- Technical Paper -

NUMERICAL INVESTIGATION OF EFFECT OF THROUGH CRACK ON SHEAR STRENGTH DEGRADATION OF RC COLUMN

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ABSTRACT

When a RC member is subjected to cyclic loading, shear failure often occurs after flexural yielding because of shear strength degradation. The effect of through crack on shear strength degradation was numerically evaluated by assuming that through cracks, caused by residual deformation of tension rebar after yielding, probably lead to shear strength degradation. As a result, by generating through cracks at around the height of column effective depth, the knowledge that shear strength degraded remarkably with increase of crack width was acquired.

Keywords: RC column, cyclic loading, through crack, shear strength degradation

1. INTRODUCTION

It is well-known that a flexural yield type RC member subjected to monotonic loading usually suffers flexural failure and shows good deformation performance. Under cyclic loading, however, its load carrying capacity often suddenly decreases within a relatively small displacement ductility after flexural yielding of tension reinforcing bars and subsequently shear failure occurs (called as shear failure after flexural yielding in this research).

As shown in Fig. 1, the reason of shear failure after flexural yielding has been conceptually explained as that shear strength degrades gradually with the increase of displacement level and ultimately becomes smaller than the shear demand for the flexural strength, which leads to the decrease of load carrying capacity. Corresponding to this failure mode, many empirical shear strength degradation curves have been proposed based on extensive cyclic loading test results [1, 2], and they have been proved to be useful in current deformation based seismic design to judge the occurrence of shear failure after flexural yielding [3].

Because the evaluation and understanding of shear strength degradation behavior is important, the authors have simulated the shear failure of a flexural yield type RC column subjected to cyclic loading, and quantitatively evaluated the shear strength degradation behavior with increasing displacement ductility numerically [4]. However, the primary reason of shear strength degradation of RC member subjected to cyclic loading is still not clear.

This study tried to find the reason of shear strength degradation under cyclic loading. A different behavior between monotonic and cyclic loading is the generation of flexural through cracks at column cross section due to residual deformation of longitudinal reinforcing bars after yielding under cyclic loading, that is, flexural crack propagates from one side then connected by another flexural crack propagates from opposite side under loading from opposite side. Considering this difference, we assumed that the initiation of through cracks in cyclic loading is a primary reason of shear strength degradation. Based on this assumption, a numerical method to evaluate shear strength of RC member with an initial through crack, generated by yielding of longitudinal reinforcing bars was presented, and additionally the effects of through cracks on shear strength degradation was investigated.

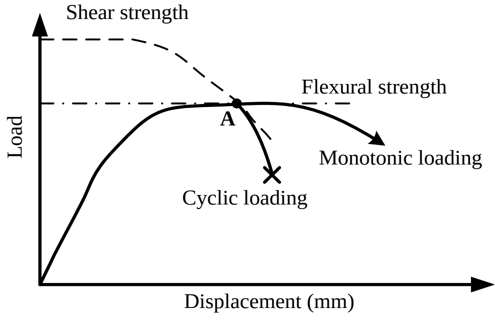

Fig.1 Reason of shear failure after flexural yielding

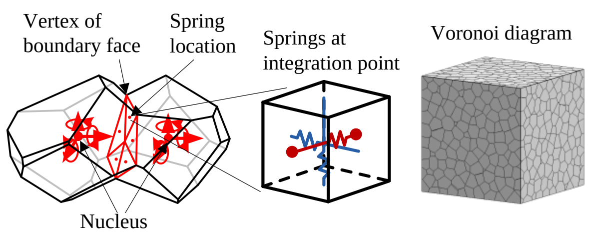

Fig. 2 3-D RBSM

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2. EVALUATION METHOD OF SHEAR STRENGTH DEGRADATION OF FLEXURAL YIELD TYPE RC MEMBER

This chapter first introduced the numerical evaluation method of shear strength of a flexural yield type RC member and afterwards discussed the evaluation method of shear strength degradation of a flexural yield type RC column subjected to cyclic loading and one-side repeated loading by three dimensional Rigid-Body-Spring-Method (3-D RBSM).

