# EXPERIMENTAL STUDY ON STRUCYURAL PERFORMANCE OF HISTORIC BRICK MASONRY BUILDINGS

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**ABSTRACT :**
The tests of bending out of plane in size of original were conducted, in order to confirm the basic performance of masonry in this study.
In order to confirm the structural characteristic of the brick walls was bended out of plane, the bending tests in size of original were conducted. The test pieces were designed based on the wall 2 bricks thick by English bond. Two types of the methods of stuffing with the joint mortar were made. One was stuffed the vertical joints with the joint mortar completely in order to identify the masonry structural system, the other was not stuffed completely because the nomal brick walls were not constructed completely. In addition, the tests of the brick walls strengthened were conducted. The strengthening was infusing the polymer cement mortar into the void spaces in the joint mortar (slurry).
From the results of the tests, the ultimate bending moments were 9.9 to 12.7 kN・m. The ultimate bending moments almost were not differed between all the test pieces.
In addition, the tension, compression, and shear tests of masonry elements were conducted in order to know the structural characteristics of the masonry structure. The shear tests were conducted with the compressive stresses that were loaded at right angle to the shear direction. From the results of the shear tests, shear strength and shear stiffness increase in proportion to the compressive stress.

**KEYWORDS:**
Brick, Masonry, Bending test, Out of plane, Strengthening

## 1. INTRODUCTION

Brick masonry buildings were introduced from the West into Japan in the middle of the 19th century. The domestic bricks were produced in the early 20th century, and many bricks buildings were built then. The Great Kanto Earthquake occurred in 1923, and many brick buildings collapsed. After the earthquake, the construct of brick masonry buildings stopped because they are weak against the earthquakes.
Recently, the brick buildings have been given the attention as historical buildings, and it has been discussed the way to conserve and to utilize them. When their conservation plans are made, the problem that their structural performances are impossible to be evaluated happens because there are few technological studies of brick masonry in Japan.

## 2. PLAN OF TESTS

The purpose of this study is that the destructed method and the strength of the brick wall against the bending moment out of plane are confirmed. The study of Sano T. was the previous brick study in Japan. According to the study, the bending strength of brick wall out of plane depends on the strength of the brick or the joint of bricks. So the strength tests of masonry elements were conducted in addition to the tests of bending out of plane in size of the original wall.
In order to confirm the structural characteristic of the brick walls that was bended out of plane, the bending tests in size of original were conducted. In addition, the tests of the strengthened brick walls were conducted. The strengthening was infusing the void spaces in the joint mortar with the polymer cement mortar (slurry).
The tension, compression, and shear tests of masonry elements were conducted in order to identify the structural

characteristics of the masonry structure. The axial compressive stresses at right angle to the shear direction were loaded in the shear tests, taking account of the vertical loads submitting to the wall.

## 3. MATERIAL TESTS

In the material tests of bricks, the average compressive strength, the average bending strength and the average percentage of water absorption were 58.1 MPa, 4.56 MPa and 9.56%, respectively.
The joint mortar consisted of cement, lime, and sand. The ratio of their volume was that cement : lime : sand =1 : 3.3 : 6.6. The average compressive strength and average cleavage strength of the joint mortar was 4.75MPa, 0.524 MPa, respectively. The average compressive strength of the cement slurry, which was stuffed into the void spaces, was 0.939 MPa.

## 4. TESTS OF MASONRY ELEMENTS

There are no standard methods of the tests about masonry elements in Japan, so that the test pieces of the compressive tests, shear tests, and tension tests were originally designed shown in Figure 1.
The compressive test pieces were made by laying three bricks that were cut in half with the joint mortar. The compressive tests were carried out by using Amsler material testing machine. The average compressive strength of the material elements was 25.0 MPa.
The shear test pieces were made by laying two bricks. This test was the single shear test with the compressive stress that was loaded at right angle to the shear direction. The compressive stresses meant the loads that were added on the wall from upside. The compress stresses were three kinds of the loads, 0.08 MPa, 0.35 MPa, 0.70 MPa. The device of the shear tests is shown in Figure 2.
The results of the shear tests are shown in Figure 3, Table 1 and 2. Figure 3 shows the relationships between the shear strength and displacement. Table 1 and 2 show the shear strengths and the shear stiffness, respectively. The shear stiffness is calculated by the grade of the line that is joined 10% to 80% of the maximum shear strength (Figure 4). The more the compressive stress increased, the more the shear strength and the shear stiffness increased. All the test pieces failed between the brick and joint mortar.

