- Technical Paper -

INFLUENCE OF SECTIONAL PRE-CRACK ON SHEAR STREGNTH OF RC BEAMS

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ABSTRACT
In order to investigate the influence of crack through section, which often generates under cyclic loading, on shear behavior and strength of RC beam, a RC beam with a 1.0 mm pre-crack in a section (the effective depth away from loading point) was tested. It was found that the pre-crack led to a significant degradation of shear strength by comparing with the non-cracked beam. Moreover, the production of sectional pre-crack and its influence on shear strength were simulated by 3-D RBSM analysis. At last, the different shear cracking behavior and strength between the pre-cracked and non-cracked beams were clarified.
Keywords: shear strength, RC beam, sectional pre-crack, 3-D RBSM, Z-shape crack

1. INTRODUCTION

An obvious different behavior of RC structure under cyclic loading from that under monotonic loading is that flexural cracks will propagate from two sides of reversed loading and form flexural sectional cracks running through the entire cross section. The authors have numerically investigated the influence of induced sectional crack (pre-crack for short) in a RC column, and showed that the pre-crack in the section around the effective depth away from footing will lead to a significant degradation of shear strength. This degradation of shear strength might be the primary reason why a cyclic-loaded RC structure will suffer shear failure after flexure yielding with remarkable shear behavior, although it is designed in flexure [1]. However, the influence of pre-crack on shear strength has not yet sufficiently verified by experiments.

Pimanmas et al. [2] induced sectional pre-cracks, as one of the most common initial defects in RC structures during their service life, for RC beams (shear span to effective depth ratio *a*/*d* is 2.42) in shear by four point reversed flexural loading and then investigated the influence of pre-cracks, the widths of which varied from 0.02 to 3.0 mm, on the shear behavior and strength by test method. The width, position in shear span (nearly uniformed distributed) and number of pre-cracks (3 to 4) were not controlled in the test. The test showed that shear strength of RC beam increased due to the influence of sectional pre-cracks, which is converse to our numerical result [1].

Therefore, in this study, we proposed a test method for inducing an accurate 1.0 mm pre-crack, for simulation of a sectional crack, in a RC beam and investigated its influence on shear strength by comparing with non-cracked beam. Moreover, the production of pre-crack and its influence on shear behavior and strength were simulated by three dimensional rigid-body-spring-model (3-D RBSM for short) analysis. At last, the reason why sectional pre-crack led to a degradation of shear strength was explained by the difference of crack propagation behaviors between non-cracked and pre-cracked beams.

2. TEST SETUP

2.1 Specimen and Material Properties

One non-cracked RC short beam (No. A), as reference case, and one pre-cracked beam (No. B) were tested. The two beams are designed in shear failure and have same dimension and material property, as referred in Table 1 and Fig. 1. The shear span to effective depth ratio is 2.35. The tension reinforcement ratio is 3.36% and the compressive strength of concrete is 34.1 MPa. Both beams were shear reinforced in one shear span to

Table 1 Tested RC beams

Specimen No.	a/d	Tension rebar (D29)			Compressive strength of concrete f_c (MPa)	Width of pre-crack w (mm)	Design shear cracking load V_c (kN)	Design shear strength V_u (kN)
		ρ_t (%)	f_y (MPa)	E_s (GPa)				
A	2.35	3.36	358	182	34.1	-	125	168
B						1.0		

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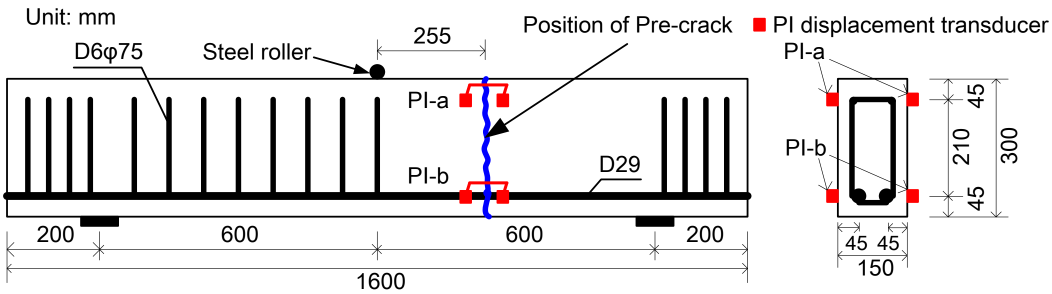


Fig. 1 Designed RC beam specimens

ensure a shear failure in the target span (right span in Fig. 1). According to the researches by Niwa et al. [3, 4], for non-cracked beam, the shear cracking load V_c was predicted to be 125 kN, and the shear strength V_u was calculated to be 168 kN and it was the lowest limitation because the width of loading plate, on which the load was applied through a steel roller, was neglected. Therefore, the actual shear strength should be greater than the prediction.

