ORIGINAL ARTICLE

Behavior and failure mode of reinforced concrete members damaged by pre-cracking

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Abstract

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Behavior and failure mode of reinforced concrete members damaged by pre-cracking

Songklanakarin J. Sci. Technol., 2007, 29(4) : 1039-1048

The effect of pre-cracking on the behavior and failure mode of reinforced concrete beams damaged by pre-cracking is experimentally studied in this paper. The control beam was designed to fail in ductile flexural yielding under four-point bending and in brittle shear under three-point bending. The effect of pre-cracking is studied under both four-point bending and three point bending. In the former, pre-cracks are inclined with respect to the beam axis and the shear span is short, hence the external load is resisted by diagonal compression strut. In the latter, pre-cracks are orthogonal to the beam axis and the shear span is moderately long, hence the external force is transferred through concrete tensile strength, i.e., shear in moderately slender beam. The tests under these two load conditions therefore cover the effect of pre-cracking on concrete under compression and tension where the mode of load resistance is different. It is shown that when the shear span is short, pre-crack reduces the shear crushing capacity due to the reduction in effective contact area and compressive strength deterioration due to micro-fracturing damages. The presence of pre-cracks can change the failure mode from ductile flexure to brittle shear. On the other hand, when the shear span is longer, pre-crack elevates the shear capacity through crack arrest mechanism. In both cases, the pre-cracking is demonstrated to be structurally significant and should be properly taken into account when analyzing existing members.

Key words : pre-crack, load history, crack arrest, shear crushing capacity, failure mode

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Received, 10 July 2006 Accepted, 8 January 2007

บทคัดย่อ

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พฤติกรรมและรูปแบบการวิบัติขององค์อาคารคอนกรีตเสริมเหล็กที่ได้รับความเสียหายจากรอยร้าวล่วงหน้า

ว. สงขลานครินทร์ วทท. 2550 29(4) : 1039-1048

บทความนี้เสนอการทดลองเพื่อศึกษาผลของรอยร้างล่วงหน้าต่อพฤติกรรมและรูปแบบการวิบัติของคานคอนกรีตเสริมเหล็ก ชิ้นทดสอบควบคุมถูกออกแบบให้มีการวิบัติแบบดัดเหนียวภายใต้น้ำหนักเชิงดัดแบบ 4 จุด และให้มีการวิบัติแบบเฉือนเปราะภายใต้น้ำหนักเชิงดัดแบบ 3 จุด การศึกษาผลของรอยร้าวล่วงหน้าได้กระทำทั้งภายใต้น้ำหนักเชิงดัดแบบ 4 จุด และ 3 จุด ภายใต้น้ำหนักเชิงดัดแบบ 4 จุดนั้น รอยร้าวล่วงหน้ามีทิศทำมุมเอียงกับแกนคาน และคานมีช่วงการเฉือนที่สั้น ซึ่งทำให้การต้านทานแรงภายนอกของคานนั้นใช้กลไกของท่อนแรงอัดทแยง ส่วนภายใต้น้ำหนักเชิงดัดแบบ 3 จุดนั้น รอยร้าวล่วงหน้ามีทิศตั้งฉากกับแกนคาน และคานมีช่วงการเฉือนที่ยาวปานกลาง ซึ่งทำให้กลไกการต้านทานแรงเฉือนนั้นอาศัยแรงดึงของคอนกรีตเป็นหลัก ดังนั้นการทดสอบทั้งสองกรณีนี้จะครอบคลุมการศึกษาผลของรอยร้าวล่วงหน้าทั้งในสภาพที่คอนกรีตรับแรงอัดและแรงดึง ผลการทดสอบแสดงให้เห็นว่าในกรณีที่คานมีช่วงการเฉือนสั้น รอยร้าวล่วงหน้าทำให้กำลังต้านทานแรงเฉือนอัดลดลง เนื่องจากรอยร้าวล่วงหน้าทำให้พื้นที่สัมผัสประสิทธิผลของคอนกรีตลดลง และทำให้กำลังรับแรงอัดของคอนกรีตบริเวณใกล้รอยร้าวลดต่ำลงเนื่องจากเนื้อคอนกรีตบริเวณรอยร้าวเกิดความเสียหายจากรอยแตกในระดับจุลภาค นอกจากนี้รูปแบบการวิบัติก็เปลี่ยนแปลงจากการวิบัติแบบดัดเหนียว เป็นแบบเฉือนเปราะ ในทางตรงกันข้าม ในกรณีที่คานมีช่วงการเฉือนยาวปานกลาง รอยร้าวล่วงหน้ามีผลทำให้กำลังต้านทานแรงเฉือนของคานสูงขึ้น เนื่องจากกลไกการหยุดรอยร้าวในทั้งสองกรณีนั้น พบว่า รอยร้าวล่วงหน้ามีผลต่อพฤติกรรมโครงสร้างของคานเป็นอย่างมาก ดังนั้นในการวิเคราะห์องค์อาคารที่มีอยู่เดิมนั้น จะต้องพิจารณาผลของรอยร้าวล่วงหน้าด้วย