2.1 Introduction of 3-D RBSM Numerical Method

The authors have developed the 3-D RBSM in order to quantitatively evaluate the mechanical responses including softening and localization fractures, and have shown that the model can well simulate the cracking and failure behaviors of RC members [4]. In RBSM, concrete is modeled as an assemblage of rigid particles interconnected by springs at their boundary surfaces (Fig. 2). The crack development is affected by mesh design as cracks initiate and propagate through interface boundaries of particles. Therefore, a random geometry of rigid particles is generated by Voronoi tessellation, which can reduce mesh bias on the initiation and propagation of potential cracks.

Moreover, reinforcing bar is modeled as a series of regular beam elements (Fig. 3) that can simulate the bending effects. In this model, the reinforcement can be freely positioned within the member, regardless of the mesh design of concrete. The reinforcement is attached to the concrete particles by zero-size link elements, which provides a load-transfer mechanism between a concrete particle and a beam node. The details of 3-D RBSM and the constitutive models can be referred to the previous work by Yamamoto [5].

2.2 Numerical Evaluation Method of Shear Strength of Flexural Yield Type RC Member

Fig. 4 illustrates the image of numerical evaluation method of shear strength of flexural yield type RC member. When a flexural yield designed RC member, in which the shear strength (V_u) is required to be larger than the shear demand for flexural strength (P_u), is subjected to monotonic loading, it can maintain the load carrying capacity of flexural strength until a relatively large displacement ductility. Hence the shear strength cannot be investigated by load test directly. But based on the knowledge that flexural strength can be increased by increasing yield stress of tension reinforcing bar without influence on shear strength according to the evaluation formulae proposed by JSCE specification [3], in numerical analysis, the shear strength of a RC member can be investigated by monotonic loading analysis, in which, the original flexural strength (P_u) is enhanced to a larger level (P_u') than shear strength by the way enhancing yield stress of tension reinforcing bar (f_y) to an extreme large value.

As shown in Fig. 4, from the ultimate deformation comparison before and after enhancing yield stress (f_y) of a sample RC column, it was confirmed that after enhancing yield stress (f_y), the original flexural failure with a large bending deformation transferred to the shear failure mode with a large inclined shear deformation.

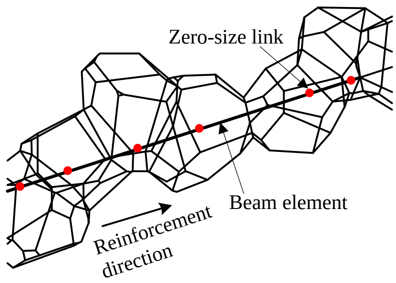


Fig. 3 Reinforcing bar model

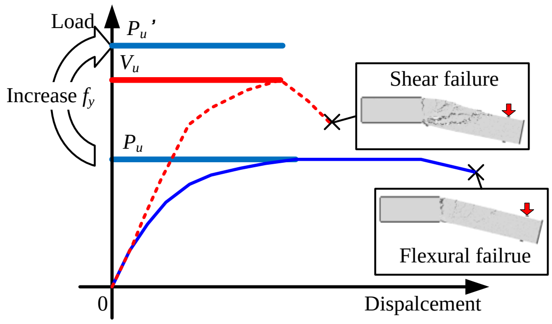
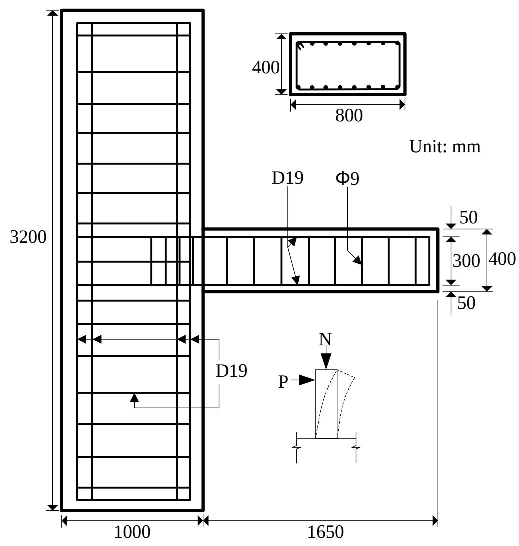
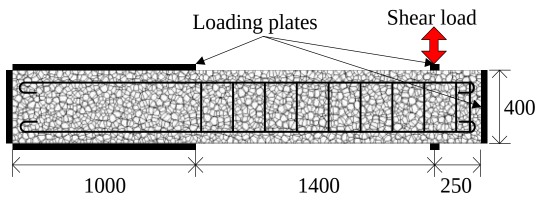


