Experimental Evaluations for Peeling and Shear Strength of Masonry Arch Bridges

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SUMMARY:
Recently, masonry arch bridges have been focused as the industrial heritages in Japan; however, many masonry arch bridges were already replaced and few remained were deteriorated by aging and disasters. To conserve historical masonry arch bridges, immediate repairing or reinforcement is required. Modelling masonry arch bridge with precise failure mechanism and analyzing seismic responses of numerical model are necessary to evaluate the seismic performance. In this paper, peeling and shear strength of masonry constructions are described due to reveal the parameters of failure mechanism in numerical calculation.

Keywords: Experimental test, peeling strength, shear strength, masonry arch bridges

1. INTRODUCTION

Brick have been used as a typical material to construct structures since ancient era in Europe. Many masonry structures were constructed from the last quarter of 18th century to the first quarter of 19th century in Japan, however, many masonry buildings were lost due to two huge earthquakes in Meiji and Taisho era. Nowadays, few masonry arch bridges were remained as the infrastructures. Recently, such masonry arch bridges have been focused as the industrial heritages and investigated of seismic capacity to carry out for next generation.

Some investigations for cultural heritages are conducted, however, the investigation methods are applied differently in each sight. Then, the evaluation criteria of seismic capacity depend on each researcher. In addition, on sight investigations were not conducted sufficiently, because target structures were designated as cultural assets of national importance. It is necessary to investigate the mechanical attributes and to estimate the failure patterns of masonry arch bridges during the natural disasters to maintain the safety as the infrastructures.

Bourzam et al. (2008) conducted the lateral loading tests for confined masonry wall to predict shear capacity in numerical analysis, and a diagonal test (ASTM 519/C1391) was conducted to estimate tensile strength and modulus of shear elasticity of brick prism. The parameters were calculated in two-dimensional problem and the materials were assumed homogeneous.

Kino et al. (2001) conducted core sampling tests from an existing masonry structure, and the compressive strength, the tensile strength and the elastic modulus were calculated from experimental tests of the core samples. In addition, Tadokoro et al. (2004) conducted bending tests of masonry piers to verify the relation between the failure condition and the strength.

Authors (2011) conducted some compression tests of masonry specimens to estimate the fundamental mechanical properties of a masonry arch bridge; however, the failure mechanisms of masonry constructions has not been evaluated, yet.

In this study, two experimental tests were conducted to verify the failure mechanism of masonry arch bridges. This paper focused on the tensile strength and the shear strength between brick and mortar, because the failure mechanism would be affected by these parameters. Peeling and shear strength tests were conducted to estimate these parameters.

2. EXPERIMENTAL TEST

Specimens were prepared for peeling strength test and shear strength test. The mortar of which masonry specimens consist was compounded by the defined ratio of cement to fine aggregate in JIS R 5210.

2.1. Compressive and tensile strength tests of mortar

Compressive and tensile strengths of mortar were observed before conducting peeling and shear strength tests of masonry constructions.

First, the compound ratio of Portland cement to fine aggregate (sand) was one to three, and W/C was 0.5 as shown in Table1. The fine aggregate was air dry state.

Table 1. Compounding ratio of mortar

Quantity of material per unit volume (kg/m^3)			Water-cement ratio (%)
Cement	Fine aggregate (sand)	Water	
464	1392	232	50

Next, the mortar specimens were fabricated in cylindrical shape, which has dimensions of 50 mm in diameter and 100 mm in length as shown in Fig. 1. Twelve specimens were prepared to conduct the compressive and the tensile strength tests, and each test used six specimens.

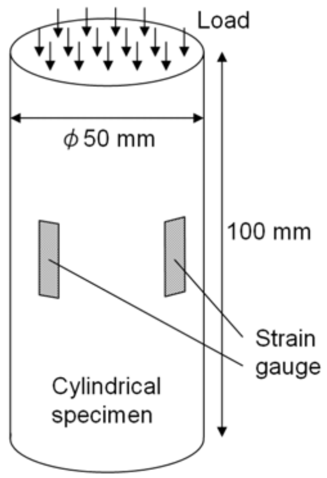


Figure 1. Cylindrical mortar specimen

A vibrator device was used for molding cylindrical specimens as indicated in JIS R 5210; and these specimens were air-cured only due to conform the curing condition of masonry specimens. It is impossible to cure masonry structures in water in usual cases; then mortar joint was exposed in air. Mortar specimens were cured inside laboratory to stay attuned to the curing condition easily. Then, the mortar specimens were cured 28 days.

