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AXIAL COMPRESSION BEHAVIOUR OF BURNT CLAY MASONRY UNITS AND IMPROVING LOAD BEARING CAPACITY ON BRICK ASSEMBLAGES WITH INJECTION MATERIALS

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Abstract

This paper deals with uniaxial compression behaviours of burnt clay masonry units, which were picked up from Japanese cultural heritages and repaired assemblages in order to improve aseismicity. Several injection methods were selected from actual repairs, which had been adopted as an appropriate material in Japan. Mechanical characteristics such as the strength, Young's modulus, Poisson's ratio, and fracture processes of masonry units and assemblages were experimented on the basis of an advanced method regarding about fracture process evaluations. As a result, it was clarified that units picked up from the cultural heritages had a large capacity of deformation. In compressive behaviours of repaired assemblages, increases in Young's modulus, and decreases in Poisson's ratio were observed. The mechanical experiments and results stated in this study are thought to be effective for deciding a repair plan in order to improve the earthquake resistance of historical brick masonry structures.

Key Words

burnt clay masonry, cultural heritages, compressive behaviour, injection materials,

1 Introduction

Brick masonry is one of the most populer construction method around the world. But its structures have been very valuable in Japan. In 1850s (the end of edo era), this construction method was introduced for the modernization in Japan. By this introduction, brick masonry had been populerized as the construction method for the several kinds of common buildings and factory buildings. However, brick masonry buildings were hardly built after the KANTO big earthquake in 1923. Therefore, the

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development of brick masonry as a construction method of Buildings had became weak and changed to the development of concrete block masonry and reinforced concrete. Recently, still existed clay brick masonry structures built in 1880s to 1900s (from Meiji to Taisho era in Japan) has been preserved as cultural assets. However, as these preservations are actively, several kinds of problems are happen such as the repair and reinforcement method with improvements of durability and aseismicity. Because physical qualities of brick masonry units and assemblages included joints (called masonry prisms) aren't still clarified.

This paper deals with experimental study in two phases for the long term preservation of brick masonry structures. The first phase deals with compressive behaviours of original masonry unit picked up from one of the actual clay brick masonry structure in 1880s (Meiji era). The second phase deals with compressive behaviours of clay brick masonry prisms (present commercial) , which repaied by injection materials, to examinate effects of injection repairing material. This study is thought to be one of the evaluations of repair method for Japanese historical brick masonry structures.

2 Test Methods and Specifications

2.1 Masonry units

A test apparatus, whose capacity is 20t, was used for the masonry unit series. Specimens for this type of compressive test were cut from brick masonry units. The size of specimens was about 3cmx3cmx6cm. All the loading surfaces of specimens were capped with high strong gypsum plaster. The strain gauge was applied to the surface of specimen in vertical and horizontal as Figure1.

A tentative stress-strain relationship is shown in figure2. When a specimen is subjected to increasing uniaxial compressive, its Poisson's ratio start to increase continuously and significantly on attaining a certain stress level called initiation stress. ε_{in} shows uniaxial strain at initiation stress. At a higher stress called critical stress, the volume of the specimen starts to increase rather than continuing to decrease. ε_{cr} shows uniaxial strain at critical stress. Macroscopically, critical stress seems to indicate the beginning of significant crack growth. ε_{ul} shows uniaxial strain at ultimate stress. Volumetric strain can be calculated and the critical stress of masonry units is found and discussed for structural designs.

In the case of masonry unit test, several kinds of numerical value (**f_{cu}, $E_{1/3}$, ν , ε_v**) were calculated as follows by Eq. (1) (2) (3) (4) (5).

The compressive strength of masonry units; f_{cu}

$$f_{cu} = P_{max} / A_u \tag{1}$$

Where,

P_{max} : Maximum load (N)

A_u : Sectional area of masonry unit specimen (mm^2)

Young's modulus; E (Secant Young's modulus; $E_{1/3}$)

$$E = \sigma / \varepsilon \tag{2}$$

$$E_{1/3} = \sigma_{1/3} / \varepsilon_{1/3} \tag{3}$$

Where,

σ : Uniaxial stress at every point measured,

ε : Uniaxial strain at every point measured

$\sigma_{1/3}$: Uniaxial stress at one third of ultimate strength(N/mm^2)

$\varepsilon_{1/3}$: Uniaxial strain when $\sigma = \sigma_{1/3}$

Poisson's ratio; ν

$$\nu = -\varepsilon_{2(3)} / \varepsilon_1 \quad (4)$$

Where,

$\varepsilon_{2(3)}$: Lateral strain in the two or three directions

The value of Poisson's ratio when $\sigma = \sigma_{1/3}$ was calculated in the same manner as secant Young's modulus, $E_{1/3}$.

