J. Materials, Conc. Struct., Pavements, JSCE, No.669／V-50, 277-291, 2001 February

INFLUENCE OF PRE-CRACK ON RC BEHAVIOR IN SHEAR

Amorn PIMANMAS[1] and Koichi MAEKAWA[2]

[1] Member of JSCE, Ph.D., Research fellow, Dept. of Civil Eng., The University of Tokyo
(Hongo 7-3-1, Bunkyo-ku, Tokyo 113, Japan)
[2] Member of JSCE, Dr. of Eng., Professor, Dept. of Civil Eng., The University of Tokyo
(Hongo 7-3-1, Bunkyo-ku, Tokyo 113, Japan)

This paper aims to investigate the influence of pre-cracks on the behavior of reinforced concrete beam in shear. For real RC members under severe environments, these pre-cracks are sometimes inevitable. For this purpose, an experimental program was implemented. Experimental results demonstrated significant difference between pre-cracked and non pre-cracked beams. It is found that pre-cracked beam can reach much higher capacity. Moreover, substantial difference in failure characteristics and load-displacement relationship was also discerned. Rationale in fundamental mechanics exists, that can explain the behavior of pre-cracked beam

Key Words: crack interaction, Z-crack, crack arrest and diversion, shear anisotropy co-axiality principle

1. INTRODUCTION

Researches on reinforced concrete have primarily focused on members and structures with very few initial defects. Comprehensive scrutiny of reinforced concrete through experimental and theoretical methodologies has provided the recent advanced understanding in reinforced concrete mechanics[1),2)]. However, it is necessary to recognize that current gigantic volume of knowledge base was mostly accomplished in the experimental laboratory where the well-controlled conditions can be acquired. One of the most underlying assumptions following conventional research methodology is that RC member is devoid of initial defects. As a result, researchers then intentionally prepare the specimens as perfectly as possible to minimize the undesired original damages. It is only these typical near-perfect RC members that we can claim to have the advanced insight.

As a matter of fact, real reinforced concrete member is hardly exempt from initial defects. The difference in real and laboratory members can be explained by **Fig.1**. Real RC members live much longer than laboratory ones. In terms of structural behavior, it is quite common that a majority of laboratory specimen stays up to at most 2 months since casting time until testing date. Moreover, during young age period, they are so well nurtured that cracking attack becomes a minor problem. On the contrary, real RC members may live up to 50 years under generic environmental conditions, which are perhaps grossly different from those available in the experimental room. This much longer time scale allows the time dependent deteriorating mechanism to attack concrete. Moreover, during the life time of RC members, they may be subjected to unexpected non-proportional loading condition. Concrete is a highly path-dependent material memorizing the loading history through which it has experienced. Previous loading may result in cracking, state of stress/strain, state of residual deformation. These characteristics are of anisotropic nature and may play crucial role in the next loading event.

Cracking is one of the most dominant events representing previous loading history of the RC members. This paper aims to clarify the influence of perpendicular pre-cracks on the structural behavior of RC members. In terms of structural concern, two major behaviors may be recognized, namely shear and flexure. As commonly accepted, flexure is governed by a sectional behavior. The flexural capacity is rooted in the internal couple of compressive force provided by concrete and tension force by reinforcing bars. In this respect, pre-cracks do not seem to affect the flexural capacity since concrete can still acquire compression once the closure of pre-cracks while reinforcement tension is hardly affected by the presence of pre-cracks. On the other hand, the shear behavior may offer

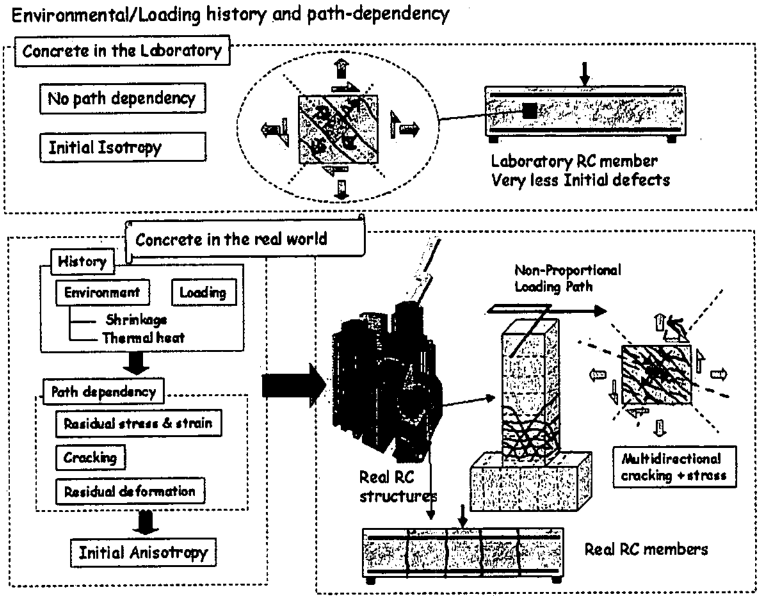
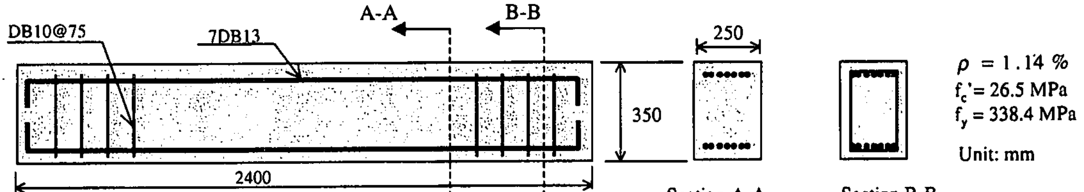


Fig.1 Real and Laboratory RC members



Section A-A

Section B-B

Fig.2 Beam dimension and cross sections

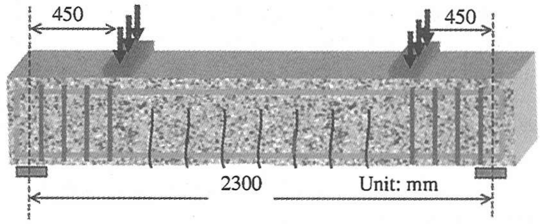
a different story. The behavior in shear is characterized by the propagation of a diagonal shear crack in the member scale. In this case, the propagation of shear crack must encounter the pre-crack planes. This multi-crack situation is the target of interest in this paper. Previous researches on this line investigated the shear capacity of RC beam subjected to axial tension$^{3),4),5)}$. In their work, axial tension is applied first, maintained on the beam and then shear is superimposed. The first step axial tension may simultaneously induce pre-cracks as well as the state of pre-stress inside the RC members. In this case, it is hardly possible to differentiate the sole influence of pre-crack from the pre-stress state.

Unlike the previous investigation$^{3),4),5)}$, the authors aim to experimentally examine the sole influence of pre-cracks in terms of non-orthogonal crack interaction. In the experimental program, the axial tensile stress is not introduced into the beam. Pre-cracks penetrating the entire section will be introduced into the RC members by mechanical loading. This way of introducing cracks may be different from the shrinkage and thermal heat mechanism but the authors suppose that the mechanical behavior of the crack would be the same regardless of how it would be formed. In this paper, the authors focus on the mechanics of crack interaction to extract the basic influence of pre-cracks. It is assumed that the investigation here would be applicable to members with pre-cracks including those due to shrinkage, thermal heat attack or other mechanical forces.