Compressive strength test of mortar was conducted following JIS R 5201 and tensile split test of mortar was conducted in JIS A 1113. Single axis strain gauges were applied vertically on four sides of the cylindrical specimens.

2.2. Peeling strength test of masonry specimen

Adhesive force between brick and mortar was defined as peeling strength, and peeling test of masonry specimen was adopted from the experiment procedure proposed by Kahlaf (2005) as shown in Fig. 2.

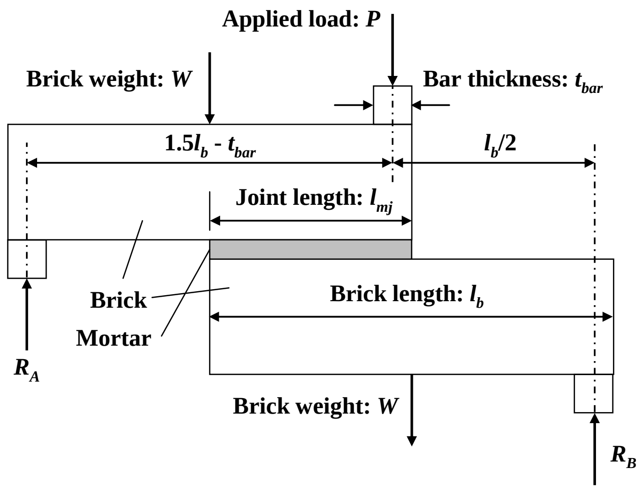


Figure 2. Masonry specimen of peeling strength test

Peeling strength test specimens consisted of two bricks staggered with mortar as shown in Fig. 2. Vertical load was applied on point P in Fig. 2, and the peeling strength was calculated from Eqn. 1 to 3. The vertical load was increased until peeling of mortar joint

Bricks were dunked in water 24 hours before making masonry specimens to prevent the absorption of water content of mortar, Mortar thickness of masonry specimens were 10 mm. Nine specimens were prepared to consider the variation of experimental results.

Peeling strengths were calculated based on the experimental report of Kahlaf (2005). A free body diagram of peeling strength test is shown in Fig. 3. Point H was assumed the hinge in moment calculation, and reaction force R_A and peeling strength f_{fb} were calculated;

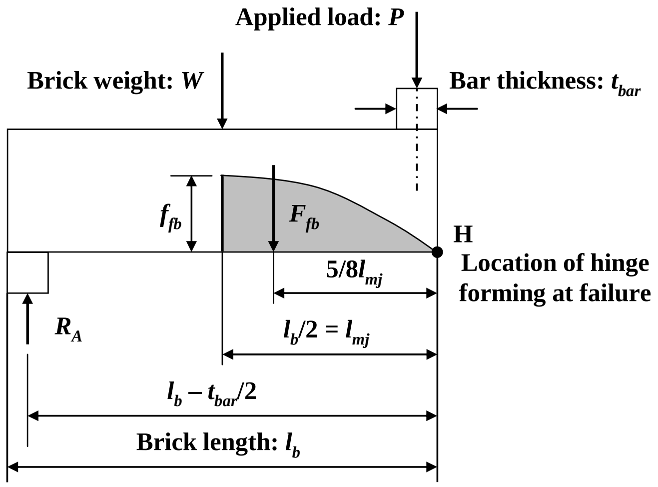


Figure 3. Free body diagram of peeling strength test

$$R_A\left(l_b - 0.5t_{bar}\right) = 0.5l_bW + 0.667l_{mj}F_{fb} + 0.5t_{bar}P \tag{1}$$

$$f_{fb} = \frac{\left(0.5l_b^2 - l_b t_{bar} + 0.5t_{bar}^2\right)P + \left(0.75t_b^2 + 1.25l_b t_{bar} + 0.5t_{bar}^2\right)W}{\left(0.44l_{mj}^2 w_b\right)\left(1.5l_b - t_{bar}\right)} \tag{2}$$

$$F_{fb} = 0.667\left(l_{mj} f_{fb} w_b\right) \tag{3}$$

where, R_A is reaction force, f_{fb} is peeling strength, l_b is length of brick, t_{bar} is thickness of jig, P is applied load, W is weight of brick, l_{mj} is adhesion length of brick and mortar joint, w_b is width of brick, F_{fb} is total force of peeling strength.