2.2 Method for Inducing Pre-crack

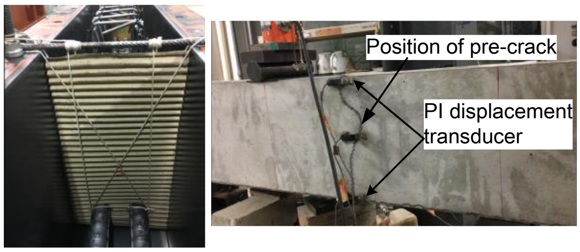
In the pre-cracked beam, a 1.0 mm sectional pre-crack was introduced in the section the effective depth (255 mm) away from the loading point, because it was considered that the sectional cracks caused by cyclic load ordinarily can be observed nearby this section. A pre-crack was produced by a relatively soft wave-shaped cardboard (obtained from the inlayers of common carton box) with an approximate thickness of 1.0 mm, which was set inside the framework at the target section before concrete casting (Fig. 2). Cotton thread was utilized to fix the cardboard, with the purpose of prevention of movement of the cardboard when casting (Fig. 2(a)), and the cardboard was remained there in the entire experimental process. In the process of shear loading, not only the shear load and the vertical displacements of loading point and support points were measured but also the opening and closure behaviors of the pre-crack were recorded by PI displacement transducers, which were set along the pre-crack on the compression (PI-a) and tension (PI-b) sides (Fig. 1 and Fig. 2(b)), respectively.

3. TEST RESULT

3.1 Load-displacement Relation and Failure Mode

The test load-displacement relations of the two beams are displayed by solid curves in Fig. 3, and the test shear cracking load V_{cr} and shear strength V_{ur} are listed in Table 2. It was notable that the initial stiffness of the pre-cracked beam significantly decreased compared with the non-cracked beam one, which was attributed to the closure behavior of pre-crack.

The test shear cracking load of non-cracked beam (A3, 136 kN) was slightly greater than the prediction (125 kN, Table 1), and the test shear strength could reach 234 kN (A5), which was 39% higher than the calculation, as expected (168 kN, Table 1). Ultimately the shear compression failure occurred nearby the loading point with a severe spalling of



(a) Cardboard setting (b) Pre-crack by cardboard

Fig. 2 Production of initial through crack

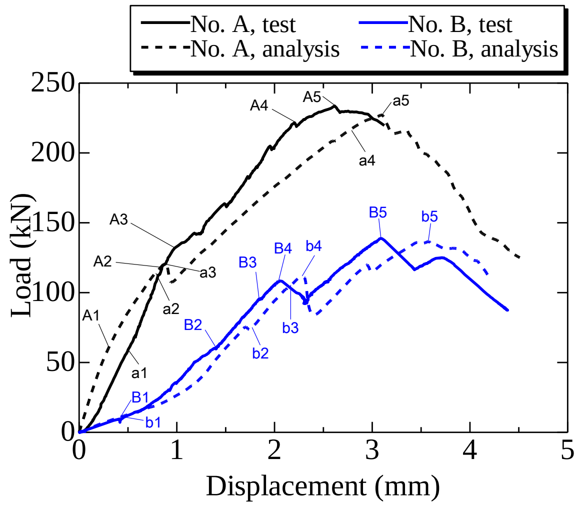


Fig. 3 Load-displacement relation

Table 2 Critical shear loads

Specimen No.	Width of pre-crack w (mm)	Tested V_{cr} (kN)	Numerical V_{cr} (kN)	Tested V_{ur} (kN)	Numerical V_{ur} (kN)
A	0.0	136 (A3)	131 (a3)	234 (A5)	227 (a5)
B	1.0	108 (B4)	111 (b4)	139 (B5)	137 (b5)

concrete (Fig. 4(a)).

