BEHAVIORS OF FRAMED MASONRY WALLS

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SUMMARY

The structural behaviors of the framed masonry wall subjected to in plane monotonic loading are investigated by a full-scale test and the method of discontinuous deformation analysis (DDA). Three test specimens--a RC frame, a RC frame partially filled with masonry wall, and a RC frame completely filled with masonry wall are studied. The failures of concrete and mortar are considered in the numerical model. Both the tensile failure and shear failure are investigated. The shear failure is assumed to follow the Mohr-Coulomb criterion. The structures are cut into sub-blocks by artificial joints in DDA. The reinforcements are assumed to be perfect bond with concrete, and they are modeled by the bolt elements in DDA. The numerical solutions are compared with experimental results. A satisfactory agreement is obtained.

The experimental results show that the cracks initiate from the tensile stress regions of the RC frame, then the mortar starts to failure, and the framed masonry structure eventually becomes a discontinuous block system. The filled masonry wall affects the behavior of framed masonry structure dominantly. The partially filled masonry wall, as expected, induces a short column effect and leads to a severe failure of column. On the other hand, the completely filled masonry wall increases the stiffness of the structure and the adjacent column fails in the configuration of nearly uniform cracks.

INTRODUCTION

The behaviors of masonry structures had been extensively studied [1-4, 6-10, 12, 14]. The failure of the masonry wall is frequently initiated from the cracking of mortar and separation of bricks. Structure failure induced by cracking and separation usually causes discontinuous and nonlinear behaviors.

The cracking and separation phenomena occurring in the masonry structures cause distinct block elements. The nature and orientation of discrete blocks play an important role in the performance of masonry structures. Recently, El Shabrawi and Verdel [9] applied the distinct element method (DEM) [5] to study the behavior of ancient masonry structures under dynamic loads. The DEM has been proved to be indispensable to many engineers in approaching rock analysis. Because fractured rock masses and masonry buildings are similar in the nature of their materials, the use of the DEM is justified. An alternative method for analyzing the block system is the method of discontinuous deformation analysis (DDA) [13]. DDA is an implicit method, and it possesses some unique features such as complete block kinematics, perfect first-order displacement approximation, strict postulate of equilibrium, and correct energy consumption. These features make DDA a rigorous analysis for discrete blocks.

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The structure behaviors of framed masonry walls subjected to in plane monotonic loading are investigated by a 1full-scale test and DDA in this study. To increase the computational efficiency, the concept of an artificial joint

[11] is adopted to refine DDA in this study. The artificial joints improve the prototype of DDA; however, they are not satisfactory in every way. On the failure analysis of block system, the failure directions of blocks are predetermined provided the failures of blocks are assumed to be along the artificial joints. In the following, the experimental system and fundamentals of the refined DDA are presented first. Then the structural behaviors of framed masonry walls are fully studied by a full-scale test and DDA.

EXPERIMENTAL SYSTEMAND TEST SPECIMENS

A full-scale test is arranged to study the behaviors of framed masonry walls and verify the numerical solutions. The experimental system is shown in Fig. 1. The lateral force is created by the jack, and the magnitudes of force and lateral displacement are measured by the load cell and the clip-on gage, respectively. Three specimens--a RC frame (Fig. 2a), a RC frame partially filled with masonry wall (Fig. 2b), and a RC frame completely filled with masonry wall (Fig. 2c) are studied. The dimension of the specimen is 320 cm $\times$ 300 cm. The cross sections of the beam and column elements are 35 cm $\times$ 40 cm and 30 cm $\times$ 35 cm, respectively. The tension and compression reinforcements for beam and columns are taken to be $4-\#7$ steels. The height of the masonry wall of the partially filled frame is 110 cm, and there is a wooden window in the opening area.