Volumetric strain of masonry units; ε_v

$$\varepsilon_v = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \quad (5)$$

Where,

ε_1 : uniaxial strain of masonry units, $\varepsilon_2, \varepsilon_3$: biaxial strain of masonry units

2.2 Masonry Prisms

A test apparatus, whose capacity is 100t, was used for the uniaxial compression test of masonry prisms. The shape of masonry prisms is shown in Figure1. This specimen is composed in 3 bricks and 2 joints. The size of prism specimens was about 10cmx10cmx20cm. The strain gauge was applied to the middle layer brick surface of prism specimen in vertical and horizontal as Figure2. Displacement transducers are applied to the centre surface of upper brick and lower brick. Therefore, stress-strain relationship is shown in the middle layer brick and the whole masonry prism.

A tentative stress-strain relationship of masonry prism is shown in figure3.

In the case of masonry Prism test, several kinds of numerical value (**f_{cm},$E_{m1/3}$,** ν_m **,** ε_{vm} **,** ε_j) were calculated as follows by Eq. (1)' (2)' (3)' (4)' (5)' (6).

The compressive strength of masonry Prisms; f_{cm}

$$f_{cm} = P_{max} / A_m \quad (1)'$$

Where,

P_{max} : Maximum load (N), A_m : Sectional area of masonry prism specimen (mm^2)

Young's modulus; $E_{m1/3}$

$$E_m = \sigma / \varepsilon_{m1} \quad (2)'$$

$$E_{m1/3} = \sigma_{1/3} / \varepsilon_{m1/3} \quad (3)'$$

Where,

σ : Uniaxial stress of masonry prisms at every point measured

ε_{m1} : Uniaxial strain of masonry prisms at every point measured

$\sigma_{1/3}$: Uniaxial stress of masonry prisms at one third of ultimate strength (N/mm^2)

$\varepsilon_{m1/3}$: Uniaxial strain of masonry prisms when $\sigma = \sigma_{1/3}$

Poisson's ratio; ν_m

$$\nu_m = -\varepsilon_{m2(3)} / \varepsilon_{m1} \quad (4)'$$

Where,

$\varepsilon_{2(3)}$: Lateral strain in the two or three directions

Volumetric strain; ε_{vm}

$$\varepsilon_{vm} = \varepsilon_{m1} + \varepsilon_{m2} + \varepsilon_{m3} \quad (5)'$$

Where,

ε_{m1} : Uniaxial strain of prisms, $\varepsilon_{m2}, \varepsilon_{m3}$: Biaxial strain of prisms,

Uniaxial strain of joints; ε_j

$$\varepsilon_j = (\varepsilon_{m1} \times h_m - \varepsilon_{u1} \times h_u) / h_j \quad (6)$$

Where,

ε_{m1} : Uniaxial strain of prisms, ε_{u1} : Uniaxial strain of units

h_m : length of between 2 points applied Displacement transducers

h_u : height of bricks (between 2 points applied Displacement transducers)

h_j : height of joints (2 parts)

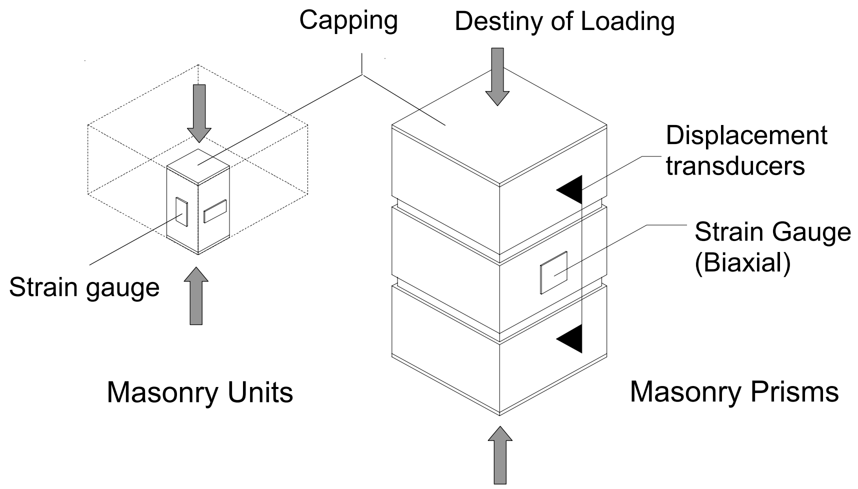

Figure1 Test Methods for Determining the Compressive Strength of Cray Masonry Units and Assemblages (Prisms)