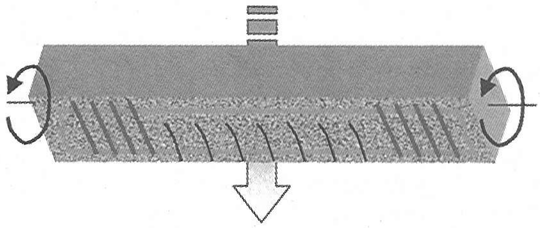
2. EXPERIMENTAL PROGRAM

(1) Test specimen and material properties

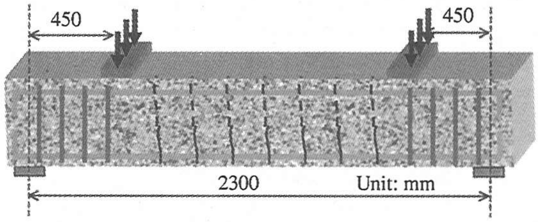
A total number of four reinforced concrete beams was tested. The size and dimension of beams as well as main and web reinforcing bars used are shown in **Fig.2**. The top and bottom main reinforcements were provided for the reversed flexural loading. The main reinforcement ratio was designed to be 1.14 %. Tested concrete compressive strength is 26.5 MPa. Tested tensile yield strength of main and tie bars is 338.4 MPa.



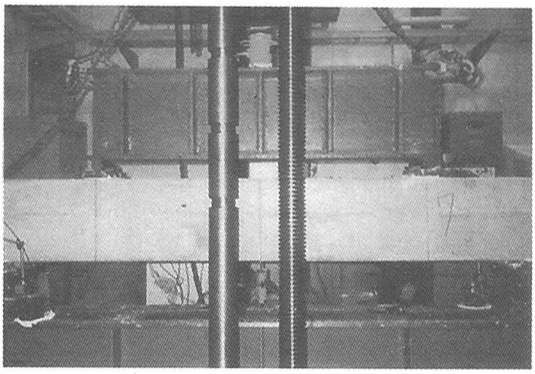
(a) first flexural loading



(b) rotation of beam through 180°,
turning upside down the beam



(c) second (reversed) flexure to penetrate the vertical cracks



(d) experimental set-up

Fig.3 Experimental set-up for reversed flexure

(2) Experimental setup

a) Setup for reversed flexural loading

In order to introduce the penetrating cracks in the beam, a few methods are available with a different degree of difficulty in experimental works. Two possible loading methods for inducing pre-cracks were considered, direct tensile and reversed flexural loading. Direct tensile loading limits the use of large-sized beam since large reaction wall is needed for equilibrating the applied tension. Consequently, we used reversed flexural loading due to its relative simplicity. Reversed flexural loading is needed for the flexural cracks to penetrate the entire sections. The set up for reversed flexural loading is shown in **Fig.3**. In the experimental room, this reversed flexure cannot be implemented in a single test set-up due to the limitation of testing machine as well as the inherent character of beam test. To circumvent the problem, the reversed flexure was carried out in two steps. The first flexural loading resulted in vertical cracks in the flexural span as shown in **Fig.3a**. The beam was then rotated through 180 degree, i.e., turned upside down (**Fig.3b**) and the second (reversed) flexure was subsequently conducted. This second (reversed) flexure enabled vertical cracks to penetrate the entire sections as shown in **Fig.3c**.

Two-point loading setup was employed for the reverse flexure. Here, a steel girder was employed to transfer the single applied load from testing machine to the two specified points on the beam as shown in **Fig.3d**. This loading arrangement was adopted since it created the pure and constant bending moment over the flexural span without inducing shear force. Notice in the figure, it is possible that premature shear failure can take place at both end portions of the beam. In order to prevent this, sufficient web reinforcements were provided therein. (see **Fig. 2**).

Higher level of flexural loading, i.e., up to two times yielding, was intentionally employed for some beams to introduce large pre-cracks so that the effect of crack interaction can be clearly investigated. Note that the pre-crack condition in the authors' experiment is considerably severer than that in previous works[3),4),5)]. Pre-crack condition after reversed flexure to be reported later reflects the level of flexural loading used in the experiment.

b) Set up for shear loading

The second loading step is for inducing shear crack to propagate across the pre-crack planes. To implement this, loading arrangement must be changed from the first step reversed flexure. This was accomplished by shifting both bearing supports towards the beam's mid-span so that the shear span to effective depth ratio became 2.42 as shown in **Fig.4**. Shear loading was then applied to the beam by one-point loading at the mid-span section. Through rotation of beam as well as re-arrangement of loading and support conditions, complex non-proportional loading path became possible with the available experimental facility.

Since our main objective is the crack interaction and the effect of pre-crack on the beam, neither web reinforcements were provided within the shear span

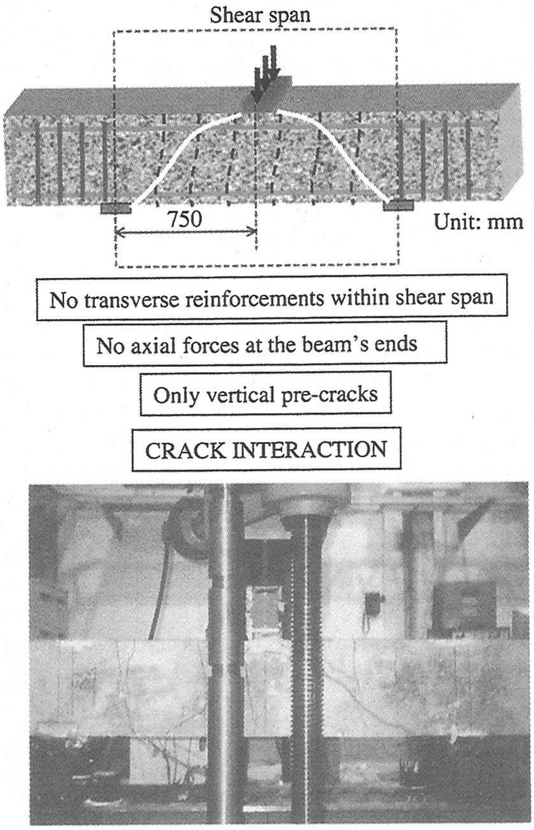


Fig. 4 Experimental set-up for shear

nor axial tension was given during shear loading. The load from testing machine was transferred through load cell to the beam with the one-point loading set-up. Displacement transducers were attached to the mid-span of the beams and at the two supports. All load and displacement measurements were electronically passed to a data logger connected to a microcomputer for the real time data processing and graphical display of results.

(3) Sectional capacity

Based on the material properties and geometry of cross section, the yielding moment capacity is calculated based on sectional analysis. Shear capacity is predicted by Modified Okamura-Higai equation[1]. These sectional capacities are given for non pre-cracked beam as a reference case in **Table1.**

(4) Test results and observation

a) Observation after flexural test

Reversed flexural loading resulted in several vertical cracks penetrating the entire sections of the beam. As these vertical cracks might play important role on the shear behavior in the next loading step, after the test, we recorded carefully the number of cracks, the maximum residual crack width, crack inclination and the side of the beam, which contained more severe cracking. Since the number of cracks was quite the same in each side of each beam, the severity of cracking was judged by the width of pre-cracks. This information is graphically summarized in **Fig. 5**

Note that the width of pre-crack is various, ranging from the smallest 0.02 mm to 5.0 mm. Some striking features of initial crack observation in each beam should be mentioned since they would greatly affect the following shear behavior as will be indicated later. First, the cracking extent, i.e., judged by the width of these pre-cracks, was generally not equal between the left and right side of the beam even though the number of cracks was more or less the same. Particular notice is directed to beam 3 which showed considerably more severe cracking in the left side. Most of the vertical pre-cracks in beam 2, on the other hand, had approximately the same width. Additionally, in beam 4, only one or two cracks in each side of the beam, specifically the one located near the center of shear span was noticeably larger than other nearby cracks.

