diaphragm performance. So, an in-plane horizontal bracing consisting of two No.14 rebars was welded on the floor joists. Moreover, under floor, two parallel rods (No.14) were welded perpendicular to joists to reduce the relative displacement of joists and torsion of two side joists due to gravity load (Fig. 9).

Other geometry specifications were similar to the 2nd specimen. Lateral loading direction was parallel to the girders and perpendicular to the joists like the specimen 2. Because there is not a clear proposition relevant to number of x-strapping for a distinctive area of floor, another objective of this specimen was to disclose whether adding just a series of x-bracing rebars on the floor with almost 16 m^2 area could sufficiently improve seismic behavior of structure.

Fig. 9 Specimen-3 retrofitted by single x-bracing diagonal rebar based on FEMA 356 and Iranian standard No. 2800.

Specimen 4 (Test codes: 4-G, 4-GL)

Two-way slab specimen was also tested based on the procedure presented by Maheri and Rahimi (2003) [7]. As illustrated earlier in Fig. 3, two transverse beams in each slab panel were installed in this specimen. In other words, a number of transverse steel beams were spanned between the cross I-beams (joists) to form a steel grid allowing the vertical load to be transferred in two directions. This feature also enhances the transfer of in-plane forces. In fact, by using the steel grid, the grid acts as the main load-carrying element in the slab, while the brick arches act mainly as in-fill panels. The two-way steel grid is prescribed in favor of reducing the dynamic interaction between two different kinds of materials. In this test, lateral loading direction was parallel to the girders and perpendicular to the joists like the specimen 2 and 3. Again it is noteworthy that all connections between transverse and cross beams (joists) were pin.

Specimen 5 (Tests codes: 5-G, 5-GL)

The scenario of this specimen was to apply two in-plane bracings each covering a half of the floor, to form a horizontal double X strapping, DXS (Fig. 10).

Fig. 10 Specimen-5 retrofitted by DXS on the floor under construction

Also, between these two bracings, a rebar (No. 14) was welded on the floor, perpendicular to joists and parallel to lateral load direction, to decrease the torsion of adjacent

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joists. Lateral loading was directed parallel to the girders and perpendicular to joists like specimens 2, 3, and 4. It was expected that the DXS system could effectively enhance the in-plane stiffness of the diaphragm and reduce the relative displacement between joists.

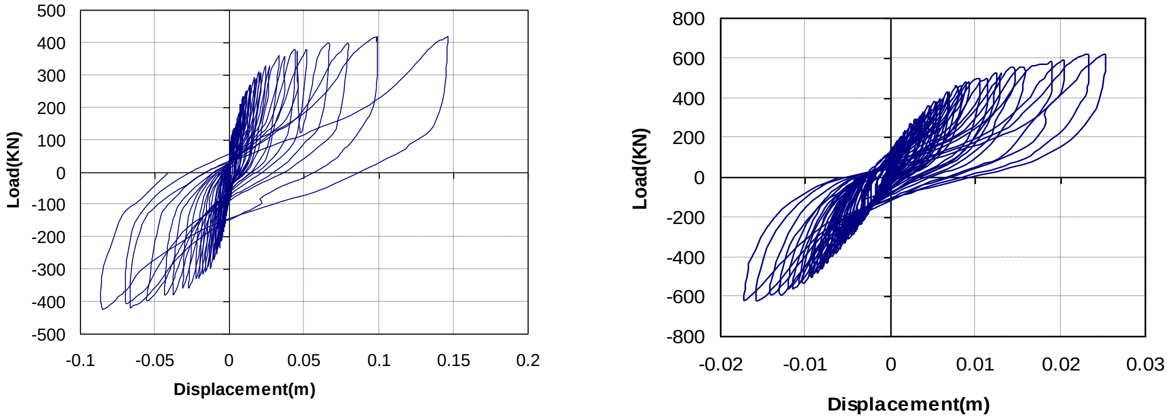
4. Test Results

For all specimens, the most important seismic parameters of the diaphragms, namely in-plane stiffness, lateral load capacity, and diaphragm flexibility were evaluated and compared.

4.1. Stiffness evaluation

Stiffness is one of the major parameters used to study seismic behavior of diaphragms, especially in the case of low-rise rigid structures. In other words, according to earlier studies by Tena-Colunga and Abrams (1996) [11], and Zhang (2001) [12], flexible diaphragms can impose excessive lateral forces into the vertical lateral load resisting elements.

