EXPERIMENTAL AND NUMERICAL STUDY OF CONFINED MASONRY WALL UNDER CYCLIC LOADING

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ABSTRACT

Experimental study and numerical simulation are carried out to investigate the response of confined masonry wall. Three specimens each of red brick, conblock, and conblock wall with horizontal reinforcement are analyzed in this study. These specimens are exited cyclically according to certain displacement history. All specimens are of the same geometry of 870 mm wide and 1,330 mm high. Test data show that red brick specimen has higher lateral force resistance than that of the conblock one. The conblock with horizontal reinforcement attains least lateral force resistance in this study. It is observed that the first significant cracks occur at early cycles for all specimens. The red brick, conblock, and conblock wall with horizontal reinforcement specimens can withstand lateral force of 5.6 kN, 4.29 kN, and 1.93 kN, respectively. The first significant cracks occur at drift ratio of 0.6/1000 at first cycle for red brick, 0.63/1000 at first cycle for conblock, and 1.3/1000 at second cycle for conblock wall with horizontal reinforcement. One complete cycle that contains the first significant cracks is further studied numerically. Based on this complete cycle, numerical simulation is performed to determine the constitutive relation, the hardening rule, and the yield criteria of these specimens. Numerical analysis shows that constitutive model approximated by concrete model yields the best fit. This model combined with Drucker-Prager yield criteria and a combination of isotropic and kinematic hardening is used to compare the experimental results with the simulation. Some guidance to numerically analyze these walls is proposed.

Keywords: confined masonry wall, constitutive model, displacement history, hardening rule, and yield criteria.

INTRODUCTION

Most housings in Indonesia, especially the low cost ones, use masonry wall system for their first choice of material selection. Confined masonry wall, either brick ones or conblock, is the most popular material being used up to these days. It is very unfortunate that the way of building these housings belongs to the class of the so-called non-engineered structures. The behavior of such structures cannot be well predicted under various loadings combination that can come from real phenomena. Earthquake prone countries such as Indonesia must in their best effort improve the performance of such kind of building structures in order to prevent massive casualties in case of ground motion. Data collected during Bengkulu earthquake on June 4th, 2000, for instance, show that many residential buildings suffer heavy damage. Most of the buildings are constructed of confined masonry wall system[6,7]. These facts suggest the need of practical guidance to improve the behavior of confined masonry wall system at least to be the simple-and-safe engineered buildings.

Some aspects should be investigated such as brick or conblock forming, bricklaying techniques, effects of confinement, and wall reinforcement. Beca Carter & Hollings[1] performed in-plane and out-of-plane loading test of brick masonry specimens and proposed some recommendation on how to improve brick wall performance. UNDP[8] also performed several experimental studies to

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investigate masonry properties of the local brickwork. Their results, however, are unable to predict the behavior of masonry wall system when subjected to ground motion effect. More investigations need to be done to provide additional data and to develop practical guidance or manual. This study is carried out with the objective to achieve the latter.

EXPERIMENTAL PROGRAME

Specimens of brick and conblock masonry wall are prepared to be subjected to cyclic loading. Three of them with dimensions of 870 x 1,330 (mm^2) are tested. The specimens, shown in Fig. 1, are as follows:

Red Brick Wall (RB) This specimen is composed of clayey red brick with tile size of 190 x 95 x 50 (mm^3), joined by using cement-sand mortar with 1:4 mixture compositions. The brick tile has compressive strength of 2.38 MPa while the mortar's is 6.38 MPa according to SNI standard test. The wall is confined by two 100 x 100 (mm^2) reinforced concrete columns (f_c' = 17.6 MPa) at its vertical sides, is fixed at the base, and is subjected to specified displacement at the topside. Two stub beams provide the fixity at the base and at the displacement side.

Conblock Wall (CW) Similar to the red brick, 190 x 390 x 90 (mm^3) hollow conblock (concrete block) tiles are used to construct the masonry wall. The hollow conblock tile contains two caves formed by two edges and one intermediate pole and enclosed by two side and top walls; its bottom remains open[7]. The pole and the wall thickness is 20 mm. Compressive strength of the conblock is 0.47 MPa.

Conblock Wall with Horizontal Reinforcement (CWHR) Horizontal reinforcement was inserted into CW specimen at every horizontal mortar joint to form CWHR. The reinforcement is of plain rebar of 4 mm in diameter and is hooked and anchored to the side concrete columns.

Each specimen is then installed in the testing apparatus. Lateral displacement is applied at the top stub beam according to lateral displacement history[7].

