SHEAR BEHAVIOR OF PRESTRESSED CONCRETE BEAMS WITH LARGE ECCENTRIC EXTERNAL TENDONS

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1. INTRODUCTION

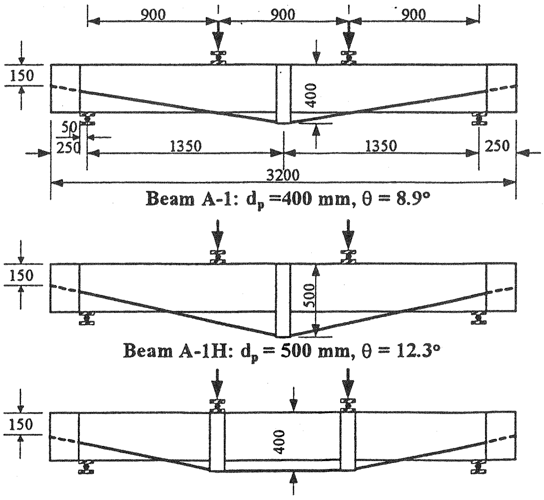
External prestressing is a post-tensioning method in which external tendons are placed outside the concrete section by deviating at the intermediate deviations and anchored to the ends of the structure. In case external tendons are arranged at the level below or above the total depth of concrete structures, it is particularly considered as beam with large eccentricity. Recently, the concept of external prestressing has been widely utilized not only for designing new bridge structures but also for strengthening existing concrete structures, particularly for enhancing the ultimate flexural strength [1]. Although, there have been numerous reports on flexural behavior of PC beams with external tendons, only a few reports on the shear behavior have been published. To obtain a better understanding of the shear capacity of PC beams with large eccentric external tendons, an experimental and analytical study was carried out with emphasis on the influence of the profile of external tendon.

2. EXPERIMENTAL PROGRAM

Test specimens consisted of four simply supported beams, where three of which were prestressed with different profile of external tendons as shown in Fig. 1. The test variables and material properties are summarized in Table 1 and 2, respectively. Beam A-0 was designated as a RC beam without external tendon. Beam A-1 has the same

Table 1 Test variables

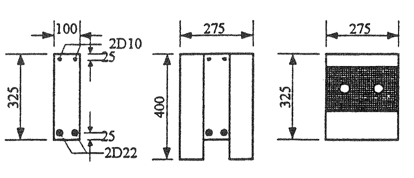
Beam	Tendon's depth (mm)	Shear span (mm)	f_c' (Mpa)	Main reinforcement		Effective Prestressing Force	Parameters
				Top	Bottom		
A-0	-	900 (a/d = 3.0)	37.6	2D10	2D22 (2.6%)	-	Control beam
A-1	400		40.4			16 kN (8.8% f_{pu}) SWPR7A - 2T9.3 mm (A_{ps} = 103.2 mm^2)	One deviator
A-1H	500		39.3				Tendon's depth
A-2	400		38.7				Two deviators



Beam A-1: d_p =400 mm, θ = 8.9°

Beam A-1H: d_p = 500 mm, θ = 12.3°

Beam A-2: d_p = 400 mm, Two deviators, θ = 12.3°



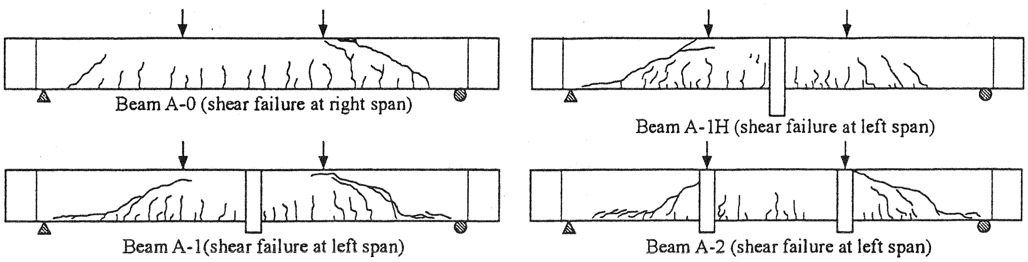
Typical section Deviator section End section

Table 2 Material properties

Type	Yield Stress (N/mm^2)	Breaking Stress (N/mm^2)	Modulus of Elasticity (N/mm^2)
SWPR7A ϕ 9.3 mm	1686	1860	192300
SD345D10	416	577	201000
SD345D22	407	557	199000

(All dimensions in mm.)