สถาบันเทคโนโลยีนานาชาติสิรินธร ตู้ ปณ. 22 ศูนย์ไปรษณีย์รังสิต จังหวัดปทุมธานี 12121

Existing reinforced concrete structures in current service may experience various load events throughout their service life. For example, RC structures in seismic zones may experience earthquake loading that causes pre-cracks in beams, columns and other components. The function of concrete structure may also change from time to time. Concrete is a path-dependent material, hence, the past loading may create cracking, residual stress and strain in the members. This paper attempts to investigate the effect of past load history, especially existing cracks resulting from previous load stages, on the structural behavior at ultimate state in the next load stages. The past load history is not only limited to external forces but also includes environmental actions. Shrinkage and temperature cracks are examples of such environmental effects. In the past, the effect of pre-cracking was mainly studied in terms of serviceability of reinforced concrete members. The primary concern for excessive cracking is of serviceability matter including appearance, leakage and corrosion. To the author's knowledge, the effect of pre-cracking on the ultimate capacity has not been discussed or fully understood (Pornpongsaroj and Pimanmas, 2002; Yamada *et al.*, 1995). Previous researches investigated the shear capacity of RC members subjected to axial tension (Tamura *et al.*, 1991, 1999). In their works, axial tension was applied first, maintained on the beam and then shear was superimposed. The first state axial tension may simultaneously induce pre-cracks as well as prestress inside the beam. In this case, it is hardly possible to differentiate the sole influence of precrack from the pre-stress state. Unlike previous investigation, this paper aims to experimentally examine the sole influence of pre-cracks in terms of crack interaction. In the experimental program, the axial tensile stress is not introduced into the beam. Only pre-cracks are induced.

The author believes that the study of reinforced concrete members experiencing past load history would be of prime importance for the evaluation of the structural performance of existing structures. This paper presents an experimental research concerning the structural effect of pre-cracking on the ultimate limit state of reinforced concrete members. The primary concern is the ultimate shear capacity of RC members with initial pre-cracks.

Significance of Research

During the service life of concrete structures, they may be subjected to various loading types and environmental conditions. The crack systems generated by different load effects may be unrelated. The cracks caused by previous load effects are initial damages that may structurally affect the behavior in the next loading events. Most current design methods aim at new structures. Specifically, they are suitable to undamaged reinforced concrete members. The study of pre-cracking effect on structural behavior is needed for the evaluation of existing structures. This paper experimentally investigates the effect of pre-cracking and demonstrates its structural importance.

Experimental program

1. Specimen Design, Beam Dimensions and Reinforcement Detailing

The dimension and reinforcement detailing of the tested beams are shown in Figure 1. Two beams, B1 and B2, with identical cross sectional dimension and reinforcement detailing were tested. The bottom longitudinal reinforcement consisted of 2DB25 (25-mm deformed bar) with the area A_s of 982 mm^2. The top longitudinal reinforcement consisted of 2DB25 (25-mm deformed bar) with the area A'_s of 982 mm^2. The longitudinal reinforcement ratio was 1.95%. The stirrups consisted of RB6 (6-mm plain bar) spaced at 120 mm center to center in the 1200 mm central portion of the span and RB9 (9-mm plain bar) spaced at 70 mm center to center in each 500 mm end as shown in Figure 1. The effective depth was 247.5 mm. The clear concrete cover was 30 mm. The beam dimension and reinforcement detailing were designed such that the effect of pre-cracking on flexural and shear failure mode of the beam could be investigated within the same specimen.