The hysteresis loops related to tests 4-GL and 5-GL, illustrated in Fig. 11, disclose the lateral performance of jack arch slabs. It should be noted that the recorded displacement is the horizontal deflection at the center of the diaphragm. According to Fig. 11, the slope of the curve in 5-GL is steeper than that of 4-GL while having smaller range of displacements. In other words, 5-GL represents a stiffer diaphragm compared with 4-GL in which all joists are connected through transverse beams to work together leading to increasing in-plane stiffness compared with non-retrofitted slab. In 5-GL, however, the in-plane stiffness increases because of the presence of horizontal double X strapping. The merit of horizontal X strapping over the two-way jack arch slab is due to the fact that, X straps increase diaphragm stiffness by their axial stiffness while two-way slab benefits from flexural stiffness of joists. Besides, in 5-GL chord elements, i.e. side joists perpendicular to the lateral force direction, are restrained by diagonal straps, while according to the configuration of 4-GL, chord elements are not effectively restrained.



(a) (b)

Fig. 11 Hysteretic curves recorded at the middle of the floor span: (a) 4-GL, (b) 5-GL

Results of all specimens are presented in Table 1. It is clear that the maximum load before cracking or final step of linear behavior was recorded in the 5-GL test. This structure had stiffer slab, and during the cycle with 207kN lateral loading, the non-linear phase as well as deep cracks were observed. The lowest lateral load was captured in specimen 4-GL, in which the flexible steel frame acted against lateral forces.

Table 1 Stiffness and lateral loading process in all specimens.

	Elastic Stiffness(kN/m)		Lateral Loading (kN)	
Tests(1)	Maximum[1](2)	Minimum[2](3)	Maximum Linear[2](4)	Failure Load (5)
1-GL	135576	62400	74	417
2-GL	240807	77381	74	421
3-GL	310000	72200	81	451
4-GL	303988	89444	49	413
5-GL	360591	71472	207	606

Note: 1- Initial stiffness before loading. 2- Final step of linear behavior, when some cracks under the slab appeared.

Also, in an effort to evaluate the ultimate capacity of the diaphragms, the lateral loading process was progressively followed until failure of the slabs. The load of 606kN was needed to destroy the robust retrofitted model of 5-GL. This loading caused about 0.0224 m deflection at the center of the diaphragm. On the contrary, the maximum load bearing for 4-GL was about 413kN at a deflection of 0.0981 m. Therefore, the low load-carrying capacity and high flexibility for specimen 4 with simple connections in comparison with other proposed models should be regarded as a weak point for design purposes.

According to Table 1, column 3, the highest amount of elastic stiffness (final step of linear behavior before cracks and inelastic deflection) is 894440kN/m. This characteristic can be related to the fact that bricks in 4-GL have a minor effect on in-plane stiffness. As a result, cracks on the bricks also have a minor effect on in-plane stiffness.

As it was predictable, the peak amount of initial stiffness was reported by 5-GL about 360591 kN/m (Table 1, column 2). From this point of view, increasing the number of x-bracings on the plane can cause more initial stiffness and better structural behavior related to diaphragm rigidity. The minimum value of this stiffness was observed in 1-GL test where the lateral loading on this non-retrofitted model was parallel to the joists.

4.2. Force-deflection and stiffness-force curves

After evaluation of the hysteresis loop, it is worthwhile to look more closely at force-deflection curves of the slabs. A similar behavior for all specimens is observed. After a linear initial phase in graphs, the deflection changes non-linearly (Fig. 12). Moreover, to discover how structural behavior is related to presence of gravity overburden, Fig. 11 can be considered.