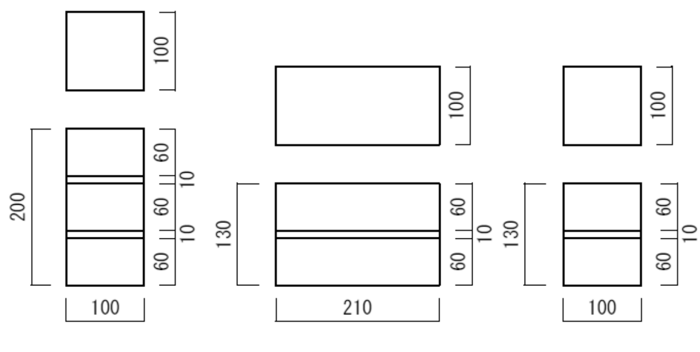


Figure 1: Test pieces of masonry elements

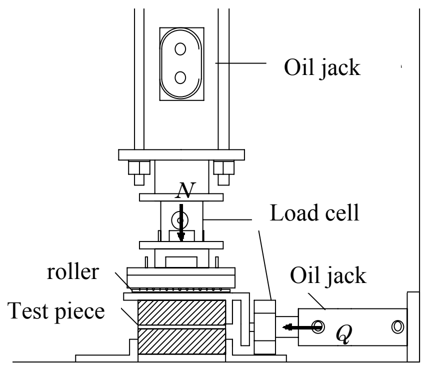


Figure 2: Shear test device of masonry elements

The relationships between the shear strength and compressive stress are shown in Figure 5, and the relationships between the shear stiffness and compressive stresses are shown in Figure 6. The regression equation between the shear strength $\tau$ and the compressive load $\sigma$ and the regression equation between the shear rigidity $K$ and the compressive load $\sigma$ are represented as follows,

$$\tau = 0.852\ \sigma + 0.402\ (\ \tau\ [\mathrm{MPa}],\ \sigma\ [\mathrm{MPa}]\ ) \tag{4.1}$$
$$K = 10.01\ \sigma + 0.615\ (\ K\ [\times 10^4\ \mathrm{N/mm}],\ \sigma\ [\mathrm{MPa}]\ ) \tag{4.2}$$

The tension test pieces were made by laying two bricks that were cut in half. The average tensile strength of the material elements was 0.293 MPa. Two test pieces were failed between the brick and the joint, one failed inside the joint.

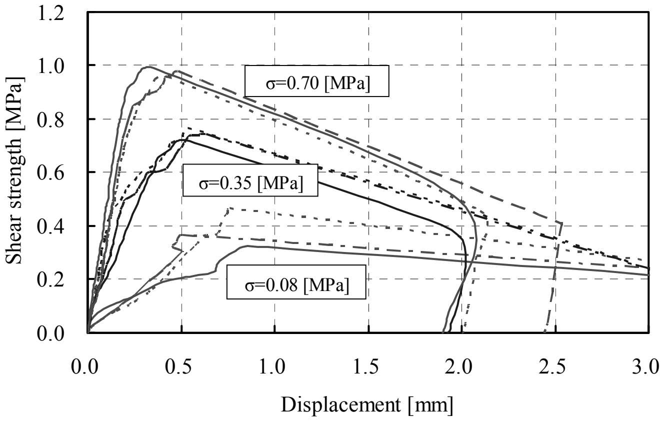



Figure 3: Relationships between shear strengths and displacements of masonry elements

