SEISMIC RETROFIT OF UNREINFORCED CLAY BRICK MASONRY WALL USING POLYMER-CEMENT MORTAR

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ABSTRACT :

The present study is to investigate the seismic performance of unreinforced masonry (URM) wall retrofitted with reinforced polymer-cement mortar (PCM). Four unreinforced clay brick masonry wall specimens with 100 mm in wall thickness were constructed first, then three of them were retrofitted with PCM applied on one of their surfaces forming a thickness of 40 mm, in which different vertical and horizontal steel bars had been arranged. The specimens were tested under cycle reversal loading method. Test results demonstrate that the application of reinforced PCM wall provides higher lateral load carrying capacity to URM wall, and also different failure modes were observed in three retrofit wall specimens. Ultimate lateral strength of the URM wall retrofitted with reinforced PCM wall is discussed by employing existing methods to predict flexural and shear strengths for masonry and R/C walls, respectively.

KEYWORDS: polymer-cement mortar (PCM), seismic retrofit, unreinforced masonry (URM)

1. OBJECTIVE

Polymer-cement mortar (PCM) is an advanced material with high adhesive strength and durability as well as fireproof properties. It has been used in seismic retrofit and repair of existing R/C building and civil engineering structures. Sugiyama et. al. (2005) reported that application of PCM for retrofit R/C wing wall is quite effective even in the case that any of dowel and shear keys were not provided between existing R/C wing wall and reinforced PCM wall.

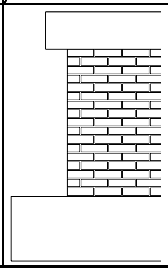
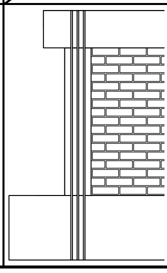
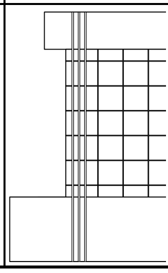
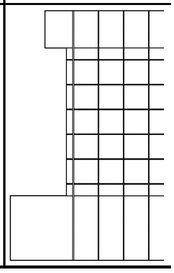
This paper addresses a seismic retrofit method for unreinforced clay brick masonry (URM) buildings or walls. Weakness point of the masonry is low tensile strength that leads to low flexural capacity and to low shear capacity, hence, the application of PCM and the inclusion of steel reinforcing bars is expected to provide an increment in the lateral load carrying capacity of this type of masonry. The present study is to investigate the seismic performance of URM wall retrofitted with reinforced PCM wall.

2. TEST SPECIMENS

Table 2.1 gives list of four test specimens used in the present study. Figure 2.1 shows dimensions and reinforcing details for Specimen No.3, which is retrofitted with reinforced thin PCM wall. For all the retrofit specimens, the PCM was pasted on the one side of URM wall as shown in Figure 2.2. Thickness of the PCM wall is 40 mm, which is common to all the retrofit specimens.

Specimen No.1 is an URM wall without any retrofit. Dimensions of the clay brick masonry unit are 210x100x60 in mm, and thickness of the joint mortar is 10 mm.

Table 2.1 List of test specimens

Specimen		No.1	No.2	No.3	No.4
Details of Reinfoced PCM walls	wall thickness (mm)		40	40	40
	Flexural reinforcing bars		3-D13 (#4)	3-D13 (#4)	1-D10 (#3)
	Vertical steel bars			D6 (#2) @200 (Not anchored)	D6 (#2) @200 (Anchored)
	Horizontal steel bars			D6 (#2) @200	D6 (#2) @200
Elevation					