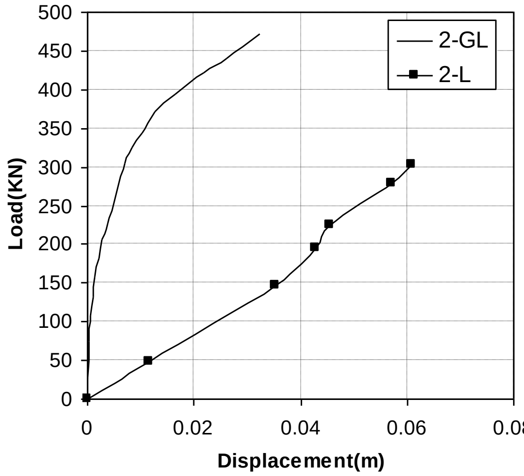


Fig. 12 Load vs. displacement of 2-GL and 2-L tests, where nonlinear behavior is observed for 2-GL

The most important outcomes are dealt with the specimen 2, by comparing 2-GL and 2-L (only lateral loading) tests. It is noticeable that 2-L test shows an entirely linear behavior until a distinctive load and then a sudden collapse occurs but in 2-GL test a non-linear softening behavior is perceived. Bricks in 2-L are unconfined as a result their limit state is governed by uplift movement and interrupting arch action of the slab in lieu of their strength. Failure load in 2-GL test is about 50 percent more than 2-L pointing to the positive effect of gravity load appearance on non-linear behavior and resistance of the diaphragm. In 2-GL, the gravity load makes an adequate confinement condition for the bricks such that makes crack development. As a result, the considered diaphragm will resist lateral loads up to its ultimate strength capacity.

Another significant point is related to the force-stiffness curves. Initial stiffnesses for samples of 4-GL and 5-GL were almost 300000 and 360000 kN/m, respectively (Fig. 13). The stiffness trend of 4-GL test discloses an initially intense reduction; in contrast, the 5-GL test has a mild and logical reduction. In the two-way slab (4-GL) a noticeable portion of the initial stiffness is due to un-cracked bricks. By increasing the lateral load, bricks would suddenly crack and get vanished from the total in-plane stiffness of the two-way slab. As a result, model 4-GL faces an abrupt fall in its stiffness.

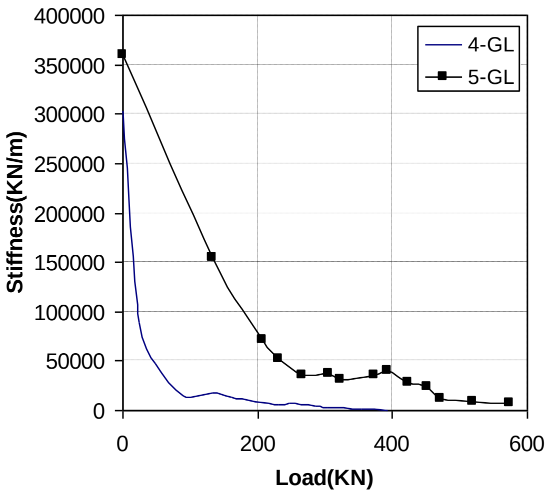


Fig. 13 Stiffness vs. lateral load, 4-GL compared to 5-GL showing different slopes of changes

4.3. Diaphragm performance analysis

In building floor systems, which usually transfer the gravity loads to the vertical structural systems, it is also required to transfer the lateral inertia forces to the vertical lateral load resisting systems through floor diaphragm action. It is common practice to assume a rigid diaphragm in the case of typical multistory buildings. However, for some classes of structural systems, the effect of diaphragm flexibility cannot be disregarded, especially in the case of rectangular buildings with large aspect ratios where considerable inelastic floor slab behavior is expected [13]. The diaphragm behavior of different types of floor systems usually differs substantially and depends on the details of the floor system and in some cases the diaphragm behavior might be unknown, so the experiments can be useful to understand the diaphragm behavior, as most studies on this subject have been experimentally conducted.

According to ASCE7 (2005) [14], floor diaphragm should be considered in the structural analysis, unless the

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diaphragm can be classified as either rigid or flexible. Considering the floor diaphragm into the structural analysis significantly increases required analysis time and it is more reasonable to classify the diaphragm as either rigid or flexible if it is possible. Definitely, from both structural and architectural aspects, it is more preferred to have a rigid diaphragm. Typical rigid or flexible floor diaphragms are reported in different codes. However, there are some general methods to classify a diaphragm, such as that reported by ASCE7 (section 12.3.1.3).

For rigidity assessment, diaphragms can be classified as follows (Iranian code of practice, Standard No. 2800, 1999): 1- when α (=$\Delta_{diaph}/\Delta_{story}$, where Δ_{diaph} is the highest value of the deflection of the diaphragm and Δ_{story} is the story drift as shown in Fig. 14) is lower than 0.5, the diaphragm can be considered to be rigid; 2- If all of the diaphragm supports have high rigidity, (small Δ_{story}), or when α value is greater than 0.5, diaphragm acts as a continuous beam on the rigid supports and the diaphragm would be flexible. However, ASCE7 [14] considers a diaphragm to be flexible if the parameter α is greater than 2.