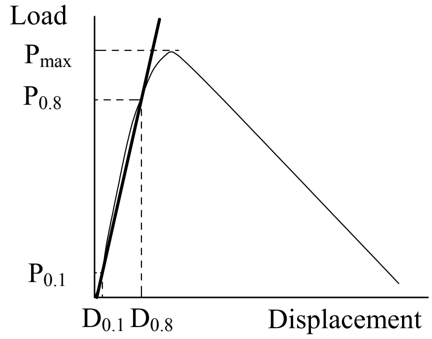



Figure 4: Calculating stiffness

Table 1: Shear strength of masonry element [MPa]

| | Compressive stress [MPa] | | |
|---|---|---|---|
| | 0.08 | 0.35 | 0.70 |
| 1 | 0.326 | 0.724 | 0.990 |
| 2 | 0.464 | 0.768 | 0.956 |
| 3 | 0.366 | 0.744 | 0.980 |
| Ave. | 0.385 | 0.745 | 0.976 |

Table 2: Shear stiffness of masonry element [$\times 10^4$N/mm]

| | Compressive stress [MPa] | | |
|---|---|---|---|
| | 0.08 | 0.35 | 0.70 |
| 1 | 0.643 | 3.43 | 8.75 |
| 2 | 1.08 | 3.61 | 6.84 |
| 3 | 1.23 | 3.63 | 8.13 |
| Ave. | 0.984 | 3.56 | 7.91 |

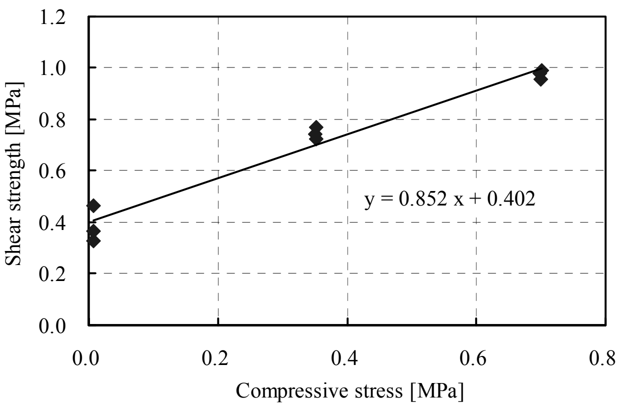



Figure 5: Relationships between shear strengths and compressive stresses of masonry elements

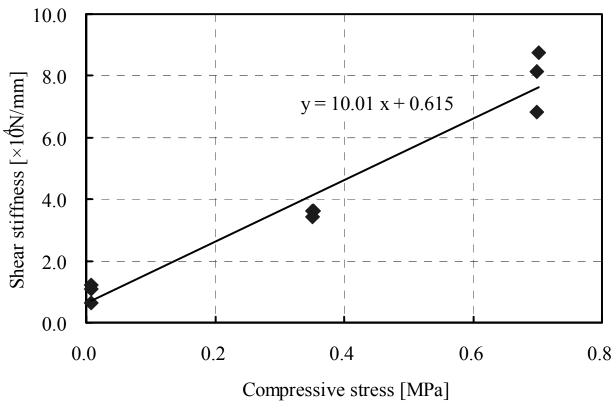



Figure 6: Relationships between shear stiffness and compressive stresses of masonry elements

## 5. TESTS OF BENDING OUT OF PLANE IN SIZE OF ORIGINAL BRICK WALL

### *5.1. Test pieces*

The test pieces were designed based on the wall 2 bricks thick by English bond. The shape of the test piece is shown in Figure 6. The test piece was 7 bricks long, 2 bricks thick, and 6 bricks lay.

There were two types of the methods of stuffing with the joint mortar. One was stuffed the vertical joints with the joint mortar completely, the other was not. Because, in general, there are few brick walls that the vertical joints of them are stuffed with the mortar completely. According to the study of Sano T., the stuffed ratio of the vertical joints in general is 40 - 70%.

In this study, in order to strengthen the brick walls which have the void spaces in the joints, the test pieces whose void spaces were infused with the slurry were made. They were perforated the holes, that were 6 mm in diameter and 300 mm depth, per 2 bricks in long direction and 2 bricks in vertical (Figure 7), and the slurry was infused in the holes.