2. Loading method to examine the effect of pre-cracking under four-point bending

The loading arrangement to examine the effect of pre-cracking under four-point bending is shown in Figure 2(a). The beam was tested with the shear span to effective depth ratio of 2.0 which is considered as short shear span. The 1200-mm central part was subject to pure moment whereas each 500-mm end was subject to shear and moment. Under this load condition, the external load is transferred directly to the support through diagonal compression strut. The inclined cracks were generated in the end zones as shown in Figure 2(a). In the first stage, since the yielding capacity was less than the shear failure load, yielding took place before shear failure. In the second stage, the beam was rotated 180 degree about its axis. It was

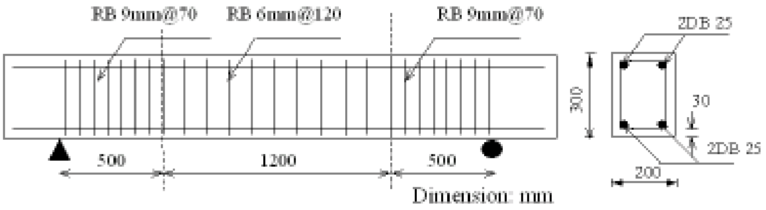
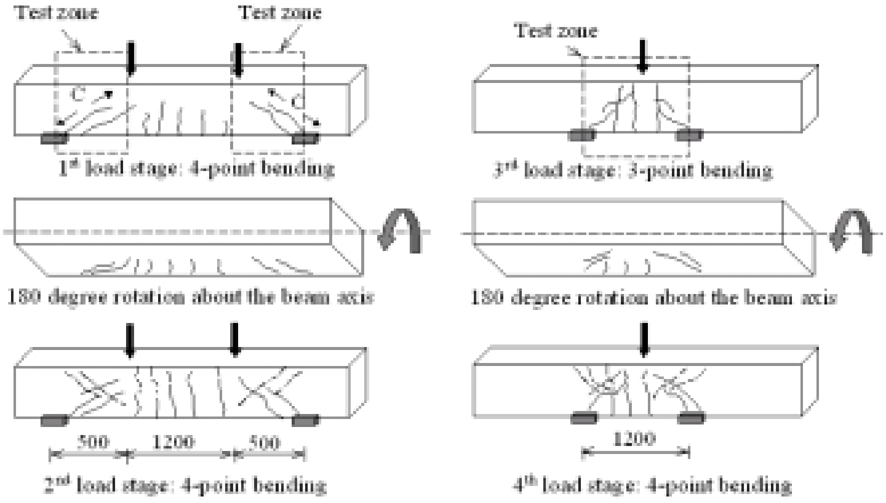


Figure 1. Beam dimension and reinforcement detailing



(a) Four-point bending

(b) Three-point bending

Figure 2. Load stages in the experiment

loaded again under four-point bending with the pre-cracking condition resulting from the first stage loading. The target of interest was the effect of inclined pre-cracking at the end zones on the shear capacity.

3. Loading method to examine the effect of pre-cracking under three-point bending

The first and second stage four-point bending also generated vertical pre-cracks in the 1200-mm central part of the member. The effect of these vertical pre-cracks on the shear response of the member was studied by applying three-point bending to the beam as shown in Figure 2(b). This was considered as the 3rd load stage. The ratio of shear span to effective depth was 2.40, which is moderately long. Under this load condition, inclined crack formed in the shear span. The effect of vertical pre-cracking on formation and propagation of the inclined crack was the target of study. After the beam was tested under the third stage of three-point bending, it was rotated by 180 degree and loaded again in three-point bending in the 4th load stage. Under the 4th load stage, the pre-cracking condition consisted of penetrating vertical pre-cracking resulted from four-point bending and inclined pre-cracking resulted from the three-point bending. The shear behavior under multi-pre-cracking condition was examined in the 4th load stage.

4. Material properties and sectional capacities

Ready mixed concrete supplied from local plant was used to cast specimens. The average tested compressive strength of standard 150×300 mm cylindrical concrete specimens at 28 days was 29.6 MPa. The tested yield strengths of RB6, RB9 and DB25 were 339.4, 372.8 and 439.5 MPa, respectively. The tested ultimate strengths of RB6, RB9 and DB25 were 467.7, 444.3 and 613.6 MPa, respectively.

