- Technical Paper -

EXPERIMENTAL STUDY ON SHEAR CRACKING BEHAVIOR IN I-SHAPED PARTIALLY PRESTRESSED CONCRETE BEAMS

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ABSTRACT

An experimental program was conducted to investigate the shear cracking behavior in I-shaped reinforced concrete and I-shaped partially prestressed concrete beams. All beams were tested under four point static monotonic loading by focusing on the influence of compressive stress in concrete due to prestress, stirrup ratio, side concrete cover, type of stirrup and longitudinal reinforcement ratio on the shear crack width. During the loading test, shear crack width was monitored close to stirrup strain gage attached by using digital microscope.

Keywords: prestressing, shear crack width, stirrup strain, principal strain

1. INTRODUCTION

Prestressed concrete beams incorporating with non-prestressed steel reinforcements are built today with an allowance of tension in concrete, which are well known as partially prestressed concrete (PPC) or prestressed reinforced concrete (PRC, in Japan). The wide cracks allow water to penetrate into concrete structure and may cause corrosion of embedded steel reinforcements, which adversely affects the long term durability performance of the structure. Comprehensive experimental studies on cracking behavior of reinforced concrete (RC) beams and PRC beams have been conducted over the last five decades. Most of the studies are concerned with flexural cracking behavior, but very few studies have been done on shear cracking behavior [1].

Mechanism of shear cracking is more complex than that of flexural cracking, because shear crack is generally not perpendicular to the stirrups. Previous studies [1] have shown that shear crack width is generally larger than flexural crack width in members with orthogonal reinforcement due to diagonal strain being larger than reinforcement bar strain. In addition, it has shown that strain in web reinforcement is the most important factor affecting the shear crack width in RC beams. Previous studies [2-4] have shown that stirrup ratio can have significant effect on shear crack width of RC beams. The shear crack spacing is mainly dependent on the longitudinal and transverse crack spacing. The recent concept by Zararis [5] also shows that the amount of web reinforcement may not be the only factor for adequate control of shear cracking. It was pointed out that the amount of longitudinal reinforcement can have a significant effect on the opening of critical shear cracks. Based on the literature review, it is clear that the mechanism of shear cracking is not fully understood, particularly influencing parameters on shear crack width of PRC beams.

Nowadays, I-shaped partially prestressed concrete structural members are widely used in the constructions field. In addition, available experimental data on shear cracking in PRC beams are very limited compared to those on flexural cracking. The objective of this study is to investigate shear cracking behavior in I-shaped RC and PRC beam, focusing on the effects of prestressing force, side concrete cover, stirrup ratio, type of stirrups and amount of longitudinal reinforcements on shear crack width.