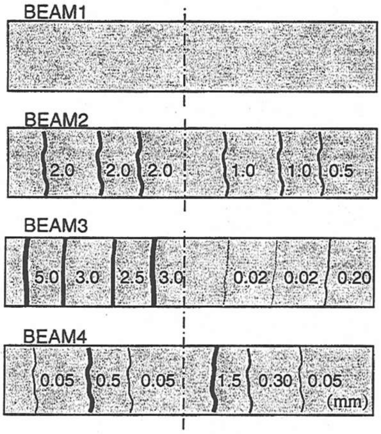
b) Test results and observation after shear loading

Summary of test results for each beam is given in **Table2**, which shows, for each beam, the load capacity, percent load increase compared with the non pre-cracked case as well as the side of the beam where shear failure took place in the experiment. First, some brief general comments are noted here. Detailed discussion regarding experimental fact will be mentioned separately for each beam in which certain peculiarity will be pointed out. Next, the associated phenomena will be explained on the basis of rational fundamental mechanics.

All of the pre-cracked beams showed the increase in loading capacity as compared to non pre-crack case (beam1). Moreover, experiments demonstrated that the percentage of this load increase is not minor (see **Table 2**). In beam 2, particularly, up to nearly 50 % capacity increase could be obtained. Moreover, all of the pre-cracked beams failed in shear in the side that had smaller cracking extent. This fact may respond to past experimental investigations[3),4),5)] that shear capacity of beam subjected to axial tension does not decrease so much. The experiment conducted by the authors showed that penetrating pre-crack could elevate the shear capacity. However it is commonly accepted as well in many design codes[2),7)] that induced tensile stress reduces shear capacity of the beam. Generally, it may be expected that the influence of pre-cracks and pre-tensile stresses are counteracting each other.

Table 1 Moment and shear capacity of cross section

Properties	**Reversed Flexural Loading(KN)**	**Shear Loading(KN)**
Shear span/effective depth(a/d)	1.45	2.42
Shear capacity of concrete(V_c) (Okamura-Higai Equation)	112.1	81.9
Shear capacity of tie (V_s)	199.5	0.0
Total shear capacity	311.7	81.9
Yielding Moment capacity(M_y)	86.9 KN-m	86.9 KN-m
Yielding Load(P_y)	385.2	230.4
Shear Failure Load(P_v)	623.3	163.8



Beam	Side of more severe damage
1	-
2	Left
3	Left
4	Right

Numbers along cracks denotes residual crack width after reverse flexure in mm

Fig. 5 Pre-cracked condition after reversed flexural loading

Table 2 Summary of loading capacity and side of shear failure

Beam	**Loading capacity(KN)**	**Percent load increase(%)**	**Side at which shear failure took place**
Beam1(non pre-cracked, reference test)	157.0	0.0	Left
Beam 2	233.5	48.8	Right
Beam3	184.9	17.8	Right
Beam4	217.3	38.4	Left

Note: The percent load increase of pre-cracked beam is computed based upon the experimental loading capacity of the reference non pre-cracked one.

Previous works[3),4),5)] did not separately study each individual effect, hence, the role of pre-crack and pre-stress was not made clear therein. As a matter of fact, it may be possible that shear capacity may be increased or decreased, which depends upon the comparative effect of pre-cracks and pre-tensile stresses.

Not only capacity increases, but the displacement ductility also increases as shown later in **Fig.7-9.** Suzuki et al. also reported the increase of displacement ductility of reinforced concrete column, which contained the slit made of steel plates[6)]. The experimental fact that vertical cracks did not harm the beam in shear is quite interesting but may not be agreeable with the common belief that cracks are the unpleasant characters of reinforced concrete. Therefore underlying phenomenon must be explained with the mechanic foundation to testify the experimental results. The hostile attitude towards pre-cracks should be reassessed.

3. GENERAL DISCUSSION FOR EACH BEAM

(1) Beam 1: Non pre-cracked beam (reference case)

Non pre-cracked beam was aimed to be the reference test. The failure crack in this beam

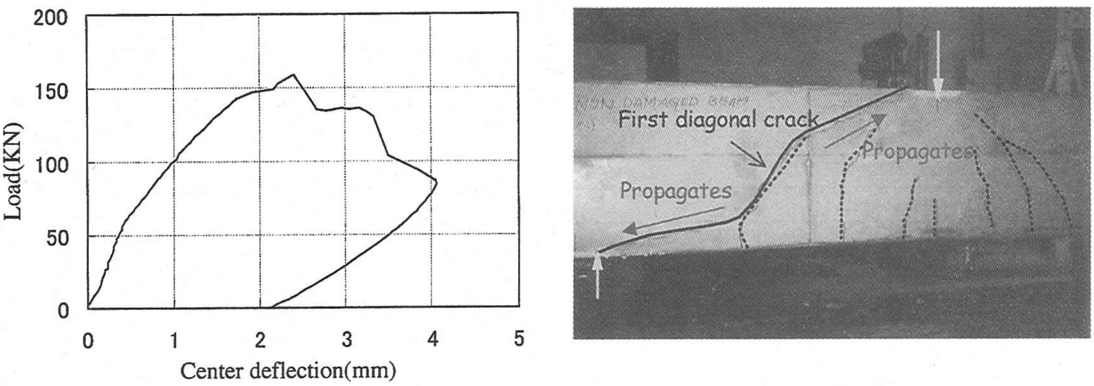


Fig.6 Load-displacement relationship and failure crack pattern of beam 1

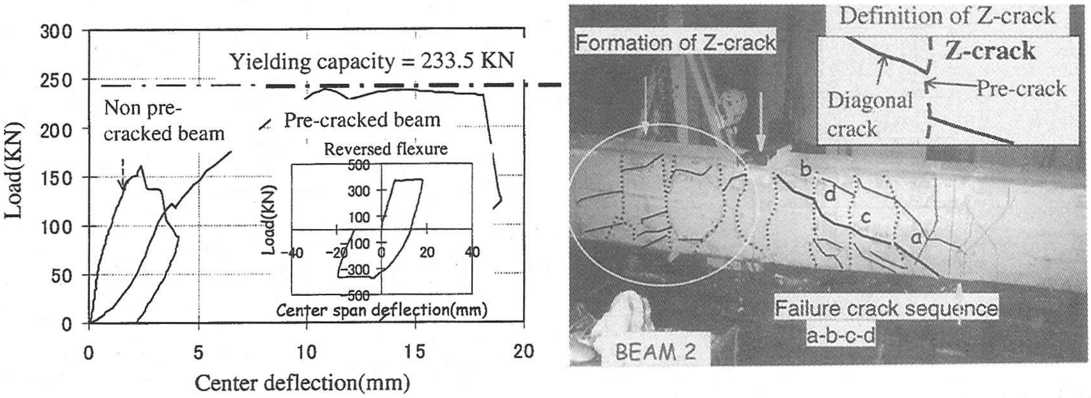


Fig.7 Load-displacement relationship and failure crack pattern of beam 2

followed the conventional shear diagonal pattern as illustrated in **Fig.6**. The failure process was initiated by the first diagonal crack formed at the web portion near the center region of shear span. Once this crack emerged, it suddenly propagated towards loading point and backward support, forming the complete failure path in just a matter of seconds. The permanent decrease in loading was therefore resulted. For the non pre-cracked beam containing no transverse reinforcements, the first diagonal crack was the only one big crack created, therefore the failure zone was very much confined in the narrow zone (see **Fig. 6**).

(2) Beam 2: Most pre-cracks were quite uniform in width (Introduction of Z-crack)

In beam 2, several large flexural cracks existed after reversed flexural loading (see **Fig.5**). During the early stage of shear loading, a pair of diagonal cracks was observed forming around each vertical pre-crack, but without propagating across it as shown in **Fig.7**. The formation of these diagonal cracks, when combined with the vertical pre-crack, resulted in a crack having the shape similar to the alphabet Z, therefore, this crack configuration will be referred hereupon to as Z-crack. As these diagonal cracks never penetrated through the companion vertical pre-crack, its formation did not suddenly fail the beam.

