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SHEAR BEHAVIOR OF PRETENSIONED PRESTRESSED CONCRETE BEAMS

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1. INTRODUCTION

In the last few decades precast concrete structural members have become very popular in the construction field due to the saving of construction time and better quality control. Among such members, pretensioned prestressed concrete members are most economical and prevalent because of easy treatment. However, problems may happen in the stress transfer region of the beam ends when a shear span-to-depth ratio is low and shear behavior is dominant.

In this paper the discussion begins with the influence of shear cracks on slippage of prestressing strands for pretensioned T-beams with typical commercialized dimensions. Then, a device for anchorage of strands is introduced, and the discussion is extended to the shear behavior of beams when the slippage of strands is restricted.

2. EXPERIMENTAL PROGRAM

The experimental program was designed mainly to study the influence of slippage of prestressing strands on shear behavior of pretensioned prestressed concrete beams. In addition, three different types of shear reinforcement were used to examine the contribution of stirrup to shear behavior of beams.

Test specimens are categorized into three groups. The first group represents typical commercialized T-beams. The cross sectional shape and dimensions are shown in Fig.1. The longitudinal tension reinforcement were two 15M deformed bars and two 13 mm 7-wire stress-relieved prestressing strands. The shear span length is 1150 mm (a/d=2.69) and the length outside a support is 250 mm. Four beams with different types of stirrup were tested statically. One out of four beams was a specimen without web reinforcement. Three different types of stirrup were conventional single legged and double legged stirrups, and welded wire fabric. A spacing of stirrup was kept constant as 152 mm. The difference lies mainly in material properties and the cross sectional area of stirrup. The details of specimens are shown in Table 1.

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For specimens in the second group, nothing was different with the shape and the dimension of specimen. Only the difference was to introduce an anchorage device at the ends of beams for prevention of slippage of prestressing strands. At each end of a beam, a bearing plate and a chuck were attached to improve embedment of strands. Two beams were tested. One was a beam without web reinforcement, and the other was with stirrup of welded wire fabric.

In order to make shear behavior prominent, the amount of longitudinal reinforcement was increased for the third group (three 20M bars were added.). In addition, the length outside a support was enlarged as 750 mm for providing adequate development length of strands. However, the cross sectional shape and the shear span length were identical to the first and the second groups, and the end anchorage device for strands was the same as used in the second group. Four beams were tested. Shear reinforcement configuration was the same as that in the first group.

Fig.2 shows the test set-up. The load was applied at *30 KN (15 KN in* one shear span) intervals up to shear crack initiation, and at 15 KN intervals up to failure. At each interval, the strains of longitudinal bars, prestressing strands and stirrups were measured. The deflection of the beam was also measured by LVDT's. These readings were recorded by the data aquisition system. Concrete strain and crack width were measured by contact strain meter at each interval. The reading was conducted manually.

