STUDY ON SHEAR RESISTANT MECHANISM OF RC MEMBER SUBJECTED TO CYCLIC LOAD

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1. INTRODUCTION

It is known that when a RC member is subjected to cyclic load, shear failure sometimes occurs after flexural yielding, although shear strength is larger than flexural strength in initial stage. The reason has been explained by the deterioration of shear strength with development of deformation, as shown in Fig. 1. However, the degradation mechanism of shear strength is still not clarified. Therefore, in this study, the process of shear strength degradation of a RC column under cyclic load is simulated by 3D rigid-body-spring-model (RBSM) analysis, and the shear resistant mechanisms are discussed by the change of beam and arch actions.

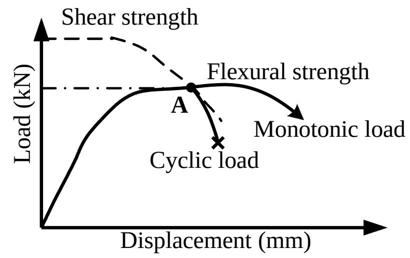

Fig. 1 Shear failure after flexural yielding

2. SHEAR STRENGTH DEGRADATION BEHIVOUR UNDER CYCLIC LOAD BY 3D RBSM ANALYSIS

In 3D RBSM analysis, concrete is modeled by an assemblage of rigid particles interconnected by springs along their boundary surfaces. A random geometry of rigid particles is generated by Voronoi diagram. The applicability of RBSM to ultimate behavior of RC member and the material models, can be confirmed in the research by Yamamoto et al. (2008). Based on the reference of Ohta et al. (1979), the objective RC column was made as shown in Fig. 2. The column showed shear failure after yielding. Fig. 3 shows the analytical model. The average element size is 30 mm. All reinforcements are modeled by beam elements. The model parameters are set by the same values of test results. In the analysis, displacement of loading plate is controlled and cyclic load with incremental yielding displacement of δy (10 mm) is applied. The load-displacement relationships of analysis and test are compared in Fig. 4. It is notable that the load carrying capacities and failure points agree with each other.

In order to find the reason of shear strength degradation, it is significant to obtain the shear strength before point A in Fig. 1, which is larger than flexural strength and difficult to investigate by test. Nakamura et al. (2015) obtained the shear strength degradation by special technique, in which larger flexural strength than shear strength under cyclic load is provided by changing the yield stress of longitudinal rebar. For example, by changing yielding stress from 370 to 900 N/mm^2 after each cyclic loops and applying monotonic load, the curves of shear strengths are obtained, as shown in Fig. 5. It is considered the peak of about 100 kN is the shear strength under monotonic load. Under cyclic load, from –δy to +2δy, by changing yield stress and applying monotonic load, the shear strength after 1 cycle of cyclic load (called 1 loop) is obtained, which decreases to about 90 kN. Then the shear strengths after 2, 3, 4 and 5 cycles of cyclic load (called 2~5 loop) are calculated, and the degradation of shear strength is obtained.