These material properties are summarized in Table 1. Based on the tested material properties and geometry of the beam specimens, the flexural capacity was calculated using the beam's sectional analysis. The concrete shear capacity was calculated using the modified Okamura-Higai equation (Okamura and Higai, 1980), which was a predictive equation rather than a conservative code equation. The stirrup shear capacity was calculated using equilibrium equation assuming yielding in all transverse stirrups cut by inclined cracks. Table 2 summarizes the shear and flexural capacities of the cross section.

Experimental results and Discussions

Table 3 summarizes the experimental loading capacities and failure modes of the tested beams. The discussion of the behavior will be given in the following sections. The behavior of beams B1 and B2 were generally similar to each other in all load stages. B1 was tested under four load stages as shown in Table 3. But B2 was tested under three load stages only because the cracking condition and deformed shape of B2 after the 3rd stage were so severe that it was not appropriate to conduct the 4th load stage on this beam.

1. Behavior of beam under four-point bending

The load versus mid-span deflection of B1 and B2 under four-point bending is shown in Figure 3. In the first stage of 4-point bending, flexural cracks were created in the central portion of the beam while diagonal cracks were created in the end portions (see Figure 5(a)). The diagonal shear cracks were observed to be inactive due to the presence of large number of stirrups. On the other hand, flexural cracks grew in size continuously corresponding with yielding of steel bars. The load versus mid-span deflection showed ductile flexural yielding (Figure 3) as designed. In the second load

Table 1. Material properties

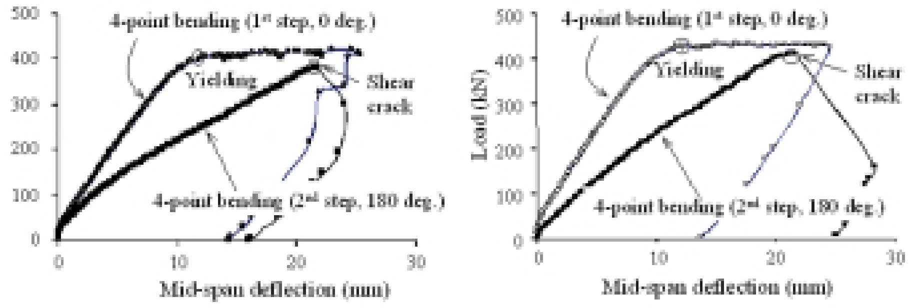
Materials	Yield strength (MPa)	Ultimate strength (MPa)
Steel DB25	439.5	613.6
Steel RB9	339.4	467.7
Steel RB6	372.8	444.3
Concrete	Tested compressive strength (f'_c) = 29.6 MPa	

Table 2. Sectional capacities

Sectional Properties	Four-point bending	Three-point bending
Shear span / effective depth (a/d)	2.0	2.4
Concrete shear capacity (V_c), kN	78.9 (Okamura H. and Higai T., 1980)	
Stirrup shear capacity (V_s), kN	153.4	44.2
Total shear capacity (V_c+V_s), kN	232.3	123.1
V_s / (V_c + V_s)	0.66	0.36
Shear failure load, kN	464.6	246.2
Flexural moment capacity, kN.m	101.0	
Yielding load, kN	404.0	336.7

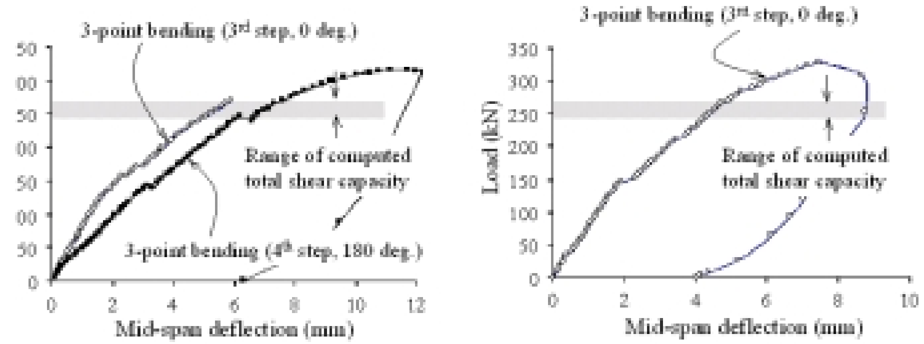
Table 3. Summary of loading capacity and failure mode