FUNDAMENTALS OF DDA

In the method of discontinuous deformation analysis (DDA) [13], the variables are displacements and the equilibrium equations are solved in the same way as the finite element method does. The blocks in DDA are independent, so connections exist only when the blocks are in contact with one another. DDA incorporates a complete block kinematics that fulfills no interpenetration and no tension between blocks at any time. The interactions between blocks are simulated by contact springs. The Mohr-Coulomb law is used to regulate contact behavior, in which friction loss along contacts is the sole source of energy consumption, without adding any artificial damping. A complete first order polynomial is chosen as the displacement function for a two-dimensional block, and this displacement function restricts the block to constant stress. By minimizing the total potential energy, the equilibrium equations for n blocks [13] are

$$\begin{bmatrix} \mathbf{K}_{11} & \mathbf{K}_{12} & \mathbf{K}_{13} & \cdots & \mathbf{K}_{1n} \\ \mathbf{K}_{21} & \mathbf{K}_{22} & \mathbf{K}_{23} & \cdots & \mathbf{K}_{2n} \\ \mathbf{K}_{31} & \mathbf{K}_{32} & \mathbf{K}_{33} & \cdots & \mathbf{K}_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{K}_{n1} & \mathbf{K}_{n2} & \mathbf{K}_{n3} & \cdots & \mathbf{K}_{nn} \end{bmatrix} \begin{Bmatrix} \mathbf{D}_1 \\ \mathbf{D}_2 \\ \mathbf{D}_3 \\ \vdots \\ \mathbf{D}_n \end{Bmatrix} = \begin{Bmatrix} \mathbf{F}_1 \\ \mathbf{F}_2 \\ \mathbf{F}_3 \\ \vdots \\ \mathbf{F}_n \end{Bmatrix} \tag{1}$$

where [Di]T= $(u_0, v_0, r_0, \varepsilon_x, \varepsilon_y, \gamma_{xy})_i$ is the displacement vector of block i, (u0, v0) are the rigid body translation, r0 is the rigid body rotation, and $(\varepsilon_x, \varepsilon_y, \gamma_{xy})$ are the strain components in a two-dimensional geometry (Fig. 3); Kij is the component of stiffness matrix, Kii depends on the material modulus and inertia effect of block i, Kij $(i \neq j)$ depends on the contacts or bolt connection between block i and block j; and Fi is the force vector of block i. The coefficients for Kij and Fi are written as

$$(K_{rs})_{ij} = \frac{\partial^2 \Pi}{\partial d_{ri} \partial d_{sj}} \qquad r, s = 1, 2, \ldots, 6 \tag{2}$$

$$(F_r)_i = -\frac{\partial \Pi(0)}{\partial d_{ri}} \qquad r = 1, 2, \ldots, 6 \tag{3}$$

where Π is the total potential energy. The potential energy includes the contributions of inertia forces, initial stresses, internal strains, point loading, body forces, contact spring deformations, etc. The inclusion of inertia term makes the global stiffness matrix positively and diagonally dominant, without numerical hazard.

DDA is refined by the concept of artificial joint [11] in this study. Fig. 4 shows two blocks (Blocks i and j) just in contact at time t = 0. In DDA, two half angle-half angle contacts are identified at the start. Contact A is formed by the contact of Vertex 1 of Block i with Vertex 3 of Block j; Contact B is formed by the contact of Vertex 2 of Block i with Vertex 4 of Block j. To model the joint between Blocks i and j, one normal spring and one shear spring are added to Contact A and Contact B. At the end of iteration, if neither the Mohr-Coulomb test nor a test for separation of Contacts A and B reveals failure, the springs will retain operation unchanged at the contacts so that these two blocks are permanently tied together. Therefore, as the stiffness of the springs is increased, these two blocks behave more and more like a continuous body; very strong springs will force the

sides of the block in contact with each other to displace compatibility. The characteristic of contact springs initiates the concept of artificial joints. However, on the failure analysis of structure, if the structure failure is assumed to be along the boundaries of prescribed artificial joints, the artificial joints become incipient with the finite strength of the block material

MODELING OF FRAMED MASONRY WALLS

Mortar is usually the weak plane of the masonry structure and crack is frequently initiated from there. The cracking of the mortar and separation of the bricks usually cause discontinuous and nonlinear behavior. The failure modes of mortar are classified into two types—tensile failure and shear failure. The mixed mode failure of mortar is neglected in this study. The characteristic of the tensile failure is similar to the condition of no tension between blocks in DDA, while the shear failure is similar to the friction behavior between blocks. The masonry walls are cut into sub-blocks by the artificial joints, which become incipient with finite strength of mortar. The bricks are simulated by the sub-blocks and these sub-blocks are connected with one another by contact springs. The stiffness of the contact springs is proportional to the strength of mortar and has dimension of force per length. The strength of mortar is represented by its resultant forces, which are determined by the effective length times either the tensile strength or the shear strength of the mortar.

