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Experimental Evaluation of Out-of-Plane Performance of Non-Structural Brick Masonry Wall Using Shaking Table Test

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2. 構造―2. 振動―h. 振動実験・観測
Brick wall, Infill wall, Nonstructural element, Out-of-plane, Shaking table

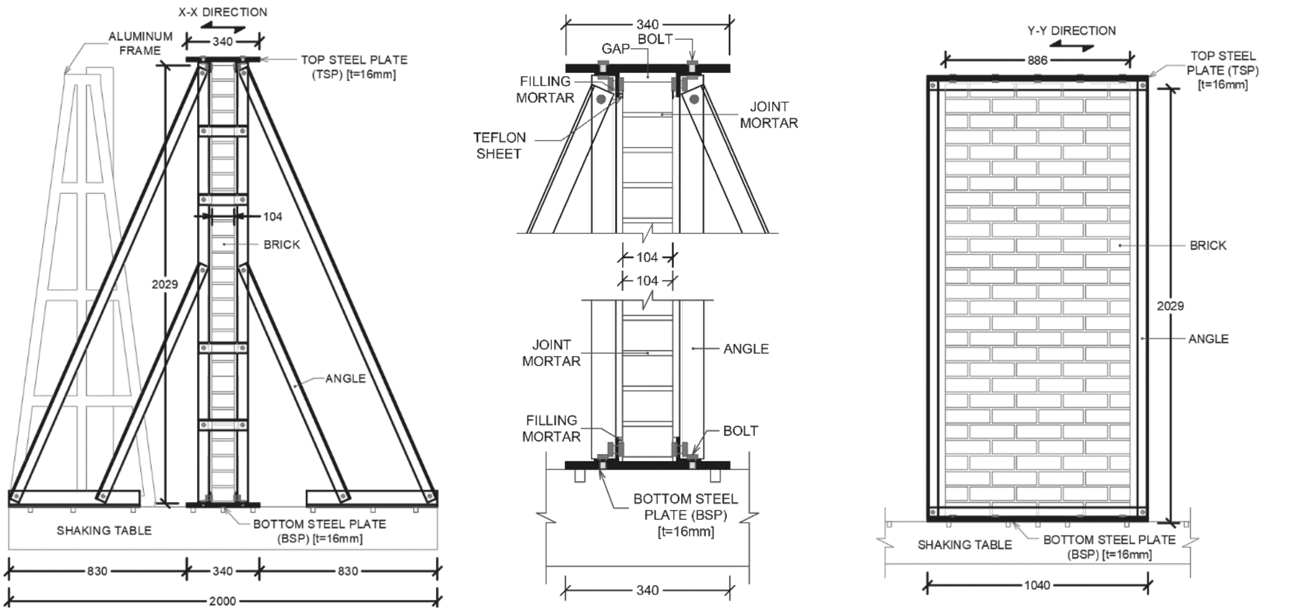
1. Introduction

Infill walls are usually considered as “nonstructural” elements, and their effects on the behavior of buildings are not taken into account in the design process[1)]. Yet, infill walls affect positively or negatively the behavior of buildings. Positive effects translate to improvement of stiffness and lateral strength to seismic forces, while negative effects are related to unexpected failure such as formation of soft story and shortening columns. In Bangladesh, brick infill walls are commonly used due to their low cost of production and unrequired technical skills from the worker. Meanwhile, the country lies enclosed by seismic active zones[2)]. It has been observed in past earthquakes that the infill walls tend to fail in the out-of-plane direction[1)], however, suggesting that these elements sustain seismic forces and dissipate seismic energy according to their potential capacity[3)]. The purpose of this research is to experimentally investigate the out-of-plane behavior of brick walls under seismic motion according to the Bangladesh response spectrum using a shaking table, and propose an analytical model to estimate the out-of-plane plane resistance of brick walls.