Fig. 4 Evaluation method of shear strength of flexural yield type RC member



(a) Specimen outline



(b) Numerical model

Fig. 5 Specimen outline and numerical model

2.3 Evaluation Method of Shear Strength Degradation due to Cyclic Loading

Following the basic introduction of numerical evaluation method of shear strength of flexural yield type RC member, in this section the evaluation method of shear strength degradation due to cyclic loading of a RC column, proposed by Nakamura [4], is discussed.

The objective RC column for 3-D RBSM simulation was the cyclic loading tested by Ohta [6], and it has been confirmed that the analysis was able to simulate the deformation behavior until the failure stage accurately [4]. As shown in Fig. 5-(a), the RC column was 1650mm in height with a cross section of 800mm×400mm (effective depth was 350mm) and the shear span-to-depth ratio was 4.0. The yield strengths of longitudinal reinforcing bars (D19 type) and stirrups (Φ9 type, arranged with the space of 200mm) were 365.5MPa and 372.2MPa, respectively, and the compression strength of concrete was 28.6MPa.

Regarding the numerical model, in order to reduce computing time, the one-quarter model by 3-D RBSM (cross section: 200mm×400mm) was constructed (Fig. 5-(b)) with the average element size of 30mm and the reinforcing bars were modeled by beam and zero-link elements discretely.

Afterwards, the proposed numerical method for the evaluation of degraded shear strengths after load cycles would be explained and the image is shown in Fig. 6. The black curve represents the cyclic load hysteresis of the RC column, and it was known that the load carrying capacity reflects the level of flexural strength. As mentioned before, the initial shear strength of the RC column was able to be investigated by monotonic loading (dotted red curve) with an initial large yield stress of tension reinforcing bar (f_y=900MPa). As for the evaluation of shear strength degradation in 3-D RBSM analysis, for example, the degraded shear strength after first load cycle can be investigated by the way that enhance yield stress of tension reinforcing bar (f_y=900MPa) after unloading (point A) of the first load cycle, in which, regular yield stress (f_y=365.5MPa) was used; then impose monotonic loading (dotted blue curve) to the failure stage. The peak load from monotonic loading was regarded as the degraded shear strength after first load cycle.

Fig. 7 shows the load-displacement relations in first quadrant to determine the shear strengths after each load cycle (displacement in each load cycle was increased stepwise by yield deformation of δ_y, which was around 10mm), combined with the load-displacement relations of monotonic loading (f_y=365.5MPa) and the envelope curve of cyclic loading (f_y=365.5MPa). With the increased in load cycles, the obvious decreased in shear strength was observed and after fourth load cycle, the shear strength was decreased to a much smaller level than the flexural strength, which led to the occurrence of shear failure. The shear failure after fourth load cycle could also be confirmed in the envelope curve of cyclic loading analysis.

Moreover, the load-displacement relations to determine the shear strengths after each cycle of one-side repeated loading (displacement in each load cycle was increased stepwise by yield deformation) is shown in Fig. 8. It was noted that the shear strength also degraded with the increase of load cycle. However, compared with cyclic loading, the degradation rate was much lower and after fifth load cycle, the degraded