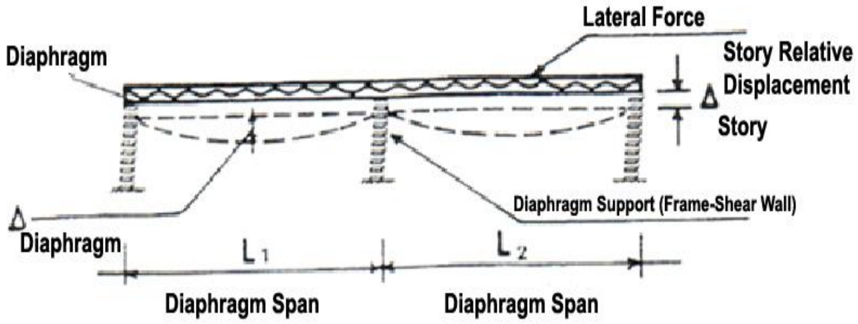

Fig. 14 Diaphragm analysis of masonry slab and its displacements

Rigidity assessments are carried out on the test specimens. It should be mentioned that the corresponding loads of the recorded deformations are the lateral forces adopted by the Iranian code of practice, Standard No. 2800 which in this case are similar to those specified by UBC 94 [15].

Among all test specimens in which the lateral loading is perpendicular to the joists (2-GL, 2-L, 3-GL, 4-GL, and 5-GL), the lowest value of α=0.35 is perceived in 5-GL as shown in Table 2. Imposing two x-strapping on the slab, strengthens the ability of structure to react as a rigid diaphragm. The second-best is 3-GL with α=0.55 (with one x-strapping), so the more in-plane x-strapping, the better diaphragm performance. The two-way slab has shown the worst performance in comparison to others as if no retrofitting procedure has been considered or even worse than the 2-GL without any retrofitting mechanism. It is obvious that by involving transverse beams in specimen 4 (4-GL) not only the in-plane stiffness of the diaphragm has been noticeably reduced after cracking of the bricks, as illustrated in Fig. 13, but also the floor slab is a kind of flexible diaphragm which is not a good feature for seismic application. Therefore, this proposed steel mesh cannot meet satisfactory conditions. Note that, more practical web connections were considered in this study for the connections of transverse beams to the joists compared to Maheri and Rahimi (2003) [7] who tried to create full fixity for their connections. Moreover, the two-way jack arch slab is a costly scheme due to existence of the transverse beams.

Table 2 Diaphragm performance analysis

Experimental Specimens	α	Diaphragm Rigidity
1-GL	1.0	NO
2-GL	0.7	NO
2-L	1.5	NO
3-GL	0.55	NO
4-GL	1.9	NO
5-GL	0.35	OK

According to Table 2, it is worth noting that the gravity loading has caused decreasing of α; in other word, in case 2-GL α was 0.7, while in 2-L test α is 1.5. This huge distinction may be related to the appearance of gravity overburdens as these two models just differ in terms of gravity loading. From this point of view, the gravity load can improve the diaphragm performance because the gravity overburden on the floor can prevent further upward rise of brick arch due to lateral forces. In fact, gravity loads in this case have the same role as confinement reinforcements in RC columns. This feature was earlier depicted in Fig. 13.

4.4. Energy dissipation and damping parameter (ξ)

Damping ratio is one the most important parameters evaluating the ability of a structure to dissipate seismic energy. In other words, buildings which are more capable of dissipating energy have better reaction against earthquake because in these structures the imposed earthquake energy can be better absorbed. Following Bruneau (1994) [4], the relationship between the slab

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inertia force and its displacement is described as non-linear elastic; it draws a linear curve until first cracking of the floor slab, reaches a maximum acceleration corresponding to a point of maximum static stability, and progressively returns to zero under much larger displacements. Since the area under this curve is associated with the total energy needed to fail the slab, Priestley (1985) [16] suggested that a linear elastic model, whose ultimate limit would be selected to yield the same energy to failure as the actual nonlinear model, would be a good indicator of dynamic stability.

