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Collapse Mechanism of Adobe and Masonry Structures During the 2003 Iran Bam Earthquake

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Abstract

An earthquake of magnitude MW 6.5 occurred at 05: 26 on December 26, 2003 in Bam City, Kerman State, Iran. The epicenter was located at 29.01N and 58.26E. More than 26,000 people were killed, and about 90% of the adobe and masonry structures collapsed. The earthquake was recorded at the center of the city by BHRC. Peak accelerations for longitudinal, transversal, and vertical components were 778.2, 623.4, and 979.9 (gal), respectively. We carried out simple in situ tests to examine bonding strength in the shear and separation directions using a spring balance. From the results of these tests, it was found that bonding strength was very weak and was the cause of collapse of adobe and masonry structures.

Key words: the 2003 Iran Bam earthquake, adobe structure, masonry structure, shear strength, bonding force, in situ test, collapse mechanism

1. Introduction

An earthquake of magnitude MW 6.5 (Ms 6.7 USGS) occurred at 05: 26 on December 26, 2003 in Bam City, Kerman State, Iran. The epicenter was located at 29.01 N and 58.26 E. The total population of Bam and Barvat was about 120,000. There were about 26,000 victims [1]. The historic citadel of Bam, one of the wonders of Iran's heritage, was almost completely destroyed by the quake. The 2000-year-old citadel was the largest mud-brick structure in the world. It was one of the major tourist attractions of Iran and was devastated by the earthquake.

Adobe buildings and non-reinforced masonry structures, which were the most common structures in the city, almost all collapsed. The collapsed buildings did not leave any voids for the people trapped inside, and constituted one of the causes of more than 26,000 fatalities. Figure 1 shows the distribution of collapsed buildings in Bam city [2].

In addition, the Building and Housing Research Center (BHRC) in Iran recorded the unique main shock of the earthquake. The maximum accelerations of 2 horizontal and 1 vertical components of the earthquake after correction were 778.28 (L), 623.44 (T), and 979.95 (V), respectively. The maximum horizontal velocity was about 120 kine (Fig. 2) [3].

The up and down motion of the vertical component showed a very large amplitude. Because the direction of the accelerometer for the (L) component was N278E, this shows vibration approximately in the east-west direction. Based on this fact, it is understood that the record is the normal component of the earthquake that occurred at the right lateral fault.

One of the reasons for the collapse of adobe and non-reinforced masonry buildings and the many victims, was the improper bonding strength of mortar. In this study, some simple experiments were carried out at the site to measure the bonding strength of the mortar between the sun-dried (adobe) and baked bricks. The experiment method and the results are reported in this paper, and the collapse mechanism studied is presented.

2. State of damage to adobe and non-reinforced masonry buildings

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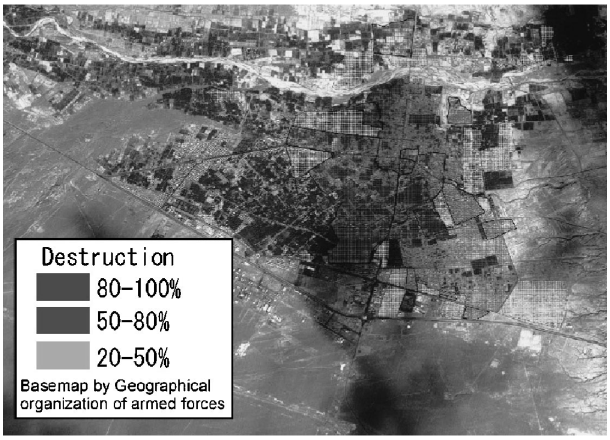

Fig. 1. Distribution of damage to buildings in Bam City [2].