Loading	Beam B1		Beam B2	
	Ultimate Load, kN	Failure mode	Ultimate Load, kN	Failure mode
Four-point bending (0°) 1st stage	421.40	Flexural yielding	432.50	Flexural yielding
Four-point bending (180°) 2nd stage	380.60	Shear failure	411.53	Shear failure
Three-point bending (0°) 3rd stage	270.97	Shear failure	329.95	Shear failure
Three-point bending (180°) 4th stage	315.86	Shear failure	-	-



(a) For beam B1 (b) For beam B2

Figure 3. Load versus mid-span deflection of tested beam under four-point bending



(a) For beam B1 (b) For beam B2

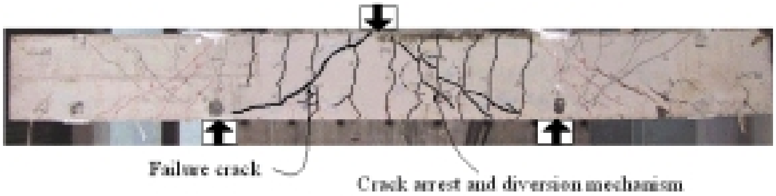
Figure 4. Load versus mid-span deflection of tested beam under three-point bending

stage of 4-point bending, the beam failed in brittle shear rather than flexural yielding. A large shear crack suddenly formed while the growth of the flexural crack was not active (Figure 5(b)). The maximum load attained was 380.6 kN compared with 421.4 kN (yielding load) in the first load stage. This experiment showed that the existing pre-cracking could change the failure mode of the beam from ductile flexure to brittle shear. In the first load stage, the yielding load was designed to be lower than the shear failure load (see Table 3). Due to pre-cracking, however, the yielding load became higher than the shear failure load in the 2nd stage. This indicated that the pre-cracking could significantly affect the original design condition. It was supposed that pre-cracking would bring about the brittleness to the beam. The source of brittleness was derived from the reduction in compressive strength of pre-cracked concrete.

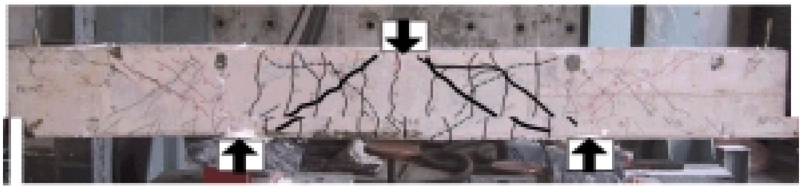
The web concrete in the end portion of the beam was subjected to a large diagonal compressive force as a result of the transfer of an external load to the support through two main mechanisms: direct compression strut and truss mechanism. The inclined pre-cracking created in the 1st load stage was roughly orthogonal to the diagonal compression in the 2nd load stage. Owing to pre-crack, the contact area through which the compressive force could be transferred was apparently reduced. Additionally, it is supposed that the compressive strength of concrete close to the pre-crack was degraded because of micro-fracturing damages (Maekawa *et al.*, 2003). These two mechanisms are explained in Figure 6. As a result, the compressive capacity of concrete was reduced, leading to the decrease in shear capacity according to strut and truss mechanism.

(a) Beam under the first stage of four-point bending

(b) Beam under the second stage of four-point bending



(c) Beam under the third stage of three-point bending



(d) Beam under the fourth stage of three-point bending

Figure 5. Crack pattern observed in each loading stage for a typical beam
(Color figure can be viewed in the electronic version)