However, the above crack pattern did result in much more severe damages given to the beam in the wider zone as opposed to the localized zone of conventional shear failure observed in the non pre-cracked case. Nonetheless, though threatened by such severe damages, the beam could still carry further load. The constituent diagonal cracks in a Z-crack widened so much locally. The opening mode of diagonal crack must be compatible with sliding deformation along pre-crack. Through direct sliding of pre-cracks as well as compatible opening mode of

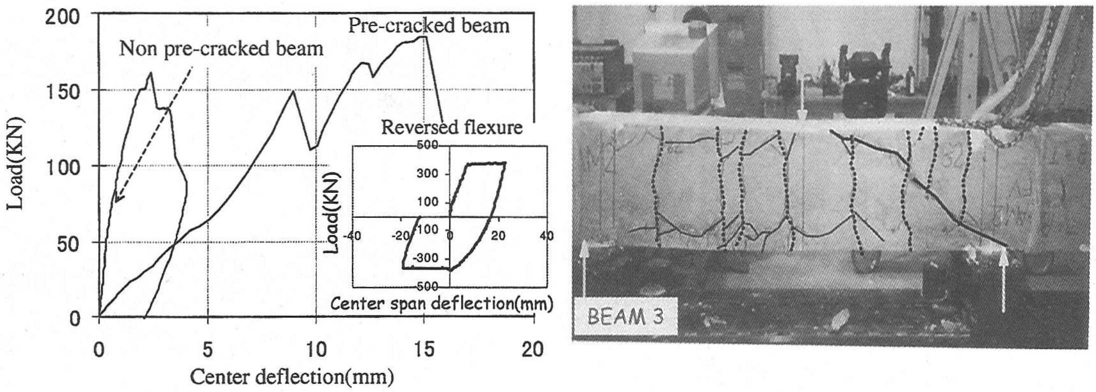


Fig.8 Load-displacement relationship and failure crack pattern of beam 3

associated diagonal cracks, the beam could dissipate the energy in the stable manner.

It was the significant sliding along pre-cracks, that relieved the injurious effect of diagonal cracks and clearly distinguished the failure pattern from the non pre-cracked one. Here, vertical pre-crack shared a certain (not negligible) role also and the Z-crack was therefore a logical consequence. Without vertical pre-cracks as in the reference case, only a single diagonal crack prevailed and thus an unstable propagation of this crack immediately led to failure. The experiment disclosed the significant influence of vertical pre-cracks on the behavior of beam in shear.

As diagonal cracks could not succeed in continual propagation, the beam could survive higher applied load up to yielding of main bars. It is noticed that this load level is a significant increase from the designed shear capacity of reference beam without pre-cracks. After yielding, beam could sustain the load with increasing deflection at mid-span. Failure crack pattern **Fig.7** occurred in the right side of the beam. The failure observation might misleadingly appear to be accomplished by a single diagonal crack. In reality, four independent diagonal cracks must be identified since they were not formed concurrently. Experimental observation marked the cracks *a* and *b* first at load around 128 KN. As already described, the beam was not failed, but could resist more load until yielding at 233 KN. The beam could further deform after yielding of main bars. Finally, crack *c* and *d* were instantly formed and merged with crack *a* and *b*, thus finalized the failure process.

(3) Beam 3: Much more severe cracking extent in the left side

In beam 3, it was previously indicated that the left side was far more severely cracked by reversed flexural loading than the right side (see **Fig.5**). The failure crack pattern of this beam under shear loading is shown in **Fig.8**. It is noted that no diagonal shear crack penetrated through the web portion in the left side of the beam. Several diagonal cracks with flatter inclination were observed around each large pre-crack instead. It was the right side, side of smaller cracking extent, that diagonal shear crack took place and failed the beam. Relationship between load and deflection is shown in the same figure. Loading capacity was lower than beam 2 but still higher than the non pre-cracked beam. This is justifiable since the width of pre-cracks in the failure side of this beam was considerably less than those of beam 2.

By the same reason as described previously, the smaller width of pre-cracks means less contribution of slip along pre-cracks, while the normal and shear deformational mode of diagonal cracks became more prominent. Consequently, this motivated the unstable crack propagation more promptly than beam 2.

In fact, not only beam 3, in all other beams in which cracking extent was unequal between the left and right sides, shear failure always took place in the side which had smaller width of pre-cracks. This verifies that vertical pre-crack is not necessarily harmful to the beam, at least in terms of structural behavior.

(4) Beam 4: Large spacing of pre-crack

As noted before, in case of beam 4, due to lower level of reversed flexural loading, only one or two large vertical pre-crack(s) appeared in each side of the beam before applying shear load (see **Fig.5**). These cracks, even if comparatively larger than neighboring ones, were still smaller than those in beam 2. Furthermore, they were located approximately around the central portion of shear

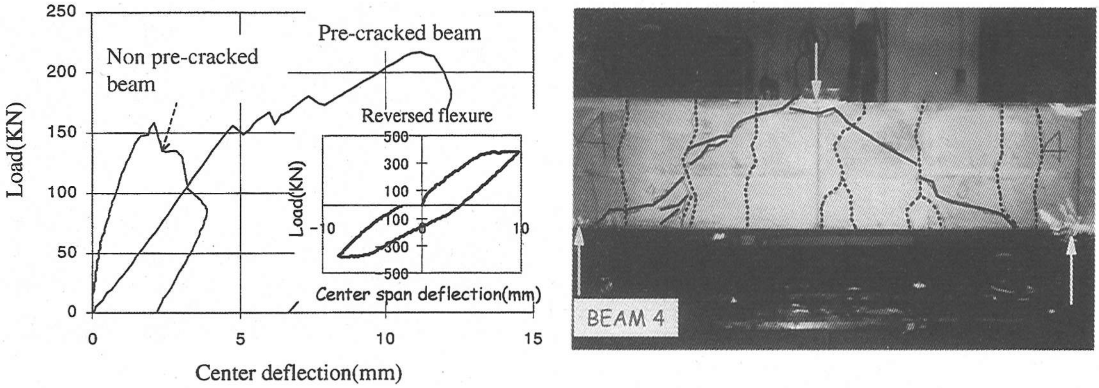


Fig.9 Load-displacement relationship and failure crack pattern of beam 4

span. Failure crack pattern is shown in **Fig.9**. Z-crack could be observed but the geometry was noticeably different from beam 2. The Z-crack in this beam appears to consist in larger part of diagonal cracks than in beam 2. This is logical since in this beam, the width of pre-crack as well as crack spacing was larger as pointed out before.