2. Experimental Program

2.1 Specimen and Material Properties

The specimen aimed to recreate a masonry wall made out of brick units, with similar properties as in Bangladesh. Figure 1 shows the specimen details. Its dimensions were approximately 2000 x 900 x 100 mm in height, length and thickness, respectively, which possessed 28 layers of bricks. Mortar with a volumetric cement to sand ratio of 1:6 was used to bond the bricks, which was a ratio commonly used for masonry construction in the country. The bed and vertical joints had an approx. thickness of 10 mm. The specimen was built within the steel frame: first a layer of



(a)Specimen X-X direction (b) Top and Bottom (c) Specimen Y-Y direction

Figure 1 Details of specimen (Unit: mm)

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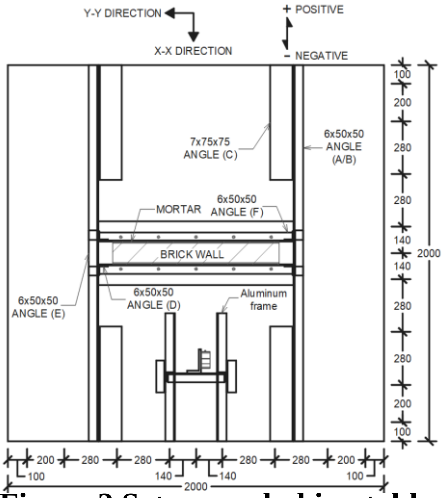


Figure 2 Setup on shaking table (Unit: mm)

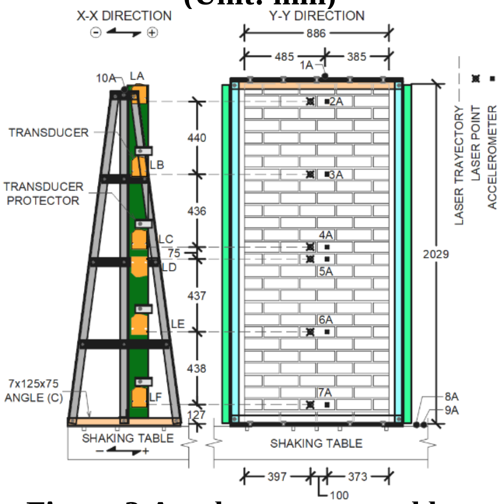


Figure 3 Accelerometers and laser transducer (Unit: mm)

1:6 mortar, then a layer of 4 brick units where the vertical joints were filled with the 1:6 mortar. Another layer of the same mortar was set on the bricks, followed by an alternated layer of bricks. This process was repeated until the 14th layer, where the construction was stopped; thus, the overall construction finished the following day. To avoid the development of vertical force on the specimen due to vertical confinement by the steel frame, a vertical gap of approximately 20 mm was left between the specimen and the top steel plate. Whereas, a 1:1 mortar filled horizontal gaps between the specimen and the L-shaped angles which were placed beside the specimen at both top and bottom ends, to prevent horizontal slip of the specimen on/at the bottom/top steel plates during excitation, as shown in Figure 1(b). Thus, a roller condition with a freedom in the vertical direction was created at the top by inserting Teflon sheet between the 1:1 mortar and the brick wall, preventing vertical friction. Brick and mortar cylinder samples were tested under uniaxial compression. Their mechanical properties are shown in Table 1 to Table 3. A secant modulus, the slope of the line joining the origin and the highest value of strain, was defined for bricks and 1:6 mortar, considering their unclear initial stiffness, and an elastic modulus was defined according to the Japan Industrial Standards[4)] for the 1:1 mortar. Also, in order to evaluate the flexural tensile strength of the 1:6 mortar, several prism specimens with 7-layer bricks were constructed, which failed under self-weight, indicating, at most, a value of flexural tensile strength equivalent to σ_t=0.012 N/mm^2.

2.2. Loading and Measurement Methods

A shaking table of 2 x 2 meters, as seen in Figure 2, was used for the test. It had a maximum earthquake acceleration of 8.9 m/s^2 in the X-X direction and 5.7 m/s^2 in the Y-Y direction, with a restricting weight of 1,000 kg. To measure displacement and acceleration over the specimen's height during the test, six laser transducers and ten accelerometers were installed at different locations, as shown in Figure 3. A response spectrum was created based on the Bangladesh National Building Code[5)], which defined the design spectral acceleration (S_a) as:

$$S_a = \frac{2}{3}\frac{ZI}{R}C_s \qquad (1)$$

Table 1. Material properties of bricks

Type	Compressive strength (N/mm^2)	Secant modulus (N/mm^2)
Brick #1	14.19	1,977
Brick #2	16.12	1,424
Brick #3	14.03	1,478
Brick #4	16.94	2,082
Average	15.32	1,740