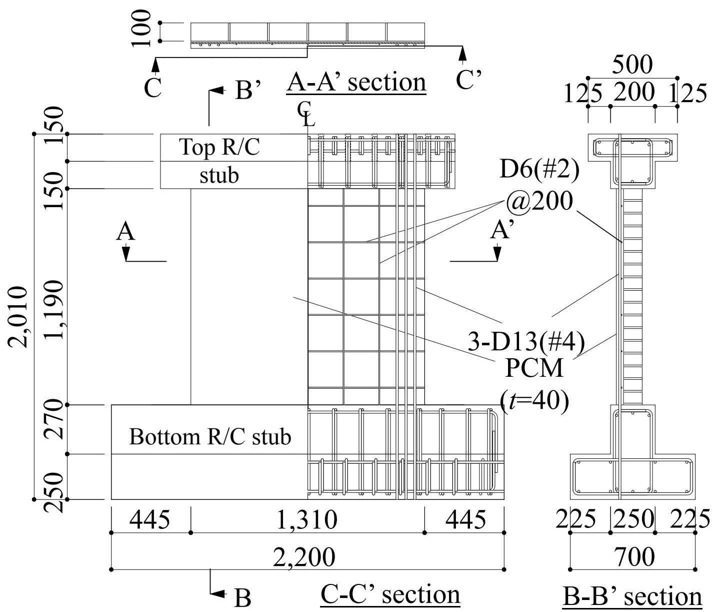


Figure 2.1 Dimensions and reinforcing details for Specimen No.3

Figure 2.2 Construction of reinforced PCM wall

Specimen No.2 is retrofitted with partial PCM walls of 210 mm width at right and left edges of the masonry wall. Longitudinal steel bars of 3-D13 (3-#4) are placed in each PCM wall as flexural reinforcement, where the steel bars are anchored to the top and bottom R/C stubs on the assumption that development length for the steel bars are considered to secure in the application of this retrofit method to the actual buildings.

Specimen No.3 is retrofitted with an overall PCM wall. In addition to the flexural reinforcement of 3-D13 (3-#4), vertical and horizontal steel bars with bar size of D6 (#2) are placed with spacing of 200 mm as shear reinforcement. The vertical steel bars are not anchored in the R/C stubs. Also, Any hooks are not provided at the ends of horizontal steel bars.

Specimen No.4 is retrofitted with an overall PCM wall. The PCM wall is reinforced with flexural reinforcement of 1-D10 (1-#3), and vertical and horizontal steel bars that composed of D6 (#2) bars with spacing of 200 mm. Amount of the flexural reinforcement of this specimen is much smaller than that of Specimens No.2 and No.3. However, vertical steel bars are expected to act as the flexural reinforcement as well as the shear reinforcement because they are anchored to the top and bottom R/C stubs.

Table 2.2 gives compressive strengths of the PCM, joint mortar and masonry prism. Mechanical properties of the steel bars are given in Table 2.3.

Table 2.2 Compressive strengths of PCM, joint mortar, and masonry prism

Specimen	PCM		Joint mortal		Masonry prism
	Compressive strength (MPa)	Elastic modulus (GPa)	Compressive strength (MPa)	Elastic modulus (GPa)	Compressive strength (MPa)
No.1			25.8	19.5	49.7
No.2	35.5	17.8	27.7	19.3	47.8
No.3	31.8	17.5	26.4	19.2	42.0
No.4	28.0	17.7	26.2	19.1	37.6

Table 2.3 Mechanical properties of steel bars

Bar size	Yield strength (MPa)	Elastic modulus (GPa)	Tensile strength (MPa)	Elongation (%)
D6 (#2)	324*	174	526	22
D10 (#3)	377	194	536	20
D13 (#4)	360	188	528	23

* 0.2 % offset strength

3. LOADING METHOD

Figure 3.1 shows loading apparatus used in the experiments of the present study. A constant vertical axial load was applied by a hydraulic jack, and alternate repeated lateral forces were applied by the other double acting hydraulic jack. Magnitude of the constant vertical axial load applied to the test specimens is 62.9 kN in compression that corresponds to the axial stress (σ_0) of 0.48 MPa. Height of the application point of lateral forces (h) is 1,265 mm measured from the top of bottom R/C stub.

4. THEORETICAL PREDICTIONS OF ULTIMATE LATERAL STRENGTHS

4.1. Ultimate Lateral Strength for Flexural Failure Mode

The ultimate lateral strength for flexural failure mode (Q_{mu}) is predicted by Eqn. 4.1.

$$Q_{mu} = {}_bQ_{mu} + {}_pQ_{mu} \tag{4.1}$$

${}_bQ_{mu}$ is lateral strength of the masonry wall based on the overturning moment after the crack is formed throughout the bed joint just above the bottom R/C stub, which is given by Eqn. 4.2.

