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Experimental and Numerical Study on Seismic Behavior of An Infilled Masonry Wall Compared to An Arched Masonry Wall

Amir Hossein Karimi [a,*], Mohammad Saeed Karimi [b], Ali Kheyroddin [b], Abdulazim Amir Shahkarami [c]

[a] *Department of Civil Engineering, Semnan University, Semnan, Iran*
[b] *Department of Civil Engineering, Semnan University, Semnan, Iran*
[c] *Department of Civil & Environmental Engineering, Amir Kabir University of Technology, Tehran, Iran*

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ABSTRACT

Sassanid era arches are among the oldest arches in Persian architecture. In this study, an infilled masonry wall and a similar Sassanid era arched masonry wall, both with clay bricks (square bricks of 195 mm long) and clay and gypsum mortar, are compared and their seismic behaviors are tested under cyclic loading (as per protocol). The dimensions of both the walls are of L 1720 mm, W 1500 mm and H 195 mm. The diameter of the vault is 900 mm. For loading, first, pre-pressure of 58 kN is applied on the specimens; then, upon this constant pre-pressure, the lateral cyclic loading is applied on the specimens. The results indicate that the arched wall can well withstand seismic forces. The maximum lateral force of 26.4 kN resulted in a 18.12 mm lateral displacement tolerated by the arched wall, while the infilled wall tolerated a maximum force of 56.53 kN at displacement of 9.12 mm. In the hysteresis curve of the arched specimen the pinching effect is observed, while in the hysteresis curve of the infilled specimen this effect is not visible. The infilled specimen in relation to the arched specimen has more energy dissipation. In specimen with arched opening, three plastic hinges occur. The first plastic hinge occurs at the arch crown and two hinges appear on the bottom of the side piers. The fracture mechanism in the arched wall is of crushing at the pressure toes of the wall and the same in the infilled wall is of crushing at the same points in addition to emergence of diagonal cracks in the wall and their expansion under increased load range. In order to validate the experimental results, the walls are modeled in ABAQUS software and concrete is used as masonry material in simulation. Concrete damaged plasticity model and macro modeling approach are adopted in this simulation. The hysteresis curves found for numerical modeling in both specimens are in good agreement with laboratory findings.

1. Introduction

Unreinforced masonry buildings constitute a high volume of the existing buildings in the world, many of which are of high cultural and historical values. The effect of recent earthquakes like: Sumatra, Christchurch, Kobe, Manjil, Bam, and Nepal, on the vulnerability of historical masonry buildings are frequently reported. For the same reason, the vulnerability assessment of these buildings and their treatment is an important global issue. Over the past decades, scientists have studied the in-plane behavior of unreinforced masonry walls [1,2]. Various experiments are performed on the in-plane behavior of masonry walls, where, the effects of masonry walls with openings in four-sided frames are assessed. Tasnimi and Mohebkhah [3] conducted an experimental study to assess the seismic behavior of brick-infilled steel frames with openings. In their study, the masonry walls with openings of different dimensions in the middle of the wall were put under in-plane cyclic loading. The effect of masonry wall with openings was assessed on the metal frame behavior. The results indicate that the masonry walls acting as the frame filling element can improve the seismic behavior of steel frame, with and without openings.

Liu and Manesh [4] performed an experimental study on the concrete masonry infilled bounded in steel frames and assessed the behavior of various types of the same. Their obtained results were compared against the American and Canadian codes and revealed that the Canadian codes operate conservatively with respect to infilled frame designs, while the American codes provide more accurate estimates of the strength and stiffness of the subject infilled walls. In some studies, new techniques and innovations are introduced for reinforcement of masonry walls. Da Porto et al. [5] assessed the behavior of a masonry wall reinforced by horizontal metal trusses. The trusses were built with steel bars like roof block joists and placed horizontally in the mortar with their ends braced in vertical brick holes on the edge of the wall as joints. They evaluated parameters like ductility, energy dissipation, damping, strengthening effect, the effect of axial force and reinforcing types.

* Corresponding author.
E-mail address: a_karimi_sazeh@yahoo.com (A.H. Karimi).

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In references [6–20], different methods are introduced for strengthening masonry walls like: use of metal bars, sheets and FRP bars, metal sheets and the bars of post tension. In references [21–24], the effect of openings on masonry walls are assessed.

There exist different studies about finite element modeling of masonry arches. Reccia et al. [25] applied the homogenization approach to assess masonry arched bridges behavior, when the Venice Arched Bridge was the subject of the study. They applied different methods to assess the nonlinear behavior of the subject. They applied commercial and non-commercial software in their modeling. The bridge has been subject to service loads and the obtained results from non-linear analysis have been compared with the limit analysis. Milani et al. [26] have analyzed a masonry vault with intense damage containing various distributed crack-patterns numerically through advanced methods like FEM and limit analysis. They considered all the nonlinearity in interfaces between adjacent elements in their analysis. Their findings indicate that the approach in studying vaults with assembling individual arches does not always assure safety and sometimes the failure loads and mechanisms do not correspond with actual findings. Other numerical and experimental studies have been done about masonry arches and vaults [27–33].