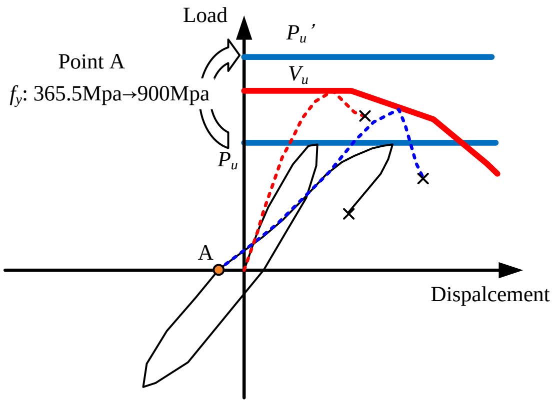


Fig. 6 Evaluation method of shear strength degradation due to cyclic loading

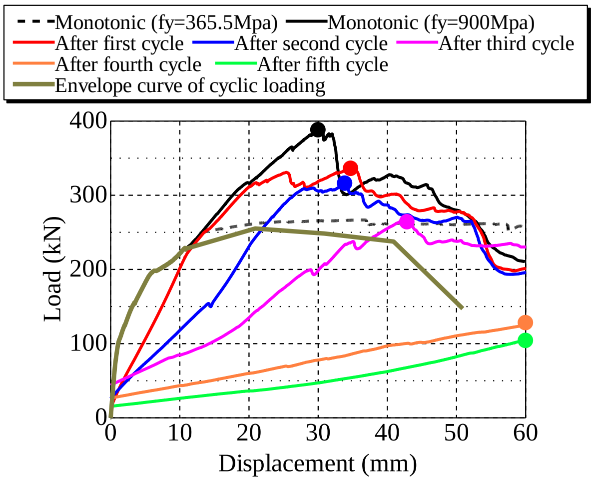


Fig. 7 Load-displacement relations for evaluation of degraded shear strengths after each load cycle of cyclic loading

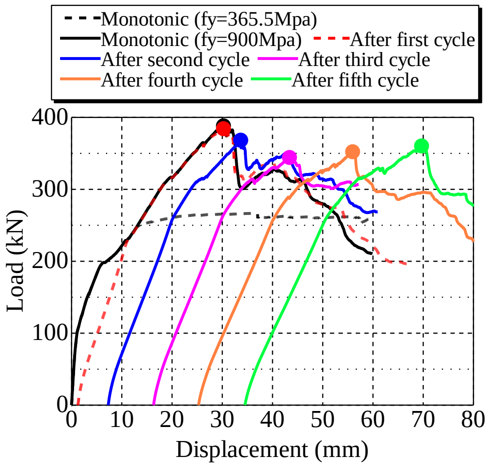


Fig. 8 Load-displacement relations for evaluation of degraded shear strengths after each load cycle of one-side repeated loading

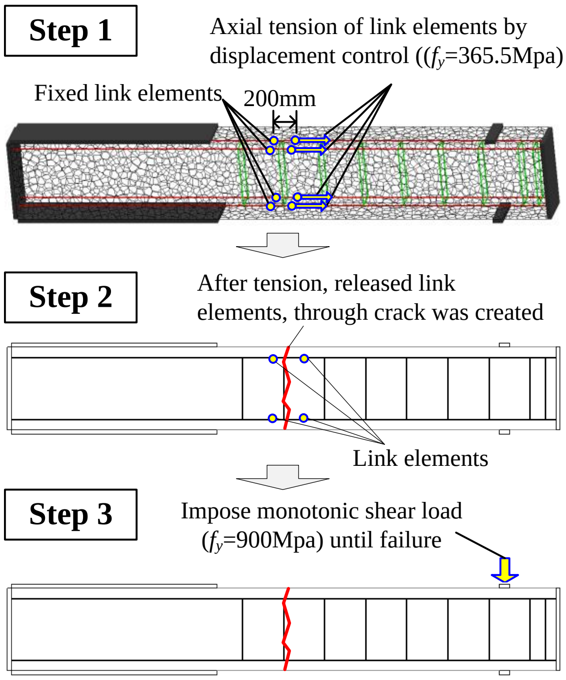


Fig. 9 Evaluation method of shear strength after creating initial through crack

shear strength was still larger than the flexural strength, therefore shear failure did not occur in one-side repeated loading, which has been confirmed in test result.

Based on the proposed numerical method and the corresponding results, it was clarified that the different shear strength degradation behaviors between cyclic loading and one-side repeated loading could be quantitatively evaluated by 3-D RBSM.