$${}_bQ_{mu} = \frac{(N+w)\cdot \frac{l}{2}}{h} \tag{4.2}$$

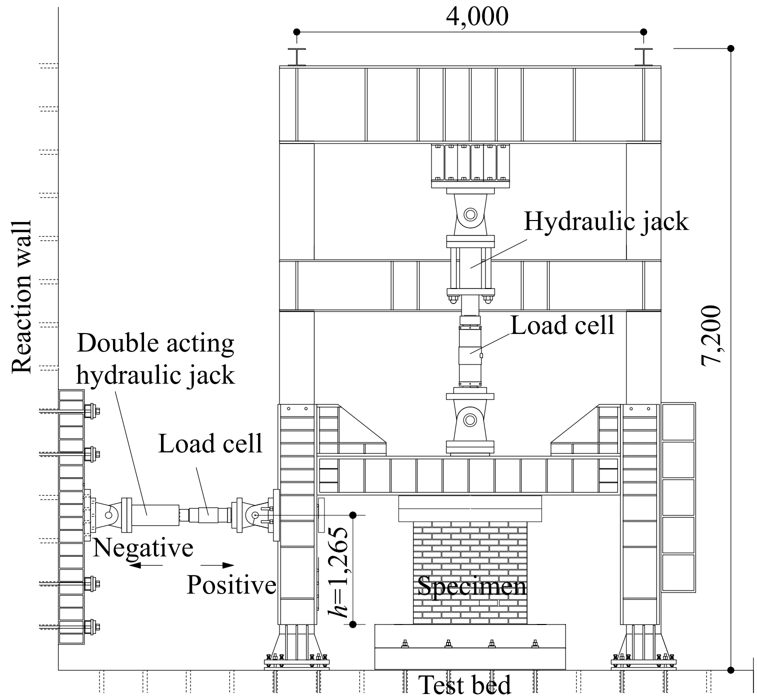


Figure 3.1 Loading apparatus

in which N is applied axial load, w is self-weight of the wall including collar beam, l is overall length of the wall, h is height of the application point of lateral forces.

${}_pQ_{mu}$ is lateral strength of the reinforced PCM wall based on the ultimate flexural strength of the bottom section (${}_pM_u$), which is given by Eqn. 4.3. ${}_pM_u$ is given by Eqn. 4.4 [Architectural Institute of Japan (1990)].

$$ {}_pQ_{mu} = \frac{{}_pM_u}{h} \tag{4.3} $$

$$ {}_pM_u = \Sigma a_t \sigma_y \cdot l' + 0.5 \cdot \Sigma a_w \sigma_{wy} \cdot l' \tag{4.4} $$

in which a_t and σ_y are cross-sectional area and yield strength of the flexural reinforcing bars, respectively, a_w and σ_{wy} are cross-sectional area and yield strength of the intermediate vertical steel bars, respectively, l' can be taken as 0.9 times the overall length of wall (l).

4.2. Ultimate Lateral Strength for Shear Failure Mode

The ultimate lateral strength for shear failure mode (Q_{su}) is predicted by Eqn. 4.5.

$$ Q_{su} = {}_bQ_{su} + {}_pQ_{su} \tag{4.5} $$

${}_bQ_{su}$ is ultimate shear strength of the masonry wall, which is given by Eqn. 4.6 [National Standards of P.R. of China (1989)].

$$ {}_bQ_{su} = \left\{ f_v \frac{1}{1.2} \sqrt{1 + 0.45 \frac{\sigma_0}{f_v}} \right\} A_w \tag{4.6} $$

in which f_v is shear strength of masonry given by Eqn. 4.7, σ_0 is axial stress due to applied axial load, A_w is horizontal cross-sectional area of the masonry wall.

$$f_v = 0.125\sqrt{f_z} \tag{4.7}$$

in which f_z is compressive strength of joint mortar in MPa.

${}_pQ_{su}$ is ultimate shear strength of the reinforced PCM wall, which is given by Eqn. 4.8 [Architectural Institute of Japan (2003)].

$${}_pQ_{su} = \left\{ \frac{0.068 \cdot p_t^{\,0.23}(f_{pcm} + 18)}{M/(Q \cdot l) + 0.12} + 0.85\sqrt{p_w \cdot \sigma_{wy}} \right\} \cdot t \cdot j \tag{4.8}$$

in which p_t is flexural reinforcement ratio in %, f_{pcm} is compressive strength of the PCM, $M/(Ql)$ is shear span ratio, p_w is horizontal reinforcement ratio, σ_{wy} is yield strength of the horizontal steel bars, t is thickness of the PCM wall, j can be taken as 7/8 times the effective depth of the PCM wall.