The test pieces were listed in Table 3.

Table 3: Test pieces of bending out of plane

| | Joints execution |
|---|---|
| CL-BF1 | Vertical joints stuffed completely |
| CL-BF2 | |
| CL-BO1 | Normal vertical joints |
| CL-BO2 | |
| CL-BS1 | Vertical joints infused slurry |
| CL-BS2 | |

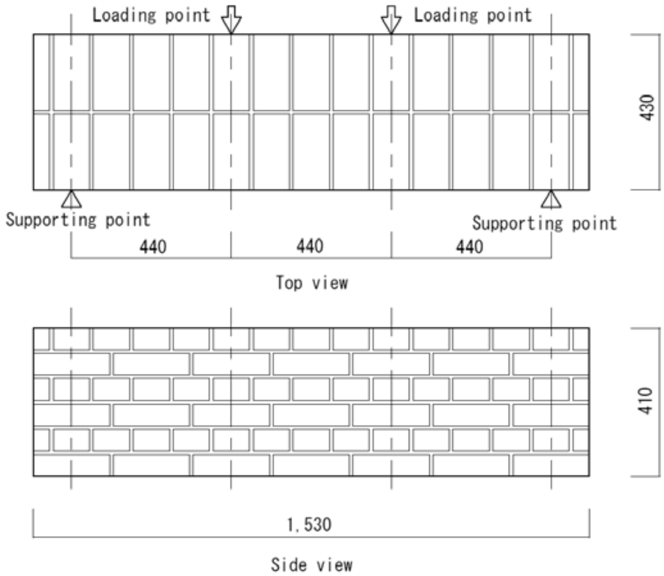



Figure 7: Shape of test piece of bending out of plane

### 5.2. *Loading*

The bending load was added from the lateral side, because the test pieces were heavy compared to the bending strength. In order to remove the effects of the shear strength, the bending test was adopted as the method of loading on two points

The test device was shown in Figure 9. In order to decrease the effects of the friction between test pieces and steel plates, the Teflon sheets 2.5 mm thick with two layers were underlaid the test pieces.

In the first phase of the tests, the slide tests were conducted, the test pieces were loaded without fixing both ends in order to measure the effects of the friction. In the second phase, the ends of test pieces were fixed, and the tests of bending out of plane were carried out.

When CL-BS2 was tested, the ends of the test piece were fixed by rubber sheets, and so the results of the test were influenced of the compressive deformation of the rubber. Accordingly, others of the test pieces were fixed by the gypsum.

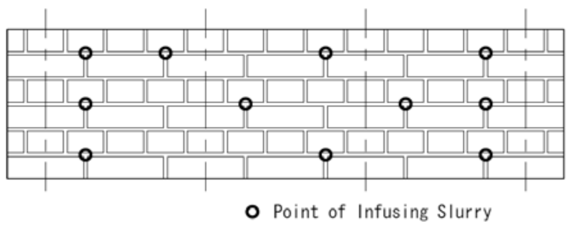



Figure 8: Position of inducing slurry

### 5.3. *Results of slide tests*

The results of the slide tests are shown in Figure 10. Figure 10 shows the relationship between the loads and the displacements. In all of the test pieces, the friction loads marked the maximum when the displacements reached about 0.5 mm, thereafter they were reduced sharply. From the displacements reached about 5.0 mm, the friction roads continued to be the constant loads. If the loading was stopped after the friction load once reached the constant load, the friction load was not over that load and the displacement increased when the loading was restarted. According to the results of the slide tests, it was obtained that it is able to get rid of the effects of the friction between the test piece and the steel plate from the results of the bending tests.