Table 2. Material properties of 1:6 mortar

Type	Compressive strength (N/mm^2)	Secant modulus (N/mm^2)
Mortar #1	1.18	1,930
Mortar #2	0.82	2,713
Mortar #3	1.05	3,288
Average	1.02	2,644

Table 3. Material properties of 1:1 mortar

Type	Compressive strength (N/mm^2)	Elastic modulus (N/mm^2)
Mortar #1	61.41	32,231
Mortar #2	42.10	15,379
Mortar #3	34.80	29,588
Mortar #4	26.82	16,428
Average	41.29	23,406

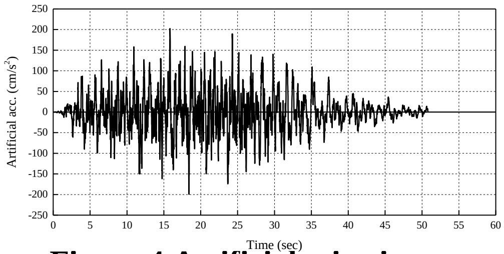


Figure 4 Artificial seismic wave

where, Z is the seismic zone coefficient (Z=0.20, Dhaka). I is the importance factor (I=1.00, occupancy I or II). R is the response reduction factor (R=1.00, elastic). C_s is the normalized acceleration response spectrum. The assumed soil classification was "SD" and a damping factor was assumed at 5%. An artificial seismic wave was created using the method suggested by a previous study[6], which defined the duration of the artificial earthquake (T_d) as:

$$T_d = 10^{0.31M-0.774} \quad (2)$$

where, M is the magnitude of the assumed earthquake. Figure 4 shows the artificial seismic wave obtained based on the above assumptions, from where the maximum acceleration is approximately 200 gal. In addition, the test was performed under 5 input stages: 10% (20 gal), 30% (60 gal), 50% (100 gal), 75% (150 gal) and 100% (200 gal) of the artificial seismic wave.

3. Experimental Results

The distributions of the maximum displacement and the maximum acceleration over the height can be seen in Figure 5 and Figure 6, respectively. Under the first two inputs, at the 10% (20 gal) and 30% (60 gal) stages, the specimen seemed to move as a rigid body and no damage was observed on it. At the 50% stage, bonding failure between the 1:6 mortar and brick was observed at the top, and the specimen (top part) slid in the negative direction; thus, a permanent slide of 5 mm remained. At the 75% stage, the magnitude of the slide increased to 20 mm, a complete disconnection between the top layer of bricks and those in the layer below was observed. At the 100% stage, the specimen collapsed towards the negative direction. Displacement was not measured at 100%, as the laser transducers were covered to avoid damage from the collapsing wall. Figure 7 shows the permanent sliding and collapse. Due to high noise in the recorded data, the moving average method was used to filter the high noise.

4. Proposal of Lateral-Resistance Evaluation Method and Verification

A conservative analytical model is proposed to predict the lateral resistance. From the distribution of the maximum acceleration over the height of the specimen, a uniform distribution of acceleration with equivalent area was determined for every instant of time, as illustrated in Figure 8. Then, a relation of the assumed uniform distributed load (w), mass (m), height (H) of the specimen, and the equivalent uniform acceleration (a) was established as (3).

$$w = \frac{m \cdot a}{H} \rightarrow a = \frac{H \cdot w}{m} \quad (3)$$

The values of w are plotted over time in Figure 9. Then, the lateral resistance of the specimen was evaluated as a capacity of w (hereafter w_c), which was dependent on the moment resistance (Mr) of the specimen. To determine the w_c of the specimen, first the moment resistance was determined by the cross-sectional analysis of the specimen. The acting forces on the cross section are the compression force (C), related to the compressive strength (σ_{MC}) of the 1:6 mortar (the weakest element), and the self-weight of the specimen (N). The flexural tensile strength (σ_t) was neglected due to its low value compared to the compressive strength (σ_{MC}).

