NONLINEAR CHARACTERISTICS OF CONFINED MASONRY WALL WITH LATERAL REINFORCEMENT IN MORTAR JOINTS

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SUMMARY

Static cyclic loading tests on confined masonry walls were executed to investigate effects of lateral reinforcement arranged in mortar joints at corner parts of the walls on their structural behavior. Nonlinear finite element analyses were also performed to simulate the tests and to clarify the effects of the lateral reinforcement and difference of axial stress.

The specimen with the reinforcement was tested under axial stress corresponding to the value at the first story of a typical five storied confined masonry building, and the other specimen was tested under 1.4 times the stress. Ultimate strength of the both specimens was observed at the horizontal deflection angle of 1/100rad., and it was approximately 0.8-0.9N/mm^2 in terms of average shear stress. Delayed appearance of diagonal cracks and dispersion of shear cracks at the corner parts were observed as the effects of the reinforcement. And the reinforcement decreased lateral spreading of the wall until the angle of 1/400rad., but the effect was not remarkable at loading over the angle of 1/200rad..

It was possible to simulate the nonlinear characteristics of the specimens by finite element analyses. An effect of the lateral reinforcement on ultimate strength of the specimens was not clear due to the discrepancy of the axial stress in the tests, but increase of the strength due to the reinforcement was verified in the analyses.

INTRODUCTION

Seismic engineering technology in Japan has been transferred to developing countries through technical cooperation represented for projects by the Japan International Cooperation Agency, training for building research and construction technology in the Building Research Institute, Ministry of Construction, Japan; BRI and so on. Research works for improving seismic performance of confined masonry buildings have been taken up as a theme of the technical cooperation in the most cases of the projects in which BRI has been concerned. It is mentioned as one of the reasons that the confined masonry structure is not only a main construction method for housing in the countries but also includes many problems on the seismic performance. Experimental studies on confined masonry walls to grasp the nonlinear characteristics have been conducted in BRI in order to advance the technical cooperation since 1989 [Kato et al., 1992], [Mizuno et al., 1994].
Static loading tests on confined masonry walls were executed to investigate effects of lateral reinforcement arranged in mortar joints at corner parts of the walls on their structural behavior in 1996. And nonlinear finite

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element analyses were also performed in order to simulate the tests and to clarify effects of the lateral reinforcement and axial stress. The experimental and analytical studies on the confined masonry walls are described in this paper.