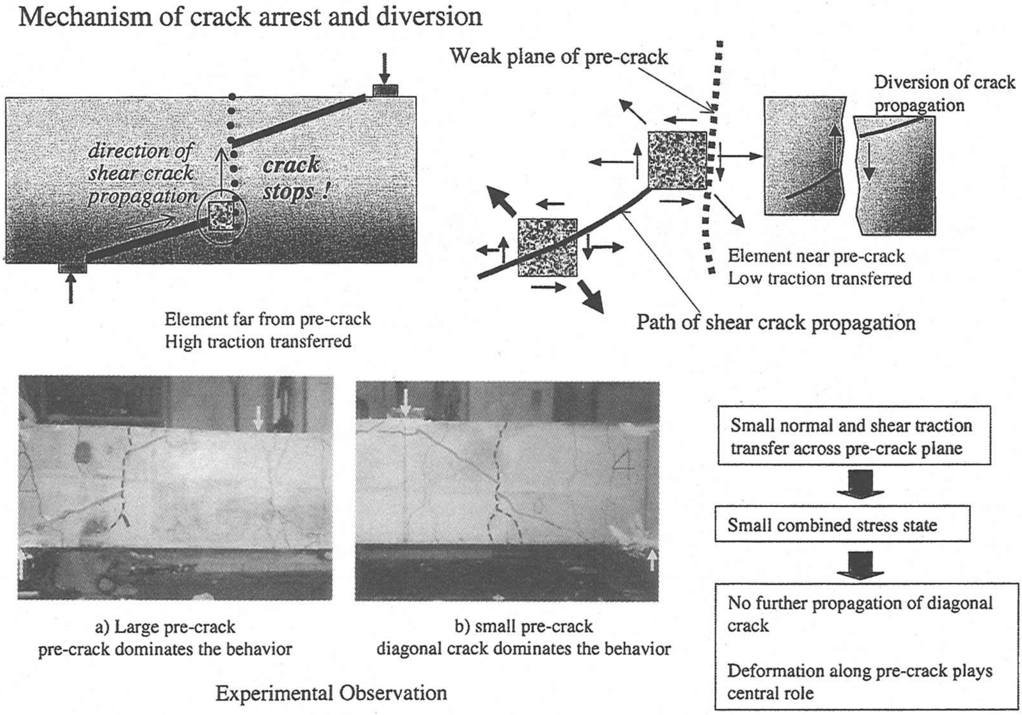
Load-displacement relationship is displayed in the same figure. Nearly 40% increase in shear capacity is noticed. As the role of sliding of pre-crack is less than in beam 2, this smaller increase in loading capacity follows the expectation. However, it is seen that the characters of pre-crack could greatly affect the behavior of beam. Different characteristics of pre-crack could result in different Z-crack geometry, which brought about the different degree in the comparative deformation between pre-cracks and diagonal crack. The relative deformational characteristic was identified to account for the deviation in structural behavior of pre-cracked beam from the non pre-cracked one.

Failure characteristics must be noted and difference from beam 2 in this respect needs to be pointed out. In beam 2, the geometry of Z-crack was such that two component diagonal cracks were too far apart for them to merge each other and failed the beam. The failure process was thus implemented by the development of new diagonal cracks around the web zone, which suddenly merged with previously formed diagonal cracks and failed the beam. This process happened in the very late stage after yielding of main bars. In beam 4, on the other hand, the situation was quite different. As shown in the figure, the constituent diagonal cracks were not located much far away from each other, and thus, they could merge each other and finalized the beam failure. However, this is not the instant process, thus higher load was required to cause the ultimate failure.

4.PHENOMENON OF CRACK ARREST AND DIVERSION

Experimental results have demonstrated that vertical pre-cracks significantly affect the shear behavior of the beam in terms of loading capacity, failure characteristics and load-displacement relationship. The experimentally observed crack pattern has shown that this is due to the presence of pre-cracks that obstructs the continuous and instant propagation of diagonal crack.

Let us consider **Fig.10** which illustrates the RC beam with one vertical pre-crack located at the central portion of shear span. The reason why diagonal crack cannot successfully penetrate across the pre-crack is attributable to the low traction, normal and shear components, transfer ability along the pre-crack. The path of diagonal crack propagation is also shown in **Fig.10**. Two elements located along this path can be differentiated, one near and the other far from the pre-crack plane. The difference between these two elements is that the far element can afford adequate stresses for further cracking, but, the stresses that can be developed in the element near pre-crack depends upon the traction that can be transferred along pre-crack. if pre-crack has sufficiently large width, it can transfer only small traction, which therefore is not enough to cause further cracking. In other words, the diagonal crack will be stopped in the element near pre-crack



a) Large pre-crack
pre-crack dominates the behavior

b) small pre-crack
diagonal crack dominates the behavior

Fig.10 Mechanism of crack arrest and diversion

plane.

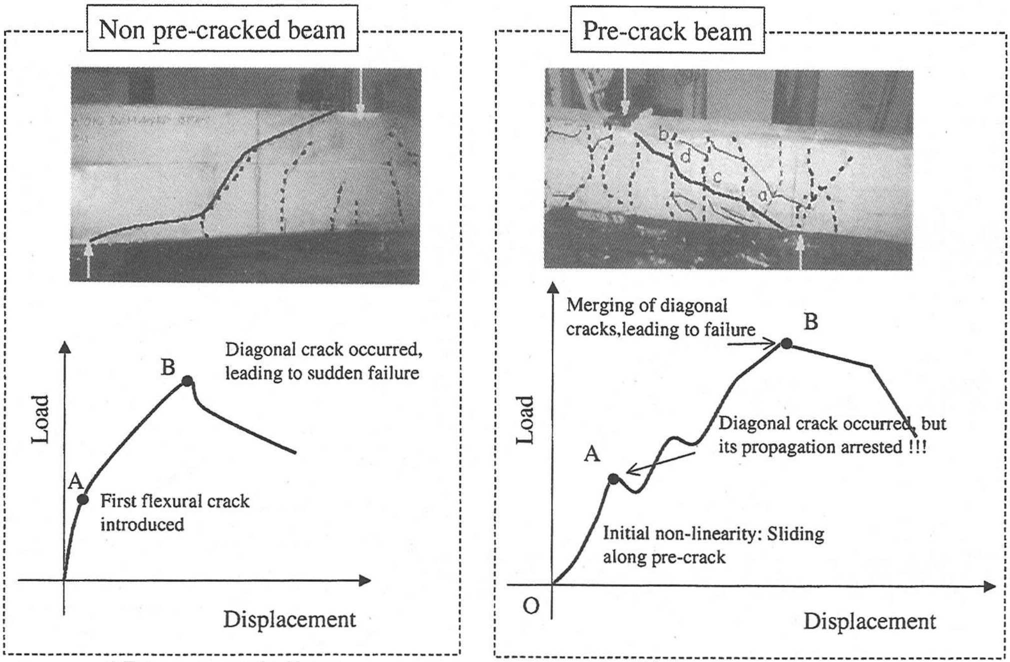
It is further discussed that slip along pre-crack must exist. This slip results in the relative movement between the left and right parts of the beam. Loading condition in the figure moves up the left part and moves down the right part of the beam. With this kinematics and associated slip along pre-crack, it appears as if, diagonal crack has been diverted into the direction of pre-crack. However, this terminology is fictitious since in reality, diagonal crack cannot be physically diverted as such. The actual meaning of crack diversion is in fact to highlight the contribution of slip along pre-crack. Experimental results have revealed the significance of slip along pre-crack by way of the resulting Z-crack pattern. In **Fig.10**, Z-crack is shown and it is by now evident to understand its existence and to understand why it is different from the conventional diagonal crack in the non pre-cracked beam where the slip of pre-crack, of course, vanishes.

The width of pre-crack directly reflects the amount of traction that can be transferred and the amount of slip. In other words, the width of pre-crack affects its relative contribution in the shape of resulting Z-crack. **Fig.10** illustrates two Z-cracks with geometrical difference mirroring the unequal contribution of pre-crack deformation. Perhaps, it can be easily understood that vertical pre-crack in the left figure must be larger than that in the right one since the resulting Z-crack exhibits larger portion of pre-crack.

5.DIFFERENCE IN LOAD-DISPLACEMENT RELATIONSHIP BETWEEN PRE-CRACKED AND NON PRE-CRACKED BEAM

Not only loading capacity and displacement ductility of pre-cracked beams are higher than the non pre-cracked one, but also the load-displacement relationship is greatly different. The comparison between load-displacement relationship of non pre-cracked and pre-cracked beams as shown in **Fig. 7-9** shows this fact. Here, the schematic load-displacement relationship of non pre-cracked and pre-cracked beams are shown in **Fig.11** for comparison.