Fig. 1 Details of beams strengthened with external tendons


Beam A-0 (shear failure at right span)

Beam A-1H (shear failure at left span)

Beam A-1(shear failure at left span)

Beam A-2 (shear failure at left span)

Fig. 2 Cracking patterns and failure mode

variables as beam A-0 except the provision of external tendons at the depth of 400 mm by one deviator at the midspan section (draped tendon's profile). To investigate the effect of tendon's depth, beam A-1H was prestressed with larger eccentric external tendons (d_p= 500 mm). Beam A-2 was provided with two deviators at the one-third span sections having the tendon's depth of 400 mm. The inclination of external tendon of beam A-2 was designed to be identical as that of beam A-1H (θ = 12.3°). It should be noted that the deviators were post-attached to the concrete beams by epoxy resin and steel bolts to provide a fixed connection with the beam. The maximum permissible prestressing force of 16 kN was applied to the external tendons, without exceeding the allowable tensile stress at the top fiber of concrete section. The specimens were tested up to failure by two-point static loading, having a span length of 900 mm, resulting in a shear span-to-effective depth ratio (a/d) of 3.0.

3. TEST RESULTS AND DISCUSSIONS

3.1 Cracking patterns and failure mode

The cracking patterns and failure mode are shown in Fig. 2. It can be seen that, in all beams, flexural cracks were first observed in pure bending moment region. As the load was increased, flexural shear cracks also developed in the shear span region of the beams. Furthermore, it was found that the inclination of diagonal crack in beam A-0 (RC beam) was slightly smaller than that of beams prestressed with external tendons, implying that the prestressing by external tendons has influenced the direction of principal stress. However, the effect of tendon's depth and location of deviators on the crack patterns of beams with external tendons was found to be insignificant in this test program. At the ultimate state, all the test beams failed in diagonal-shear mode in which one major diagonal crack that extended up to the loading point from the support was observed.

3.2 Load-deflection characteristic

The relationship of load and midspan deflection is shown in Fig. 3. It can be seen that beam A-0 (control beam) registered lower stiffness throughout all steps of loading compared to those of beams prestressed with external tendons. The effect of tendon's depth could be investigated by comparing beam A-1 (d_p = 400 mm) with beam A-1H (d_p = 500 mm). Beam A-1H, which was provided with larger eccentric external tendon, showed slightly higher stiffness as well as the ultimate shear strength. As for beam A-2, in which deviators were provided at the one-third span sections, the overall structural behavior was almost the same as that of beam A-1H. This is because the stress

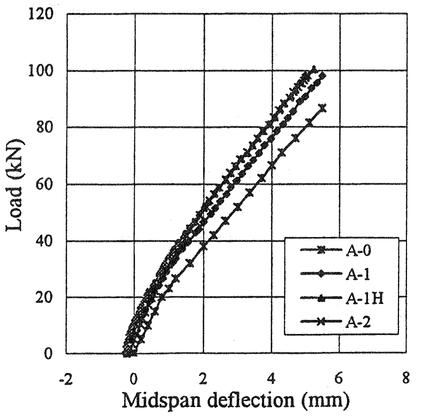


Fig. 3 Load and midspan deflection relationship

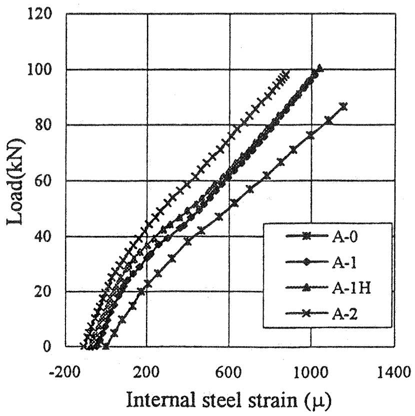


Fig. 4 Strain in nonprestressed reinforcement

increase in external tendon of these two beams was similar as load was increased, thus providing the same influence on the overall behavior of the beams. The ultimate strength of beam A-2 (P_u = 98.1 kN), however, was found to be slightly less than that of beam A-1H (P_u=100.4 kN). This may be caused by the lower actual compressive concrete strength at testing of beam A-2. Considering the ultimate shear strength, it can be observed that beams prestressed with external tendons showed an increase of approximately 17% over the control RC beam (beam A-0).

3.3 Strain in nonprestressed reinforcement

Figure 4 shows the variation in strain in longitudinal nonprestressed reinforcement at the critical sections of the beams. It can be seen that the rate of increase in internal steel strain was faster after cracking than before cracking and similar behavior was observed for all the beams. At the same loading, all strengthened beams with external tendons exhibited lower strain in longitudinal nonprestressed reinforcement compared to that of RC beam (A-0), indicating the influence of external prestressing with large eccentric tendons.