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2. EXPERIMENTAL PROGRAM

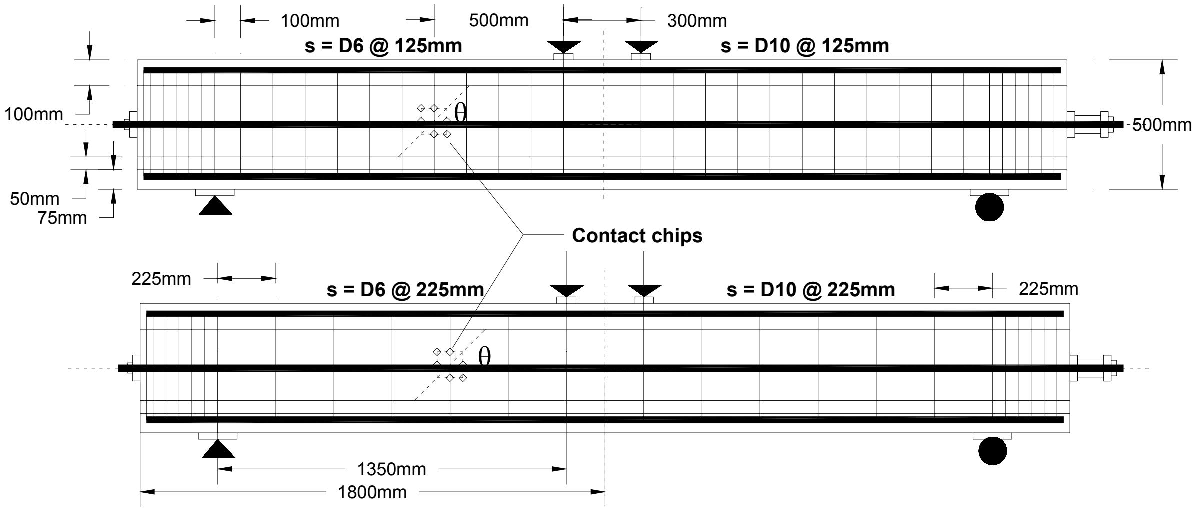


Fig. 1 Layout of the specimens

Table 1 Experimental variables

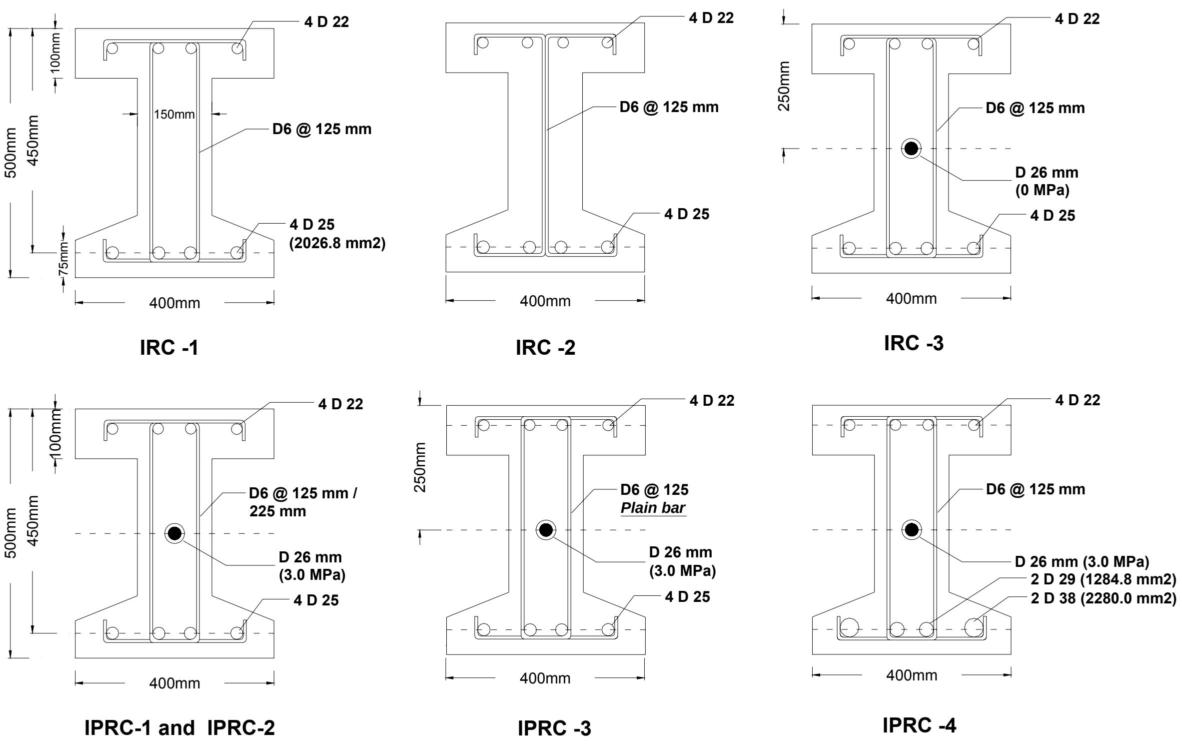
Beam #	Non-prestressed reinforcement		Prestressing force (kN)	Stirrup spacing (mm)
	Top	Bottom		
IRC-1	4 D22 (ds'=40 mm)	4 D25 (*ds*=450 mm)	-	125
IRC-2				125**
IRC-3			0*	125
IPRC-1			375.0 (3.0 MPa)	125
IPRC-2				225
IPRC-3				125***
IPRC-4		2 D29 and 2 D38 (*ds*=450 mm)		125

* no prestressing
** maximum side concrete cover (69mm)
*** plain stirrups

Table 2 Mechanical properties of reinforcements

Type of bar	Φ (mm)	Type	*fy* (MPa)	Es x 10^3 (MPa)
Plain bar	Φ6	SWM-B	353	167.7
Deformed bar	D6	SD 345	438	180.4
	D10		376	200
	D22		397	
	D25	USD 685	720	206
	D29		735	
	D38		726	
PC bar	26	SBPR 1080/1230	1205	200