The load-displacement behavior of a non pre-cracked beam is characterized by the linear elastic portion up to the arrival of the first flexural crack (point A in **Fig.11a**). After that, the stiffness decreases while the beam can continue bearing the load until the formation of the diagonal crack at point B. After the emergence of this diagonal crack,



a) For non pre-cracked beam

b) For pre-cracked beam

Fig.11 Schematic load displacement relationship

the load decreases suddenly and leads to the failure characterized by the unstable propagation of the formed diagonal crack. This typical behavior is well understood and commonly accepted by engineers and researchers.

Conversely the pre-cracked beam shows different and far more complex behavior with higher non-linearity in the load-displacement relation. The representative load-displacement relationship of a pre-cracked beam is shown in **Fig.11b**. The beam displays non-linearity even from the initial stage of loading, which is ascribed to the sliding and opening/closing deformation mode of pre-cracks. This corresponds to the S-curved pattern (line OA) in the load-displacement curve. Point A marks the arrival of first diagonal crack. Accompanying this crack, load temporarily drops but can increase again since the diagonal crack cannot propagate further due to the existence of vertical pre-cracks.

Instead, beam can continue carrying load. The portion AB of the load-displacement relationship corresponds to this load recovery period. As shown in the figure, the behavior during this period is highly non-linear, described by relative deformation behavior of pre-crack and newly formed diagonal cracks with strong crack interaction. Load increases with reduced stiffness. Possible new diagonal cracks can form, which results in the temporary load drop and increase periodically. Accompanying the formation of these new diagonal cracks is the observable gradual degradation in stiffness. Point B represents the point at which several independently formed diagonal cracks merge together along the path connecting loading point to support. Point B therefore means the complete failure path construction. Beams containing pre-cracks show much more severe damages after shear loading due to formation of several discontinuous diagonal cracks at different times in the loading process. As a result of the deformation of these independent diagonal cracks, the stiffness is greatly reduced, the displacement ductility is increased and considerably more energy is required to execute the ultimate failure.

6. BEHAVIOR OF Z-CRACK

Z-crack, one of the main findings from this experiment, is the combined result of diagonal crack and pre-crack. The behavior of a Z-crack is considerably important since it determines the failure characteristics and the ultimate capacity of the beam. Experiments have disclosed a diverse variety of Z-crack geometry, which is affected by physical and geometrical properties of pre-crack. On one extreme, if no pre-crack exists, then diagonal crack totally dominates the behavior. The

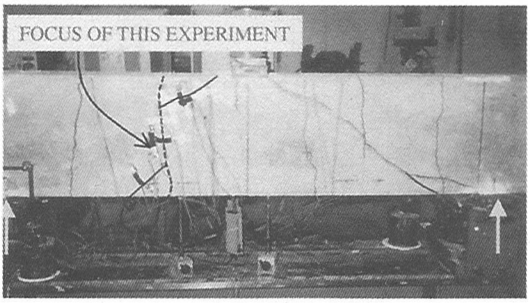
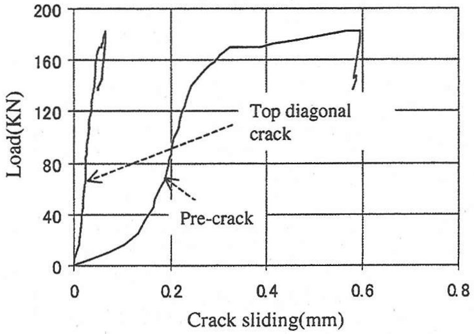
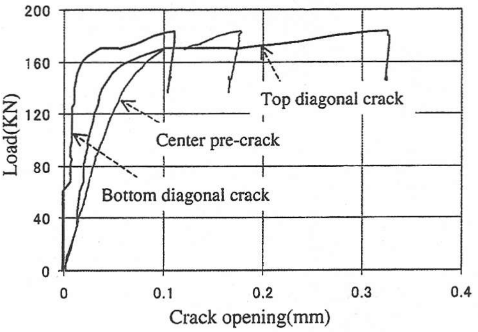


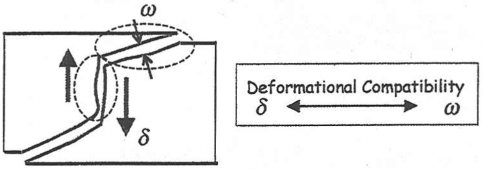
Fig. 12 Z-crack in which crack deformation was measured



(a) Load-crack sliding relationship



(b) Load-crack opening relationship



(c) Deformational compatibility

Fig.13 Load-crack deformation relationship for Z-crack showing the influence of crack interaction

failure is described by the unstable propagation of diagonal crack as already reported.

In the beam with pre-cracks, the geometry of resulted Z-crack governs its characteristics and thereby plays great roles on the beam behavior as already explained in chapter 3. It is supposed that the pronounced slip along pre-crack is closely related to the inactive deformation of diagonal cracks. This represents the clear manifestation of crack interaction, which forms the basis for the mechanics of Z-crack as well as the overall behavior of the beam.

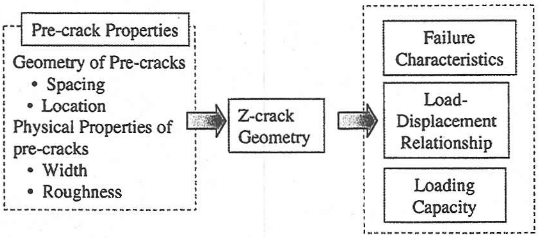


Fig. 14 Influence of pre-crack properties on beam behavior through Z-crack

In order to check the notion of this crack interaction phenomenon, crack deformation was experimentally measured in the experiment. The Z-crack is shown in **Fig.12.** Notice that Z-crack here is largely occupied by vertical pre-crack portion than diagonal crack. The relationship between load and sliding displacement for pre-crack and diagonal crack is shown in **Fig13a.** It can be clearly observed that the sliding along vertical pre-crack is significantly larger than that of diagonal crack, thus verifying its active mobilization.

The relationship between load and crack opening is shown in **Fig13b**. It is observed that both pre-cracks and diagonal cracks have more or less the same order of crack opening. In contrast to the sliding behavior, diagonal crack has been shown to be active in the opening mode. The opening of this diagonal crack results from the deformational compatibility with the sliding of pre-crack as shown in **Fig.13c**. However, this opening is stable and effective in dissipating energy out of the beam. In the experiment, large opening of these diagonal cracks can actually be observed.

In sum, it should be recognized that in a pre-cracked beam, there exist two deformational modes, one relates to pre-cracks and the other to conventional diagonal crack. Kinematics of pre-crack thus differentiates the pre-cracked beam from non pre-cracked one. The two deformational systems compound interactively each other and result in the Z-crack pattern. As concluded in **Fig.14**, several features of pre-cracks such as, the crack width, crack spacing, crack asperity can affect the relative deformation mode, which in turn affects the geometry of Z-crack and the beam behavior.

Fig.15 schematically shows different Z-crack geometry as well as experimental counterparts.