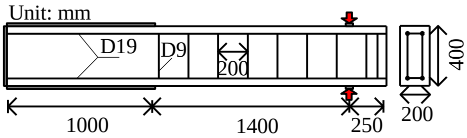

Fig. 2 Dimension of specimen

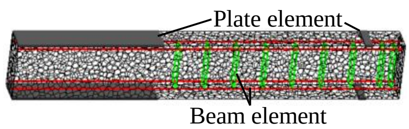

Fig. 3 Analytical model

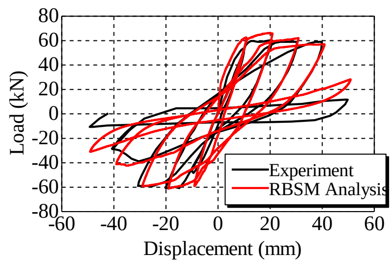

Fig. 4 Load-displacement relationship

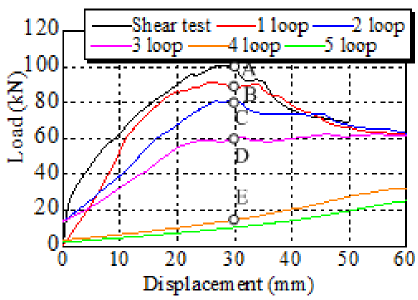

Fig. 5 Shear strength degradation

3. SEPARATION METHOD OF BEAM AND ARCH ACTIONS

Based on the reference of Ichinose et al. (1988), for any column cross section, the balance of moment can be expressed by Eq. (1), as shown in Fig. 6-(a).

$$M=(T+C_s)\cdot j_s/2+C_c\cdot j_c \qquad (1)$$

Where, M is acting moment, T and C_s are tension and compression forces of longitudinal rebar; C_c is compression force of concrete on cross section; j_s is distance between tension and compression longitudinal rebar; j_c is distance between compression center of concrete and column axis.

If differentiating Eq. (1) at a small interval of dx between two adjacent sections, the Eq. (2)~(4) are derived to separate the beam and arch actions. V_t and V_a are the shear forces resisted by beam and arch actions. The force conditions of beam and arch actions can be referred in Fig. 6-(b) and (c). Beam action is defined by the variations of rebar forces and concrete compression, while arch action is caused by the variation of compression center of concrete between two adjacent

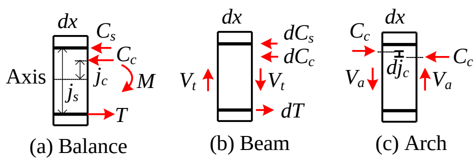

Fig. 6 Concept of beam and arch actions

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sections. Besides, based on the truss theory, the truss action V_s provided by stirrups can be calculated by Eq. (5).

$$V=dM/dx=V_t+V_a \quad (2) \qquad V_t=(dT/dx+dC_s/dx)\cdot j_s/2+dC_c/dx\cdot j_c \quad (3)$$

$$V_a=C_c\cdot dj_c/dx \quad (4) \qquad V_s=A_w\sigma_w jd/s \quad (5)$$

Where A_w is cross section area enclosed by one stirrup; σ_w is stress of stirrup; j_d is arm length (j=1/1.15, d: effective height of column); s is the pitch between two adjacent stirrups.

The representative compression distributions of cross sections (shear test of monotonic loading, δ=30 mm) are shown in Fig. 7. The distance dx of any segment between two adjacent sections is 100 mm. It is observed that the compression center of concrete gets lower from load side to support side. By Eq. (3) and (4), the beam and arch actions can be calculated in each segment. But since the stress concentration produces near the loading and support plates, the average beam and arch actions of the middle 10 segments of 1000 mm long will be used for mechanism evaluation and the change of shear forces of beam and arch actions are shown in Fig. 8. It is noted that the sum of beam and arch actions agrees with load-displacement curve. Considering the shear force equaling to vertical load, the obtained beam and arch actions are reliable.

4. CONTRIBUTIONS OF BEAM AND ARCH ACTIONS TO SHEAR RESISTANCE

The beam, arch and truss actions of the six cases in Fig. 5 are plotted in Fig. 9, respectively. Since the truss action is one part of beam action, by subtracting truss action from beam action, the beam action provided by concrete (called *Vc*) is also obtained. It is noted that until to 3 loop, after shear cracks occur, the beam action keeps similar level of 50 kN, because the contributions of truss action and beam action of concrete also keep the similar values. On the other hand, the arch action does not produce with increase of loops. From this observation, it is understood that the decrease of maximum value of arch action is the main reason of shear strength degradation. As shown in Fig. 10 (A~E corresponds to point A~E in Fig. 5), with the development of diagonal cracks from 1 loop to 3 loop, the diagonal principal compression stress flow disappears gradually and this leads to the deterioration of arch action. From 4 loop, the maximum value of beam action reduces sharply and then the column fails. Considering the truss actions of all loops show same level of 20 kN because of the yielding of stirrups, it is understood that the sharp deterioration of beam action from 4 loop is mainly caused by the decrease of *Vc* action. And as shown in the Fig. 10-(E), at 4 loop the deformation and width of cracks develop significantly, so that the concrete loses its strength.