In order to investigate the influence of different parameters including prestressing force on shear crack width in PRC beams, the following experimental program was carried out. The compressive stress in concrete due to prestress ($\sigma_{c,pc}$), stirrup spacing, type of stirrup, side concrete cover and amount of longitudinal reinforcements were the main experimental parameters. Test specimens consisted of three RC and four PRC beams having I-shaped cross section. A total length of beam is 3600 mm. The typical layout and cross sectional details of the specimens are shown in Figs. 1 and 2, respectively. The experimental variables are summarized in Table 1. The mechanical properties of reinforcements used are listed in Table 2. In all test specimens, stirrups were provided in two different sizes of stirrup bars; D6 bars were in the left span of the beams and D10 bars were in the right span of the beams. This was necessary to ensure the main shear crack would occur in the left span of the beam. Ready mixed concrete with the maximum size of aggregate of 20 mm was used. Four point symmetrical loading with a distance of 300 mm between the loading points (shear span to effective depth ratio (a/d) of 3.0) was statistically applied to all specimens. Contact chips were pasted on the concrete surface at 500 mm from the left-loading point of the beam in the shear span regions so as to measure the principal strains and their directions. A digital microscope, which has a precision of 0.001 mm, was used to capture digital photographs of the crack occurred in the left span of the beam (Fig. 3). The digital image captured at the crack location was used to measure the crack width at three arbitrary extracted points close to the location of necessity. The average of measured three crack widths was used as the crack width at that location.



All dimensions in mm.

Fig. 2 Cross sections

Fig. 3 Measuring crack width by using digital microscope

Table 3 Failure load

Beam #	Failure load (kN)	*f'c* (MPa)	Failure mode
IRC-1	559.7	40.3	Shear failure without yielding tension reinforcements. All stirrups yield.
IRC-2	579.8	45.4	
IRC-3	629.0	44.0	
IPRC-1	706.8	41.8	
IPRC-2	644.1	49.3	
IPRC-3	622.7	45.0	
IPRC-4	745.0	43.2	

3. TEST RESULTS AND DISCUSSION

3.1 Failure Mode and Crack Pattern

Crack patterns at failure for all specimens are shown in Fig. 4. All specimens failed in shear failure mode (Table 3) with wide shear cracks in the shear span region.

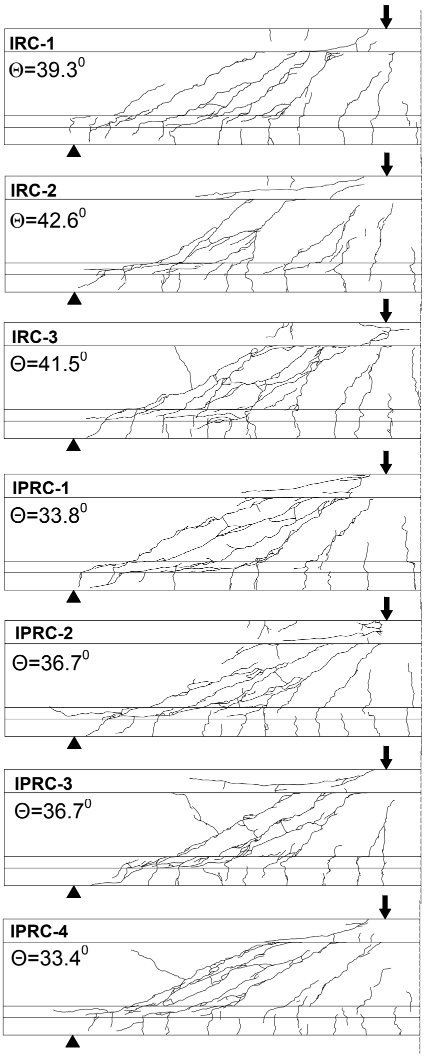


Fig. 4 Crack patterns

The inclination of shear cracks were determined by averaging the crack angle measured in the shear span region. It can be seen that the inclination of shear cracks slightly decrease in PRC beams due to prestress.

3.2 Effect of Side Concrete Cover

Fig. 5 shows the relationship between shear force and maximum shear crack width. Specimens IRC-1 and IRC-2 were designed to have side concrete cover of 25 mm and 69 mm, respectively. It can be seen that the occurrence of shear cracks were delayed in beam IRC-2 and at the same load level beam IRC-2 showed smaller shear crack width. However, maximum stirrup strain variation with shear force shows (Fig. 6) almost same increment rate of stirrup strain in both specimens. Moreover, since the crack pattern in beam IRC-2 was rather extraordinary by showing widely spaced cracks (Fig. 4), a further investigation is considered to be necessary to clarify the effect of side concrete cover on shear crack width.