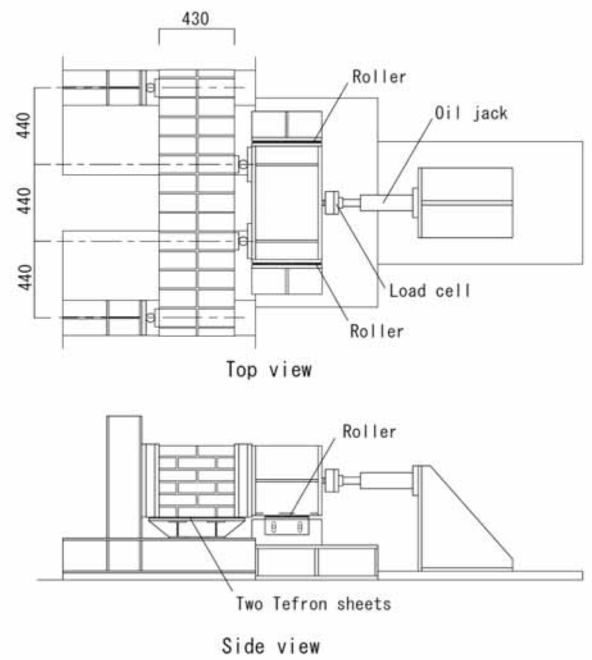



Figure 9: Device of bending tests

### *5.4. Results of tests of bending out of plane*

Figure 11, 12 shows the failure appearances of the test pieces after the bending tests. The failures of the test pieces, on the whole, tended to be occurred along the joints, on the other hand, some bricks were failed by the tensile force. The failures along the joints were occurred in the joints or around the division between the bricks and the joints. At the failure around the division, the joint mortars were remained thinly on the surface of the bricks. There was no trace that was compressed on the failure surface.
One of the test pieces infused the cement slurry was observed the slurry on the failure surface, the other was not. The slurry was not infused into all the void spaces in the joints.
Table 4 shows that the maximum loads of the tests, the friction loads, and the adjusted loads that were the loads taken the friction loads off the maximum loads, the ultimate moments, the bending stiffness, and Young's modulus. The bending stiffness is calculated by the grade of the line that is joined 10% to 80% of the maximum bending strength.
Figure 11 shows the relationships between the bending loads and the displacements. The bending rigidity of CL-BS2 was smaller than the others because of using the rubber sheets on the supporting points.