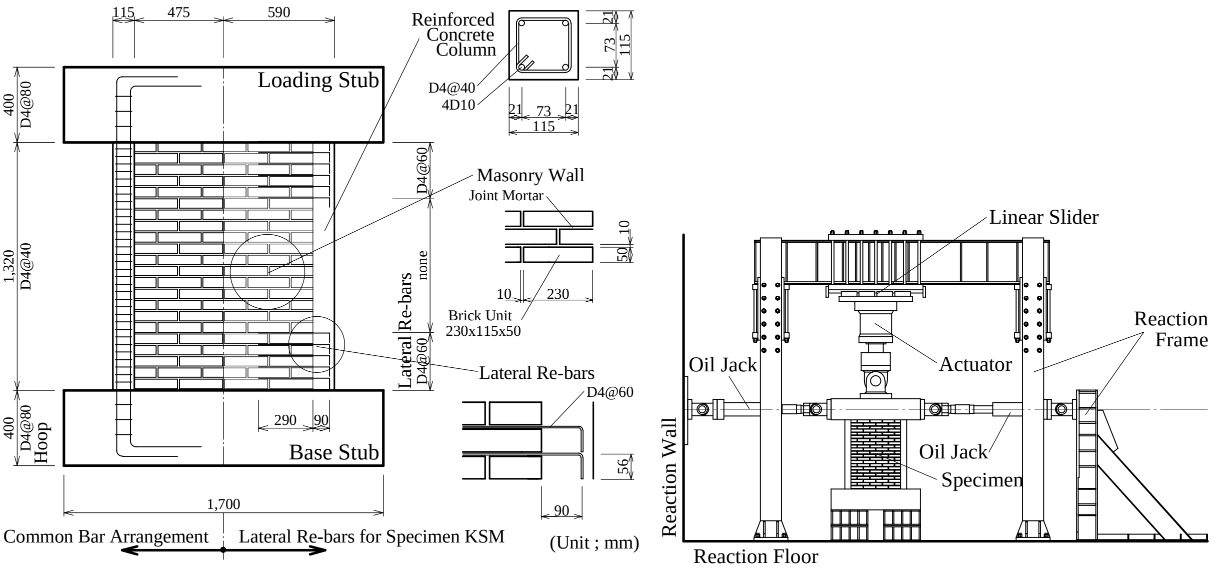
STATIC LOADING TESTS

Test specimens

Test specimens are two confined masonry walls on a scale of half size using solid brick blocks made in Mexico, and the test parameter is lateral reinforcement arranged in mortar joints. The test specimen with the lateral reinforcement is named as KSM and the other without the reinforcement is named ISM. Shape and bar arrangement of the test specimen KSM are shown in Figure 1 a). The lateral reinforcement is anchored to each reinforced concrete edge column with a bending angle of 90 degree, but it is not penetrated to the both columns and not arranged at the central portion of the wall, i.e. the reinforcement is only arranged at the corner parts of the wall. Nominal diameters of tensile and shear reinforcement arranged in the columns are 10mm and 4mm, and the reinforcement ratios are 2.16% and 0.63%, respectively. Test results of concrete, brick units, reinforcement and prism specimens, which are assemblages of six brick block units with mortar joints, are shown in Table 1.

Loading method

Loading tests were carried out using cantilever system as shown in Figure 1 b). Horizontal force was cyclically applied by two oil jacks supported by pin system at the both ends, according to the following schedule in principle; 1 cycle up to observation of an initial crack and 3 cycles at the horizontal deflection angles of 1/800rad., 1/400rad., 1/200rad., 1/150rad., 1/100rad., 1/75rad. and 1/50rad.. And vertical force was constantly applied by an actuator supported by linear slider and pin system. Although axial stress for the both specimens



a) Test specimens **b) Loading setup**

Figure 1: Testing method

Table 1: Material properties

a) Concrete (Cylinder : D=100mm, h=200mm)

Compression Strength (N/mm^2)	Young's Modulus (N/mm^2)	Strain at Compressive Strength	Poisson's Ratio	Tensile Strength (N/mm^2)
29.8	$1.90x10^4$	$2,739x10^{-6}$	0.186	2.58

b) Brick (Cube : d=65mm)

Specific Gravity (g/cm^3)	Compression Strength (N/mm^2)
1.55	13.4

c) Steel

	Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)	Young's Modulus (N/mm^2)	Strain at Yield Strength
D10	333.8	444.0	$1.83x10^5$	$1,840x10^{-6}$
D4	317.5	452.9	$2.22x10^5$	$1,440x10^{-6}$

d) Prism

Compression Strength (N/mm^2)	Young's Modulus (N/mm^2)	Strain at Compressive Strength
5.58	$0.90x10^3$	$7,767x10^{-6}$

Assemblage of 6 Blocks and Joint Mortar

Table 2: Strength of specimens

Name of Specimen	Loading Direction	Initial Crack		Diagonal Crack		Max. Strength	
		τ	R	τ	R	τ	R
ISM	Positive	-	-	0.46	0.15	0.79	1.00
	Negative	0.40	0.11	0.40	0.11	0.84	1.01
KSM	Positive	-	-	0.69	0.32	0.91	0.98
	Negative	0.51	0.10	0.50	0.19	0.77	1.00

Note; τ: Average shear stress (N/mm^2), R: Deflection angle (x10^{-2}rad.)