Iran is an ancient country where there are a lot of old buildings. Sassanid era arches are among the oldest arches in Persian architecture. In this study, an infilled masonry wall and a Sassanid era arched wall constructed in the laboratory become subject to seismic loading. First, a pre-pressure is applied to the specimens to load them; then, after the pre-pressure remained constant, the seismic force is applied to the top of the walls. To build the specimens, square clay bricks and clay and gypsum mortar is used. The results showed that the opening distributed the seismic loads well and showed appropriate behavior against seismic loads. In this study experimental results are validated by finite element analysis. For this purpose the walls are simulated in ABAQUS through macro modeling approach. The concrete material is used for modeling of the masonry. The concrete damaged plasticity model is applied for simulation.

The obtained data from laboratory tests can be applied in validating the new numerical models.

2. Laboratory program

The experimental study is performed in the laboratory of Semnan University, Iran, in order to assess the effect of openings with Sassanid era arched geometry in the masonry walls. Specimens are built on rigid frame to be tested after thirty days.

2.1. Description of specimens

Two specimens were built, measuring L of 1720, W of 1500 and H of 195 mm. The selected characteristics of specimens are tabulated in Table 1. The specifications of the specimens are similar to those of the historical masonry walls in Iran. The specimens' geometries are shown in Fig. 1. The specimens are made of clay bricks of 195 × 195 × 45 mm and clay and gypsum as mortar. The mortar thickness is 15 mm. The opening's drawing pattern of this arch is shown in Fig. 1. An arch frame support made of gypsum is shown in Fig. 2.

Table 1
Characteristics of constructed wall.

Characteristic	Infilled specimen	Arched specimen
Length (mm)	1720	1720
Width (mm)	1500	1500
Height (mm)	195	195
Brick size (mm)	195 × 195 × 45	195 × 195 × 45
Pre-compression stress (MPa)	0.17	0.17
Modulus of elasticity (MPa)	130	100
Poisson ration	0.15	0.15

2.2. Properties of the materials used in the walls' construction

The nominal dimensions of the solid clay bricks used here are 195 × 195 × 45 mm. The compressive strength of the clay brick is obtained subject to ASTM C67-02 [34], where at 20.7 MPa with a standard deviation of 6.86 MPa is found, Fig. 3a. The flexure test is performed on the clay bricks according to ASTM C67-02 [34], Fig. 3b. The modulus of brick rupture is obtained through the following equations at 84.04 Pa with a standard deviation of 19.51 Pa.

$$S = 3 * W(l/2-x)/bd^2 \tag{1}$$

where, S is the modulus of rupture at the plane of failure based on Pascal, W is the maximum load indicated by testing machine registered in Newton, l is the distance between the supports in mm, b is the net width of specimen at the plane of failure in mm, d is the depth of the specimen at the plane of failure in mm, and x is the average distance from the midspan of the specimen to the plane of failure measured in the direction of the span along the centerline of the bed surface subject to tension in mm.

Gypsum and clay mortar applied in constructing these two walls have a volumetric composition of 1:1. The thickness of gypsum and clay mortar measured is 15 mm. The compressive strength of the gypsum and clay mortar sample is obtained according to ASTM C109/109M-99 [35], where 5.13 MPa with a standard deviation of 1.53 MPa is found, Fig. 3c. The flexure strength of the specimens is obtained according to ASTM C348-02 [36], where 3.148 MPa with a standard deviation of 0.364 MPa is found, Fig. 3d. The compressive strength tests on the masonry prisms are performed according to ASTM C314-02A [37]. The specimens made with three rows of bricks (triple specimens) have an average compressive strength of 7.22 MPa and the standard deviation of 1.71 MPa, Fig. 3e. The specimens made with five rows of bricks (quintuple specimens) have an average compressive strength of 4.11 MPa and the standard deviation of 0.67 MPa, Fig. 3f. The uniaxial compressive stress-strain curve for brick, mortar and masonry prisms are shown in Fig. 4a; the load-displacement curve obtained from three point flexure tests for brick and mortar are shown in Fig. 4b.

2.3. Test setup and instrumentation

The test setup including specimen, loading system, and steel frames are shown in Fig. 5a. The lateral cyclic loading is applied by using two 100 kN hydraulic jacks on either sides of the specimen. Each full cycle loading consists of two half-cycle loading: the first half-cycle loading begins from left to right and the second one begins from right to left. The left hydraulic jack presses the specimen from left to right, and after unloading (release of hydraulic pressure), the right hydraulic jack presses the specimen in the opposite direction. The lateral displacement of the specimens is measured by using two linear variable displacement transducers (LVDTs) placed on the top two corners of the wall lengthwise, Fig. 5a. The two 100 kN load cells are placed between the specimen and the loading frame to measure the load pressure amount. An automatic data logger is used to record the measured forces and displacements in a continuous manner. Static vertical loading is applied on the top of the specimens using a 200 kN hydraulic jack. Vertical load is evenly distributed on the top of the specimen through a rigid steel beam. The displacement control method is applied here. The loading frame is installed securely on the rigid laboratory floor. All specimens are secured against out of plane motions by lateral bracings, Fig. 5a.

2.4. Loading procedure

Constant vertical axial load of 58 kN is applied as the force control load on the top of the specimens through a rigid steel beam to simulate gravity loads normally applied on the masonry walls. Lateral in-plane

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