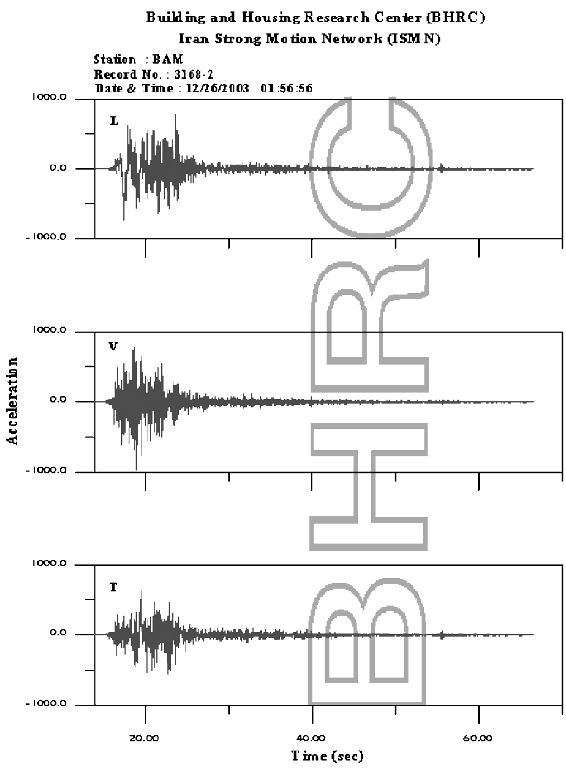

Fig. 2. Strong motions recorded in Bam city [2].

Photo 1 shows a village near Bam in which the adobe buildings were not damaged. The beautiful buildings mostly have arched roofs.

To support this arched roof, a building has thick, massive side walls. On the other hand, photo 2 and photo 3 show a collapsed adobe building and a heavily damaged non-reinforced masonry building, respectively, in Bam city. In the collapsed adobe building, adobe bricks filled the rooms and left almost no

Photo 1. Undamaged adobe buildings (suburbs of Bam city).

Photo 2. Collapsed adobe building (Bam City).

Photo 3. Severe damage to non-reinforced masonry building.

Photo 4. Measuring shear strength of mortar of sun-dried bricks.

Photo 5. Measuring tension strength of mortar of sun-dried bricks.

space for the trapped inhabitants.

Moreover, in the masonry buildings, the damage ratio of non-reinforced masonry buildings was obviously more than that for confined masonry buildings. A high collapse rate was observed when a large amount of sand was used in the mortar between the bricks.

3. Simple experiment to estimate bonding strength between bricks

To study the bonding strength between sun-dried and baked bricks in adobe buildings and non-reinforced masonry buildings, shear and tension tests were carried out at the site using a spring type scale.

Photos 4 and 5 show the situation of the simple shear and tension test carried out on sun-dried bricks. Bonding strength was defined as the force measured by the spring scale pulling the wire winding the sample when adhesion was lost.

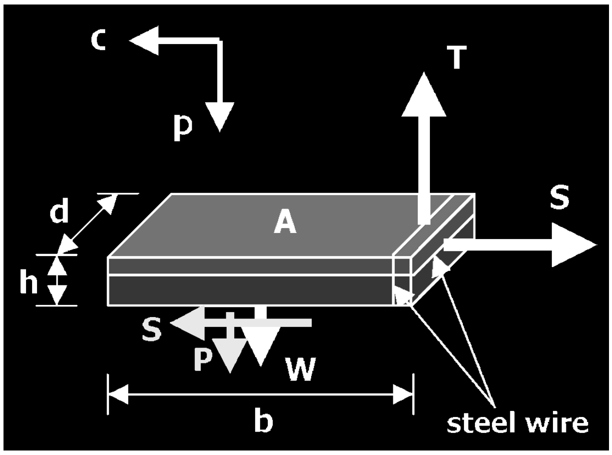

Fig. 3. Shear and tension strength estimation method.

4. Estimation of bonding strength between the bricks

Figure 3 is a schematic diagram showing the parameters used when estimating the bonding stress between bricks. d (cm), b (cm), h (cm), and A (cm^2) are width, length, height, and area of the section of the brick. The force produced in the wire winding of the brick in the horizontal direction (shear) is S (kgf) and in the vertical direction (tension) is P (kgf). The bonding stress corresponding to these in the horizontal direction and the vertical direction are c (kgf/cm^2) and p (kgf/cm^2), respectively. Considering W (kgf) to be the weight of the brick, the bonding stress in the cross horizontal and vertical direction can be calculated by equating the forces in the horizontal and vertical directions using the following equations. Because the tension force is made to act as the moment in the experiment, it is assumed that the moment has an equilibrium corresponding to the axes at the left down side of the brick. Moreover, to consider the influence of the weight above the objective area, friction coefficient μ is required. Other experiments were also carried out to find out this coefficient.