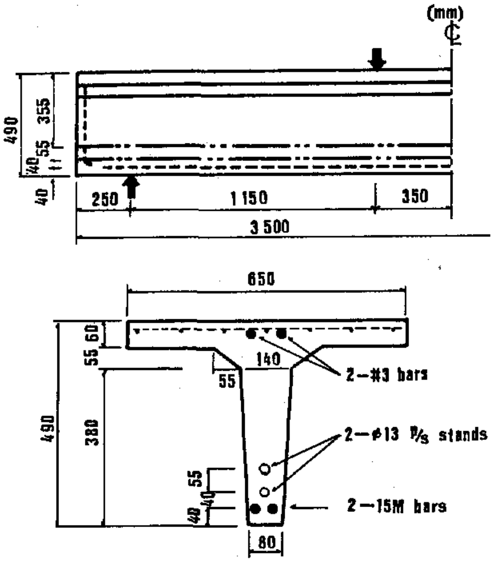

Fig. 1 Test Specimen

Table 1 Details of Specimen

Specimen	Stirrup	A_v (mm^2)	s (mm)	f_{vy} (MPa)	A_s (mm^2)	f_y (MPa)
PS1-0	Non	---	---	---	400	400
PS2-S6M	single leg	29.0	152	536		
PS3-D2	double leg	62.3	152	335		
PS4-WD	WWF, D4.7	25.9	152	645		
PS5-0-E	Non	---	---	---	400	400
PS6-WD-E	WWF, D4.7	25.9	152	645		
PSN1-0	Non	---	---	---	1300	400
PSN2-S6M	single leg	29.0	152	536		
PSN3-D2	double leg	62.3	152	335		
PSN4-WD	WWF, D4.7	25.9	152	645		
All beams have two P/S strands; A_p=198 mm^2, f_{pu}=1860 MPa.						

Note: -E ; Second Group, with end anchorage device
PSN-; Third Group, with additional three 20M bars and end anchorage device

3. TEST RESULTS AND DISCUSSION

Prestress Losses

The prestress losses were evaluated by readings of strain gages attached to the prestressing strands. The readings of strains were taken by strain indicators periodically from the time of prestressing to the testing day. Fig. 3 shows the distribution of prestress losses after 30 days of casting.

As to the transfer length, the ACI code[1)] specifies it as 50 d_b. The test results showed very good agreement with the code. The prestress loss at the mid span was about 18 %. The value is a little higher than the calculated one which is about 15 % based on the PCI Recommendations for Estimating Prestress Losses[2)]. The age of testing varied from 31 days to 56 days after casting. However, the change of prestress losses after 30 days was observed very little.

Failure Mode

Fig. 4 shows typical crack pattern and the stress in prestressing strands. At the load of 90 - 105 KN the first shear crack initiated with steep inclination beneath the loading point. With increase of load a couple of shear cracks appeared. As shown in Fig. 4, shear cracks change the stress distribution in prestressing strands. When a large shear crack crosses the strand, the strand picks up large force at the crack crossing point. Then, an arch action becomes dominant in the load transfer mechanism. This results in inadequate embedment of prestressing strands.