On the other side, the test shear cracking load of pre-cracked beam was 21% lower than the non-cracked beam one. It was worthy note that after shear cracking the load of pre-cracked beam was not able to increase as much as the non-cracked beam one, and its shear strength (B5, 139 kN) significantly reduced by 41% compared with the former one. Therefore, it became clear that a 1.0 mm pre-crack in the section effective depth away from the loading point would lead to a significant reduction of shear strength. As the failure mode, it was observed that the critical shear crack in pre-cracked beam crossed the pre-crack and displayed a similar pattern to that of the non-cracked beam, and ultimately the compression failure occurred at loading point. However, as different cracking behavior from the non-cracked beam, one flat diagonal crack near beam top surface and one horizontal crack along tension reinforcing bar were observed. Both the cracks initiated through the section of pre-crack (Fig. 4(b)), and will be further discussed in chapter 5.

3.2 Pre-crack Opening and Closure Behaviors

The crack opening and closure behaviors of the pre-crack recorded by PI displacement transducers are displayed in Fig. 5, combined with the load-displacement relation, and the solid curves are test result. Herein, the average measurement of PI-a or PI-b on front and back surfaces are utilized, and the negative width means closure process.

In terms of closure behavior by PI-a at compression side, it was noted that the pre-crack closed gradually with a constant rate from the start of loading to the stage of D1, where the displacement was 1.12 mm. Afterwards, the closure rate began reduce rapidly and the closure behavior completely stopped from the stage of D2 (displacement was 2.08 mm), where the critical shear crack occurred, because after the stage of D2, instead of flexural behavior shear behavior became dominant. In addition, it was considered that the closure width at stage of D1, where the closure rate began reduce, roughly reflected the pre-crack width (1.22 mm), which reached our target 1.0 mm.

In terms of opening behavior by PI-b at tension side, it was seen that the pre-crack opened with a nearly constant rate until the occurrence of critical shear crack at the stage of D2, and afterwards since the change in behavior from flexure to shear, the opening rate decreased a lot.

Through the above opening and closure behaviors of pre-crack, it became clear that the method for inducing pre-crack was probably practical and effective. In particular, the target pre-crack width was achieved.

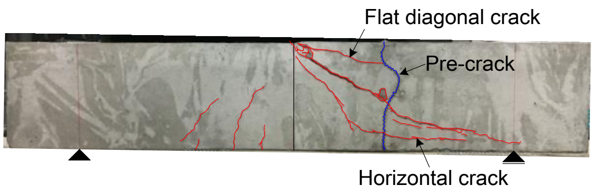
4. NUMERICAL ANALYSIS

4.1 Numerical Method

In chapter 3, the influence of a 1.0 mm pre-crack on shear cracking load and shear strength of RC short beam has been explained by test method. In order to further demonstrate the applicability and effectiveness of the test method for inducing pre-crack, we have attempted to utilize numerical analysis to simulate a pre-crack with a same width and confirmed its influence on shear behavior.

The method for inducing sectional pre-crack in a RC column with 3-D RBSM has been proposed by Fu et al. [1] and was applied in this study. In 3-D RBSM, concrete is modeled as an assemblage of rigid particles interconnected by springs at their boundary surfaces (Fig. 6). Since the crack propagation is affected by mesh design, a random geometry of rigid particles is generated by Voronoi tessellation, which can reduce mesh bias on the development of potential crack.