DISCUSSION OF THE RESULTS

Hysteretic response Response of the three specimens undergoing specified displacement history is presented in Figs. 2, 3, and 4 for RB, CW, and CWHR respectively. Some parameters on strength, stiffness, and energy dissipation are evaluated. It is observed from the hysteretic loop that RB specimen exhibits the highest resistance among the three specimens. On the other hand, CWHR shows the lowest strength. Crack pattern of each specimen during testing is monitored continuously[7].

First crack in RB occurred at first cycle where the lateral force of 5.6 kN (99% of maximum lateral load) is achieved. The drift ratio at this cycle is 0.6/1000. The lateral load resistance decreases to 3.38 kN (60% of maximum load) at third cycle with drift ratio of 1.2/1000. At subsequent cycle the specimen regains its strength and increases its lateral resistance to maximum of 5.63 kN at drift ratio of 4.9/1000 at 13th cycle. The strength decreases considerably after this cycle and considered inoperational at cycle 14th where the strength degrades by as much as 29%. The specimen is failed in brittle mode with relatively low energy absorption and minor pinching phenomenon.

CW specimen exhibits lower lateral strength at first cycle. First diagonal crack occurs at 1st cycle with lateral load of 2.23 kN or 52% of maximum load at drift ratio of 0.62/1000. The specimen continues to develop its resistance to 3.13 kN (72% of maximum load) at 4th cycle and finally reaches the maximum load of 4.29 kN at 13th cycle. The cracks have been distributed over the wall face and its resistance degrades by as much as 25% at 18th cycle. At this point the specimen is considered to be inoperational. The fact that CW specimen shows much lower lateral load resistance than that of RB specimen can be explained by three factors. The first one is that the CW material has lower compressive strength than RB specimen. The second is due to physical differences between the RB masonry, which is massive, and CW which is hollow. The caves in the conblock cause the assembled wall to have strong pole in the vertical joint between the tiles and weak one between the strong poles. This situation results in non-uniformity in strength in the conblock wall. The third factor is in the difference of mortar volume consumed in respective specimen due to different tile size, i.e., some 20% volume in RB, and some 7.4% volume in CW. Noting that mortar has higher compressive strength than that of red brick and conblock this difference will affect the over all wall strength.

Under the same displacement history CWHR specimen performs contrarily to the expectation. Test shows that the first crack occurs at 2nd cycle where lateral load is 1.19 kN (62% maximum) at drift ratio of 1.3/1000. Cracks continue to form and lateral load resistance increases to 1.46 kN (76% maximum) at drift ratio of 2/1000 at 4th cycle. Maximum lateral load resistance is achieved at 13th cycle of 1.93 kN, and the drift ratio is 5.1/1000. Cracks continue to develop and strength degrades by as much as 25% of the maximum load at 15th cycle at which the specimen is considered inoperational. The noticeable effect of the horizontal reinforcement is in its ability to reduce the separation between the two confining columns. Cracks are also distributed more uniformly in this specimen.

Stiffness degradation Cyclic stiffness is defined as the slope of the line joining the origin and the peak value of the respective cycle[7]. Propagation of cracks during cyclic loading causes the stiffness degradation in the specimen. The stiffness degradation of every cycle can be plotted and is shown in Fig. 5. The ordinate represents the ratio between the stiffness at particular cycle with respect to the first one. It can be seen that RB shows the largest stiffness degradation among the three specimens, they are 64.2% at 3rd cycle and 55.7% at 2nd cycle in the opposite direction for RB, 36.7% at 2nd cycle and 54.6% at 2nd cycle in the opposite direction for CW, and 29.1% at 2nd cycle and 30.55% at 2nd in the opposite direction for CWHR.

Energy dissipation Dissipated energy is the area enclosed by load-deflection hysteresis curve and the energy input is the sum of energy dissipation and the restorable elastic energy and mathematically is expressed in Eq. (1).

$$E_I = E_E + E_D \tag{1}$$

where E_I is the total energy input, E_E is the restorable elastic energy, E_D is the dissipated energy.

Energy dissipation capacity, defined as the ratio between the dissipated energy and the total energy input, is shown in Fig. 6. Fig. 6 shows that RB has the highest energy dissipation capacity, followed by CW, and by CWHR, in low cycles. This is consistent with the loss of stiffness that is the largest for RB, followed by CW, and by CWHR.