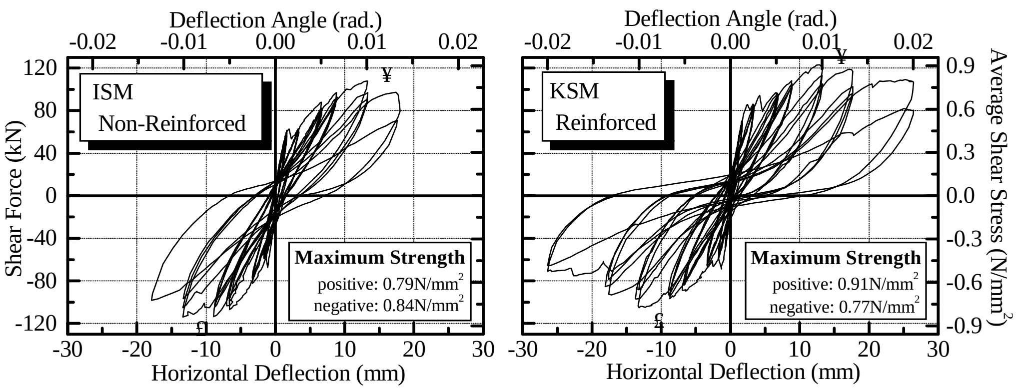
was planned corresponding to the value at the first story of a typical five storied confined masonry building, the stress was different from each other due to a trouble of the system. The test specimen KSM with the lateral reinforcement was tested under the target axial stress of 0.96N/mm^2, but the other specimen ISM without the reinforcement was tested under the stress of 1.36N/mm^2 which was more than 1.4 times the target value. Effects of the discrepancy are discussed through results of nonlinear finite element analyses.

EXPERIMENTAL RESULTS

Strengths, hysteresis loops and crack patterns at the deflection angle of 1/400rad. and at the final stage, of the both specimens are shown in Table 2 and Figures 2 and 3, respectively. In the case of the test specimen KSM with the lateral reinforcement, remarkable strength deterioration was observed after loading at the horizontal deflection angle of 1/50rad., and the specimen ISM without the reinforcement could not sustain the axial force during loading at the deflection angle of 1/75rad.. Ultimate strength of the both specimens was observed at the deflection angle of 1/100rad., and it was approximately 0.8-0.9N/mm^2 in terms of average shear stress.

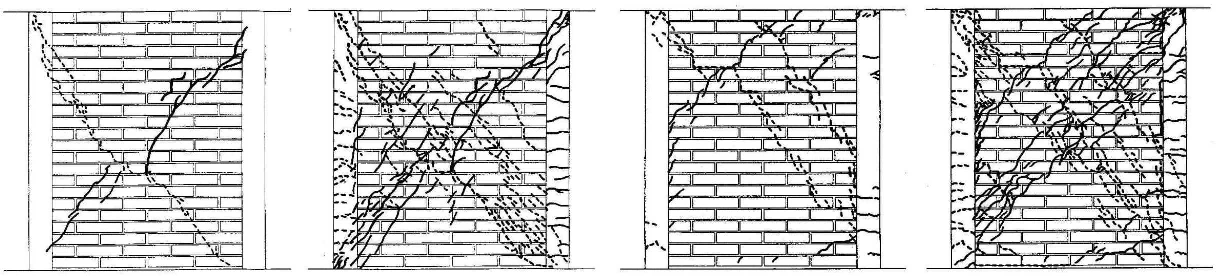
Crack patterns

In the case of the specimen ISM without the lateral reinforcement, diagonal cracks were occurred with vertical cracks along the boundary between edge columns and the masonry wall part at the deflection angle of 1/900rad.. The diagonal cracks were completely developed at the deflection angle of 1/400rad. as shown in Figure 3 a).



a) Specimen ISM (Non-Reinforced) **b) Specimen KSM (Reinforced)**

Figure 2: Hysteresis loops



after 1/400rad.-1 Final (after 1/75rad.-1) after 1/400rad.-1 Final (after 1/50rad.-2)