3. EFFECT OF THROUGH CRACK ON SHEAR STRENGTH DEGRADATION

It has been mentioned that the different behavior of RC member between monotonic and cyclic loadings are the generation of through cracks. In this chapter, the authors developed a numerical method to generate initial through cracks at arbitrary column cross sections and then investigated the effect of through crack on shear strength degradation.

3.1 Evaluation Method of Effect of Through Crack on Shear Strength Degradation

As shown in Fig. 9, the initial through crack at arbitrary column cross section could be generated by the way in step 1, in which, four link elements of longitudinal reinforcing bar in a cross section at footing side were fixed and another four link elements in another cross section at load side were tensioned by displacement control. By this method, the position of through crack could be limited to the range between the two sections (200mm in this study), where link elements located and the through crack width could be controlled by tension displacement. Then in step 2, after the generation of through crack at the target cross section, the tensioned and fixed link elements were released (unloading), and the crack width would remain due to the plastic behavior of longitudinal reinforcing bars. Finally in step 3, referring to the method in chapter 2.3, after enhancing the yield stress of longitudinal rebar to 900MPa, monotonic loading analysis was conducted and the peak load was regarded as the shear strength affected by through crack.

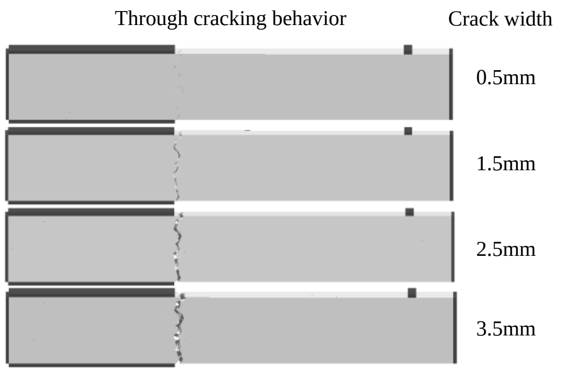


Fig. 10 Through cracks by tension of link elements (case 1)

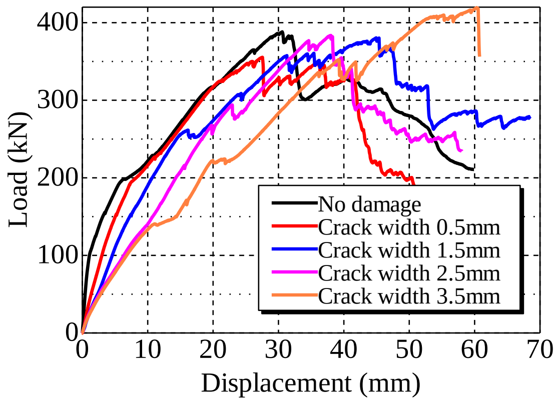


Fig. 11 Shear load-displacement relations (case 1)

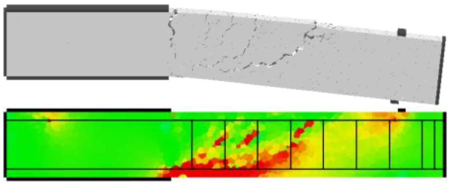
3.2 Investigation of Shear Strength Degradation due to Through Cracks at Different Positions

In order to determine the effect of through crack on shear strength, the authors generated through cracks at three different column cross sections, which were the sections at column base, the height of column effective depth and the mid-height of column, respectively. Moreover, in each case, four levels of residual crack widths (0.5, 1.5, 2.5, 3.5mm) were considered. The residual displacements of tensioned link elements were identified as the initial through crack width.

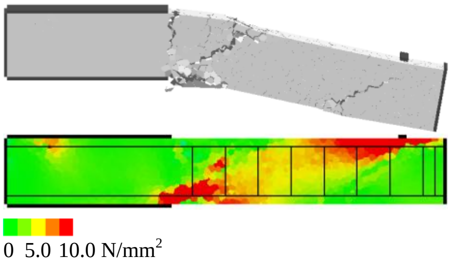
(1) Case 1: through crack at column base section

The numerical results of case 1, in which, through crack located at column base section, were discussed first. The through cracking conditions for each initial crack (deformations were magnified by ten times) are illustrated in Fig. 10, and it was observed that the through cracks were successfully generated by the way described in Fig. 9.