(a) Specimen No. A



(b) Specimen No. B

Fig. 4 Crack patterns after failure

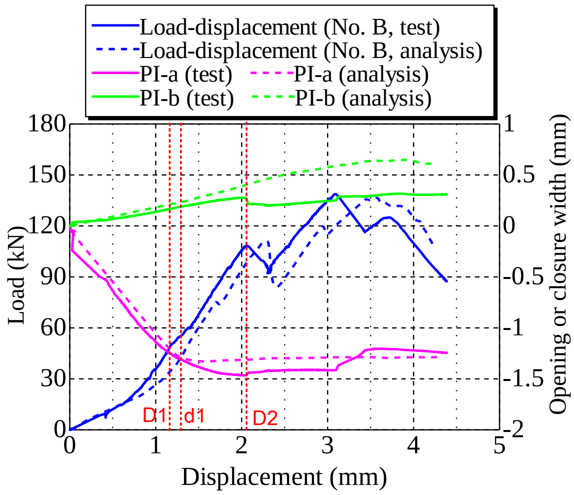


Fig. 5 Result of PI displacement transducer

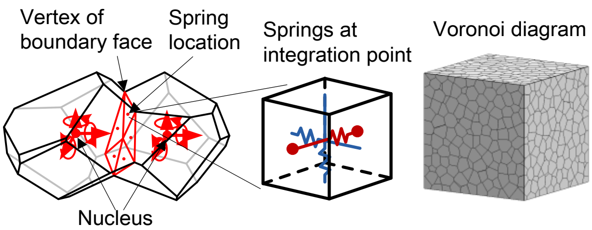


Fig. 6 3-D RBSM

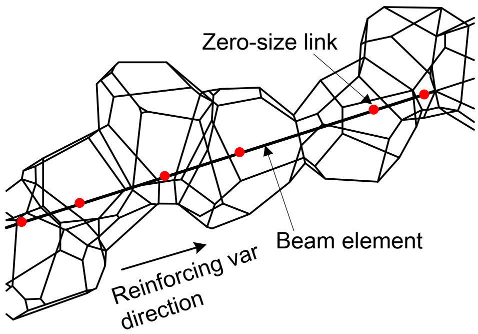


Fig. 7 Model of reinforcing bar

In terms of reinforcing bar model, it is modeled by a series of regular beam elements (Fig. 7), which can simulate bending effect. In this model, the beam elements are freely arranged in the member, without consideration of mesh design of concrete elements.

Moreover, beam elements are attached to concrete elements by zero-size link elements, which provide a load-transfer mechanism between concrete particle and beam element. The parameters and constitutive models applied in 3-D RBSM can be referred in the research by Yamamoto et al. [5]. The numerical model of the test RC beams can be seen in Fig. 8, and the same material properties of concrete and reinforcing bar as test ones shown in Table 1 were utilized.

4.2 Numerical Method for Inducing Pre-crack

The numerical approach for inducing a 1.0 mm pre-crack in RC beam will be explained by the steps shown in Fig. 8. Above all, a pre-crack at the target beam cross section was induced by the way in step 1, in which, four link elements of longitudinal reinforcing bar in same section 100 mm away from the pre-crack section were fixed while another four link elements in same section at the other side of the pre-crack were tensioned by displacement control. The position of the pre-crack was limited between the two sections where the link elements located in, and the pre-crack width were accurately controlled by the tension displacement. Then in step 2, if the pre-crack with desired width was achieved at the target section, the previously tensioned and fixed link elements were unloaded soon and became completely free in movement. However, the pre-crack remained due to the plastic behavior of longitudinal reinforcing bars. At last, in step 3, the force-bearing effect of compressive reinforcing bars, which were merely for inducing pre-crack, were vanished, because we did not arrange compressive reinforcing bars in the target shear span in actual test. Afterwards, the shear loading was applied as ordinary shear load analysis by displacement control and simultaneously the load sustained by tension rebar elastically developed without plastic behaviorIn the process of shear loading, the opening and closure behaviors of the pre-crack was calculated by the relative displacements of link elements which were in the same measuring points of the PI displacement transducers (see step 3 in Fig. 8).

4.3 Comparison of Numerical and Test Result

The numerical load-displacement relations of the two beams are plotted in previous Fig. 3 by dotted curves, and the critical shear loads are listed in previous Table 2. It was evident that the numerical result overall captured the behaviors of the two beams including the shear cracking load (a3, b4) and the shear strength (a5, b5), with a small difference less than 5% compared with the test result. And it was notable that the significant reduction of initial stiffness of the pre-cracked beam was well simulated.

Furthermore, the opening and closure behaviors of the pre-crack obtained from the relative displacements of link elements are plotted in Fig. 5 by dotted curves. Obviously, the numerical result agreed well with the test curves, particularly the closure behavior, which almost overlaid the test curve.