The most common and physically most obvious form of damping or energy dissipation in structures is in the form of hysteresis of the force-deformation response [17]. Hysteretic damping in systems is conveniently expressed in the form of an equivalent viscous damping coefficient C_{eq} commonly expressed by the equivalent damping ratio ξ_{eq} and the critical damping coefficient C_{cr}, which is the smallest amount of damping for which no oscillation occurs in free dynamic response.

$$C_{eq} = \xi_{eq} C_{cr} \tag{1}$$

The hysteretic damping or energy loss per cycle, represented by the area A_h in Fig. 15 for one complete idealized load-displacement hysteresis loop, can then be converted for the same displacement to an equivalent viscous damping ratio:

$$\xi_{eq} = \frac{A_h}{2\pi V_m \Delta_m} = \frac{A_h}{4\pi A_e} \tag{2}$$

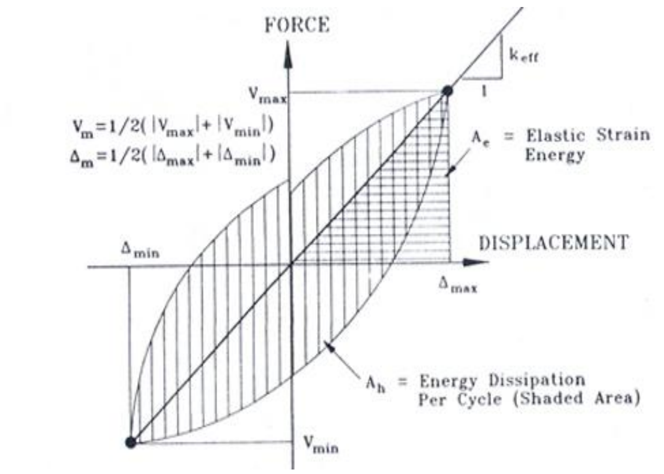

Fig. 15 Hysteretic energy dissipation and equivalent viscous damping [15]

where V_m and Δ_m represent the average peak force and displacement values. The area A_e represents the elastic strain energy stored in an equivalent linear elastic system under static conditions with effective stiffness.

$$K_{eff} = \frac{V_m}{\Delta_m} \tag{3}$$

The equivalent viscous damping coefficient can then be obtained from Eq. 1. As depicted in Fig. 16, for three retrofitted specimens, changes related to structural ability to dissipate energy have been made. For this purpose, an initial point to start analyzing was selected as 108kN and then with incremental steps of 100 kN in lateral loading, this stepwise evaluation was repeated. The 3-GL and 5-GL tests have shown more primary energy dissipation ability than 4-GL test, but it is noteworthy that the ability of these specimens to dissipate energy has been gradually reduced, after increasing lateral loading. However, in 4-GL test after a declining trend, an unexpected increase was observed. These structural differences in behavior can be related to mechanism of retrofitting in which 4-GL can maintain its ability to dissipate energy in larger displacement cycles. This phenomenon was justified due to the quality of carrying lateral load by transverse mesh beams.

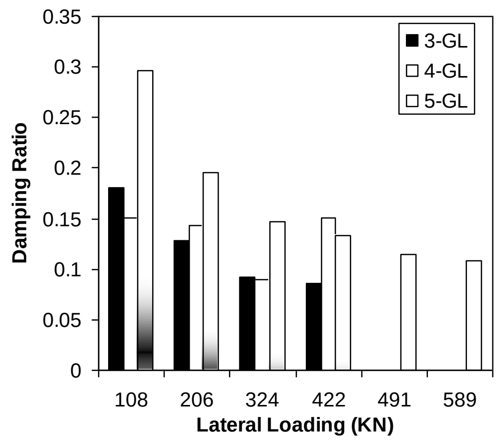

Fig. 16 Energy dissipation in different cycles of lateral loading in retrofitted specimens.

