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Effects of vertical stresses and flanges on seismic behavior of unreinforced brick masonry

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A B S T R A C T

Lateral in-plane response plays crucial role in seismic behavior of masonry structures. The aim of this article is to experimentally investigate the effects of vertical stresses and flanges (transverse walls) on the lateral in-plane response of the unreinforced brick masonry (URBM) walls. The experimental work included lateral in-plane quasi-static cyclic tests on full-scale walls (both with & without flanges). The vertical stresses resulting from typical single and two story unreinforced masonry buildings were simulated on full scale URBM walls. Flanges were introduced at both ends of the in-plane wall in single direction. In essence, the lateral in-plane stiffness & strength, deformability and energy dissipation of the two classes of walls are compared and the differences are quantified to help understand the effects of flanges on the in-plane response of masonry walls. The resulting damage mechanism and failure modes for each case are critically analyzed. The experimental results indicate that both vertical stresses and flanges incorporation significantly improved seismic response of URBM walls. In addition, the participation of flanges is critical in both vertical stress conditions.

1. Introduction

Brick masonry is one of the most widely used building material in construction industry throughout the world. For centuries, masonry construction has been preferred primarily due to plentiful and inexpensive availability of constituent materials and ease of construction. Historically, such type of construction is located in areas that are prone to seismic activity [1]. URBM offers a weak response when subjected to lateral loads such as earthquake. As witnessed in 2005 Kashmir, Pakistan earthquake, and November 2015 earthquake in Afghanistan and Pakistan, URBM suffered heavy damages [2–8]. Masonry structures (brick and stone) suffered yet again in the more recent earthquakes of 2009 and 2016 in Italy [9–12] and 2015 in Nepal [13,14]. These events have further strengthened the need of continuing research to understand and improve unreinforced masonry construction. It is evident, that such type of construction, although more economical and popular, pose high risk to the safety of masses during earthquakes. Extensive research has been carried out and more work is in progress to understand the behavior of masonry structures and to develop better design guidelines for the same.

Seismic capacity of masonry structure is affected by a variety of parameters that include aspect ratio, level of vertical stress, mechanical properties of masonry and its constituents and flanges This paper investigates the effects of vertical stresses and boundary conditions (flanges) on the in-plane behavior of the URBM structures.

Vertical stresses are inherently present in all load-bearing URBM structures. Vertical stresses resulting from the diaphragm, adjacent parts of the buildings and occupancy loads, constitute one of the important parameter which influence the behavior of URBM under the action of lateral loads. A number of researchers have studied vertical stresses for their effects on masonry behavior and response. Research work carried out by (Magenes, G., Calvi [15], Irimies & Bia [16]; Yi et al. [17]; Haach et al. [18]; Tomaževič & Weiss [19]; Salmanpour et al. [20]; Salmanpour et al. [21], Salmanpour et al. [22]; Javed et al. [23]) utilized both solid and hollow brick and block masonry to study the effects of vertical stresses. Quasi-static cyclic testing has been performed in most of these studies due to its advantages over other types of testing techniques [24].

Most of these researchers tested isolated masonry piers or walls either full scale or half scaled. However, Irimies & Bia [16] also incorporated flanges in the specimens. Axial loads, masonry unit types, geometrical characteristics and material strengths were varied to study their effects on response parameters. All the researchers concluded that vertical stress is a principal parameter that affects the strength and deformability characteristics of the masonry.

Apart from vertical stresses, boundary conditions, particularly flanges, also play important role in the load in the behavior of URBM. Boundary conditions though inherently present in the brick masonry

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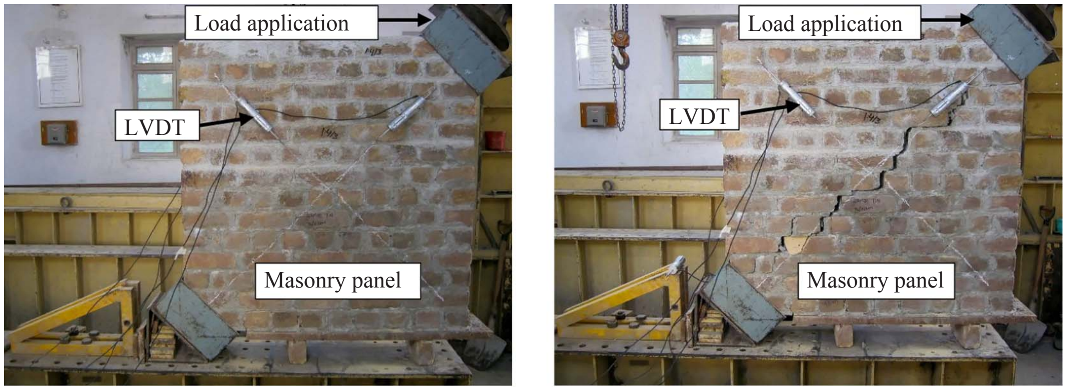

Fig. 1. Compressive strength testing of brick masonry panels.

walls, are frequently ignored in the research owing to their limited contribution. Limited research is available in literature on the contribution of flanges on the deformability and strength characteristics of URBM walls. Earliest studies on masonry carried out by Tomaževič et al. [25], Costley and Abrams [26], and Tomaževič [1] suggested the need to evaluate flanges effects on masonry response. More recent work on flanges participation was reported by Paquette and Bruneau [27], Moon [28] and Yi et al. [29].