2.3. Shear strength test of brick triplet specimen

Simple brick triplet specimens were used to obtain the shear strength of the interface between brick and mortar as shown in Fig. 4. Bricks were dunked in water 24 hours before making brick triplet specimens and mortar thickness were 10 mm as same as peeling test specimens.

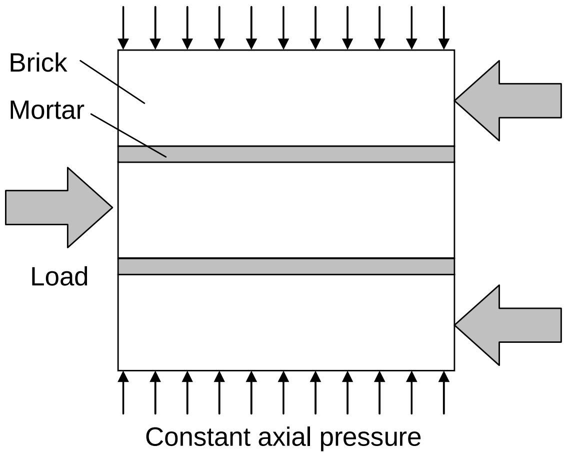


Figure 4. Brick triplet specimen of shear strength test

First, a constant axial load was applied to the brick triplet specimens by jack. Then, the lateral load was applied gradually on the middle piece of the specimens till the interface failed. A test set up is shown in Photo 1. The axial load was varied in three levels (0, 10, 20 and 30 kN) to estimate the shear failure envelope with the contact pressure.

Photo 1. Devices of shear strength test

Appling the axial load to the specimens has three aims which are representation of the weight of actual structures, prevention for the rotation of the specimens by applying lateral load and consideration of the pressure dependence of shear strength. Ten specimens were prepared of each axial load levels; however, four specimens were tested only in 30 kN of axial load case due to the short of experimental conditions.

3. RESULTS OF EXPERIMENTAL TESTS

3.1. Compressive and tensile strength of mortar

The average values and the coefficients of variation of the experimental results are shown in Table 2. The criterion of compressive strength of mortar is not defined in JIS. The results of mortar compressive tests were compared with the criterion of cement's compressive strength in JIS (JIS R 5210 in 1992), and the compressive strengths of five specimens were lower than the criterion value of JIS.

Table 2. Results of strength test of mortar

	Average (MPa)	C.V. (%)
Compressive strength	28.4	4.2
Tensile strength	2.5	9.7
Elastic modulus	14430	5.4

Air-dried condition of the fine aggregate used for mortar would affect the decrease of the compressive strength of the mortar specimens. Additional water content was not corrected at the composition of mortar in this research, because additional water absorption of the fine aggregate was not considered. Generally, the strength and the elastic modulus of mortar decrease in case of the fine aggregate which has small density and large water absorption. Then, compressive strengths of the mortar specimens were lower than the criterion value.

Tensile strength of the mortar specimens were approximately 9 % of the compressive strength as shown in Table 2. The elastic modulus was calculated based on the elastic tangent of the stress-strain curve in the range lower than 0.001 as shown in Fig.5. The each coefficient of variation of the experimental results was lower than 10 %.