The analysis of reinforced concrete structures is similar to that of masonry structures. The concrete structures are cut into sub-blocks by artificial joints. The artificial joints become incipient with finite strength of concrete. Both the tensile failure and shear failure of concrete blocks are investigated. The shear failure of concrete is assumed to follow the Mohr-Coulomb criterion. The reinforcements are assumed to be perfect bond with concrete, and they are modeled by the bolt elements in DDA. The stress-strain relation of the reinforcement is assumed to be bi-linear, and the plastic modulus of the reinforcement is chosen to be $E_p = 0.02E_s$, where Es is the elastic modulus of the reinforcement.

RESULTS AND DISCUSSION

The monotonic loading is adopted in this study. The wooden window in the partially filled masonry wall is neglected in the numerical model. The RC frame is cut into 498 triangular concrete sub-blocks, the tension and compression reinforcements are modeled as 114 bolts, and the stirrups are modeled as 54 bolts. Since the specimens are over-reinforced, the effect of the space of stirrups on the behavior of RC frame is not significant. For simplicity, the stirrups modeled by the bolts are thus arranged in equal space. The input material properties are the same as those of experimental specimens, which are determined by test. The elastic modulus of steel is

$E_s = 1.96 \times 10^7$ N/cm2, and yield stress $f_{sy} = 3.74 \times 10^4$ N/cm2. The compressive strength of the concrete is $f_c^{'} = 26.66$ MPa, and the elastic modulus $E_c = 4696\sqrt{f_c^{'}} = 2.4247 \times 10^6$ N/cm2. The tensile strength of the concrete is $f_t^{'} = 271$ N/cm2. The cohesion is chosen to be 280 N/cm2. The elastic modulus of the brick is $E_b = 2.087 \times 10^6$ N/cm2. The tensile strength of the interface mortar is 98 N/cm2, and its shear strength is

$$\tau_f = 3.64 + 0.75\sigma_n \text{ (Kg/cm2)} \qquad (4)$$

The stiffness of contact springs is chosen to be $k_n = k_s = 1.96 \times 10^7$ N/mm.

Fig. 5 illustrates the failure behavior of the RC frame after yielding of the structure. Referring to Fig. 5, it is observed that the failure regions of the experimental specimen concentrate on the top and bottom of the columns, the left and right ends of the beam, and the joints of the column and the beam. As expected, most of the failures of columns and beam are flexural failure, while there will be mixed failures at the joints of column and beam. It is found that there are a lot of inclined cracks at the joints of test specimen. The load-deflection relation of the RC frame is presented in Fig. 6. It is found that the numerical solutions agree satisfactorily with the experimental results.

Similar studies were made for the framed masonry wall. Fig. 7 shows the failure of this framed wall after yielding of the structure. During experiment, it is observed that the failures concentrate on the RC frame, while there is no obvious crack found in the masonry wall. A lot of horizontal cracks are found to concentrate on the center region of the left column around the left upper corner of the wall. Numerous cracks are also found in the top and bottom of the left column. The failure of the right column is found to be similar to that of the pure RC frame, while there are some cracks in the upper side of the beam. The reason for the different failure configuration of the left column is that the partially filled masonry wall induces the short column effect on the left column. Thus the failure of the left column concentrates on the contact area of the column and the wall. The load-deflection relation of the RC frame partially filled with the masonry wall is presented in Fig. 8. It is found that the DDA solutions agree well with the experimental results. However, since the wooden window is neglected in the numerical model, the defections predicted by DDA are larger than the experimental results.