5. CONCLUSIONS

It is summarized that for the RC column under cyclic load, shear resistant mechanisms of beam and arch actions can be separated by using the local stress distribution obtained by RBSM. Under cyclic load, it is found that the deterioration of arch action is dominated to the shear strength degradation initially. Then after losing arch action, due to the strength loss of concrete (*Vc*), beam action decreases rapidly so that the column fails.

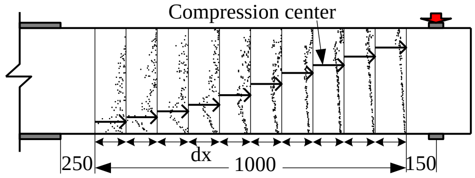

Fig. 7 Concrete compression distributions

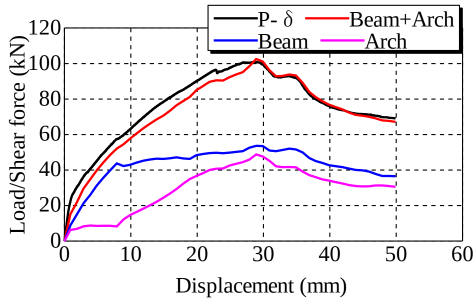

Fig. 8 Beam and arch actions (shear test)

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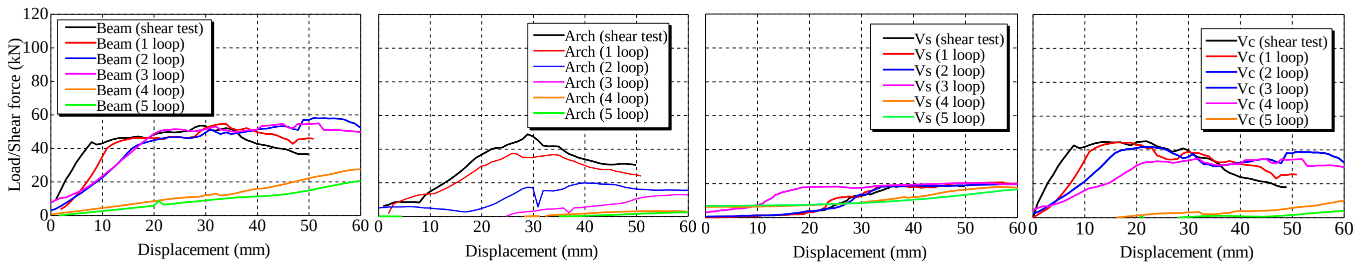
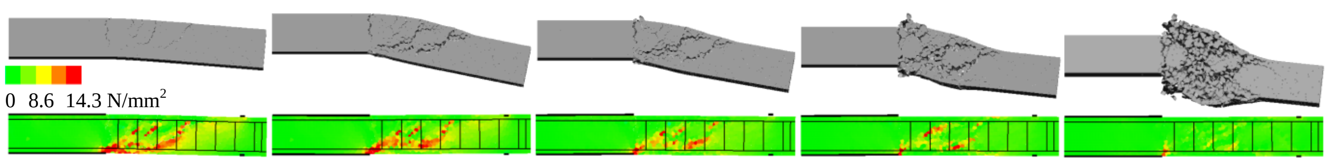


(a) Beam action (b) Arch action (c) Truss action *Vs* (d) Beam-Truss *Vc*

Fig. 9 Comparison of shear resistant mechanisms



(A) Shear test (B) 1 loop (C) 2 loop (D) 3 loop (E) 4 loop

Fig. 10 Deformations and principal stress distributions (δ=30mm)