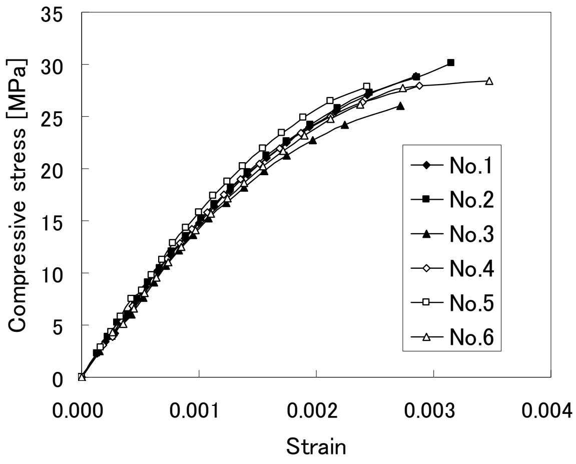


Figure 5. Stress-strain relations of mortar

3.2. Result of peeling strength test

The average and the coefficient of variation calculated from the results of the peeling strength tests are shown in Table 3. The peeling strength of the masonry specimens is 20 % of the tensile strength of the mortar specimens, and the coefficient of variation is 15 % of the mortar experimental result.

The all rupture patterns of the masonry specimens were peeling at the interface between upper part brick and mortar joint as same as Kahlaf's experimental results as shown in Photo 2. Then, the equations showed by Kahlaf were used to calculate the peeling strengths of the masonry specimens.

Table 3. Results of peeling strength test of masonry specimen

	Average (MPa)	C.V. (%)
Peeling strength	0.51	14.7

The large variation of the peeling strengths compared with the result of mortar experimental test was affected from the shape of the bricks in the masonry specimens. As the production difference is large for bricks, the variation of the brick shapes affects the experimental results.

Photo 2. Failed specimen of peeling strength test

Splitting failure of the mortar joint was also prospected before conducting the experimental tests, however, the results shows that the possibility of the peeling failure between brick and mortar joint is higher than the splitting failure of the mortar joint in case that masonry structures are loaded in tension vertically.

3.3. Result of shear strength test

Comparing the shear strength and peeling strength shows that the shear strength is higher than the peeling strength as shown in Table 4. The relation between the initial axial load and shear strength increases proportionally except the case of 30 kN as shown in Fig.6. The all coefficients of variation are higher than 20 % and these values are also greater than the result of the peeling strength tests. The large values of the coefficients of variation were affected by the adhesive area between brick and mortar joint.

Table 4. Results of shear strength test of brick triplet specimens

Initial axial load (kN)	Average (MPa)	C.V. (%)
0	2.9	25.2
10	4.7	36.2
20	6.4	28.7
30	6.1	20.4

Two types of rupture patterns were confirmed in the shear strength test. One is splitting at the interface between brick and mortar joint as shown in Photos 3(a) and 3(b), and the other is failure of mortar joint as shown in Photo 3(c). The probability of diagonal crack at mortar joint was increased with the elevation of the initial axial load.

The stress state of the specimens was estimated as biaxial stress state as shown in Fig. 7 due to the vertical contact pressure and lateral load in shear strength test, and the stress state of the element at mortar joint was estimated as the combined action of normal stress σ_y and shear stress τ_{xy} as shown in Fig. 8. The normal force was acted in single direction, because the pure shear was occurred due to the condition of the lateral loads. Mohr's circle of the stress state in Fig. 8 is described based on the relation of single normal stress and conjugate shear stress.

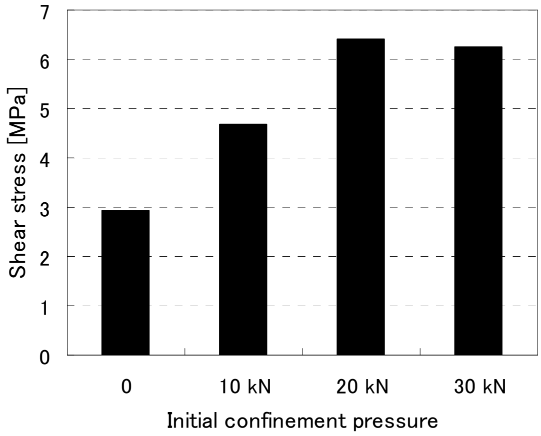
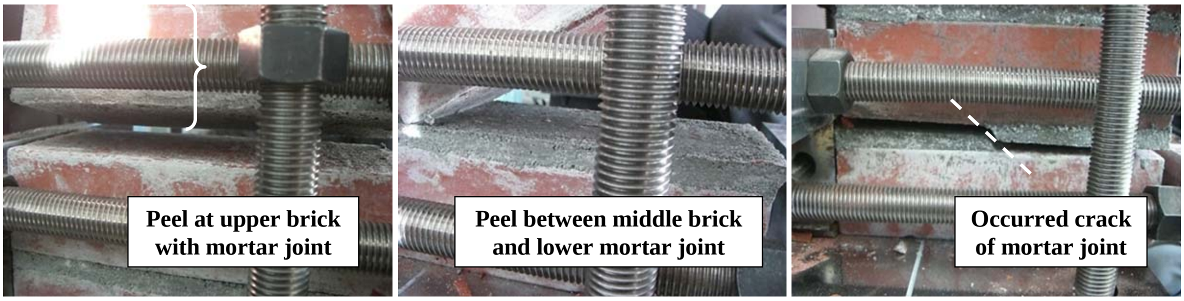