In terms of closure process, a same behavior was seen that the pre-crack closed with a constant rate from

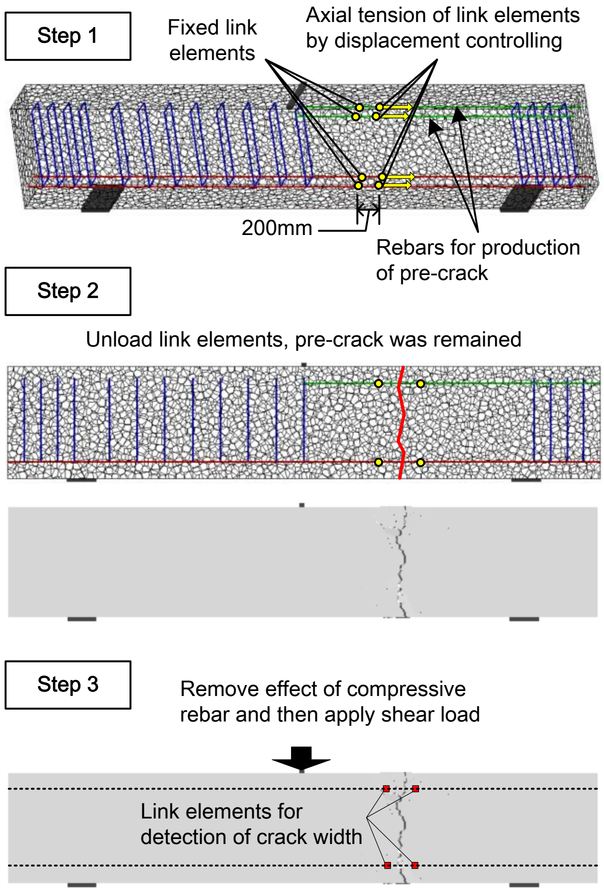


Fig. 8 Numerical method for production of pre-crack

the start of loading until the stage of d1 where the displacement was 1.21 mm, and the corresponding closure width was 1.24 mm, which was regarded as the pre-crack width in analysis. From the stage of d1, the closure rate suddenly deceased to nearly zero, which indicated that the pre-crack completely closed and the shear behavior became dominant.

In terms of opening process, the analysis well captured the behavior of constant increasing of width before the occurrence of critical shear crack. After shear cracking, the opening rate began decrease like in test, but was relatively higher than the test result.

Therefore, through the above comparison of test and numerical results, it was demonstrated that the inducing methods of pre-crack in test and analysis are probably applicable and they are of great significance when it needs to investigate sectional pre-crack with specific position and accurate width on the behavior of a RC beam or column. The failure modes and crack propagations in analysis will be further discussed, combined with the test result, in chapter 5.

5. EVALUATION OF SHEAR BEHAVIOR

5.1 Shear Behavior of Non-cracked Beam

In this chapter, in order to find out the reason why the pre-cracked beam could not fully develop a shear load capacity as great as the non-cracked beam one, the deformation behaviors of the two beams will