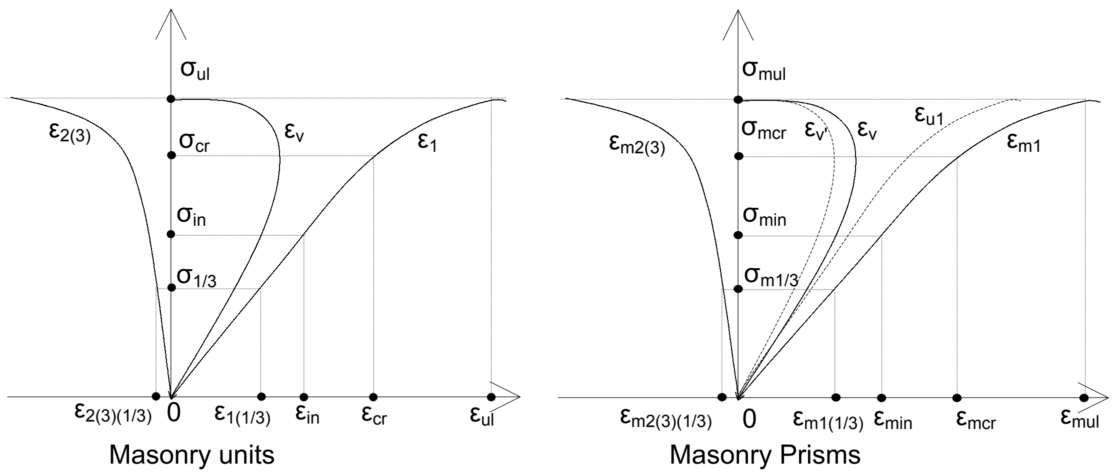

Figure2 Tentative Stress-Strain Relationship

3 Experimental result

3.1 Uniaxial compressive behaviours test of brick masonry units and prisms

3.1.1 Masonry units

Masonry units used in this experiment are listed in Table1. These Units are different in production time, moulding method. In this experiment, 4 kinds of clay bricks, which the change of quality on clay brick masonry clearly observed in Japan, were adopted. These were used in bottle kilns for production of Portland cement in Yamaguchi, which preserved as a cultural asset.

Furthermore, 2 kinds of clay bricks were adopted as the comparison with historical bricks. The measuring results of these units are shown in Table2 and Figure3.

Table1 Specimens of Compression Test for Clay Masonry Units

Series No.	Specimens	Comments
U-1	Kiln (Establishment)	Cast moulding (1883)
U-2	Kiln (Named Hunter brick)	Press moulding (1889)
U-3	Kiln (Upperside)	Cast moulding (1889)
U-4	Kiln (Repairing)	Extrusion moulding (1891)
U-5	Present commercial	Extrusion moulding (Orange color)
U-6	Present commercial	Extrusion moulding (Red color)

U-1; Cast moulding (Produced in 1883)
Compressive strength of this specimen was about 20MPa. Though, some units have extremely low strength (about 13MPa). Ununiformity of mixing of materials and production temperature were supposed. However, this unit had a large capacity of deformation such as 6000 ($\times 10^{-6}$) in uniaxial strain.

U-2; Press moulding (Produced in 1889)
This unit had been thought to have higher strength compared with U-1. However, it was clarified that this masonry unit had lower strength on the average. As the destruction was progressed, peeling was observed in specimens on the whole. After the destruction, small gaps were observed in the section. It can be supposed that deterioration of strength was caused because of these small gaps. Maximum of uniaxial strain is 4500~6000 ($\times 10^{-6}$). In some units, Maximum of uniaxial strain is 10000 ($\times 10^{-6}$) over. These result shows that production of bricks by press moulding hadn't been proficient in those days.