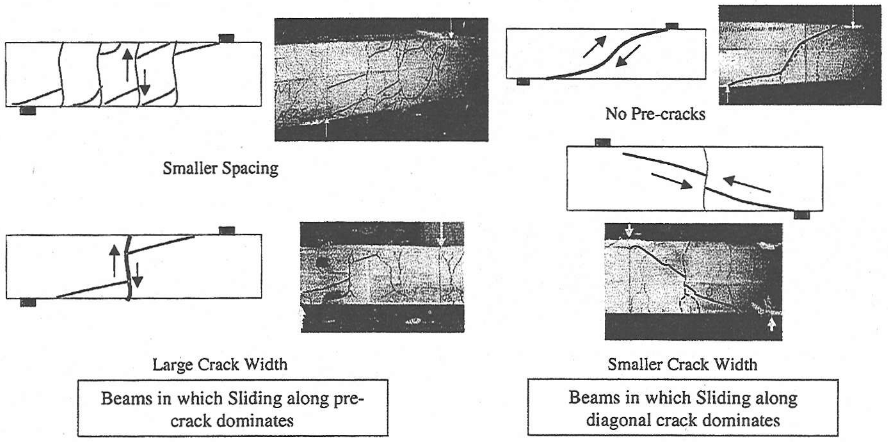


Fig. 15 Influence of pre-crack properties and geometry of Z-crack

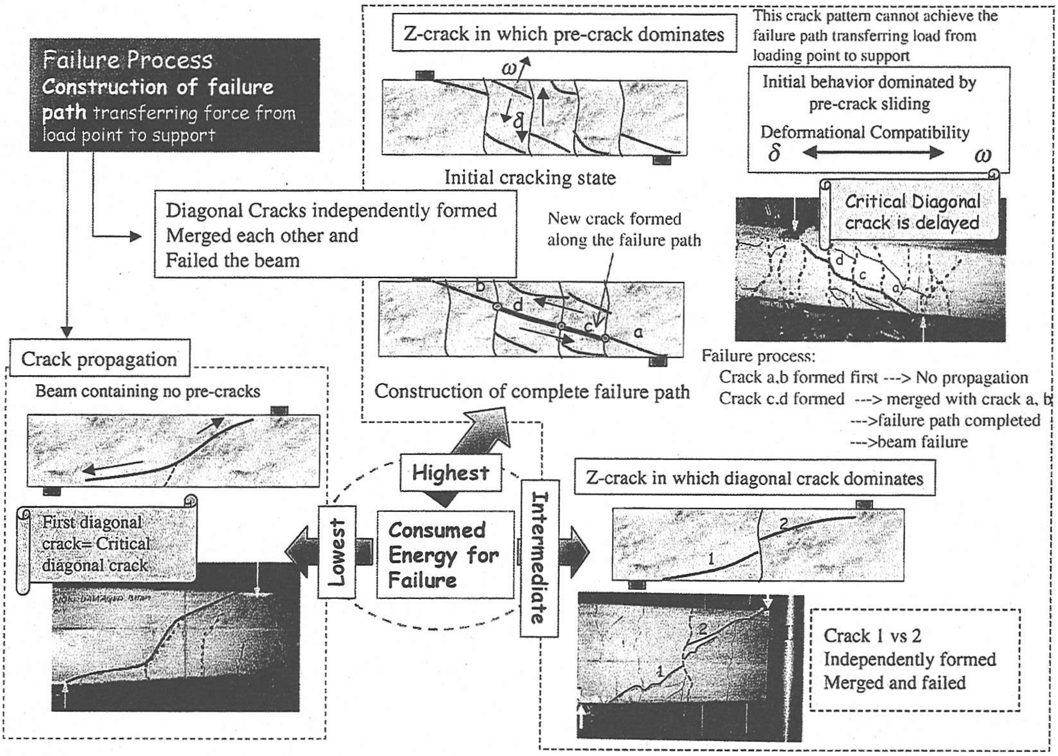


Fig.16 Failure characteristics of pre-cracked beams

For aiding our insight, two groups of beams have been illustrated, reflecting different contribution of pre-cracks and diagonal cracks. For vertical pre-cracks, larger crack width and smaller crack spacing enhances pre-crack contribution. This is classified into the left group. The converse is shown in the right group where diagonal crack dominates if the pre-crack has smaller width or larger crack spacing.

7. FAILURE CHARACTERISTICS OF PRE-CRACKED BEAMS AND CONSTRUCTION OF FAILURE PATH

Failure is defined as the process in which complete crack path is created linking the loading point to the support. The discussion herein aims to indicate the fundamental difference of this process between non pre-cracked and pre-cracked beams. As shown in **Fig.16,** the failure path in a non pre-cracked beam is characterized by the unstable propagation of a single diagonal crack as explained in chapter 3. This kind of failure requires comparatively minimum energy.

On the other hand, beam with pre-cracks shows substantially different behavior. The failure of the beam does no longer exclusively depend upon the propagation of a single diagonal crack. Let us consider the figure, the formed diagonal cracks cannot continuously propagate since they are arrested by vertical pre-cracks. The mechanism of crack arrest promotes the independence in the development of diagonal cracks, and relaxes the degree of localization characterizing the propagation failure.

Therefore, in pre-cracked beams, final diagonal failure cracks result from the merging of several diagonal cracks developed independently rather than the propagation of a single diagonal crack. Typical failure patterns of pre-cracked beams are shown in **Fig.16 (right)**. In a pre-cracked beam, much more energy is required to complete the failure.

8. INITIATION OF DIAGONAL CRACK IN THE PRE-CRACKED ELEMENT

In the previous sections, the main discussion was directed towards the relative deformational characteristics between pre-cracks and diagonal cracks. This highlights the significance of crack interaction that affects the post-diagonal crack behavior. In contrast, post diagonal crack behavior in a non pre-cracked beam involves no crack interaction and thus characterized by abrupt failure. However, the pre-crack not only influences the post-diagonal crack behavior but also affects the generation of a new diagonal crack in the pre-cracked element as well as the non-linearity in the pre-diagonal crack period. This is reasonable since pre-crack exists initially before the application of shear load, and hence allows its kinematics to take effect from the origin.

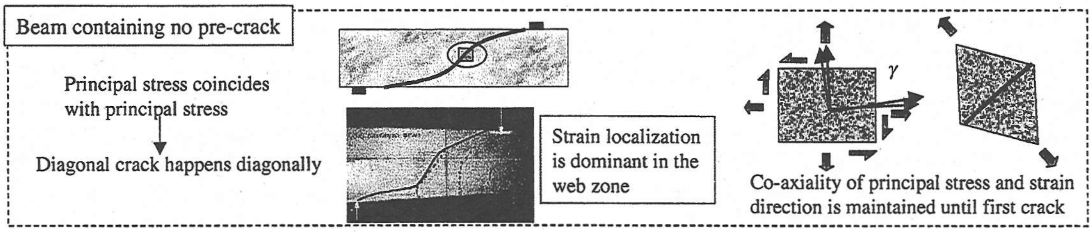
Not only post-diagonal crack manifestation, experiment also demonstrated that the initiation of diagonal crack in a pre-cracked beam greatly differed from that in the non pre-cracked one. In the beam with no pre-cracks, elastic isotropy in behavior may be assumed. This isotropy is consequential as it supports the coincidence between principal stress and principal strain direction, which is well-known as the co-axiality principle. Co-axiality principle is the characteristics of isotropic linear elastic material defined by two parameters, namely, elastic modulus and Poisson ratio. Of course un-cracked concrete solid is neither ideally elastic nor isotropic due to the presence of micro-cracks as well as a certain difference between tension and compression behaviors. Therefore, in the exact sense, this co-axiality principle will never be satisfied for concrete material. However, it can be supposed that concrete element behaves in the isotropically elastic fashion before substantial cracks take place.

As to the formation of a new diagonal crack in a non pre-cracked beam (see **Fig. 17a**), the element at web portion is most strained by the shear action. Due to co-axiality principle, this shear strain induces corresponding shear stress in the diagonal direction, hence leading to the generation of a new diagonal crack there once tensile strength is violated.