Bonding stress in the horizontal direction c

$$S/A = c + \mu \frac{W}{A} \tag{1}$$

Bonding stress in the vertical direction p

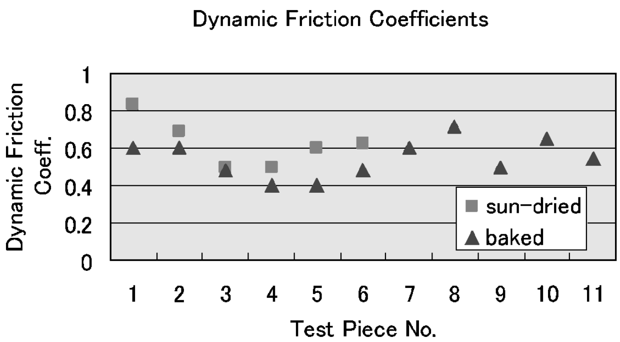

Fig. 4. The coefficient of friction for sun-dried (rectangular) and baked bricks (triangle).

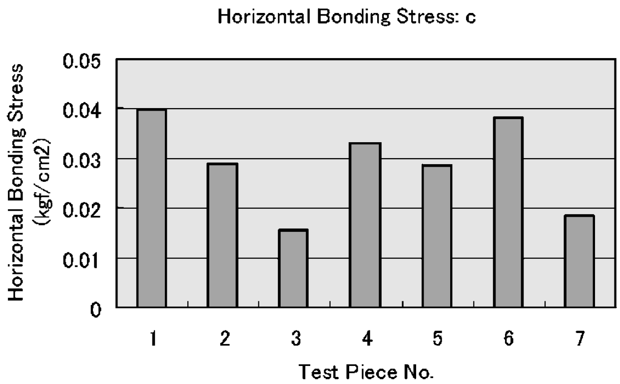

Fig. 5. Bonding strength in the horizontal direction (shear) for sun-dried bricks.

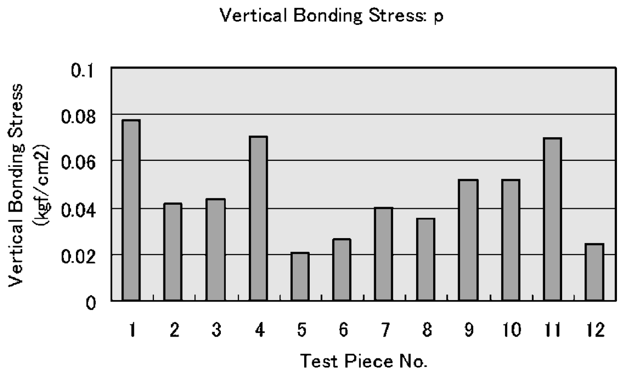

Fig. 6. Bonding strength in the vertical direction (tension) for sun-dried bricks.

$$Tb = \frac{pAb}{2} + \frac{Wb}{2} \tag{2}$$

$$\frac{2T}{A} = p + \frac{W}{A} \tag{3}$$

The numbers of tests performed at the site are as follows: for sun-dried bricks, shear test 7, tension test 12; for baked bricks, shear test 8, tension test 6. Figures 4∼8 show the results of these tests and tests to find the friction coefficient μ. The results show considerable variation in the values. The average value of the friction coefficient μ for sun-dried bricks is 0.62, and in baked bricks is 0.54. The friction coefficient value in sun-dried bricks is greater. The results of bonding stress for sun-dried bricks and baked bricks are shown in Table 1.

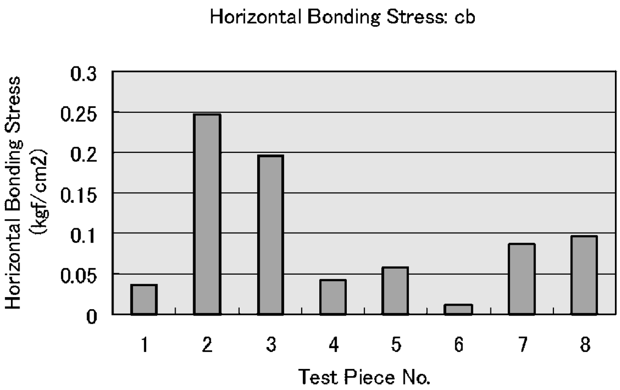

Fig. 7. Bonding strength in cross-section direction for baked bricks.

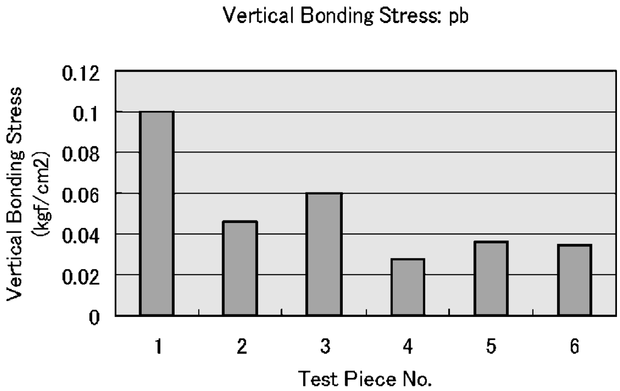

Fig. 8. Bonding strength in tension direction for baked bricks.