After the generation of through crack with different width, the monotonic loadings (yield stress of longitudinal reinforcing bar was 900Mpa) were



(a) Original case without through cracking



(b) Through crack width of 3.5mm (case 1)

Fig. 12 Comparison of deformation behaviors and principal stress distributions in column central section

imposed and the shear load-displacement relations are plotted in Fig. 11. It was noted that with the increase of crack width, although the stiffness of RC column was decreased gradually, the peak load was almost not reduced, which means that the through cracking at column base section has little effect on shear strength.

Furthermore, the deformation behaviors and principal stress distributions (positive stress represents compression) at peak loads of original case without through crack and the case 1 with through crack width of 3.5mm are compared in Fig. 12. Compared with the original case, although a large through crack was generated, the principal stress distribution at peak load at uncracked zone also shared the same intensity, which was an arch shape, thereby the RC column was able to maintain its shear capacity.

(2) Case 2: through crack at height of column effective depth

By the same approach, the monotonic loading analyses for evaluation of shear strengths of the cases with through cracks at the height of column effective depth (about 350mm distant from column base) were conducted and the shear load-displacement relations are shown in Fig. 13. It was noted that if the through crack width was larger than 1.5mm, the shear strength was obviously reduced with the increased through crack width, and the shear strength was reduced around 25% and became the similar level to flexural strength when the through crack width reached 2.5mm.

In order to find out the reason of shear strength degradation due to through crack, the deformation behaviors and principal stress distributions of case 2 with through crack width of 3.5mm is shown in Fig. 14. At the displacement of 12.0mm (point a in Fig. 13), aside from the initial through crack, flexural crack at column base section was observed (Fig. 14-(a)) and the principal stress at this time localized at the compression side of column base area, which was a typical bending behavior. Then at the displacement of 23.0mm (point b in Fig. 13), small inclined shear cracks initiated at the position of initial through crack and the principal stress along shear cracks were observed (Fig. 14-(b)). After that, the shear deformation became dominant and at the displacement of 34.0mm (point c in Fig. 13), it was seen that the shear deformation developed rapidly at the position of initial through crack and the number of shear cracks increased (Fig. 14-(c)). At this stage,

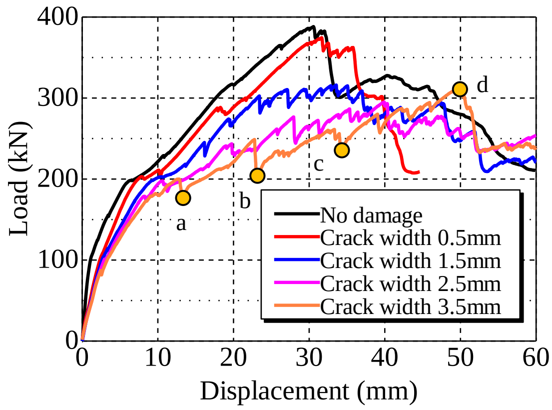
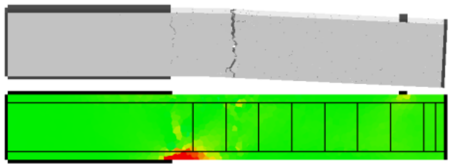
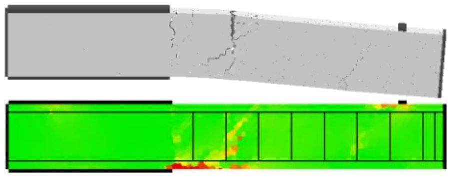


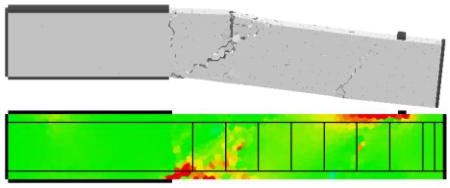
Fig. 13 Shear load-displacement relations (case 2)