Figure 6. Shear stress-initial confinement pressure relation



(a) Pattern 1 (b) Pattern 2 (c) Pattern 3

Photo 3. Rupture patterns of the specimens in shear strength tests

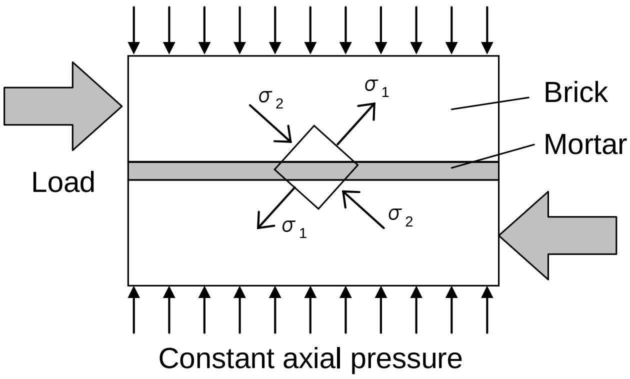


Figure 7. Stress state of the specimen in shear strength test

Maximum and minimum principal stresses are calculated from Eqn. 4;

$$\sigma_{1,2} = \frac{\sigma_x - \sigma_y}{2} \pm \frac{\sqrt{\left(\sigma_x - \sigma_y\right)^2 + 4\tau_{xy}^2}}{2} \tag{4}$$

where, σ_1 is the maximum principal stress, σ_2 is the minimum principal stress.

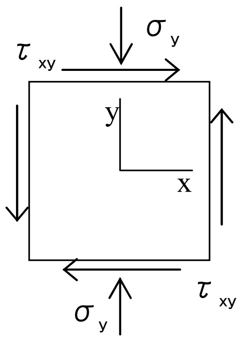


Figure 8. Stress element of biaxial stress state

The angles of principal stress were $\theta_1 = 42°52'$ and $\theta_2 = 132°52'$, and these angles coincide with the crack line of Photo 3(c).

The shear strength of the brick triplet specimens is large comparing with the tensile strength of the mortar specimens, and the difference between the shear strength and the tensile strength of mortar increased with the elevation of the initial contact pressure. Then, the failure of mortar joint was occurred, because the tensile strength of mortar is lower than the shear strength.

Masonry structure has higher strength in compression compared with tension. As masonry structures are subjected to tension and compression loading cyclically during earthquakes, it is necessary to consider the condition of cyclic loading to prevent the masonry structures from damage due to earthquake motion.

The results of experimental tests shows the peeling strength is lower than the shear strength for masonry constructions. Then, it is necessary to consider the difference of the criteria between the peeling and the shear when the seismic performance of masonry arch bridge is evaluated in numerical analyses.

4. CONCLUSIONS

This paper focused on the tensile strength and the shear strength between brick and mortar. Then, peeling strength and shear strength tests were conducted to estimate these parameters.

The results of experimental tests show the peeling strength is weaker than the shear strength of masonry constructions, and the relation between the initial axial load and the shear strength shows the proportionality.

The rupture patterns of masonry constructions under shear loading is affected by vertical pressure; including splitting between brick and mortar under low vertical pressure, and crack of mortar under high vertical pressure.

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