a) Specimen ISM (Non-Reinforced) **b) Specimen KSM (Reinforced)**

Figure 3: Crack patterns

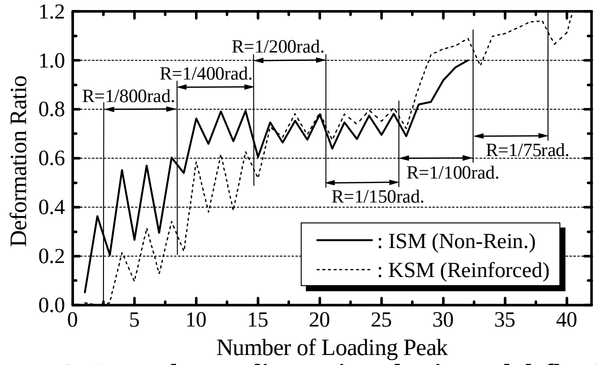


Figure 4: Lateral spreading ratio to horizontal deflection

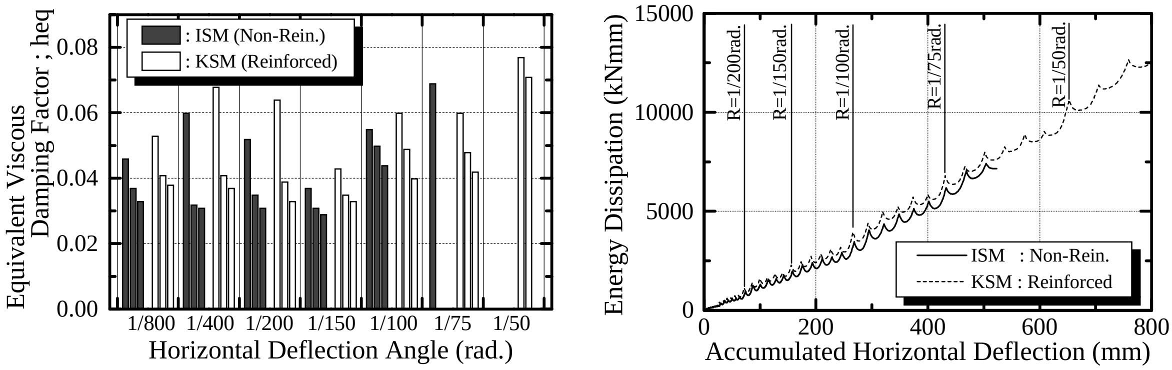
As regards the specimen KSM with the lateral reinforcement, shear cracks at the top part of the wall were developed with the precedence to the diagonal cracks at the angle of 1/520rad.. Diagonal cracks were observed in negative loading direction at the angle of 1/400rad. as shown in Figure 3 b), and completely formed at the angle of 1/200rad.. Difference with the specimen ISM without the reinforcement was observed in developing process of the diagonal cracks. Width of shear cracks at the corner parts of the specimen KSM was narrower than that of the specimen ISM, because the reinforcement dispersed shear cracks.

Lateral spreading ratio to horizontal deflection

Ratios of lateral spreading between both edge columns at the central portion to horizontal deflection at the peak deflection in loading cycles are shown in Figure 4. The ratio of the specimen ISM without the lateral reinforcement was larger than that of the specimen KSM with the reinforcement until the deflection angle of 1/400rad., and this was corresponding to crack characteristics of the specimen KSM, i.e. diagonal cracks were not developed easily. Though the ratio was also stabilized on the both specimens at about 0.7-0.8 until the deflection angle of 1/150rad., the ratio of the specimen KSM surpassed the ratio of the specimen ISM over the angle of 1/100rad. and it has finally reached 1.3.. It is important to keep the lateral spreading ratio low in order to retain the strength of the test specimens, and it is vital to penetrate lateral reinforcement between both edge columns.

Energy dissipation capacity

Equivalent viscous damping factors and relationships between accumulated horizontal deflection and hysteretic energy dissipation are shown in Figure 5. Deterioration of the damping capacity was occurred due to repetition of cyclic loading at the same peak deflection, and the damping factor was stabilized at about 0.03-0.04 until the deflection angle of 1/150rad. in reference to the second and the third loading cycles at the same peak deflection. There was a tendency that the factors decreased gradually according to increase of the deflection angle, and the factor of the specimen KSM with the lateral reinforcement slightly exceeded that of the specimen ISM without the reinforcement. The factors of the both specimens at the deflection angle of 1/100rad. became about 1.4 times that at the angle of 1/150rad.. And the factor of the specimen ISM exceeded that of the specimen KSM over the angle of 1/100rad. at which the ultimate strength was observed, but the specimen ISM could not sustain the axial



a) Equivalent viscous damping **b) Energy dissipation**

Figure 5: Hysteresis characteristics

force during loading at the angle of 1/75rad.. Time with occurrence of this phenomenon was almost corresponding to the loading step when the lateral spreading ratio of the specimen KSM began to greatly exceed that of the specimen ISM.