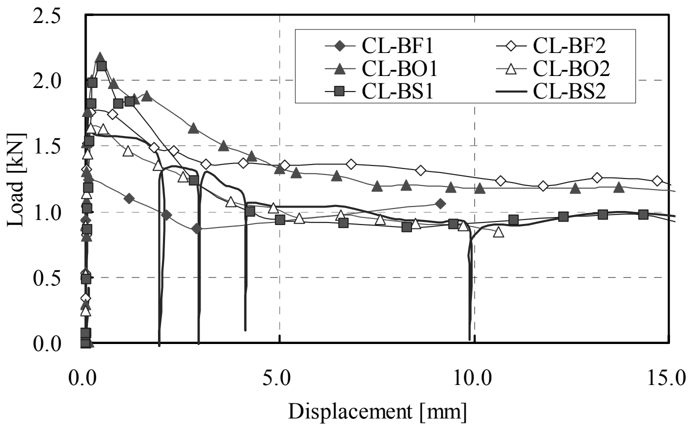



Figure 10: Relationships between friction loads and displacements

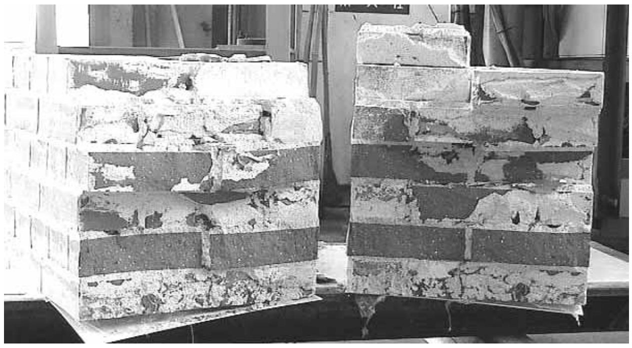
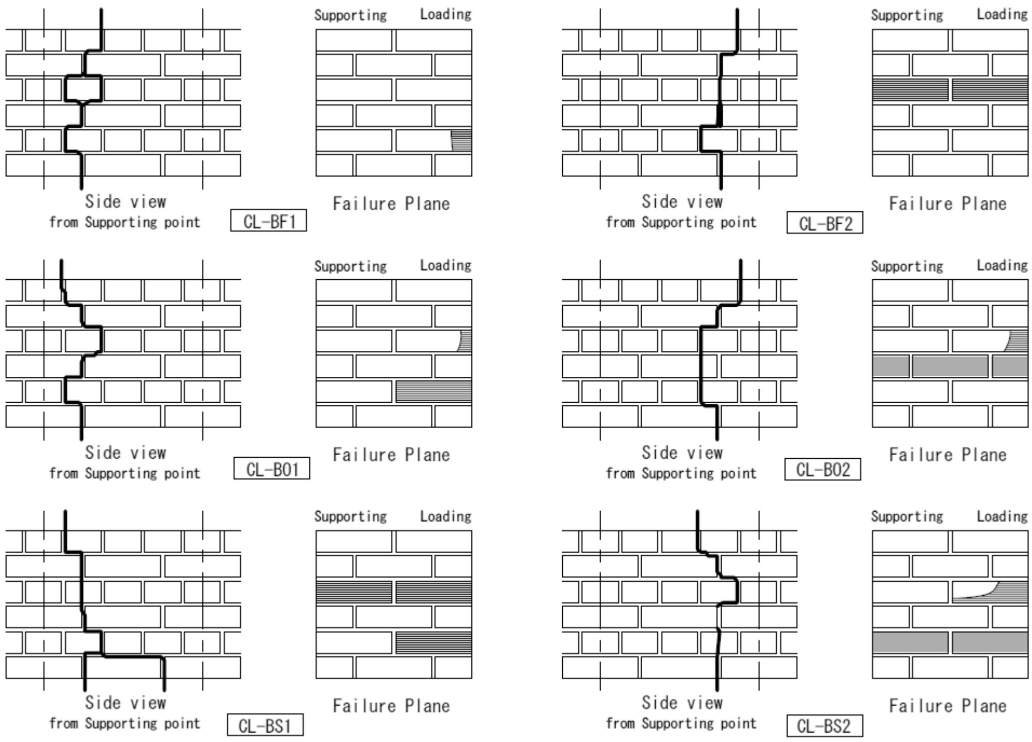


Figure 11: Failure appearances of test pieces



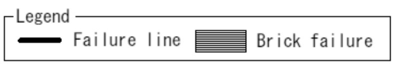
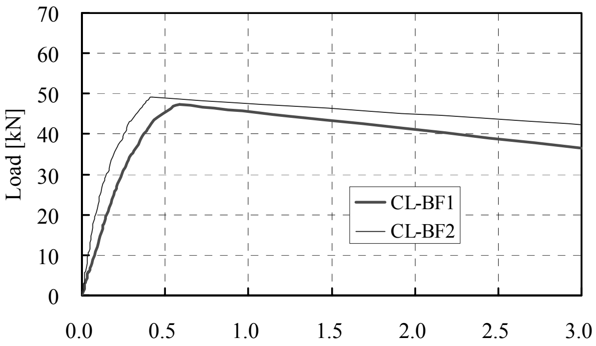
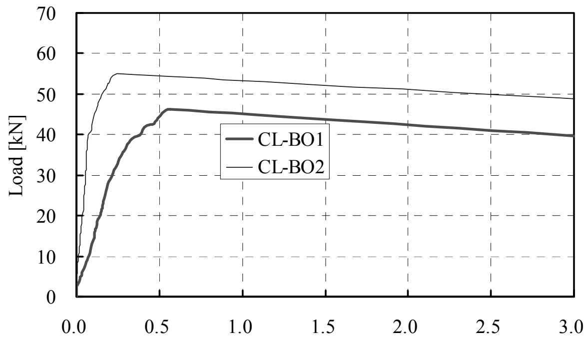