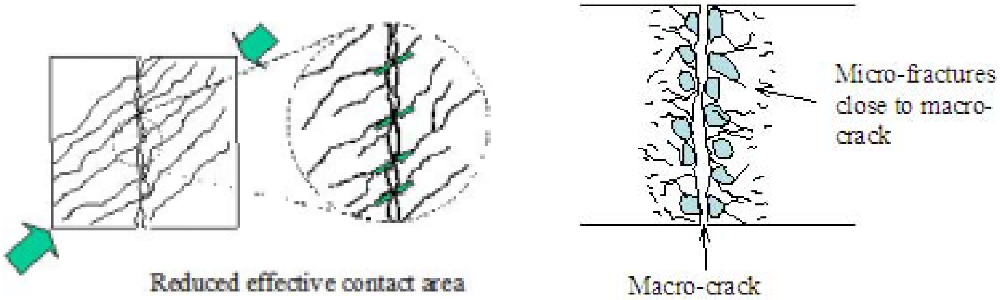


Figure 6. Compressive strength degradation mechanisms of pre-cracked concrete

2. Behavior of beam under three-point bending

The load versus mid-span deflection of B1 and B2 under four-point bending is shown in Figure 4. After the beam was tested under four-point bending, the vertical pre-cracking damage was induced in the beam. The average crack width caused by four point bending was observed to 1.8 and 1.6 mm for beam B1 and B2, respectively. The beam was then tested under three-point bending. The target zone of study was the 1200-mm central span with penetrating vertical pre-cracking (Figure 2(b)) created in the 1st and 2nd load stages. Under three-point bending, the beam was designed to have the shear failure load lower than the yielding load (see Table 3) in order to study the effect of pre-cracking on the shear response. Beam B2 was loaded to failure in shear with the loading capacity of 329.95 kN in the 3rd load stage. The failure crack pattern of B2 under the 3rd load stage is shown in Figure 5(c). It was noted the beam could achieve much larger shear capacity compared with calculated values, which ranged from 246.2 to 262 kN. The former was computed using tested yield strength and the latter using tested ultimate strength of stirrups. Since the calculation of stirrup shear capacities was based on tested strengths, they should be very close to the actual values. The increase in total shear capacity must therefore be attributed to the increase in concrete shear capacity. The simple calculation showed that the increase in concrete shear capacity ranged from 43% (based on tested ultimate strength of stirrup) to 53% (based on tested yield strength of stirrup) from the Okamura-Higai, 1980 shear capacity equation.

It should be noted that the Okamura-Higai equation was the predictive equation, not a design equation. Hence, this equation should predict the shear capacity close to reality. In fact, the ACI design equation (ACI318-05) would predict the concrete shear capacity to be only 44.67 kN compared with 78.9 kN computed by the Okamura-Higai equation. The increase in concrete shear capacity was explained (Pimanmas *et al.*, 2001) to be the consequence of the crack arrest phenomenon. The mechanism of the crack arrest is illustrated in Figure 7. A beam with a pre-crack located approximately at the center of shear span is shown. Since principal stresses that can develop in the element close to pre-crack are low, the diagonal crack can hardly form in the element. As a result, the diagonal crack is apparently arrested there. This results in the increase in concrete shear capacity.

As shown in Table 3, the ratio of stirrup shear capacity was 0.66 under four-point bending and 0.36 under three-point bending. A large ratio of stirrups would put a higher demand on concrete compression. As explained, the majority of shear capacity was derived from concrete compression in the four-point bending. In contrast, under the three-point bending, the shear capacity was partly contributed by concrete tension (V_c) and partly by concrete compression associated with the truss mechanism. The concrete tension is shear capacity against sliding after the formation of a complete inclined crack that links the load point to the support. As a crack is arrested at the pre-crack