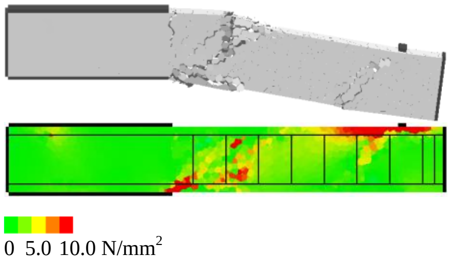
(a) Displacement of 12.0mm



(b) Displacement of 23.0mm



(c) Displacement of 34.0mm



(d) Displacement of 50.0mm (peak load)

Fig. 14 Deformation behaviors and principal stress distributions in column central section (Crack width of 3.5mm of case 2) because of the development of shear deformation, the obvious localization of principal stress along shear cracks were confirmed. Finally, at the displacement of 50.0mm (deformation at peak load, point d in Fig. 13) the shear deformation further developed, which led to the following shear failure (Fig. 14-(d)). The corresponding principal stress still localized along shear cracks and compared with that of original case (Fig. 12-(a)), it was noted that the arch stress at uncracked zone almost disappeared completely, which was considered as the reason of rapid shear strength degradation.

(3) Case 3: through crack at mid-height of column

The monotonic loading analyses for evaluation of shear strengths of the cases with through cracks at mid-height of column (about 700mm distant from column base and was twice of column effective depth) were carried out and the shear load-displacement relations are shown in Fig. 15. Similar to the result of case 2, with the increase of through crack width, the shear strength obviously decreased. And when the through crack width reached 2.5mm, the shear strength was reduced around 27% compared with that of the original strength.

From the deformation behavior and principal stress distribution at peak load of case 3 with through crack width of 3.5mm (Fig. 16), it was observed that different from original case and case 2, the position of shear deformation which led to shear failure moved right to the initial through crack location and was far away from column base section. In addition, compared with the original case (Fig. 12-(a)), the arch shape principal stress intensity at uncracked zone was decreased significantly but a relatively large principal stress flow was observed distributed along the inclined shear cracks. Therefore, it was confirmed that the through crack at mid-height of column could also cause a significant degradation of shear strength.

3. CONCLUSIONS

(1) Based on the numerical results for the evaluation of effect of through crack, which was considered as the typical deformation of RC member subjected to cyclic loading, on shear strength degradation, it was found that the through cracking at column base section almost has no effect on shear strength.

(2) The through crack which was generated at the height of column effective depth (about 350mm distant from column base section) could cause significant shear strength degradation, and with the increase of through crack width, the degradation rate increased. When the through crack width was 2.5mm, the shear strength was reduced around 25% and became the similar level to the flexural strength. As the reason of degradation, it was found that the arch shape principal stress at uncracked zone, which could be found in original case, almost disappeared.

(3) If through crack was generated at the mid-height of column (700mm distant from column base section), which was twice of the height of column effective depth, the shear strength also significantly degraded with increased through crack width. Similar to that of case 2, when through crack width reached 2.5mm, the shear strength was reduced around 27%, which was a similar level to the flexural strength.

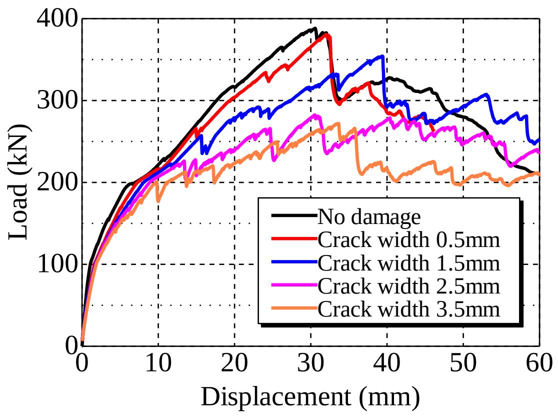


Fig. 15 Shear load-displacement relations (case 3)

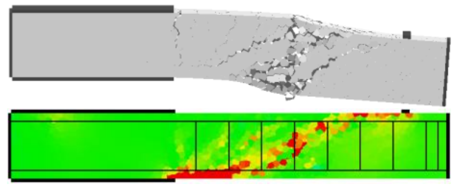


Fig. 16 Deformation behavior and principal stress distribution in column central section
(Peak load, crack width of 3.5mm of case 3)

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