The predictions obtained from Eqns. 4.1 to 4.8 are summarized in Table 4.1 with the failure mode based on those predictions. It can be understood from Eqns. 4.2, 4.4, and Eqns. 4.6, 4.8 that applied vertical axial load is assumed to work fully on the masonry wall. For Specimen No.2, reinforced PCM wall is not taking into account for the prediction of Q_{su}. This is because the PCM wall is provided not to full surface but to right and left edge surfaces of the masonry wall.

Table 4.1 Theoretical ultimate strengths and experimental maximum strengths

<table>
<tr><th rowspan="3">Spesimen</th><th colspan="7">Theoretical predictions</th><th colspan="2">Test results</th></tr>
<tr><th colspan="3">Q_m (kN)</th><th colspan="3">Q_{su} (kN)</th><th rowspan="2">Failure mode</th><th rowspan="2">Q_{max} (kN)</th><th rowspan="2">Failure mode</th></tr>
<tr><th>${}_bQ_{mu}$ (kN)</th><th>${}_pQ_{mu}$ (kN)</th><th></th><th>${}_bQ_{su}$ (kN)</th><th>${}_pQ_{su}$ (kN)</th><th></th></tr>
<tr><td>No.1</td><td rowspan="4">36</td><td></td><td>36</td><td>80</td><td></td><td>80</td><td>F</td><td>40</td><td>F</td></tr>
<tr><td>No.2</td><td>128</td><td>163</td><td>83</td><td></td><td>80</td><td>S</td><td>112</td><td>S</td></tr>
<tr><td>No.3</td><td>128</td><td>163</td><td>81</td><td>158</td><td>239</td><td>F</td><td>158</td><td>F/SL</td></tr>
<tr><td>No.4</td><td>49</td><td>85</td><td>81</td><td>114</td><td>195</td><td>F</td><td>102</td><td>F</td></tr>
</table>

[Remarks]

Q_{mu} : Theoretical lateral strength for flexural failure mode
${}_bQ_{mu}$: Contribution by masonry wall given by Eqn.4.2
${}_pQ_{mu}$: Contribution by reinforced PCM wall given by Eqn.4.3
Q_{su} : Theoretical lateral strength for shear failure mode
${}_bQ_{su}$: Contribution by masonry wall given by Eqn.4.6
${}_pQ_{su}$: Contribution by reinforced PCM wall given by Eqn.4.8
Q_{max} : Experimental maximum lateral force

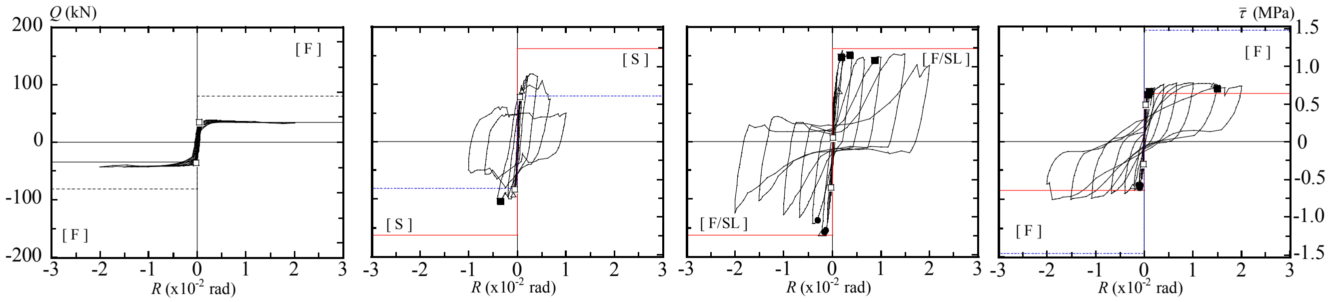
F : Flexure
S : Shear
F/SL : Flexure mixed with sliding