U-3; Cast moulding (Produced in 1889)
Compressive strength of this unit was about 30MPa. It was found that quality of cast moulding bricks had been improved for about 6 years. These units have large deformation capacity similar to series 1, which Maximum of uniaxial strain is about 7500 ($\times 10^{-6}$).

U-4; Extrusion moulding (Produced in 1891)
1890s is the time when clay brick masonry units had been produced more stable. In production method had changed from cast moulding to extrusion moulding. Compressive strength of this series is 30MPa over, which strength is higher than other Three series. Poisson's ratio is different in each unit because of anisotropy peculiar to extrusion moulding. Maximum of uniaxial strain is about 5000 ($\times 10^{-6}$), which strain was low compared with other units by cast moulding.
As the result, it was clarified that clay bricks produced in 1880~1890s had a large capacity of deformation to uniaxial load as compared that the popular strain of concrete is about 1200 ($\times 10^{-6}$).

U-5 and U-6; Extrusion moulding (Present commercial)
Compressive strength of U-5 was about 30MPa, which series show stable behaviours. Maximum of uniaxial strain is 6000 ($\times 10^{-6}$), so that this series bricks have a large capacity of deformation similar to historical clay bricks. Compressive strength of U-6 was about 40MPa, which series have higher strength than U-5.
However, maximum of uniaxial strain is 3000 ($\times 10^{-6}$), so that the capacity of deformation in U-6 specimen is smaller than No.5. It is clarified that the volume of water in mixing and burning temperature has controlled the qualities of clay bricks of present commercial. From the experimental results of U-5 and U-6, a clay brick of U-5 was adopted in the examinations of repairing with injection materials to defective joints.