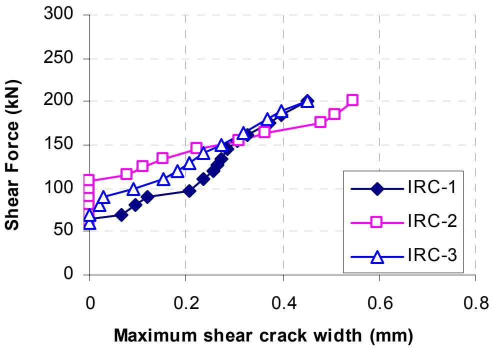


Fig. 5 Shear crack width in RC beams

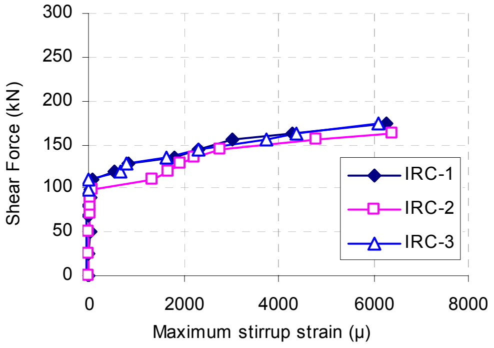


Fig. 6 Stirrup strain in RC beams

3.3 Effect of Prestressing Force on Shear Crack Width

Compressive stress in concrete due to prestress ($\sigma_{c,pc}$) in PRC specimen would increase shear cracking load compared to RC specimen. The load when the shear crack width starts to increase or stirrup strain starts to accumulate was considered as the shear cracking load. The difference in shear cracking load of RC and PRC beams was well observed in Figs. 7 and 8. In addition, $\sigma_{c,pc}$ causes a reduction in the maximum shear crack width at the same shear force level compared to IRC-3 beam. The compressive stress in concrete due to prestress ($\sigma_{c,pc}$) has an influence only on increasing the shear cracking load. After the occurrence of shear cracks, increment rate in the shear crack width seems not be affected by $\sigma_{c,pc}$.

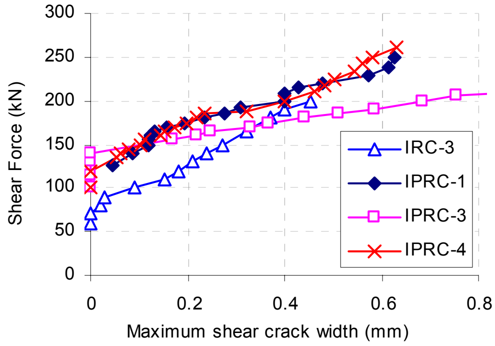


Fig. 7 Shear crack width in beams with prestressing tendon

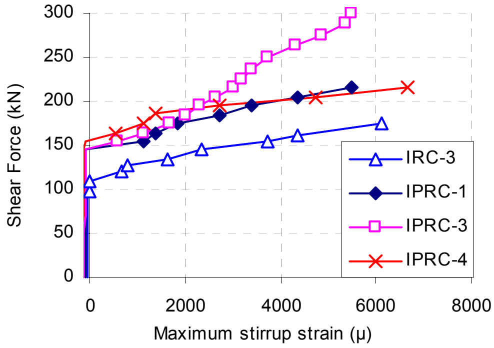


Fig. 8 Stirrup strain in beams with prestressing tendon

3.4 Type of Stirrup on Shear Crack Width

Beams IPRC-1 and IPRC-3 were designed to have deformed and plain type stirrups, respectively. Beam IPRC-3 showed larger shear crack width compared to the other PRC specimens at the same shear force level (Fig. 7). In addition, beam IPRC-3 shows higher increment rate in stirrup strain with increasing shear force. It implies that plain stirrup showed larger shear crack width due to poor bond characteristics between concrete and stirrup bar.