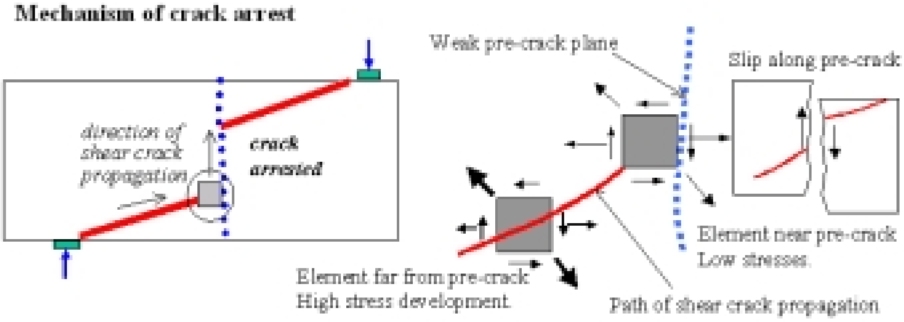


Figure 7. Mechanism of crack arrest

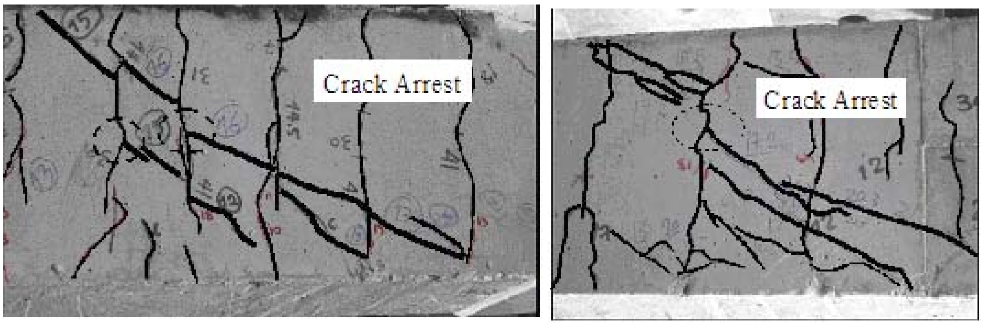


Figure 8. Crack arrest phenomenon observed in the experiment

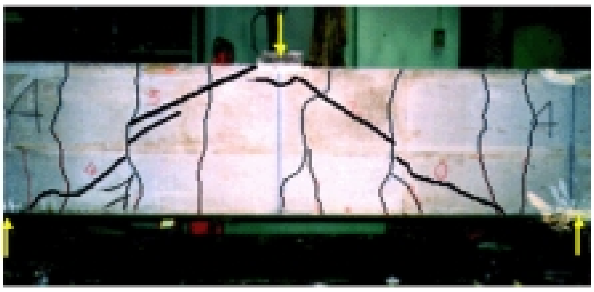


Figure 9. Crack arrest phenomenon observed by Pimanmas (Pimanmas *et al.*, 2001)

(Color figure can be viewed in the electronic version)

plane, the formation of a complete crack is inhibited, resulting in the increase in concrete shear capacity. Since there were fewer stirrups in the central 1200-mm portion, the truss mechanism in which concrete was subjected to compression was not dominant and truss shear capacity was mainly governed by the yielding of stirrups. For B2, the pre-cracking elevated the loading capacity up to 329.95 kN, almost reaching the yielding load of 336.7 kN (Table 2). Pimanmas *et al.*, 2001 experimentally showed that the beam designed to fail in shear could actually turn to fail in ductile flexural yielding due to the effect of pre-cracking. The crack arrest phenomenon demonstrated in this experiment and that observed by Pimanmas *et al.*, 2001 and shown in Figures 8 and 9, respectively.

As for B1, the beam was not loaded to failure in the 3rd load stage of three-point bending, but to 271 kN to create inclined cracks in the central portion. This was to create a multi-directional cracking state that consisted of vertical pre-cracking and inclined pre-cracking before the beam was tested in the 4th stage of three-point bending. Despite the severe pre-cracking condition, the beam could achieve very high loading capacity, well above the calculated value shown in Table 3. The crack arrest and diversion phenomenon is supposed to be responsible for the increase in concrete shear capacity. The failure condition of beam B1 under the 4th load stage is shown in Figure 5(d).

Conclusions

The significance of pre-cracking was experimentally demonstrated in this paper. The failure modes could be changed from ductile flexure to brittle shear and vice versa. In the four-point bending, the effect of pre-cracking on concrete subjected largely to compressive force was investigated. In the three-point bending, the effect of pre-cracking on concrete subjected largely to tensile force was investigated. On compression, pre-cracking reduced the compressive strength of concrete by reducing the effective contact area and compressive strength deterioration due to microfracturing damages. This leads to a drop in web crushing shear capacity. On tension, pre-cracking arrested the propagation of the diagonal crack, leading to a rise in concrete shear capacity. The effect of pre-cracking should be properly taken into account in the evaluation of the safety of pre-cracked concrete structures.

Acknowledgements

The authors are very grateful to Thailand Research Fund for providing the research fund TRG4580105 to carry out the research.

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