Table 1. Results of bonding strength test in the site.

	Shear	Tension
Sun-dried	0.029 (kgf/cm^2)	0.046 (kgf/cm^2)
Baked	0.097 (kgf/cm^2)	0.051 (kgf/cm^2)

As mentioned above, shear bonding stress and the tension bonding stress were found to be extremely small. For example, the connection of a 20 cm square brick can be broken by applying only a

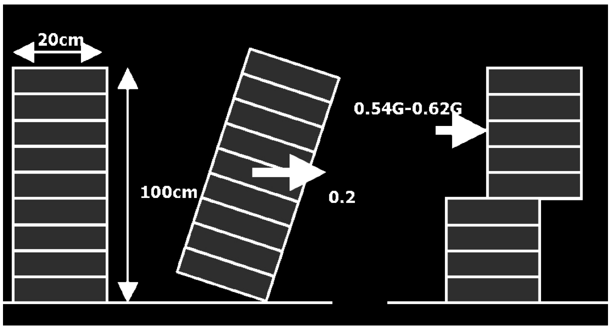

Fig. 9. Collapse modes.

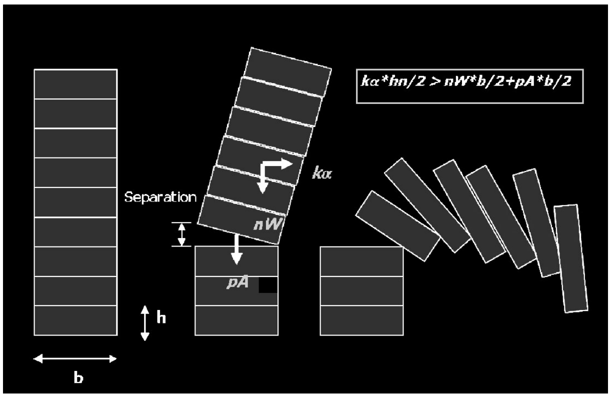

Fig. 10. Collapse mechanism of adobe buildings.

lateral force of 10 kgf. Under tension it would also break with just a force of about 20 kgf.

5. Collapse mechanism of adobe and non-reinforced masonry buildings

In Section 4, it is concluded that the bonding strength between the bricks in the adobe and non-reinforced masonry buildings is very small. The collapse mechanism of adobe buildings, therefore, is considered in the following. Assume bonding stress can be neglected. Having a coefficient of friction about 0.54～0.62 from Fig. 4, as shown at the right side of Fig. 9, with a horizontal acceleration of about 0.54～0.62 G, sliding will occur in a weak section in the wall. Now, assume that a wall is made of adobe with a width of 20 cm and a height of 200 cm, and the dead load of the wall is not taken into account, as shown at the left side of Fig. 9. A small acceleration of just 0.2 G can initiate the collapse of the wall. Bonding strength exists, however, it is small. Therefore, the resistance force to rocking is also small. Although the model of the wall is very simple, it shows that collapse is initiated by a force that is much smaller than that required for brick to shift in the transverse direction. As mentioned above, in the collapse mechanism of an adobe building or a non-reinforced masonry building, mainly bonding strength is weak, and the brick elements separate first in the area where a larger moment acts on the edge. Therefore, the whole support wall is rotated by this, and when support from the arched roof is lost, the whole structure collapses. Specifically, if the turning moment of an earthquake of the level of αk becomes more than the summation of the moment produced by the weight of n bricks nW, and bonding strength in the normal direction pA, the collapse mode illustrated in Fig. 10 occurs. The inequality is given by the following formula:

$$k\alpha\frac{hn}{2} > nW\frac{b}{2} + pA\frac{b}{2} \qquad (4)$$

6. Conclusions

The collapse of adobe structures caused a heavy toll of lives in Bam City. Here, we report the results of simple in situ tests to examine the bonding strength of shear and separation direction using a spring balance. This shows that collapse is initiated by a force that is much smaller than the force required for brick to shift in the transverse direction. We proposed an inequality equation to express the collapse mode of an adobe structure. Consequently, the bonding strength was very weak, which caused the collapse of adobe and masonry structures.

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