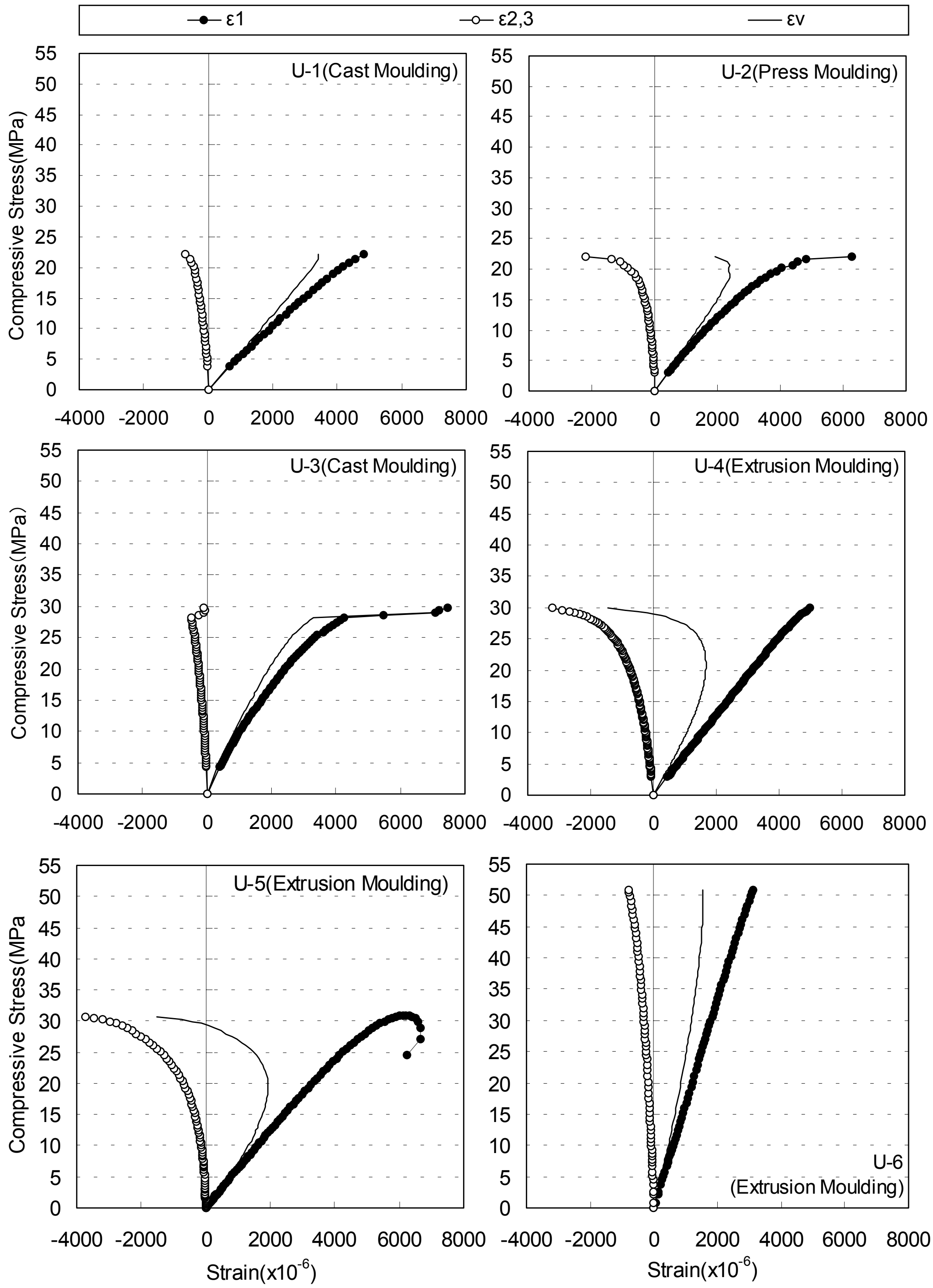

Figure3 Stress and Strain Relationship of Clay Masonry Units under Uniaxial Compressive Load

Table2 Experimental Results of Compression Test for Clay Masonry Units (Extracted)

Series No.	fcu[MPa]	Eu[GPa]	ν	εin[×10^{-6}]	εcr[×10^{-6}]	εul[×10^{-6}]
U-1	22.09	5.15	0.06	4578	4578	4847
U-2	21.96	6.54	0.07	3251	3699	6273
U-3	29.81	9.94	0.08	1845	3426	7484
U-4	29.93	6.41	0.16	2007	3108	4991
U-5	30.95	6.24	0.09	1166	3358	6664
U-6	50.87	16.87	0.12	836	2891	3126

3.1.2 Masonry prisms

Masonry prisms used in this experiment are listed in Table3. P-1 is masonry prisms cut from a brick masonry lump (clay bricks of series 1) excavated around the historical brick masonry structure. P-2 is a masonry prism that bonded by U-5 bricks (100mm x 100mm x 60mm) with lime and cement mortar. This cement is normal Portland cement. And this Lime is produced by Japanese traditional method. Sand is made in Toyoura in Yamaguchi. The mix proportion of this lime and cement mortar is 1:3:12 (cement: lime: sand). This proportion had been adopted in a certain brick masonry building, which had been constructed in 1891 in Tokyo. In this experiment, the mechanical property of specimen made by this mix property, which specimen was curing for 28 days in water, was checked by uniaxial compression test as a preliminary experiment. The result of this test is listed in Table4.

Table3 Specimens of compression test for clay masonry prisms and joint materials

Series No.	Specimens	Comments
P-1	Kiln (Establishment)	Cast moulding (1883)
P-2	Present commercial	Extrusion moulding (Orange color) Using U-5-2

Table4 Mechanical property of lime and cement mortarl used in No.7 prism

Compressive strength[Mpa]	Young's modulus[Gpa]	Poisson's rato
3.17	1.09	0.38

The measuring results of two kinds of masonry prisms are shown in Table5 and Figure4.

P-1; Cast moulding (Produced in 1883)

In P-1, compressive strength was 14.0MPa, Young's modulus was 6.14GPa, and Poisson's ratio was 0.13. Destruction condition was different from masonry unit, in the strength point, the masonry prisms destructed with crack heavily. As a result, in P-1, compressive strength of some prism was small unexpectedly. This is the phenomenon by reason of defection in bricks or joints.

Compressive strength of this series was about 1/2 compared with clay brick of U-1 (same masonry units).