NUMERICAL ANALYSIS OF CONFINED MASONRY WALL

There are two common ways to analyze confined masonry wall[1], i.e., the finite element and the strut equivalent methods. In this paper, the finite element method is employed because it is believed that this method is more powerful than strut equivalent even though it is less simple to model the structure[1]. In performing numerical analysis material non-linearity, which is reflected in the non-linear stress-strain curve, is taken into account. Material plasticity is also considered since the specimen is capable of absorbing energy through plastic deformation. One complete cycle that contains the first significant crack is analyzed. Nonlinear inelastic analysis is performed using MSC/Nastran software.

Yield Criterion Yield criterion that is dependent on the hydrostatic pressure is suitable to be used in frictional material such as brick, concrete, rock, and other cement based materials. The yield criterion that belongs to this class is, for instance, *Mohr-Coulomb*, *Drucker-Prager*, and *Mises-Schleicher*. To avoid the complication due to singular yield surface and neglecting the tensile strength of the material the *Drucker-Prager* yield criterion is employed to model the masonry specimen. Two parameters representing cohesion, c, and the internal angle of friction, ϕ, are required to describe the material. A value of ϕ=37°, which is derived from concrete material properties, is assumed to be suitable for masonry material. Masonry yield strength of $(1/3)f'_m=2c$ are considered appropriate[3].

Hardening Rule Three kinds of hardening rules are widely known, i.e., isotropic, kinematic, and their combination. To obtain a realistic description of the confined masonry system the combination hardening rule is employed in this study.

Constitutive Model The most often used constitutive model for normal concrete, i.e., the *Hognestad* model, is written here for reference, Eq. (2), and is used as the base to determine a stress-strain model for masonry.

$$f_c = f_c'\left[\frac{2\varepsilon_c}{\varepsilon_u} - \left(\frac{\varepsilon_c}{\varepsilon_u}\right)^2\right], \qquad 0 \le \varepsilon_c \le \varepsilon_u \tag{2a}$$

$$f_c = f_c'\left[1 - 0.15\frac{(\varepsilon_c - \varepsilon_u)}{(0.0038 - \varepsilon_u)}\right], \; \varepsilon_u < \varepsilon_c \le 0.0038 \tag{2b}$$

where $\varepsilon_u = \dfrac{2f_c'}{E_c}$, f_c is the concrete compressive stress (MPa), f'_c is the concrete compressive ultimate strength (MPa), ε_c is the concrete strain, ε_u is the concrete strain at ultimate strength.

Modulus of elasticity is then determined by using the widely known empirical formula for normal concrete written here for reference, Eq. (3).

$$E_m = 4{,}700\sqrt{f'_m} \;\text{(MPa)} \tag{3}$$

where E_m is the modulus elasticity of masonry (MPa), f'_m is the compressive strength of masonry (MPa).

Eq. (2) and (3) can also be used to model the two side confining columns. Some additional analysis is necessary to take into account the influence of rectangular hoops. A method proposed by Park & Paulay is used in this study[4].

The Result of Numerical Analysis The cycle contains the first significant cracks is further studied numerically for RB and CW specimens under the same displacement history. The yield criterion, hardening rule, and constitutive model are consistently applied to both. The wall panel is divided into 80 three-node-triangular plane elements and the masonry is assumed to be an isotropic-homogenous material. The side confining columns are modeled as line element beam and discretized into 10 elements. In order to obtain the most suitable constitutive model for masonry wall, five variants of the constitutive model are analyzed. These variants that are based on the Hognestad model are designated as modi0 to modi4 shown in Fig. 7 for RB and Fig. 8 for CW. The modification is performed by considering that masonry tends to be more brittle than normal concrete.

The result for RB and CW corresponds to each curve presented in Figs. 7 and 8 are obtained. The resulting load-displacement hysteretic curves are generally in good agreement with those resulting from the test[7]. More over, the curves that are associated with modi2 and modi3 present the best fits[7]. This suggests that the ultimate strain, ε_u, can be taken as the average of the yield strain, ε_y, and the limit strain, ε_l (see Fig. 9). The energy dissipation capacity *(ED/EI)* (Table 1), however, is underestimated for RB compared with the test. On the other hand, it is overestimated for CW (Table 2). This is a consequence of the pinching phenomena that is more appreciable in CW than that of in RB. The ratio of *ED/EI* differ by the average of -20.02% for RB and +7.37% for CW. A reduction factor of 0.9 will remove over estimation of the energy dissipation capacity in CW.

Why CWHR Does Not Perform as Expected?