Hysteretic energy dissipation of the specimen KSM with the reinforcement became 1.1 times that of the specimen ISM without the reinforcement until the deflection angle of 1/100rad., and 1.05 times after the first cyclic loading at the angle of 1/75rad.. Energy dissipation capacity of the specimen KSM exceeded that of the specimen ISM all the time.

NONLINEAR FINITE ELEMENT ANALYSES

Nonlinear finite element analyses were carried out in order to clarify effects of the lateral reinforcement arranged in the mortar joints and axial stress on the structural behavior of the confined masonry walls. The static nonlinear finite element analysis program for reinforced concrete structures considering material nonlinearity; FINAL which was developed at the Technical Research Institute, Obayashi Corporation was used for the analyses.

Analytical condition

Although the tests were performed under cyclic loading, the test specimens were subjected to monotonously increasing force in the analyses. The force increment was enough fine not to require convergent calculation, and the unbalanced force at every calculation step was canceled at the next step. Each specimen was analyzed in two cases with a parameter of axial stress as shown in Table 3 a). The axial stress in the cases 2 and 3 was corresponding to the experimental condition of the test specimens ISM and KSM, respectively.

Modeling of test specimens

Plane stress condition was assumed taking account of the shape of the specimens and the loading condition. It was considered that the effects of the base stub on the structural behavior of the specimens would be negligible, so the specimens were fixed completely to the stub. The masonry wall part and the surrounding reinforced concrete frame were replaced with four-node quadrilateral plane stress elements, and the thickness of the elements was equal to that of the actual members. The masonry wall was divided in block layers and modeled as composite material consisted of brick block units and joint mortar. Finite element meshes for the specimens and the loading condition were shown in Figure 6 a). Equivalent reinforcement layers with stiffness in one direction were substituted for tensile and shear reinforcement which was arranged in the surrounding reinforced concrete frame, and the layers were superimposed on the plane stress elements. Truss elements were used for the lateral reinforcement arranged in the mortar joints at the corner parts of the test specimen KSM as shown in Figure 6 b). The masonry wall was connected to the surrounding frame by two-node linkage elements consisted of two orthogonal springs in order to simulate the discontinuity, i.e. slippage and separation as shown in Figure 6 c). The mortar joints were assumed to be effective in only horizontal direction and replaced with equivalent springs on the element decomposition line.

The material properties were obtained from material tests as shown in Table 1, but uncertain values through the tests were estimated as shown in Table 3 b). The constitutive law of concrete and the masonry wall under plane condition was based on the orthotropic model, and stress-strain relationships of tensile, shear and lateral reinforcement were represented by the bi-linear model. Characteristics of the spring elements at the lateral joints and the linkage elements between the masonry wall part and the surrounding frame were defined as shown in Figures 6 d) and e), respectively.