Table5 Experimental Results of Compression Test for Clay Masonry Prisms(Extracted)

Series No.	fcm[MPa]	Em[GPa]	ν_m	εin[$\times 10^{-6}$]	εcr[$\times 10^{-6}$]	εul[$\times 10^{-6}$]
P-1	14.00	6.14	0.13	531	1696	5139
P-2	17.84	5.94	0.20	1985	4053	6318

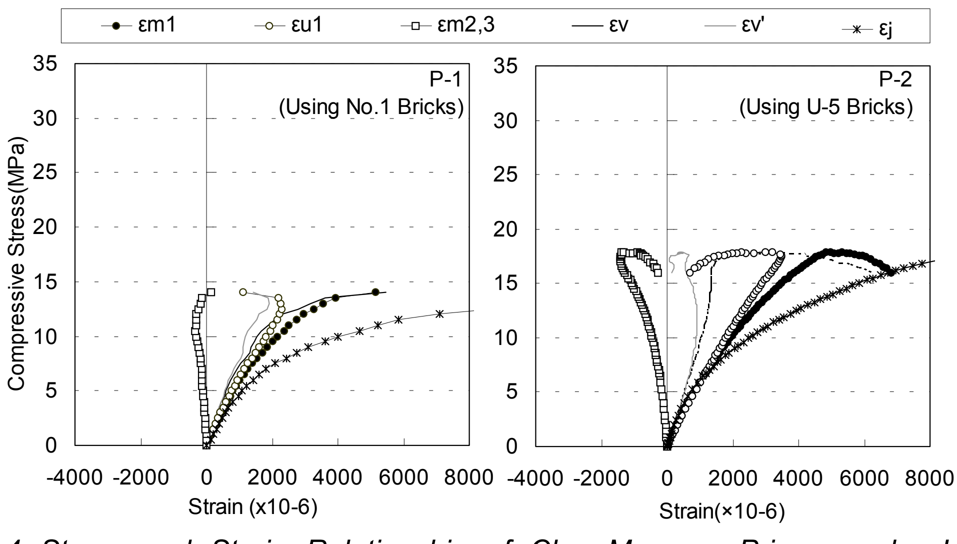

Figure4 Stress and Strain Relationship of Clay Masonry Prisms under Uniaxial Compressive Load

P-2; Extrusion moulding (Present commercial)
In P-2, compressive strength was 17.84MPa, Young’s modulus was 5.94, and Poisson’s ratio was 0.20. Maximum of uniaxial strain was 6300 (micro).
Compressive strength of this series was about 1/2 compared with clay brick of U-5 similar to P-1. This phenomenon, which compressive strength of masonry prisms is about 1/2 compared with masonry unit, is caused by the reason that a prism is components of masonry units and joints different in deformation conditions. In Japanese clay brick masonry structures, lime and cement mortar is used as joint material. In this joint material, compressive strength is smaller; Poisson’s ratio is bigger than clay brick masonry units. In other words, this kind of joint material has extremely large capacity of deformation. This deformation capacity stretches masonry units in biaxial direction. This effect causes decrease of compressive strength.

4 Simulation of repair method using injection materials

4.1 Specimen

Cracks of joints are typical deteriorations on brick masonry structures. The cracks have a bad influence in aseismicity and durability of the whole structures. In Japanese clay brick masonry buildings, the thickness of wall is thin in general. In spite of outer walls, some of them are 2 bricks in lengthwise direction. In this case, it’s difficult to fill the joints with mortar by dipping. Dipping is the method to sink bricks in the space of bonded outer brick and filled with mortar. Gaps in brick walls caused by this reason should be repaired by injection materials. In this study, the repairing effects are examined in masonry prisms with defective joints (a gap) repaired by several kinds of injection materials. The repairing effects are examined by compressive strength, Young’s modulus, Poisson’s ratio, and stress-strain relationship in uniaxial compressive test. Repairing materials used in this simulation experiment are listed in Table6. These materials are typical in Japanese repairing materials for reinforced concrete structures. The shape and specification of masonry prisms used in this experiment is showed in Figure5. P-3 is masonry prisms with no repairing. P-4-1 is masonry prisms with injection of low viscosity epoxy resin. P-4-2 is masonry prisms with injection of high viscosity epoxy resin. P-4-3 is masonry prisms with injection of SBR cement paste. The masonry prisms with injection materials were cured for 2 weeks. After curing, uniaxial compression test of these specimens were carried out.