The failure of the RC frame completely filled with masonry wall after yielding of structure is shown in Fig. 9. Referring to Fig. 9, it is found that the failures occurred in the columns, the left joint, and the masonry wall. There is no observable crack in the beam except at the left joint of beam and column. The left column carries most of the load, and there are a lot of horizontal cracks in the left column. Fig. 10 shows the load-deflection relation of the RC frame completely filled with masonry wall. It is found that the DDA solutions agree with the experimental results, but the predicted displacements are smaller. When the load is greater than 550 KN, the floor beam of the test specimen is found to be totally broken. Thus the load-deflection relation for load greater than 550 KN is not presented in Fig. 10

CONCLUSIONS

The structural behaviors of the framed masonry wall subjected to in plane monotonic loading are investigated by a full-scale test and the method of discontinuous deformation analysis (DDA). The concept of artificial joints is adopted to refine DDA. The framed masonry walls are cut into sub-blocks by the artificial joints. Each brick is simulated by a block, while the reinforced concrete frame is cut into triangular concrete sub-blocks and the reinforcements are modeled by the bolts. The reinforcements and concrete are assumed to be in perfect bond. On the failure analysis, both the tensile failure and the shear failure of mortar and concrete are considered, but the mixed mode failure is neglected. The shear failure is assumed to follow the Mohr-Coulomb failure criterion.

The experimental results show that the cracks initiate from the tensile stress regions of the RC frame, then the mortar starts to failure, and the framed masonry structure eventually becomes a discontinuous block system. The numerical model is verified by comparing the numerical solutions with the experimental results. A satisfactory agreement is obtained. The characteristic of the masonry structure is highly influenced by the failure of mortar. The failure of mortar induces discontinuous and nonlinear behavior of the masonry structures. In addition, the filled masonry wall affects the behavior of the framed masonry structure dominantly. The partially filled masonry wall induces a short column effect and leads to a severe failure of the column. On the other hand, the completely filled masonry wall increases the stiffness of the structure and the adjacent column fails in the configuration of nearly uniform cracks.

ACKNOWLEDGEMENTS

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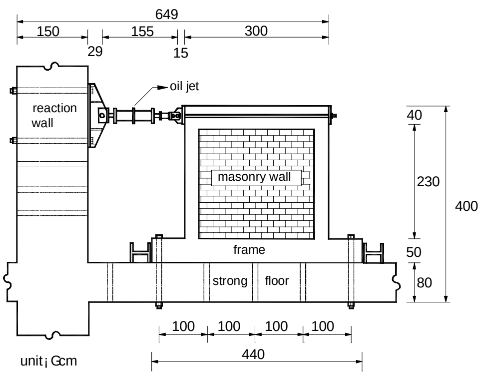