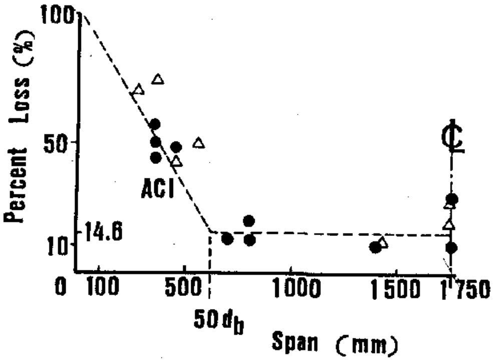

Fig. 3 Distribution of Prestress Loss

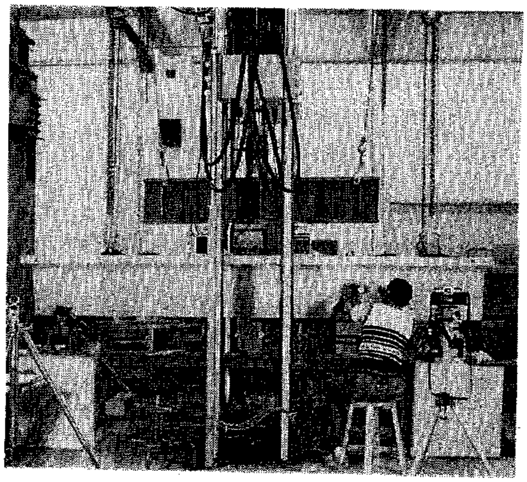

Fig. 2 Test Set-up

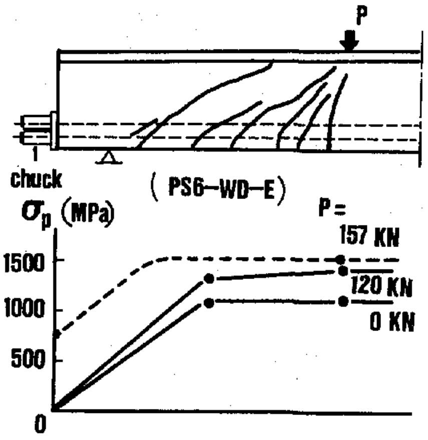

Fig. 4 Shear Crack Pattern and Strand stress

Fig.5 shows load - deflection curves. Until initiation of shear cracks, the load-deflection curve was quite identical. Beams in the first group (PS1-0, PS4-WD) showed a kind of yield behavior after slippage of strands. The end anchorage device (PS6-WD-E) proved good improvement for strand slippage. Beams with large amount of longitudinal reinforcement and enough embedment length of strand (PSN1-0, PSN4-WD) had more stiffness after initiation of shear cracks than others. It is also recognized that stirrups increase the stiffness of a beam after shear cracking.

Although large shear cracks developed in all four beams of the first group and two of the second group, shear failure was not recognized in these six beams. After reaching the maximum load, the beam could deflect in a large amount without reduction of strength. The test was terminated by the stroke limit of an actuator (100 mm). At this stage, shear crack width was more than 1.0 mm in any case. Notwithstanding large shear crack width, the concrete of top flange was neither ruptured nor crushed.

On the other hand, all four beams in the third group failed in shear, in other words, a large diagonal crack finally run through the top flange outside the loading point (See Fig.6.). The first shear crack initiation load was almost the same as the load in the first and the second group, but the maximum load (at shear failure) was quite high.

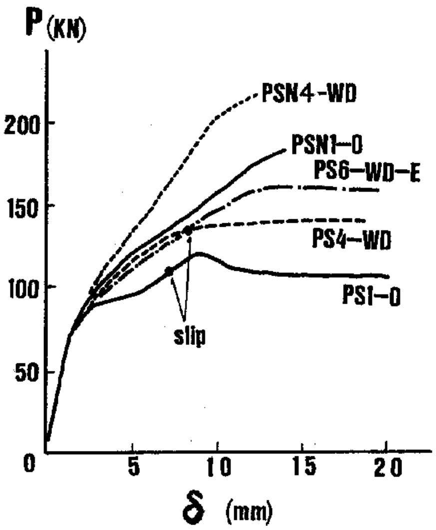

Fig.5 Load-deflection Curves

Ultimate Strength

The test results and the calculated results were summarized in Table 2. To estimate the shear strength of the beam without web reinforcement, the ACI1) code and JSCE recommendation3) were used. The contribution of web reinforcement was taken into account by the truss analogy with compression strut angle of 45 degree.

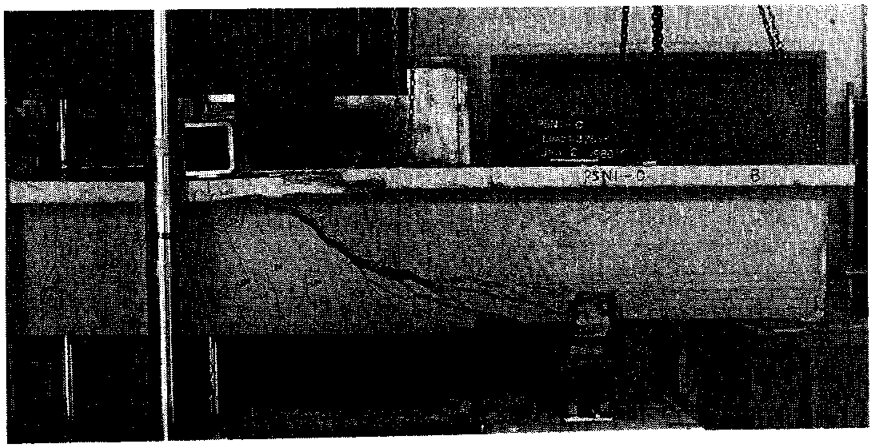

Fig.6 Shear Failure (PSN1-0)

Initially, all beams were expected to fail in shear. However, the large shear crack reduced the development length of prestressing strands, and led to premature failure in four beams of the first group. The end anchorage device in the second group might be effective to prevent slippage of strands. Since both beams with and without stirrup (PS6-WD-E, PS5-O-E) indicated the similar maximum load, the maximum load might represent the ultimate flexural strength. But, it is very curious that some stirrups of the beam PS6-WD-E had already yielded before the maximum load was reached. (See Table 2.) This suggests that the load carrying mechanism is not so simple as assumed by the truss analogy.