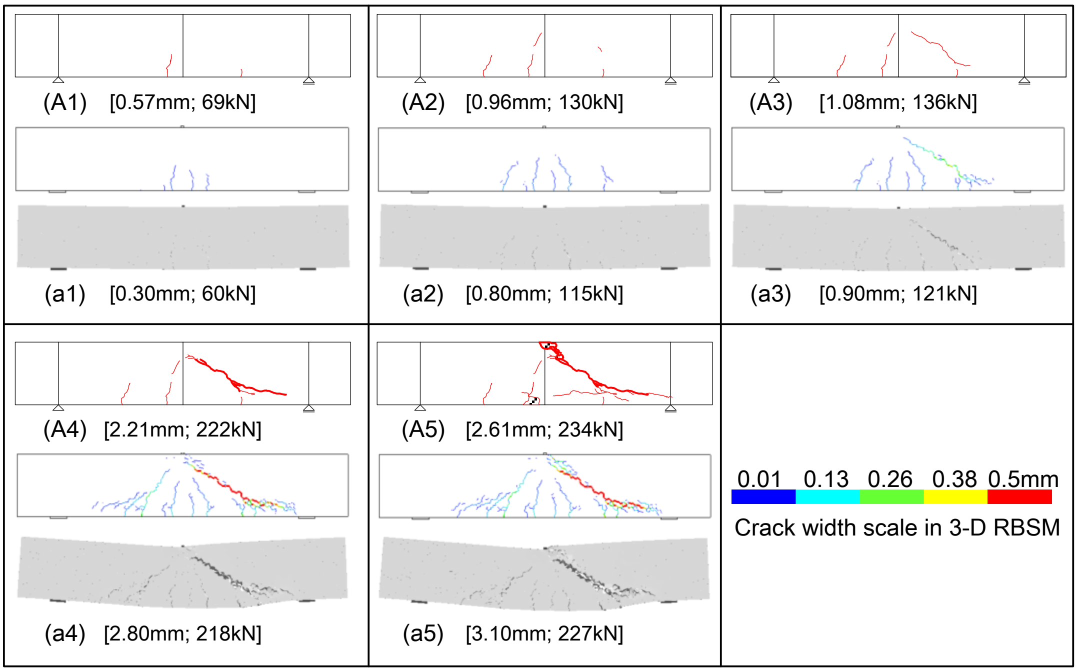


Fig. 9 Behavior of crack propagation (specimen No. A)

be described and their difference will be discussed.

Fig. 9 displays the test crack behaviors and the corresponding numerical crack patterns and deformations of the non-cracked beam at five critical points which are marked in Fig. 3. The scale of numerical crack patterns varies from 0.01 to 0.5 mm, and the numerical deformation was magnified by 15 times. At first, the flexural cracking point was focused (A1, a1), and it was observed that when the shear load was around 69 kN, the visible flexural cracks formed from bottom surface under the loading point in test, and they were well simulated by 3-D RBSM.

Subsequently, in both the test and analysis, the previous flexural cracks propagated upward towards the loading point and simultaneously new flexural cracks initiated in shear span, with the increase of displacement (see points A2 and a2).

Then at the displacement of 1.08 mm (A3), the critical shear crack began appear as the extension of one of the former flexural cracks, and this was confirmed in analysis at the displacement of 0.90 mm.

Afterwards, the shear behavior became dominant and it was observed that the former critical shear crack propagated towards the loading point and the support, with an increase of crack width, in both test (A4) and analysis (a4).

Finally, as mentioned in chapter 3, the critical shear crack further propagated to loading point and caused compression failure of concrete, as seen in test and numerical results (A5, a5). It was evident that the deformation behavior of the non-cracked beam was overall well simulated by 3-D RBSM.

5.2 Shear Behavior of Pre-crack Beam

In the same way, the test and numerical behaviors of crack propagation of the pre-cracked beam at five critical points shown in Fig. 3 will be described by using Fig. 10. The scale of numerical crack patterns and the magnification of numerical deformation are kept same as Fig. 9.

Soon after loading, in test observation, quite different from the non-cracked beam, instead of flexural crack a horizontal crack initiated through the section of pre-crack and propagated towards the support point along the tension reinforcing bar (B1). However, at this displacement stage, the horizontal crack could not be exactly confirmed in numerical result (b1), except for several minor vertical cracks close to the pre-crack which were caused by the tension of longitudinal reinforcing bar when producing pre-crack, and these minor cracks were not our target.

With the increase of displacement, a diagonal crack initiated at web zone and connected with the pre-crack, and meanwhile the formation of flexural cracks were observed (B2). On the analysis side, at a later stage (b2), not only the former horizontal crack was observed but also an flat diagonal crack close to the top surface of beam initiated through the section of the pre-crack. In addition, two minor flexural cracks like in test observation were seen as well.

Then just before the occurrence of critical shear crack (B3), a flat diagonal crack near beam top surface similar to that seen in analysis (b2) emerged in test (B3). It should be recognized that the horizontal crack appeared in B1 and the flat diagonal crack merged in B3 and the pre-crack formed a typical Z-shape crack (image shown in Fig. 10), which has been reported by Pimanmas [2], and this Z-shape crack was well reproduced by analysis (b3). Certainly, the Z-shape crack could not be seen in the non-cracked beam.