3.5 Effect of Amount of Longitudinal Reinforcement on Shear Crack Width

Beam IPRC-1 was provided longitudinal reinforcement (ρ_s) of 1.13% while IPRC-4 was provided that of 1.98%. With increasing shear force, maximum shear crack width shows same increment rate in IPRC-1 and IPRC-4 at the same shear force level (Fig. 7). In addition to that, increment rate in stirrup strain with shear force almost same in both specimens implying that the effect of longitudinal reinforcement on shear crack width is not well pronounced in PRC beams.

3.6 Effect of Stirrup Ratio on Shear Crack Width in PRC Beams

To investigate the effect of amount of stirrup ratio on shear crack width of IPRC-1 and IPRC-2, stirrup ratio was varied from 0.338% (s=125 mm) to 0.188% (s=225 mm), respectively as shown in Figs. 1 and 2. Figs. 9 and 10 show the variation of shear crack width and stirrup strain with shear force, respectively. These figures imply that shear cracking load seems not to be affected by the stirrup ratio. In addition, maximum shear crack width seems to be independent from stirrup ratio, particularly at the lower shear force in PRC specimens with higher level of prestress ($\sigma_{c,pc}$).

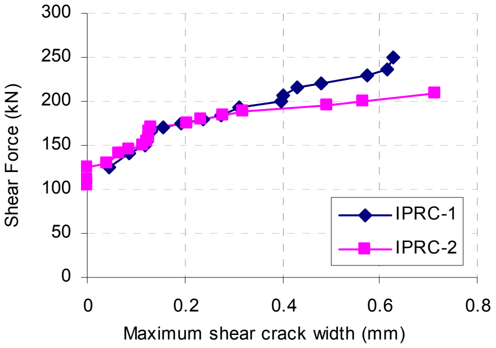


Fig. 9 Stirrup ratio on shear crack width

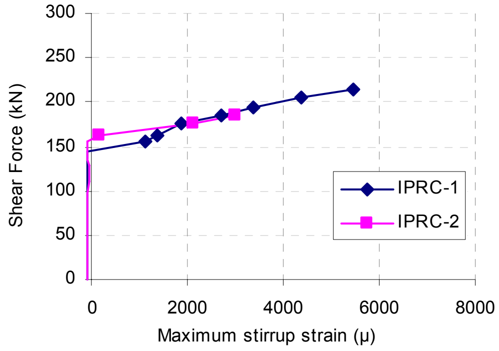


Fig. 10 Stirrup ratio on stirrup strain

3.7 Distribution of Stirrup Strain along Beams Depth

Fig. 11 shows the distribution of stirrup strain (stirrup at 500 mm from loading point) at different loading stages, along the beam depth for IRC-1, IPRC-1 and IPRC-3 specimens. It was clear that shear crack width intersected with stirrup causes sudden increment in stirrup strain gage attached close to the stirrup–shear crack intersection. Especially in case of IPRC-1specimen, shear cracks appeared slightly lesser inclination to the member axis compared to RC specimens (see Fig. 4). Therefore, there are no stirrup strain increments in the top strain gages on the stirrup-leg. However, completely different stirrup strain distribution could be seen in IPRC-3 specimen, which had plain stirrups. The uniform distribution of stirrup strain was observed due to different bond characteristics between the stirrup and concrete associated with plain stirrup. The uniform distribution of stirrup strain along the beam IPRC-3 is due to that the poor bond characteristics between the plain stirrups and the concrete caused slip during shear crack cross the stirrup leg.