4.5. Evaluations of relative displacement within cross beams (joists)

According to observations of damaged buildings in strong recent earthquakes, relative displacement within joists is one of the most important phenomena involved in jack arch slab failure. Lateral loading widens the distance between two adjacent joists, so this increased distance allows the floor slab to be free. For investigating such effect, in all specimens relative displacements are recorded. The 3-GL test has the minimum of this value. The second rank is 4-GL test, and then 5-GL. The main reason for minimum relative displacement in 3-GL is the better performance of two parallel welded rods below the jack arch slab (Fig. 17). Although in 5-GL test, where two in-plane braces and one rebar perpendicular to joists were used, and in 4-GL test where interconnected I-beams were inserted, they could not perform as well as 3-GL. Consequently, for reducing torsion in side joists and relative displacement among joists, rods perpendicular to joists and parallel to lateral load direction may be recommended. Similarly, simulation models disclose that the only effective way to decrease this hazardous movement among joists is to use rebars perpendicular to the joists.

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Fig. 17 Two parallel rods welded below the jack arch slab in specimen 3 reduced the widening between two adjacent joists

4.6. Fracture mechanism

Excessive bending or shear may cause in-plane failures, depending on the kind of the unreinforced masonry elements. For unreinforced masonry slabs, in-plane shear failures have been commonly recorded. In this research, fractures are almost observed in the places where the bricks are connected in the I-beams web. This is because of different dynamic performance between two kinds of brittle and ductile materials. Moreover, another observed crack pattern is diagonal, approximately 45 degree cracks near the columns at the slab corners as shown in Fig. 18. This distribution of cracks is due to stress concentration in columns at the corners. Due to using transverse beams and reduction of dynamic interaction, fractures have been decreased in specimen 4.

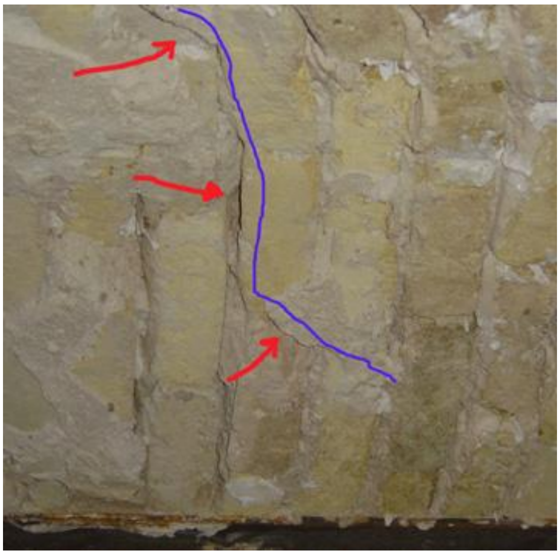

Fig. 18 Diagonal crack pattern, approximately 45 degree cracks near the columns at the slab corners

5. Conclusions

In this study, five full-scale single-story 3D steel building specimens having typical and retrofitted jack arch slabs were tested against gravity and lateral loads. According to the obtained results, retrofitted jack arch slabs using double X strapping, system, DXS improved performance of the diaphragm in comparison with both non-engineered and other retrofitted slabs. Moreover, in-plane stiffness of the retrofitted models effectively increased which resulted in better seismic performance for the floor diaphragms. For instance, in the specimen 3 and 5, the proposed method of adding x-strapping rebars disclosed the ability of the method in modifying diaphragm parameters such as ultimate strength, and in-plane stiffness.

The specimen 5 retrofitted by DXS, improved most key seismic parameters compared to other specimens such that the ultimate capacity for specimen 5 is about 1.5 times of that for the non-retrofitted specimen 2. Moreover, DXS makes a rigid diaphragm according to different code of practice, while the non-retrofitted model should be classified as flexible or semi-rigid diaphragm.

There is no definite expression in code of practice on the number of X strapping suitable for retrofitting, however to demonstrate the probable ability of system in resisting against lateral loads, two X straps are suggested for specimen 5. This proposition can improve many weak spots such as capacity of carrying lateral loads and diaphragm performance, but it seems it can show better performance by many changes such as adding parallel rods on the floor. As a result, the available prescriptions of code of practices can be regarded by some modifications to improve the seismic behavior of existing structures with jack arch slabs.

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Notations:

The following symbols are used in this paper:

A_e: elastic strain energy

A_h: the hysteretic energy loss

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C_{eq}:	equivalent viscous damping coefficient
C_{cr}:	critical damping coefficient
K_{eff}:	effective stiffness
Δ_{story}:	frame lateral movement
Δ_{diaph}:	floor mid-span displacement
ξ_{eq}:	equivalent viscous damping ratio
V_m:	average peak force value
Δ_m:	average peak displacement value

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