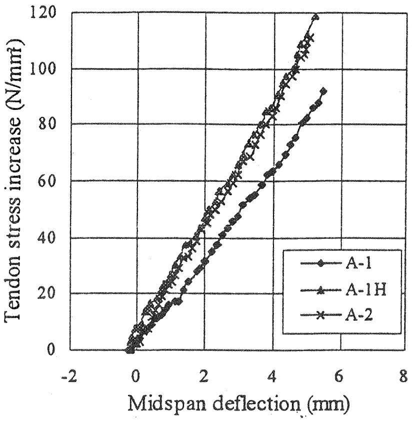


Fig. 5 Stress increase in external tendon

3.4 Stress in external tendons

As shown in Fig. 5, it can be seen that stress in external tendons increased in a linear manner with midspan deflection up to the ultimate state. However, the rate of stress increase was less in beam A-1 (17.6 MPa/mm) compared to that of beam A-1H (22.6 MPa/mm). This can be attributed to the different geometric shape of external tendons in which the effective depths of external tendon are 400 mm and 500 mm in beam A-1 and A-1H, respectively. It is important to note that the rate of tendon stress increase was almost the same in beam A-1H and A-2 (two deviators). This may result from the fact that the profile of external tendon in beam A-2 was designed to have the same inclination in the shear spans as that in beam A-1H (see Fig. 1). In addition, the loss in tendon's eccentricity, which generally influences the flexural behavior of externally PC beam, was found to be negligible as a result of small ultimate deformation of beam due to non-ductile shear failure.

4. COMPARISON WITH ANALYTICAL RESULTS

A nonlinear finite element approach (WCOMD Ver.5 [2]) was adopted to simulate the shear behavior of PC

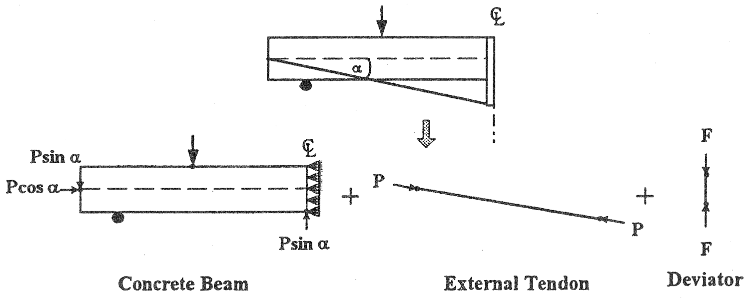


Fig. 6 Analytical model of test beams

Table 3 Comparison of experimental results with analytical prediction

Beam	Shear strength (kN)			Ultimate tendon stress (MPa)			Ultimate deflection (mm)		
	Exp.	Analysis	Correlation[*1]	Exp.	Analysis	Correlation[*1]	Exp.	Analysis	Correlation[*1]
A-0	86.6	89.1	1.029	-	-	-	5.59	6.12	1.095
A-1	98.1	101.5	1.035	241.4	259.8	1.076	5.49	5.87	1.069
A-1H	100.4	106.7	1.063	262.1	280.6	1.071	5.25	5.77	1.099
A-2	98.1	106.3	1.084	259.0	282.2	1.090	5.06	5.87	1.160

Note: *1 correlation given is the ratio of analysis/experiment beams with external tendons. The analytical model consisted of three components: concrete beam, external tendon, and strut deviator (see Fig. 6). The concrete beam was modeled using 8-node RC plate element considering as a normal RC beam and the effect of external prestressing was incorporated as externally applied axial and vertical forces at the end anchorages and deviators. The external tendon and the deviator were modeled using truss element, in which the deviator was considered as a rigid element with no deformation under loading. The comparisons between experimental and analytical results are given in Table 3. It can be seen that there is a good agreement between them, regarding the shear strength, stress in external tendon and deflection at the ultimate state. Therefore, it can be concluded that the finite element approach used in this study is able to satisfactorily simulate the shear behavior of PC beams with large eccentric external tendons.

5. CONCLUSIONS

The following conclusions can be drawn based on the experimental and analytical investigations on shear behavior of PC beams with large eccentric external tendons carried out in this study.

(1) The concept of the external prestressing with large eccentric tendons can be effectively utilized for enhancing not only the ultimate flexural strength but also the ultimate shear strength of existing concrete structures. An increase in the ultimate shear strength of approximately 17% was obtained in beams prestressed with large eccentric external tendon.

(2) The influence of tendon's profile on the enhanced shear strength, however, was found to be insignificant. This may be attributed to the fact that stress increase in external tendon was diminutive due to small deformation of the beam that failed in non-ductile shear mode.

(3) Stress increase in external tendon has a linear relationship with the midspan deflection. The amount of stress increase was greater in beams with larger tendon's depth or larger inclination of tendon, resulting in slightly higher ultimate shear strength.

(4) The finite element approach used in this study is able to satisfactorily simulate the shear behavior of PC beams with large eccentric external tendon with regard to the shear strength and stress in external tendon at the ultimate state.

REFERENCES

1) Harajli, M. H. (1993), Strengthening of Concrete Beams by External Prestressing, PCI Journal, V.38, No.6, Nov.-Dec., pp. 76-88.

2) Okamura, H. and Maekawa, K. (1991), Nonlinear Analysis and Constitutive Models of Reinforced Concrete, Gihodo Press, Tokyo.