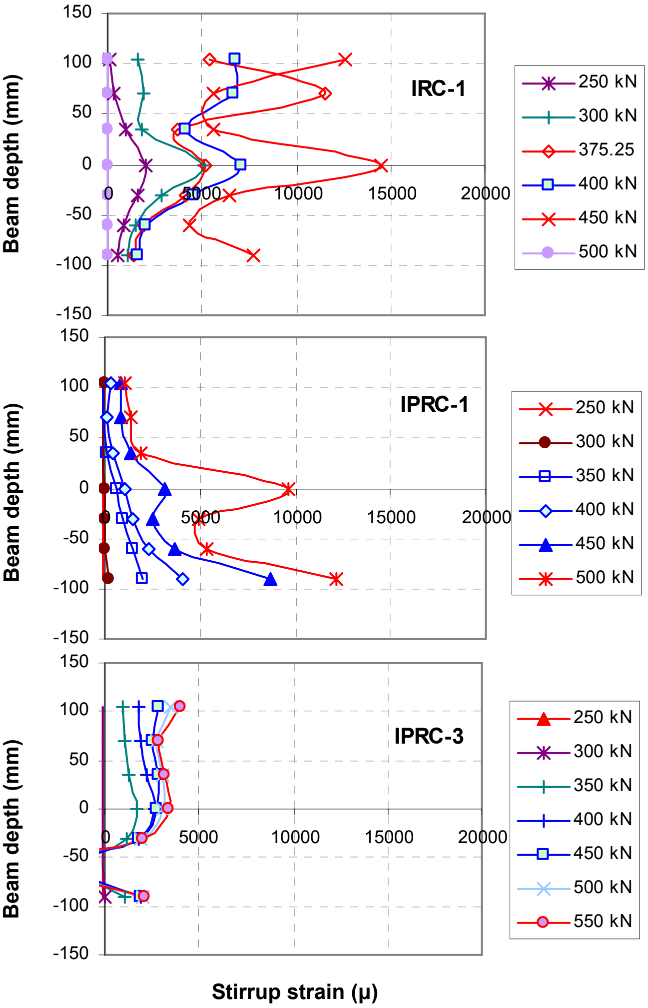


Fig. 11 Stirrup strain distribution in beam depth

3.8 Direction of Principal Strains

The direction of principal strains is important in that it is widely used to analyze the shear behavior of RC and PRC beams. The direction of principal strain (θ) was obtained from the measurement of triangular deformation (measured using contact chips as shown in Fig. 1) using a theory of Mohr's Circle. Figs. 12 and 13 show the variation of principal directions with an increase of shear force. It is clearly seen from these figures that the principal directions are almost constant until the first crack occurs. After occurring the first crack, the directions of principal strain decrease with increasing shear forces in RC and PRC beams. In addition, it was clear that initiation of first crack within the shear span region appeared at lower shear force in RC beams compared to that in PRC beams. This implies that the compressive stress in concrete due to prestress has an influence on increasing the shear cracking load in PRC beams compared to RC beams. The principal directions at the elastic load stage are about 40 ~ 50 degrees and decrease with an increase of shear force at the ultimate load stage approximately 20 to 30 degrees. The present study and study by Bhide [2] indicate that the principal directions rotate greatly with the increase of shear force. This fact can be effectively used in the shear analysis of RC and PRC beams by using truss model or modified compression field theory (MCFT) model.

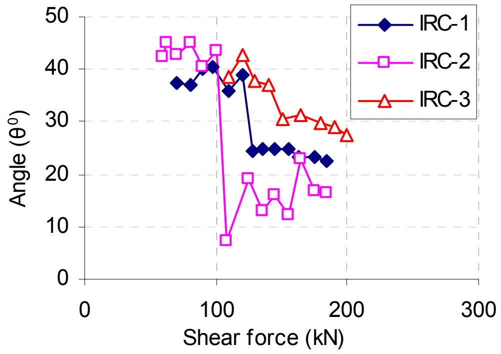


Fig. 12 Principal direction in shear span of RC beams

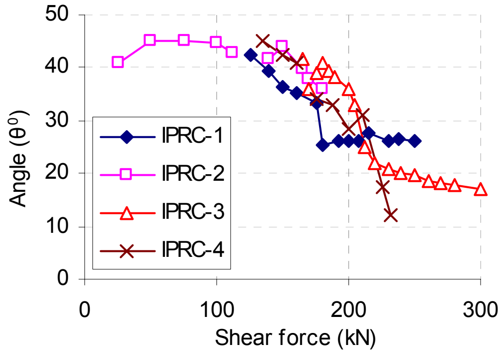


Fig. 13 Principal direction in shear span of PPC beams

4. CONCLUSIONS

The effect of compressive stress in concrete due to prestress, stirrup spacing, side concrete cover, type of stirrup and amount of longitudinal reinforcement on the shear crack width were experimentally investigated using I-shaped RC and I-shaped PRC beams under static loading. The following conclusions are derived from this study:

(1) The compressive stress in concrete due to prestress increase the shear cracking load in PRC beams; however after shear cracks appeared the effect of prestressing force was not well pronounced.
(2) The amount of longitudinal reinforcements was found to be insignificant on shear crack width in PRC beams.
(3) The effect of type of stirrups on shear crack width was found to be rather important parameter than the stirrup spacing in PRC beams. With increasing load the beam having plain stirrups shows larger shear crack width compared to other beams. This is due to the poor bond characteristics between the concrete and plain stirrup bar.

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