Moon [28] carried out one of the earliest and most comprehensive work to investigate the effects of flanges on capacity and response of URBM. Moon [28] conducted lateral load tests on a two storey full scale unreinforced masonry (URM) structure before and after retrofitting. The variables of interest included overturning effects, flanges participation and global rocking. Based on the results, a number of modifications has been suggested in the current FEMA 356 model [30] for in-plane analysis of perforated walls. For the purpose of modification in the FEMA 356 [30] model, flanges have been divided into three categories which include compressions flange, global tension flange and component tension flange. The research observed considerable participation of each category of flange in influencing the capacity and failure modes in in-plane URBM walls.

Yi et al. [31] developed a new pier model to investigate the effects of flanges on the behavior and response of URM piers. The proposed model is modification of the effective pier model developed by Yi et al. [29]. The modified model is analyzed for a non-rectangular URM pier to study flange effects. Russell and Ingham [32], Russell and Ingham [33] and Russell et al. [34] studied flanges contribution for material and loading characteristics experienced in brick masonry structures in New Zealand. Their results confirmed the accuracy of the model proposed by Yi et al. [31] for estimating strength of flanged in-plane wall. Furthermore, the results emphasized the effects of flanges on failure mode and lateral strength of unreinforced masonry.

Most recent work on flanges contribution in URBM has been reported by Khanmohammadi et al. [35] who tested four half scaled masonry specimens. The research work mainly focuses on block masonry, with either solid or perforated geometric nature and made comparisons between experimental work and proposed models that yielded acceptable prediction under controlled conditions.

Due to limited work on flanged unreinforced brick masonry (FURBM), further investigation is required to yield data for developing acceptable analytical models for capacity and behavior prediction of masonry. Furthermore, due to the variability in material characteristics and different geometric as well as loading configurations that were applied by various researchers, the results obtained do not have straightforward application to the masonry structures that constitute building stock of developing countries. The research work presented in this article encompasses the effects of target variables on baked clay solid brick units that are typically employed in construction industry in developing countries.

2. Experimental program

To investigate the effects of vertical stresses and flanges on strength and deformability characteristics of URBM, a detailed experimental scheme was designed. The experimental program included selection of representative constituent materials for construction of test specimens, determination of constituent material properties, construction of full-scale specimens and quasi-static cyclic testing of specimens.

2.1. Material properties

Prior to fabrication of specimens, a preliminary study was carried out to select representative materials to be used in the specimens. All the specimens were constructed using baked clay solid bricks having nominal size of 229 × 114 × 76 mm that are commonly used in the local construction industry in Pakistan. For brick units, initial rate of absorption and compressive strength were determined according to ASTM C67-16 [36] and the cement mortar compressive strength was determined following ASTM C109 [37]. The water-cement ratio was decided based on the consistency of the mortar in order to achieve a workable mix. To characterize the compressive strength and diagonal tension behavior of masonry, masonry assemblages were prepared and tested in compliance with test protocols of ASTM C1314 [38] and ASTM E59 [39], respectively, as shown in Fig. 1. Table 1 represents mechanical properties of constituent materials.

2.2. Construciont of full scale walls

In order to investigate the effects of variables under consideration, a total of four (04) full-scale URBM specimens were constructed. The specimens were named as S1, SF1, S2 and SF2. Specimens S1 and S2 are full scale perforated walls without incorporation of flanges. Specimens SF1 and SF2 are full scale perforated walls with incorporation of flanges. The numeric values, 1 and 2, in the specimen IDs (S1, S2, SF1,

Table 1
Mechanical properties of constituent materials.

Material	Property	Results (average)	Testing Standard
Brick units	Compressive strength (MPa)	16.20	ASTM C67-3a
Brick units	Initial rate of absorption (kg/min)	0.07	ASTM C67-14
Cement mortar (1:4)	Compressive strength (MPa)	7.95	ASTM C109
Brick masonry	Compressive strength (MPa)	4.34	ASTM C1314
Brick masonry	Diagonal tensile strength (MPa)	0.17	ASTM E519