Soon later, the critical shear crack initiated at the stage of B4 in test. It crossed the pre-crack and exhibited a similar pattern to that of the non-cracked beam. The position of critical shear crack was well

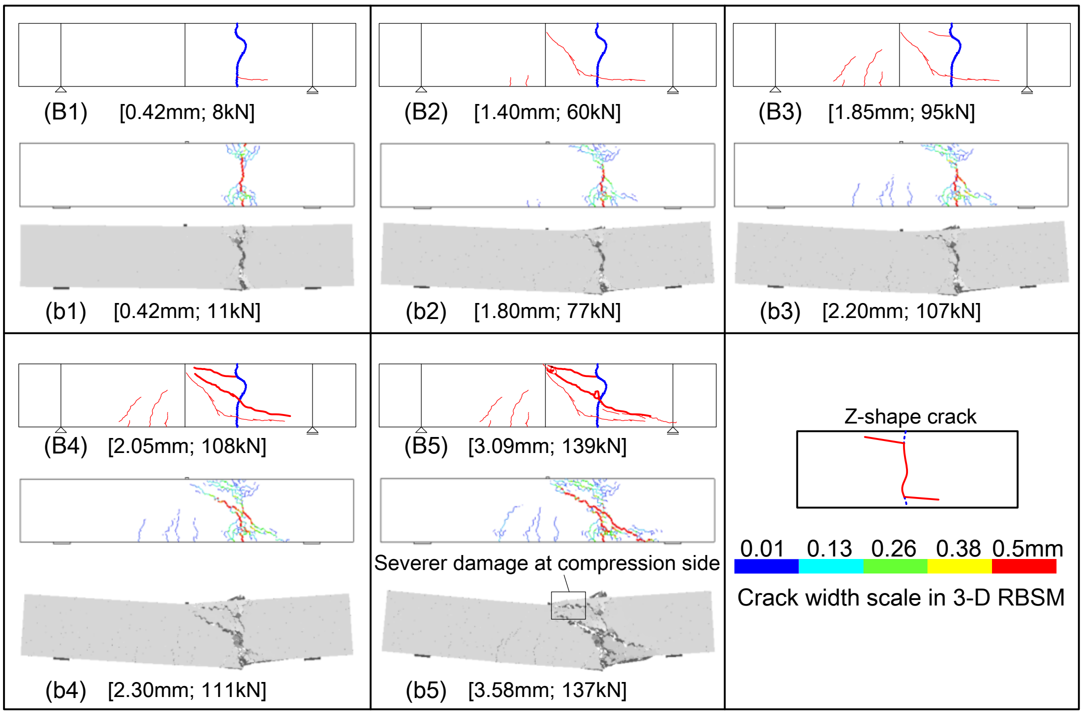


Fig. 10 Behavior of crack propagation (specimen No. B)

reproduced in analysis, but at a later stage (b4).

Ultimately, the critical shear crack severely developed and the concrete near loading point suffered compression failure (B5, b5). Herein, it should be emphasized that the single pre-crack in this study led to a significant degradation of shear strength and did not obstruct the formation of critical shear crack, which is incompatible to the findings pointed out by Pimanmas [2], where pre-cracks obstruct critical shear cracking and subsequently lead to increase of shear strength of RC beam. As a reason of lower shear strength, it was evident that in pre-cracked beam the concrete close to loading point was more easily to shear deform under compression than that of the non-cracked beam (see (b5) in Fig. 10 and (a5) in Fig. 9). And this severer damage at compression side was probably attributed to the contribution of the flat diagonal crack close to beam top surface, which was a component of Z-shape crack.

6. CONCLUSIONS

(1) A test method by utilizing cardboard for inducing a 1.0 mm pre-crack in a cross section, which was the effective depth away from loading point, of RC beam was attempted, and its effectiveness and applicability were clarified by the measurement of opening and closure behaviors of the pre-crack under shear loading.

(2) Shear loading test was conducted for the non-cracked and pre-cracked beams and it was found that the 1.0 mm pre-crack can lead to a significant degradation of shear strength compared with the non-cracked beam one.

(3) The shear loading tests for the non-cracked and pre-cracked beams were well simulated by 3-D RBSM analysis. The similar results to test of degradation rate of shear strength and the opening and closure behaviors of pre-crack were achieved.

(4) Based on the comparison of crack propagation behaviors between non-cracked and pre-cracked beams, it was concluded that the Z-shape crack resulting from the influence of pre-crack reduced the resistance of concrete near loading point so that the pre-cracked beam suffered easier shear compression failure with a much lower strength.

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