Table6 Specimens of Injection Materials used for Simulation of Repairing

Series No.	Kinds of Injection Materials	Amount of Injection Materials [g]	Yong’s Modulus (1/3 Secant) [GPa]
P-3	No Repairing	-	-
P-4-1	Low Viscosity Epoxy Resin	62.3	1 over
P-4-2	High Viscosity Epoxy Resin	92.8	1 over
P-4-3	SBR Cement Paste	152.1	19

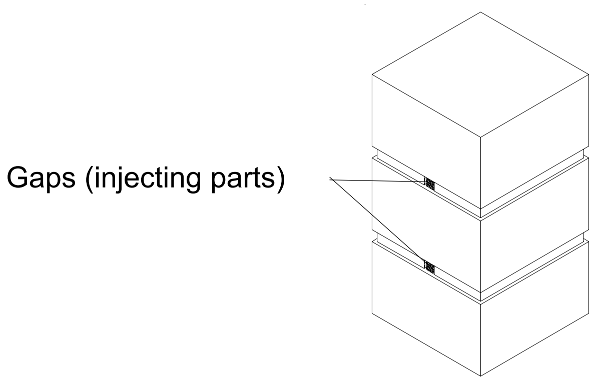

Figure5 A Specimen of Masonry Assemblage with Defective Joint

4.2 Experimental Results

The measuring results of four series are shown in Table7 and Figure6. Compressive strength of P-4-1 is higher than one of Series1. Compressive strength of P-4-2 is as well as one of No7. Therefore, epoxy resins are superior on increase of compressive strength in spite of viscosity. Especially, it can be thought that low viscosity epoxy resin sank into the not only defective part but also whole specimen and reinforced masonry prism on the whole. Compressive strength of No.P-4-3 is lower than P-4-1 and P-4-2, higher than P-3. Compressive strength of P-3 is lowest of all specimens. That is to say, it was clarified as the numerical value that masonry assemblages with cracked joint were extremely inferior in compressive strength. As the results, injection materials used in this experiment are effective as a repairing method. Poisson's ratio of No.P-4-1 and P-4-3 are smaller than other specimens.

It can be thought that high flow materials such as low viscosity epoxy and SBR cement paste reinforced porous joint with lime and cement mortar. That is to say, phenomenon which lime and cement mortar stretches masonry units in biaxial direction was mitigated by the increase of Young's modulus with the increase of density in joint material. It can be thought that high flow materials such as low viscosity epoxy and SBR cement paste reinforced porous joint with lime and cement mortar. That is to say, phenomenon which lime and cement mortar stretches masonry units in biaxial direction was mitigated by the increase of Young's modulus with the increase of density in joint material.