5. TEST RESULTS AND DISCUSSIONS

5.1. Overview of Test Results

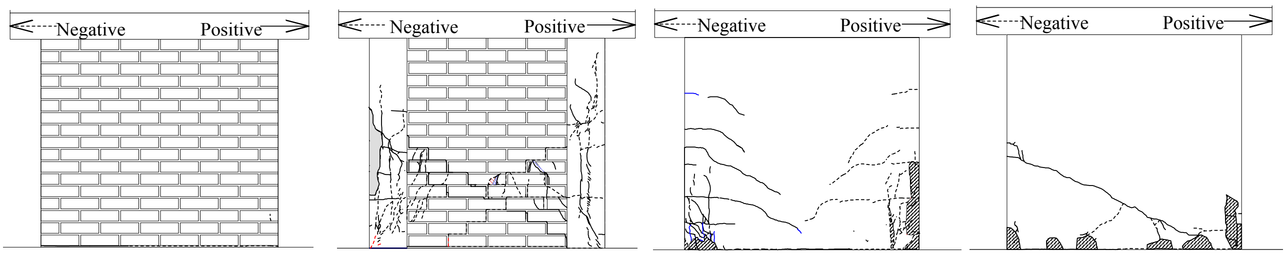
Figure 5.1 shows relation between lateral force (Q) and deformation angle (R) obtained from the experiment, in which R is defined as the lateral displacement of top R/C stub divided by its height measured from the top surface of bottom R/C stub. Right vertical axis represents mean shearing stress ($\bar{\tau}$), which is defined as the lateral force (Q) divided by the horizontal cross-sectional area of the masonry wall (A_w). Symbols in parentheses indicate failure mode observed in the experiments. Solid lines parallel to the horizontal axis represent theoretical strength for flexural failure mode (Q_{mu}), and dashed lines represent theoretical strength for shear failure mode (Q_{su}). Figure 5.2 shows final crack patterns observed in the experiments. Figure 5.3 shows Q-R envelop curves for all test specimens, which are obtained from Figure 5.1. Maximum lateral strengths and failure modes obtained from the experiments are listed in Table 4.1.

Test results and effects of the retrofits are discussed for each specimen as follows.



(a) Specimen No.1 (b) Specimen No.2 (c) Specimen No.3 (d) Specimen No.4

Figure 5.1 Relation between lateral force (Q) and deformation angle (R)



(a) Specimen No.1 (b) Specimen No.2 (c) Specimen No.3 (d) Specimen No.4

Figure 5.2 Final crack patterns

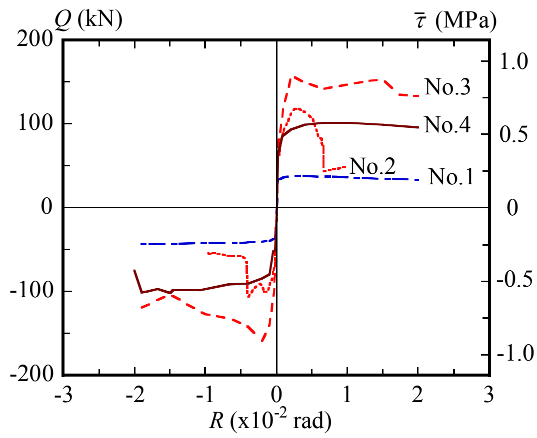


Figure 5.3 Q-R envelop curves for all test specimens

5.2. Specimen No.1 (without any retrofit)

The first flexural crack was formed along the bed joint just above the bottom R/C stub at R=0.04x10^{-2}rad and R=-0.03x10^{-2}rad in positive and negative loadings, respectively. As a result of those cracks, the bed joint just above the bottom R/C stub cracked throughout the length of wall. After that, any other cracks were not formed as can be understood from Figure 5.2 (a), and the masonry wall panel rotated rigidly side to side. This resulted in a quite low energy absorption characteristic of the wall in spite of its high deformation capacity as shown in Figure 5.1 (a).

This test specimen failed in flexural failure mode. Maximum lateral force obtained from the experiment agrees well with the theoretical strength for flexural failure mode (Q_{mu}) as shown in Figure 5.1 (a).

5.3. Specimen No.2 (with flexural retrofit)

The bed joint just above the bottom R/C stub had cracked throughout the length of wall due to the flexural moment at R=-0.05x10^{-2}rad. Extensive Shear cracks started to be formed around R=0.10x10^{-2}rad in both loading directions, and the maximum lateral force was developed at R=0.32x10^{-2}rad and R=-0.40x10^{-2}rad in positive and negative loadings, respectively. After developing the maximum lateral force, rapid deterioration in lateral load carrying capacity took place as shown in Figure 5.1 (b).