Figure 12: Failure appearances of test pieces of bending out of plane

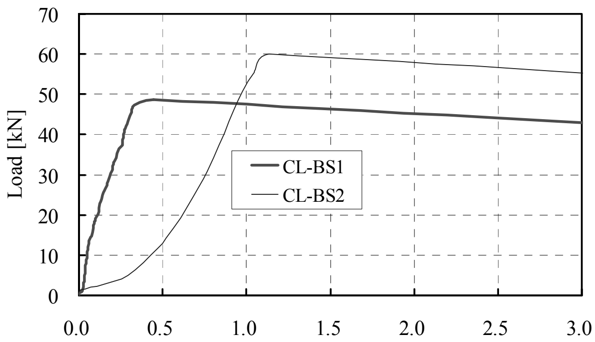
The average ultimate bending moments of the BF series, BO series, and BS series were 10.37 kN・m, 10.92 kN・m, 11.62 kN・m, respectively. In all the test pieces, CL-BS2 had the maximum bending strength, and that was only 1.28 times more than the minimum strength. It assumed that all the results of tests hardly varied, taking account of the amounts of the void spaces that were about 20 % of the joint areas and the slurry that were less than 10%.




Vertical joints stuffed [CL-BF1,2]




Npmal Vertical joints [CL-BO1,2]




Vertical joints infused slurry [CL-BS1,2]

Figure 13: Relationships between the bending loads and displacements of bending out of plane

Table 4: Results of bending tests out of plane

| | Friction load (kN) | Maximum load (kN) | Adjusted load (kN) | Ultimate moment (kN・m) | Bending Stiffness ($\times 10^5$ N/mm) | Young's modulus ($\times 10^3$ N/mm$^2$) |
|---|---|---|---|---|---|---|
| CL-BF1 | 0.97 | 47.24 | 46.27 | 10.18 | 1.068 | 1.605 |
| CL-BF2 | 1.29 | 49.25 | 47.96 | 10.55 | 1.505 | 2.262 |
| BF Ave. | — | — | 47.12 | 10.36 | — | — |
| CL-BO1 | 1.18 | 46.23 | 45.05 | 9.91 | 1.158 | 1.740 |
| CL-BO2 | 0.90 | 55.10 | 54.19 | 11.92 | 3.950 | 5.935 |
| BO Ave. | — | — | 49.62 | 10.92 | — | — |
| CL-BS1 | 0.93 | 48.74 | 47.80 | 10.52 | 1.493 | 2.244 |
| CL-BS2 | 0.98 | 58.80 | 57.82 | 12.72 | 0.674 | 1.013 |
| BS Ave. | — | — | 52.81 | 11.62 | — | — |
| All Ave. | — | — | 49.85 | 10.97 | | |

### *5.5. Consideration for strengthening of infusing slurry*

The cement slurry was not able to be infused completely into the vacant spaces in the joints by the way adopted this time. It is assumed that the extent of the spaces infused the slurry was affected by the continuity between vacant spaces. Besides, if the vacant space was surrounded by the joint mortar, the bond strength between bricks was not improved greatly because the bond strength between bricks was determined the bond strength between the brick and the joint mortar, not of the slurry.
It is assumed that the states of the vacant spaces in the joints should be researched and the effect of infusing the slurry should be obtained by the test executions and the experiments using the original walls, if the infusing the slurry was adopted for the strengthening of the brick walls.

## 6. CONCLUDING REMARKS

The following concluding remarks were obtained:

1) From the shear tests of masonry elements, shear strength and shear stiffness increase in proportion to the compressive stress that is loaded at right angle to the shear direction. The shear failure of the masonry element that is constructed with the lime-cement mortar is occurred between the brick and the joint.
2) From the tests of bending out of plane in size of the original brick walls, the ultimate moment of bending out of plane of the brick wall 2 bricks thick are estimated to be about 11.0 kN・m. Most of the failures are occurred in the joints or between the brick and the joint.
3) The states of the vacant spaces in the joints should be researched and the effect of infusing the slurry should be obtained by the test executions and the experiments using the original walls, if the infusing the slurry was adopted for the strengthening of the brick walls.

## ACKNOWLEDGEMENT

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