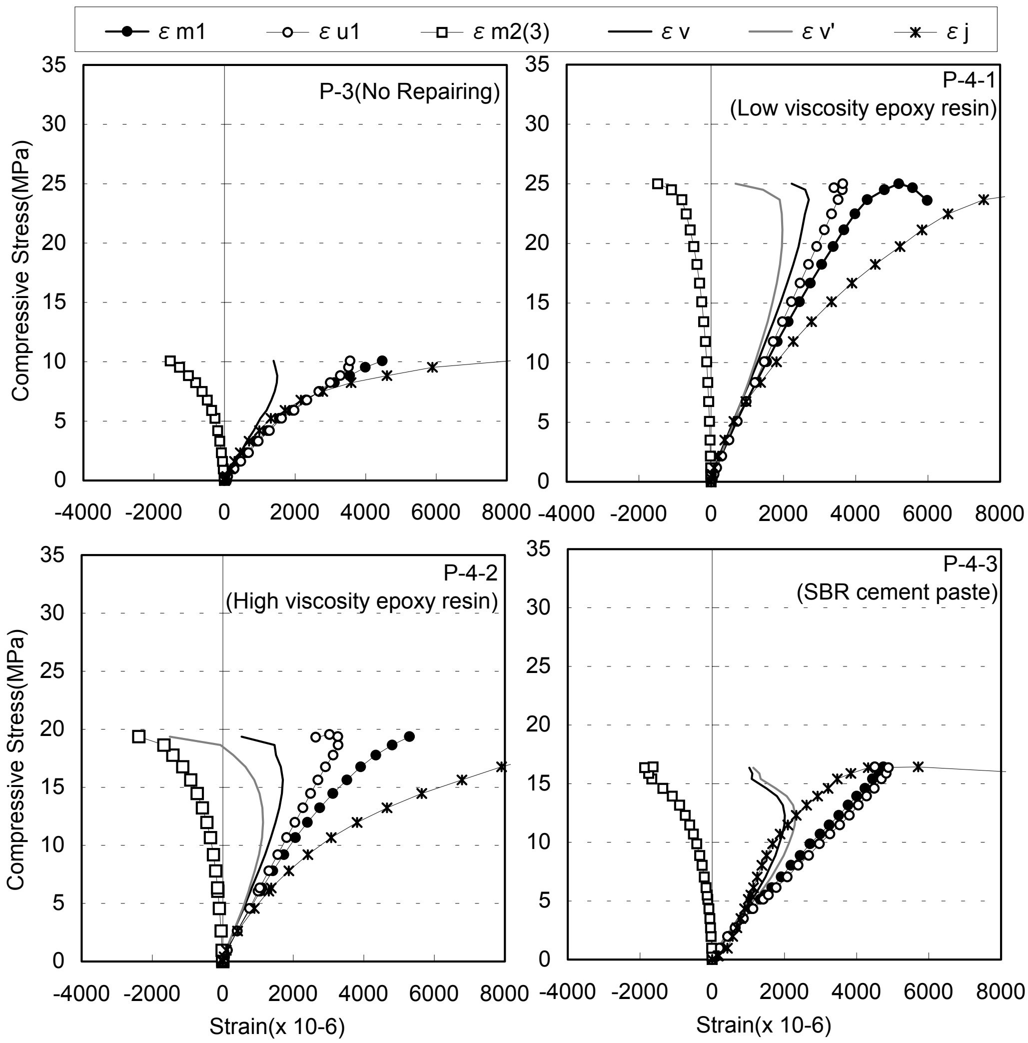

Figure6 Stress and Strain Relationship of Simulation Prisms with Injection Materials under Uniaxial Compressive Load

Table7 Experimental Results of Compression Test for Repaired Prisms (Extracted)

Series No.	fcm[MPa]	Em[GPa]	ν_m	εin[×10^{-6}]	εcr[×10^{-6}]	εul[×10^{-6}]
P-3	11.24	3.58	0.14	2060	3560	5420
P-4-1	25.14	6.55	0.08	2710	4550	5440
P-4-2	19.57	5.58	0.14	2250	3560	5340
P-4-3	16.50	3.71	0.09	2210	3600	4800

5 Conclusions and Outstanding Problems

5.1 Conclusions

According to the experimental examinations and discussions mentioned above, the following concluding remarks can be presented.

- Japanese historical clay masonry units have a large capacity of deformation in uniaxial strain.
- The mechanical characteristic of clay bricks is controlled by techniques of mixing materials and burning.
- Epoxy resins are superior on increase of compressive strength in spite of viscosity. Especially, low viscosity epoxy resin sank into the not only defective part but also whole specimen and reinforced masonry prism on the whole.
- SBR cement Paste was effective for increase of compressive strength not so as epoxy resin.
- Compressive strength of masonry prisms with defective joints is 10MPa. Therefore it was clarified as the numerical value that masonry assemblages with cracked joint were extremely inferior in compressive strength.
- High flow materials such as low viscosity epoxy and SBR cement paste have a tendency to mitigate phenomenon, which porous lime and cement mortar stretches masonry units in biaxial direction, by the increase of density in joint parts.

5.2 Outstanding Problems

This study mentioned herein is mainly restrained to clarifying the mechanical characteristics of Japanese historical clay masonry units and prisms under uniaxial compressive test and evaluating injection materials for repairing of masonry prisms with defective joints. The following items would be required in the future stage of study.

1) Influences Injection materials to water absorption of clay brick masonry assemblages (Scaling by freezing in winter)
2) Changes of condition and quality after the execution of injection repairing

Repairing materials for cultural heritage should be adopted based on consideration of characteristics and quality on original materials, not biased to only improving the strength of structures.

References

A. BABA, O. SENBU, M. WATANABE and Y. MATSUSHIMA, 1985, MECHANICAL PROPERTIES OF MASONRY UNITS AND TEST METHODS FOR DETERMING COMPRESSIVE STRENGTH, Building Research Institute Ministry of Construction, 1-51

J. YAMASHITA, A. BABA, T. WATANABE and R. KAWAHARA, 2002, A STUDY ON THE PRESERVATION OF ONODA BOTTLE KILN (PART7)-A compressive behaviour of clay units and prisms-, Proceeding of General Meeting (Japanese), Architectural Institute of Japan, 993-996

S. Suzuki, K. Takamura, 1998, Report on the restoration work at Tokyo Holy Resurrection Cathedral, an important Cultural Property, The Japanese Association for Conservation of Architectural Monuments, The Orthodox Church in Japan, 263-264