CWHR specimen is constructed by adding reinforcement in every horizontal mortar joint of CW specimen. Since the reinforcement is hooked and anchored to the two side confining columns therefore capable of reducing their separation, the expectation is that CWHR will perform better than CW specimen. However, this is not the case according to the test in this study. Instead of gaining more strength, the lateral load resistance of the specimen is decreased by approximately 45% compared to that of CW. This fact does not agree with nearly similar test performed by Goto *et al.* (1993), where the reinforcement can increase the resistance by as much as 16–27% [2]. In his specimen, Goto installs the reinforcement in specially provided grooves in the massive brick. These grooves prove to have positive effect as is shown by additional tests in this study.

An isolated test on three specimens is performed (see Fig. 10). The first specimen has no horizontal reinforcement in the mortar joint (NHR), the second one has horizontal reinforcement in the mortar joint but has no groove (HRNG), and the third one is similar to the second but with groove (HRWG). The failure of the HRNG occurs at relatively low load and the crack pattern shows that the effect of stress concentration due to the presence of the reinforcement is very severe. On the other hand, the failure of the HRWG occurs very stably and there is no indication of premature failure due to stress concentration. The failure of the HRWG is very similar to that of NHR. This explains why Goto can obtain better result by inserting horizontal reinforcement in the specially constructed groove by the mortar joint. Numerical analysis performed at particular cycle on grooved CWHR shows an increase of some 4% compared to CW[7].

SOME GUIDANCES TO ANALYZE CONFINED MASONRY WALL

Based on the analysis that has been performed thus far several points can be summarized and can be used as guidance to predict the behavior of confined masonry wall subjected to any load. The important thing is to establish the stress-strain curve for the masonry wall. This can be done as follows (see Fig. 9).

1. The modulus of elasticity can be determined by Eq. (3). This relation agrees well with the test results performed by Paulay and Priestly[5].
2. The masonry yield strength can be taken as 1/3 f'_m[3] and thus the yield strain, ε_y, can be computed.
3. The limit strain ε_l = 0.0025 - 0.003[5] is applicable for masonry as confirmed in this study[7].
4. Ultimate strain, i.e., the strain corresponds to maximum stress f'_m, for masonry can be taken as, $\varepsilon_u = \varepsilon_y + \left(\frac{\varepsilon_l - \varepsilon_y}{2}\right)$.
5. Stress strain curve shall be parabolic at $\varepsilon_y \leq \varepsilon_m \leq \varepsilon_u$, and linearly decreasing one at $\varepsilon_u \leq \varepsilon_m \leq \varepsilon_l$ to end at stress level of 85% f'_m at ε_l.

The above information is applied to analyze RB and CW. The load-deflection curve is shown in Figs. 11 and 12 for RB and CW respectively together with the test result. Aside from the pinching effect in CW, they show good agreement between the numerical analysis and the test. The dissipated energy should be multiplied by a factor of 0.9 for CW.

CONCLUSION

Three confined masonry specimens have been constructed and tested under cyclic loading. Each of the specimens is of clayey red brick of 190 x 95 x 50 (mm^3), designated as RB, hollow concrete block or conblock of 190 x 95 x 50 (mm^3), designated as CW, and conblock with horizontal reinforcement, designated as CWHR. The reinforcement is located at the horizontal mortar joint between conblocks with no groove provided. The specimen shown in Fig. 1 of 870 x 1,330 (mm^2) is subjected to certain displacement history[7]. The resulting load-displacement curves, the stiffness degradation, and the energy dissipation capacity are shown in Figs. 2 to 4, 5, and 6, respectively.

It turns out that the resistance is highest for RB, followed by CW, and CWHR. Three factors are responsible for higher resistance of RB compared to that of CW; i.e., higher tile strength of RB than that of CW, the fact that RB is massive while CW is hollow, and higher unit volume of mortar, that has higher strength than that of RB and CW, involved in RB than that in CW. CWHR specimen has least resistance. This is due to the lack of groove to lay the reinforcement. The groove will eliminate the stress concentration that causes premature failure in the test. Reinforcement groove will improve the over all performance of CWHR to at least slightly better than that of CW. The stiffness degradation is highest for RB, followed by CW, and CWHR. This is consistent with the energy dissipation capacity that is highest for RB, followed by CW, and CWHR, in low cycles.

The cycle that contains the first significant crack is further analyzed numerically. The stress-strain relation is proposed in this study. Together with Drucker-Prager yield criterion and the combination of hardening rule some comparison is made. The calculation shows good fit between test and numerical results as shown in Figs. 11 and 12. The energy dissipation capacity, however, is over estimated for CW. This over estimation can be corrected by multiplying by a factor of 0.9.

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