Table 3: Analytical condition

a) Parameters

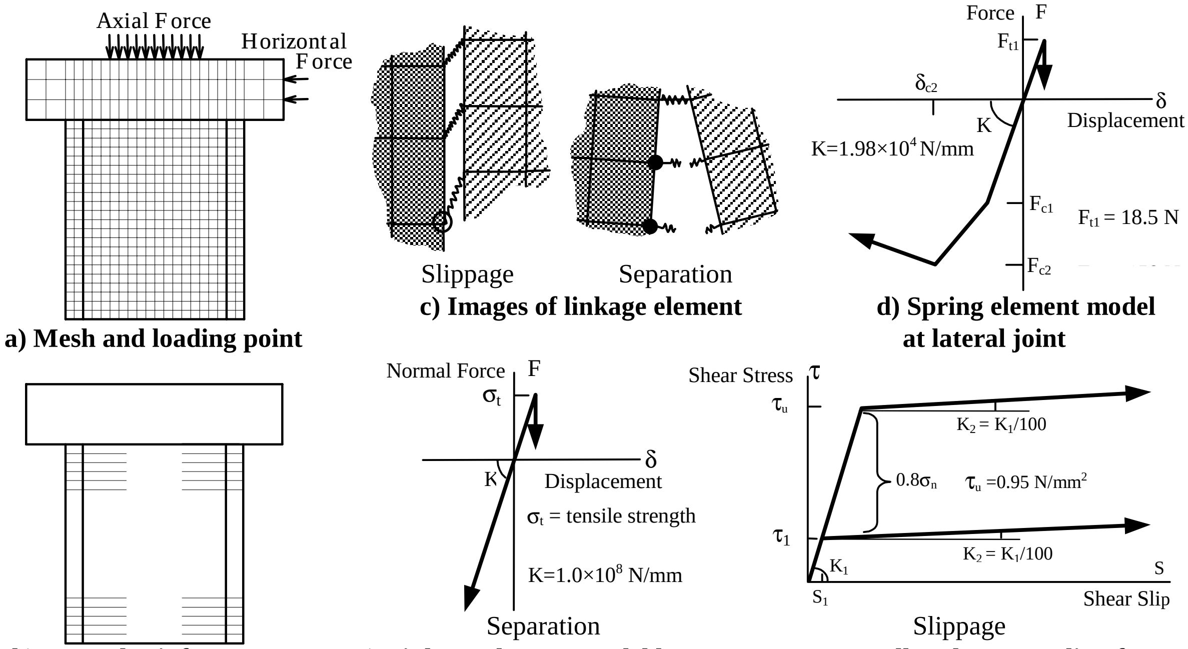
		Lateral Reinforcement	
		None [ISM]	Arranged [KSM]
Axial Stress (N/mm^2)	0.96	Case 1	[Case 3]
	1.36	[Case 2]	Case 4

Cases in brackets are corresponding to the tests.

b) Material properties (Estimated values only)

Compression Strength (N/mm^2)	Young's Modulus (N/mm^2)	Strain at Compressive Strength	Poisson's Ratio	Tensile Strength (N/mm^2)
9.80	$1.96x10^4$	$2,000x10^{-6}$	0.167	0.49
-	-	-	0.167	0.56

Upper; Joint mortar, Lower; Prism, -; Test results are used.



a) Mesh and loading point **c) Images of linkage element** **d) Spring element model at lateral joint**

b) Lateral reinforcement **e) Linkage element model between masonry wall and surrounding frame**