Fig. 1 The experimental system

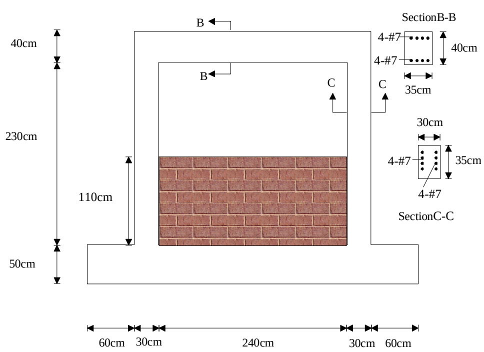

Fig. 2b RC frame partially filled with masonry wall

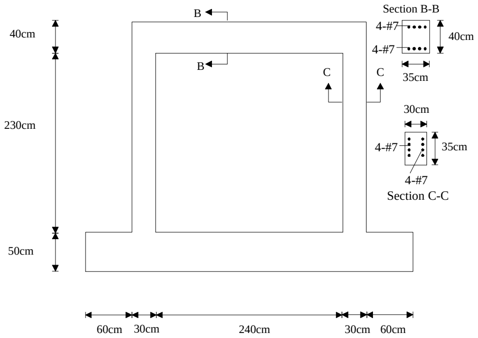

Fig. 2a RC frame

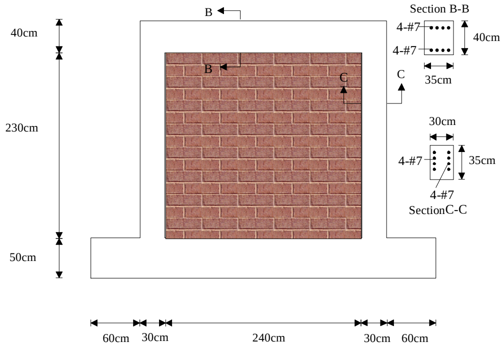

Fig. 2c RC frame completely filled with masonry wall

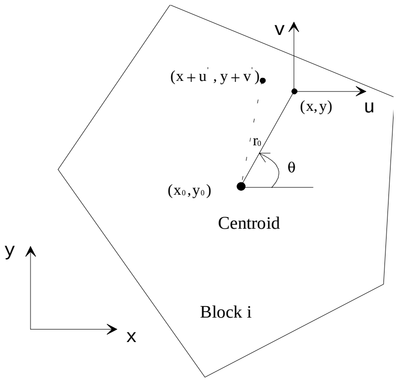

Fig. 3 Schematic configuration of a block

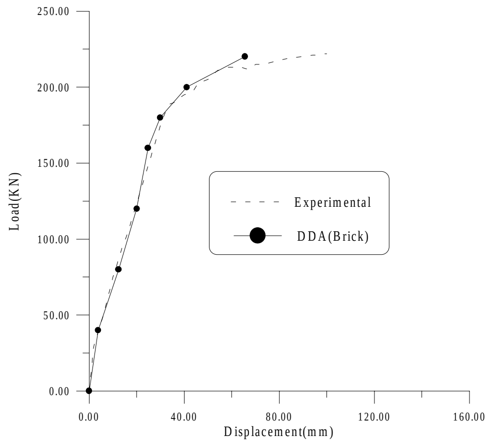

Fig. 6 Comparison of DDA solutions with experimental results: Load-deflection relation of a RC frame

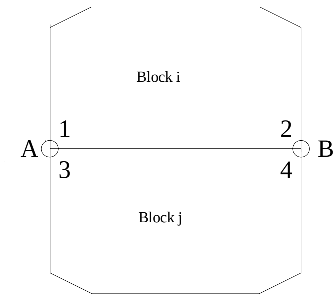

Fig. 4 Two blocks just in contact at time t = 0

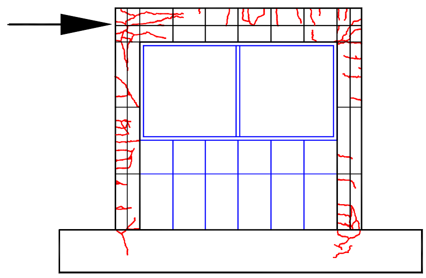

Fig. 7 Failure configuration of RC frame partially filled with masonry wall (Experimental result

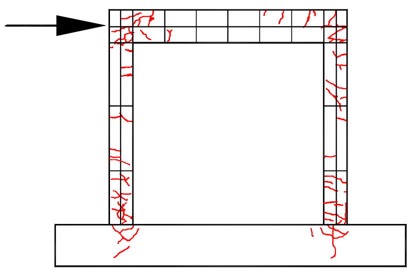

Fig. 5 Failure configuration of RC frame (Experimental result)

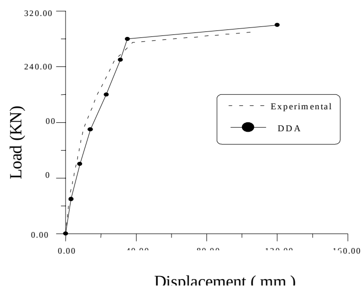

Fig. 8 Comparison of DDA solutions with experimental results: Load-deflection relation of a RC frame partially filled with masonry wall

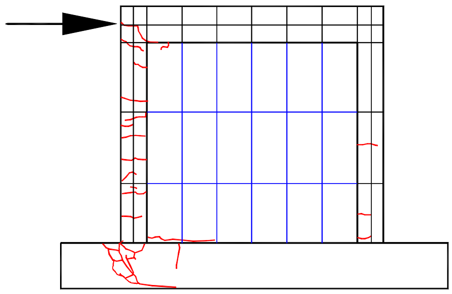

Fig. 9 Failure configuration of RC frame completely filled with masonry wall (Experimental result)

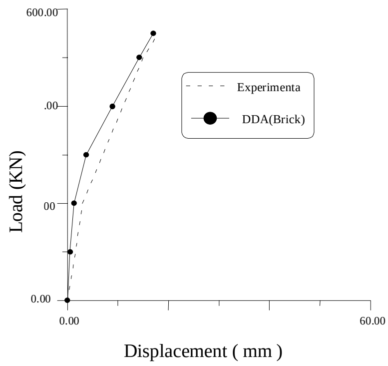

Fig.10 Comparison of DDA solutions with experimental results: Load-deflection relationof a RC frame completely filled with masonry wall