In the third group the shear strength of the beam without stirrup (PSN1-O) was unpredictably high. Moreover, the contribution of stirrup was larger than the expected value by the truss analogy. The shear crack angle became flat, and the number of yielded stirrup was more than the expectation. The similar results were reported by Robertson et al.4) for prestressed concrete T-beams.

However, as far as the shear crack initiation load is concerned, the ACI code equation gives good prediction.

Shear Crack Width

Fig.7 shows maximum crack width in various specimens. At lower load level (V<100 KN) the maximum crack does not necessarily stand for the shear crack. After the load exceeds 100 KN, the shear crack became superior in crack width. In the beams without stirrup, the shear crack propagated rapidly once it occurred (PS1-O, PSN1-O). On the other hand, in the beams with stirrup, better anchorage of prestressing strands restricted propagation of shear cracks, and increased the shear strength. The difference between beams with various types of stirrup was very little.

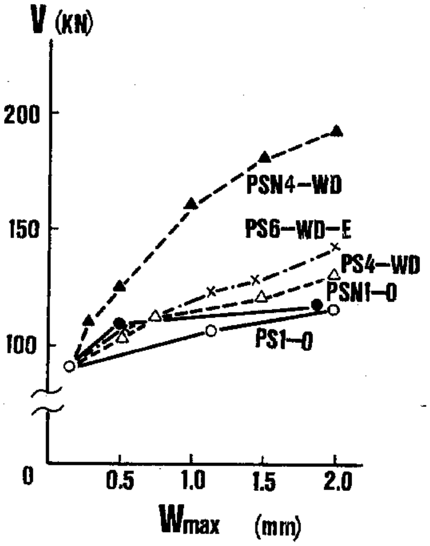

Fig.7 Maximum Crack Width

Table 2 Test and Calculated Results

Specimen	f'_c (MPa)	Load in a shear span (KN)							
		Tested				Calculated			
		Yield of stirrup	Slip of strand	V_{cr}	V_{max}	V_c ACI	V_c JSCE	V_s	M_u/a
PS1-O	44.4	---	113	90	121	95	86	---	180
PS2-S6M	43.5	135	136	98	151	95	86	38.9	
PS3-D2	44.7	135	145	95	156	95	86	52.1	
PS4-WD	38.1	120	135	101	139	93	83	41.2	
PS5-O-E	41.4	---	---	98	157	94	85	---	
PS6-WD-E	42.8	120	---	94	157	94	85	41.2	
PSN1-O	36.1	---	---	104	188	93	83	---	290
PSN2-S6M	32.5	140	---	105	254	91	82	38.9	
PSN3-D2	33.3	120	---	105	258	91	82	52.1	
PSN4-WD	38.1	135	---	98	218	93	84	41.2	

4. CONCLUSION

1) The initiation of shear cracks impairs embedment of prestressing strands, and causes slippage of strands. This results in premature failure of pretensioned prestressed concrete beams.
2) Slippage of strands decreases the flexural strength, and may prevent shear failure although it makes shear crack wide.
3) The role of stirrup in pretensioned prestressed concrete beams is not so simple as assumed by the truss analogy. The shear crack initiation load may be predicted by the ACI code equation, but the maximum load or the ultimate shear strength of a beam looks much higher than expected, especially for beams in the third group.
4) There was little difference in effectiveness of various types of stirrup on shear behavior.

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