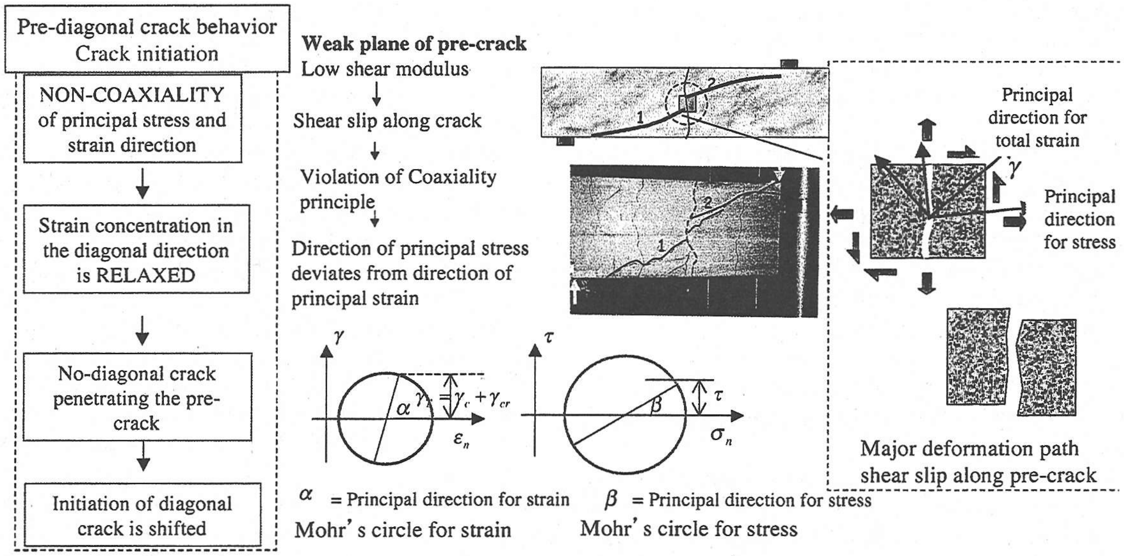
However, in the pre-cracked beam, irrespective of the inclination, but must be of sufficiently large width, no formation of diagonal cracks across the pre-crack can be noticed. In **Fig.17b**, the failure crack of beam 4 in the experiment is shown again here. The pre-cracked element at the center of shear span contains one weak plane in the vertical direction. This imparts the strong anisotropy in shear to the element. The imposed total strain to which the element is subjected must be decomposed into continuum shear strain part and shear slip along pre-crack.

As a result of low traction transfer, this imposed strain cannot proportionally develop enough shear stress on pre-crack surface, thus principal stresses cannot rotate accompanying the principal shear strain. In other words, the stress concentration along diagonal direction is relaxed, which results in no violation of tensile strength, and hence no new initiation of diagonal crack. As a result of this process, shear slip along pre-crack is becoming pronounced as another contribution to the total deformation of the element. This explanation provides the rationale in terms of mechanics of pre-cracked element. The mutual existence of the two deformational modes, one following pre-crack path and the other following conventional diagonal crack path, that supports our main discussion, finds its logical explanation in the aforementioned fundamental mechanics.

Now, the influence of the width of pre-crack is more evident and rational. It is clear that in the element with larger pre-crack, shear slip is more pronounced and therefore becomes more effective in preventing principal stress from co-rotating with principal strain. The implication is that principal stress noticeably lags behind the direction of principal strain. Therefore, a new crack is hardly formed in such element and the deformational mode



a) In a non pre-cracked element: isotropy behavior



b) In a pre-cracked element: anisotropic behavior

Fig. 17 Initiation of a new diagonal crack

basically follows that of pre-crack. The converse is true for the case of smaller crack width.

For the beam shown in the figure, the initiation of a new diagonal crack is not possible at the pre-crack location by the foregoing reasoning. This means that crack *1* and *2* must be independently developed as they are on the opposite side of pre-crack plane. Once created, they separately propagate in the manner that failure path can be made joining loading point to support, hence resulting in the geometry as shown in the figure. Of course, when the propagation reaches pre-crack, it must stop following the concept of crack arrest and diversion. Thereupon, crack interaction plays roles until the combination of these two independent cracks, which calls for the final failure.

Thus, it can be seen that the formation of diagonal cracks in a pre-cracked beam is modified by the presence of pre-cracks. More specifically, the shift in diagonal crack generation leads to the independence in diagonal crack formation and relaxes the localization due to the diagonal crack propagation observed in the non pre-cracked beam. Consequently, the loading capacity of pre-cracked beam can be significantly increased.

9. CONCLUSIONS

Experiment has been conducted to investigate the influence of pre-cracks on the behavior of RC beam in shear. Experimental results indicate the significant difference between pre-cracked beam and non pre-cracked one. RC beams containing vertical pre-cracks show considerably higher shear capacity in comparison with the non pre-cracked case. Not only loading capacity, but also failure characteristics and load displacement relationship greatly differ. Here, the width of pre-cracks has been identified to be the main factor. Explanation of the experimental results was provided in regard to the comparative deformational characteristics between pre-crack and diagonal crack in the pre-cracked beam. This relative deformational characteristics is equivalent to the crack interaction in line with the active crack scheme[8]. Phenomenon of crack arrest and diversion is identified to be the cause of discontinuous propagation of diagonal cracks. As a result, Z-crack is the sensible outcome described by the shared contribution of both pre-crack and diagonal crack.

Geometry of pre-cracks greatly affects the Z-crack geometry, which in turn influences the shear behavior of the beam. Pre-crack affects the beam behavior not only in the post-diagonal crack range but also in the pre-diagonal crack range and the initiation of new diagonal crack. The anisotropy of pre-cracked element due to low traction transfer along its surface does not allow the principal stress to co-rotate with the imposed total strain. This therefore results in no formation of diagonal crack at the location of pre-crack. Instead, large slip along pre-crack results. Here, rationale in fundamental mechanics exists, that can explain the influence of pre-cracks logically.

ACKNOWLEDGEMENT: The authors would like to express their gratitude towards TEPCO foundation in providing financial supports for carrying out the experiment.

REFERENCES

1) Okamura, H. and Higai, T.: Proposed design equation for shear strength of reinforced concrete beams without web reinforcement, *Proc. of JSCE,* Vol.300, pp.131-141, 1980.
2) ASCE-ACI committee 445 on shear and torsion: Recent approach to shear design of structural concrete, *J. Struct. Eng.,* Vol.124, pp. 1375-1417, 1998.
3) Yamada, K. and Kiyomiya, O.: Shear resistance of reinforced concrete beams with initial penetrating cracks, *JCI,* Vol.17, No.2, pp. 791-796, 1995 (In Japanese)
4) Tamura, T., Shigematsu, T. and Nakashiki, K.: About the increase in shear capacity of RC beam under axial tension, *Proc. of the 54th JSCE annual convention,* pp.608-609, 1999 (In Japanese)
5) Tamura, T., Shigematsu, T., Hara, S. and Nakano, S.: Experimental analysis of shear strength of reinforced concrete beams subjected to axial tension, *Concrete Research and Technology,* JCI, Vol.2, No.2, 1991
6) Suzuki, T., Takiguchi, K. and Hotta, H.: Control of deformation of mechanism for ductile R/C column, *Proceeding of JCI symposium on design of reinforcement and ductility of concrete structures,*1990
7) Standard Specification for design and construction of concrete structures -1986 part 1[design], JSCE
8) Okamura, H., and Maekawa, K.: *Nonlinear analysis and constitutive laws of reinforced concrete,* Gihodo-shuppan, Tokyo, Japan, 1991

(Received April 18, 2000)

せん断を受けるRC部材の挙動に及ぼす先行ひび割れの影響

ピマンマス　アモン・前川　宏一

本研究は，せん断を受ける鉄筋コンクリートはりのせん断挙動に及ぼす，先行ひび割れの影響を検討したものである．厳しい実環境下におかれる部材では，予めひび割れが導入されることは避けられない．この先行ひび割れが構造的に導入されるせん断ひび割れに及ぼす影響について，実験的検討を行った．予めひび割れが先行して存在する梁のせん断破壊挙動と，部材貫通するような先行ひび割れがない梁とでは，挙動に大きな差が見られた．せん断ひび割れに非直交する先行ひび割れによってせん断耐力が向上し，荷重-変形関係が変化することが示され，この機構について検討を加えた．