This test specimen failed in shear failure mode, in which maximum lateral force is 2.8 times as high as that of Specimen No.1. This means that the thin PCM wall with flexural reinforcing bars is effective to improve flexural strength of the URM wall. The maximum lateral force, which is defined as average of ones in positive and negative loadings, was 36 % higher than the theoretical strength for shear failure mode (Q_{su}).

A part of the wall shown by dark gray area in Figure 5.2 (b) fell off at R=-0.51x10^{-2}rad in negative loading, where separation of reinforced PCM wall and masonry wall was not observed in the part.

5.4. Specimen No.3 (with flexural and shear retrofit)

The bed joint just above the bottom R/C stub had cracked throughout the length of wall due to the flexural moment at R=0.07x10^{-2}rad. Flexural reinforcing bars in the PCM wall started to yield in tension at R=0.17x10^{-2}rad and R=-0.13x10^{-2}rad in positive and negative loadings, respectively. Maximum lateral force was developed at R=0.20x10^{-2}rad in both loading directions. At that time, sliding of the wall was also observed along the bed joint just above the bottom R/C stub. Ratio of the sliding displacement to the total displacement measured at the top R/C stub was 0.12 and 0.16 for positive and negative loadings, respectively. The sliding displacement increased remarkably just after developing the maximum lateral force, and the ratio became approximately 0.8 at the final loading cycle with R=2.0x10^{-2}rad.

This test specimen failed in flexural failure mode mixed with sliding failure mode, in which maximum lateral force is higher than that of Specimen No.2 as shown in Figure 5.3. This means that the reinforced thin PCM wall is effective to improve shear strength as well as flexural strength of the URM wall. The maximum lateral force obtained from the experiment little bit lower than the theoretical strength for flexural failure mode (Q_{mu}) as shown in Figure 5.1 (c).

Due to the buckling of flexural reinforcing bars at the bottom of wall, which started from R=0.67x10^{-2}rad, surrounding PCM were pushed away as shown in Figure 5.2 (c). Some local separations of reinforced PCM wall and masonry wall were observed around the bottom of wall after R=1.0x10^{-2}rad.

5.5. Specimen No.4 (with flexural and shear retrofit)

The bed joint just above the bottom R/C stub had cracked throughout the length of wall due to the flexural moment at R=0.05x10^{-2}rad. Flexural reinforcing bar and vertical bars in the PCM wall started to yield in tension at R=0.07x10^{-2}rad and R=-0.09x10^{-2}rad in positive and negative loadings, respectively. Maximum lateral force was developed at R=1.0x10^{-2}rad and R=-1.5x10^{-2}rad. Remarkable sliding displacement as observed in Specimen No.3 were not observed in this test specimen. A shear crack as shown in Figure 5.2 (d) was formed at R=1.42x10^{-2}rad in positive loading. However, the lateral load carrying capacity was maintained.

This test specimen failed in flexural failure mode, and developed good ductility. The maximum lateral force obtained from the experiment little bit higher than the theoretical strength for flexural failure mode (Q_{mu}) as shown in Figure 5.1 (d).

Due to the buckling of vertical steel bars at the bottom of wall, which started from R=0.67x10^{-2}rad, surrounding PCM were pushed away as shown in Figure 5.2 (d). Some local separations of reinforced PCM wall and masonry wall were observed in the bottom of wall at the final loading cycle with R=2.0x10^{-2}rad.

6. CONCLUSIONS

To investigate seismic performance of the URM walls retrofitted with thin reinforced PCM wall, an experimental investigation was carried out using four URM wall specimens with and without retrofit. Conclusions obtained are summarized as follows.

1) The test results demonstrate that the application of reinforced PCM wall provides higher lateral load carrying capacity to the URM wall.

2) The extensive separation of URM wall and reinforced PCM wall were not observed in three retrofit specimens though any of dowel and shear keys were not placed between them.

3) The ultimate flexural strength of the URM wall after retrofit with thin reinforced PCM wall can be predicted approximately by Eqn. 4.1.

4) The effect of PCM wall with vertical and horizontal steel bars on the ultimate shear strength is a subject to be investigated in a future study.

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