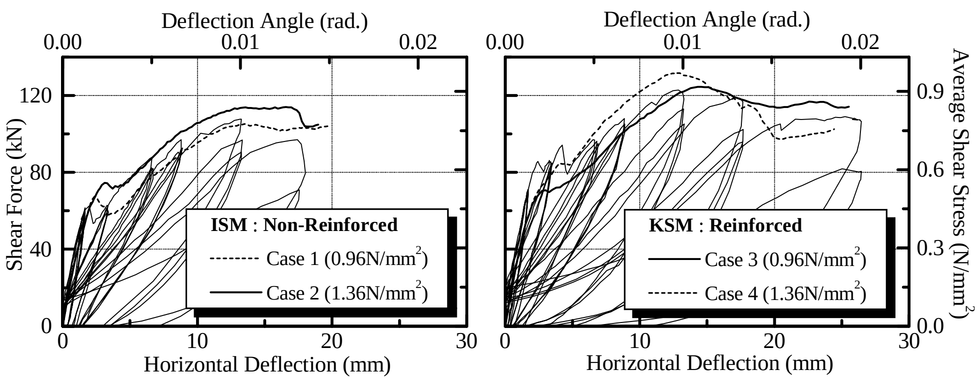
Figure 6: Analytical modeling

ANALYTICAL RESULTS

Shear force-deflection relationships

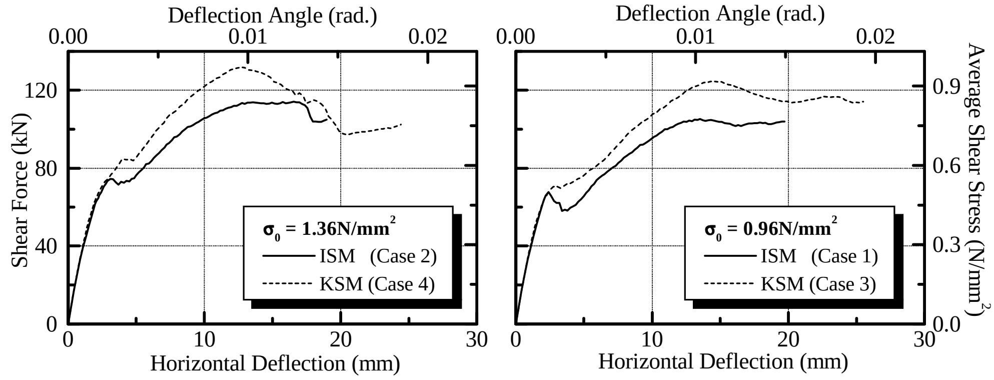
Comparison with experimental results

Comparison of shear force–deflection relationships between the experimental and analytical results is shown in Figure 7. Axial stress in the cases 2 and 3 was corresponding to the test condition of the specimens ISM without the lateral reinforcement and KSM with the reinforcement, respectively. There was no difference in the initial stiffness obtained from the analyses for each specimen. Although momentary shear force deterioration according to developing of shear cracks was observed in early loading stages in the cases of the both specimens, afterward the restoring force increased again. This phenomenon was also observed at the envelope curves of hysteresis loops obtained from the loading tests. Shear force with the momentary deterioration in the cases of 2 and 4 analyzed under axial stress of 1.36N/mm^2 was larger than that in the cases 1 and 3 under axial stress of 0.96N/mm^2, respectively. And the maximum shear force in the cases under axial stress of 1.36N/mm^2 was also larger than that in the cases under axial stress of 0.96N/mm^2. It was difficult to simulate the momentary deterioration in the case of the specimen KSM with the lateral reinforcement, but the analytical results of the cases 2 and 3 showed generally good correspondence with the experimental results of the specimens ISM and KSM after the momentary shear force deterioration, respectively.



a) Specimen ISM (Non-Reinforced) **b) Specimen KSM (Reinforced)**

Figure 7: Comparison of shear force-deflection relationship



a) Axial stress : 1.36N/mm^2 **b) Axial stress : 0.96N/mm^2**

Figure 8: Comparison of shear force-deflection relationship

Effects of lateral reinforcement

Comparison of shear force–deflection relationships according to the axial stress is shown in Figure 8. There was no difference in the initial stiffness depending upon the lateral reinforcement at the corner parts of the wall. Shear force with the momentary deterioration in the cases of 3 and 4 analyzed with the reinforcement was larger than that in the cases 1 and 2 without the reinforcement, respectively. And the maximum shear force in the cases with the reinforcement was also larger than that in the cases without the reinforcement. An Effect of the lateral reinforcement on the ultimate strength of the specimens was recognized in the analyses.

Crack patterns

Development of cracks in the cases 2 and 3 corresponding to the test condition of the specimens ISM without the lateral reinforcement and KSM with the reinforcement is shown in Figures 9 a) and b), respectively. In the case 2 for the specimen ISM, shear slippage occurred on the boundary surface between the masonry wall part and the surrounding frame. Afterward, shear cracks also occurred concentrically at the central portion of the wall. In the case 3 for the specimen KSM, cracks occurred at the central portion after occurrence of cracks at the corner parts of the wall caused by redistribution of stress. The crack patterns showed good correspondence with the experimental results, i.e. superiority of diagonal cracks of the specimen ISM and dispersion of shear cracks at the corner parts of the specimen KSM. An effect of the lateral reinforcement on crack patterns of the specimens was also confirmed in the analyses.