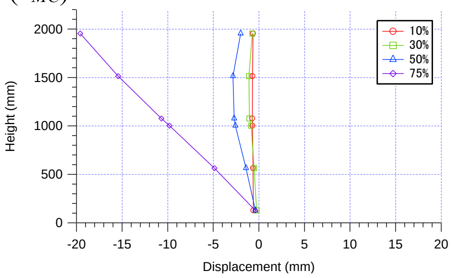


Figure 5 Max. displacement over height

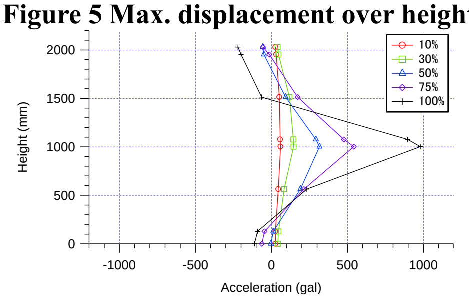
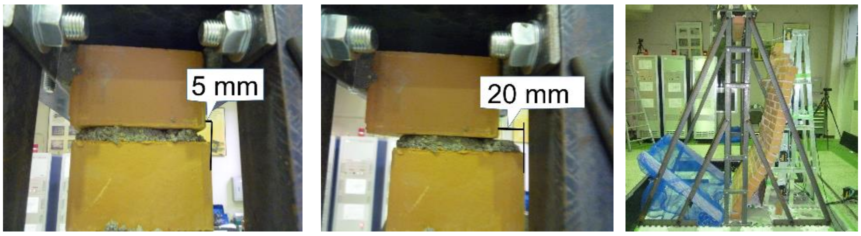


Figure 6 Max. acceleration over height

In addition, the analytical w_c was determined based on the bending moment diagram (BDM) under a roller-fixed support condition, as shown in Figure 8. At the fix bottom end, the analytical acceleration is calculated by relating the maximum moment to the Mr by (4):



Slide at 50% Slide at 75% Collapse at 100%

Figure 7 Permanent sliding development and collapse

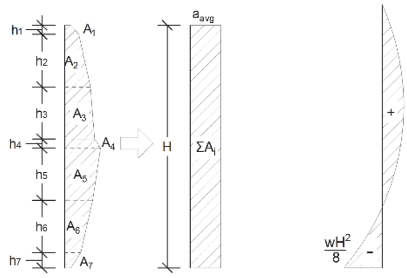


Figure 8 Equivalent acceleration and BDM

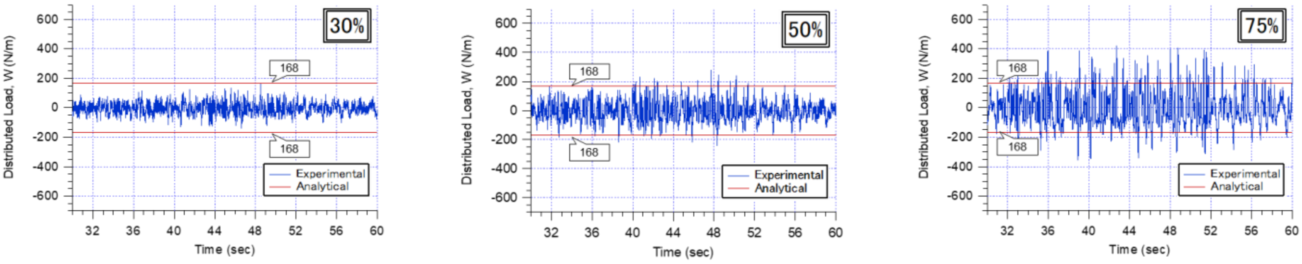


Figure 9 Comparison of the experimental uniformly distributed load with the analytically evaluated resistance

$$M_r = \frac{wH^2}{8} \rightarrow a = \frac{8M_r}{m \cdot H} \quad (4)$$

Then, using (3), the analytical w_c was determined. Figure 9 shows the comparisons of the experimental w and the analytical w_c. At the 10% and 30% stages the experimental w did not reach the capacity w_c, which correlated to the no damage during these inputs. At the 50% stage, the experimental w slightly exceeded the analytical w_c, explaining the 5 mm slide at the top. At the 75% stage, the experimental w significantly exceeded the analytical w_c, resulting in the 20 mm slide and complete collapse of the specimen during the 100% input This suggests that the proposed method can be used to conservatively predict the out-of-plane performance of the brick wall specimen.

5. Conclusions

From the experimental results and proposed model, the following conclusions were obtained:

1) Under the support conditions of the specimen applied in this study, damage/failure was observed at the top of the specimen with less axial force due to the self-weight.
2) An evaluation method of the lateral resistance of this type of wall was proposed and verified that it can be used to make a conservative prediction of the lateral resistance.

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