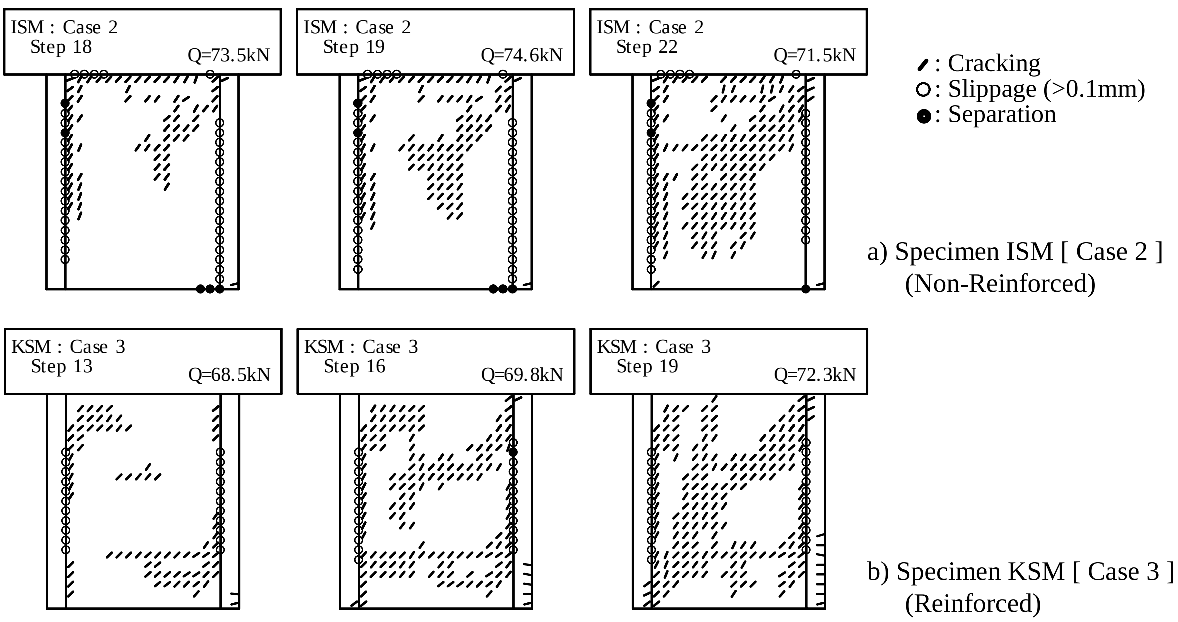


Figure 9: Crack patterns

CONCLUSIONS

Static cyclic loading tests on two confined masonry walls were carried out with a test parameter of lateral reinforcement arranged in mortar joints at corner parts of the walls. The test specimen with the lateral reinforcement was tested under the target axial stress of $0.96N/mm^2$, and the other without the reinforcement was tested under the stress of $1.36N/mm^2$ due to a trouble of loading system. Nonlinear finite element analyses were also performed to clarify effects of the lateral reinforcement and the discrepancy of the axial stress on their structural behavior.

Ultimate strength of the both specimens was observed at the horizontal deflection angle of around 1/100rad., and it was approximately $0.8\text{-}0.9N/mm^2$ in terms of average shear stress. Delayed appearance of diagonal cracks and dispersion of shear cracks at the corner parts of the wall were observed as the effects of the lateral reinforcement in the loading tests. And the reinforcement decreased lateral spreading of the wall until the angle of 1/400rad., but the effect was not remarkable at loading over the angle of 1/200rad..

It was possible to simulate the experimental results such as crack patterns and envelope curves of shear force-deflection relationship by nonlinear finite element analyses. An effect of the lateral reinforcement on ultimate strength of the specimens was not clear due to the discrepancy of the axial stress in the tests, but the analyses clarified that the reinforcement contributed to increase the strength.

Since analytical technique for nonlinear finite element method on masonry structures is not established yet, it is important to develop furthermore this simulation method.

ACKNOWLEDGMENTS

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