論文 Effect of Tendon Configuration on Shear Strength of Externally PC Beams with Large Eccentricity

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ABSTRACT: Studies on shear behavior of externally Prestressed Concrete (PC) beams have been very few compared to flexural behavior, especially in beams with large eccentricity. To have a better understanding of the shear behavior of such beams, an experimental program was carried out to investigate the effect of tendon configuration (tendon area, tendon eccentricity and effective prestress force) on the shear strength and failure mode. The results of this experimental program are presented and discussed in this paper.

KEYWORDS: prestressed beams; external prestressing; large eccentricity; shear strength

1. INTRODUCTION

The concept of external prestressing with large eccentric external tendon has been recently developed for new bridge structures. In this innovative structure, external tendons are placed outside and far lower than the depth of main girders by means of intermediate deviators and end anchorages. Aravinthan et al. [1] have conducted a research work to study the flexural behavior of externally PC beams with large eccentricity. It has been found that the ultimate flexural strength of such beams was greatly enhanced due to a substantial stress increase in large eccentric external tendon. To adopt this concept for real bridge structures, however, an understanding of the shear behavior is also necessary.

The shear failure phenomenon of externally PC beams is a sudden phenomenon due to non-ductile behavior [2]; hence, it should be prevented in general design. Nevertheless investigations on shear behavior of externally PC beams have so far been very few compared to flexural behavior, particularly in beams with large eccentricity [3]. The contribution of external tendon to resist shear force is generally considered in terms of axial compressive and vertical component of prestressing force. Consequently, the amount of force increase in external tendon, which depends on various factors such as tendon configuration [4], is an important parameter affecting the ultimate shear strength and failure mode. This study was carried out to investigate the effect of tendon configuration (tendon area, tendon eccentricity and effective prestressing force) on the ultimate shear strength of externally PC beams with large eccentricity without web reinforcement.

2. EXPERIMENTAL PROGRAM

2.1 TEST SPECIMENS AND EXPERIMENTAL VARIABLES

Previous study [5] has shown that the externally PC beam with large eccentricity has sufficient shear strength; therefore, it is not likely to collapse in shear failure. However, it is important to

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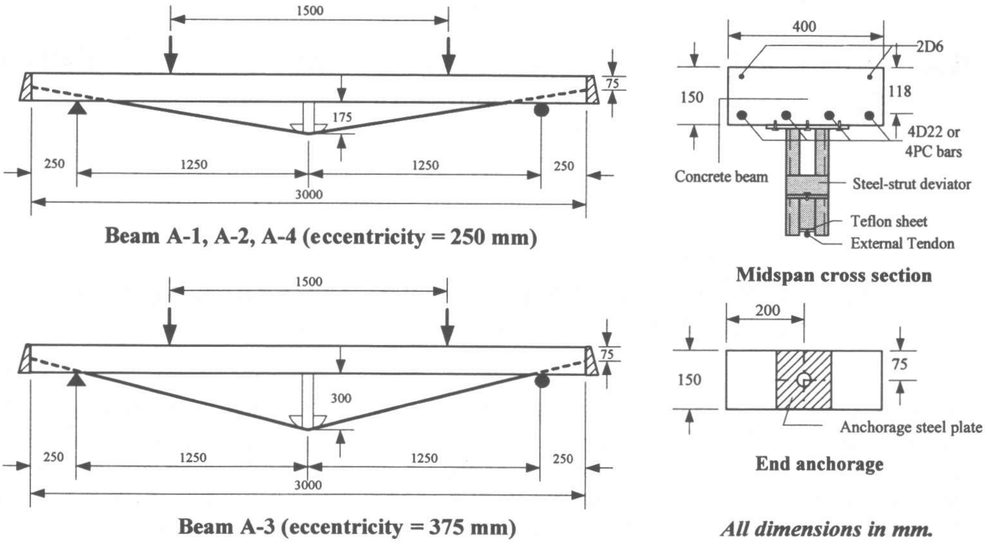

Beam A-1, A-2, A-4 (eccentricity = 250 mm)

Beam A-3 (eccentricity = 375 mm)

Midspan cross section

End anchorage

All dimensions in mm.

Fig.1 Details of test specimens

investigate the characteristic of shear failure of this structure in order to adopt this concept in real bridge structures. As a result, test beams with quite large amount of longitudinal reinforcement and without web reinforcement were used in this study. The test specimens consisted of four simply supported beams, each 3.0 m in total length and with cross section dimensions and reinforcement details as shown in Fig. 1. All test beams were prestressed with external tendons, deviated at midspan section by steel-strut deviators and anchored at the ends of the specimen, forming a single-draped tendon profile. The experimental variables are summarized as shown in Table 1. The mechanical properties of prestressing steel used for external tendons are given in Table 2.

Table 1 Experimental variables

Beam	Nonprestressed Reinforcement		External Tendon (SWPR7A-type)			f_c' (MPa)	Parameters
	Top	Bottom	Diameter	Eccentricity (mm)	Effective PS Force (kN)		
A-1	2D6	4D22	1T9.3 mm (A_{ps} = 51.61 mm^2)	250	9.5	37.8	Control beam
A-2	2D6	4D22	1T12.4 mm (A_{ps} = 92.9 mm^2)	250	10.3	38.9	Tendon area
A-3	2D6	4D22	1T9.3 mm	375	6.8	38.7	Tendon eccentricity
A-4	2D6	4PC bars ϕ 23 mm	1T12.4 mm	250	24.8	39.2	Effective prestress, Tensile strength steel

Beam A-1 was designed as the control beam in which the external tendon with diameter 9.3 mm was provided at the eccentricity 250 mm. To investigate the effect of external tendon area, beam A-2 was designed to have the same properties as beam A-1, except the area of external tendon was increased to 92.3 mm^2. In beam A-3, external tendon was arranged at larger eccentricity (375mm) compared to beam A-1 (250 mm) and applied with effective prestress force of about 7 kN. This amount of prestress force was designed to produce the same compressive stress at the concrete bottom fiber of beam A-1 during the initial prestressing. Beam A-4 was applied with higher prestress force (25 kN) to study the influence of effective prestress force on the ultimate shear strength. To reduce the influence of friction force, the teflon sheet was inserted at the surface between steel-strut deviator and external tendon. It should be noted that beam A-4 was provided with 4PC bars as longitudinal reinforcement in order to increase the ultimate flexural strength, thus to cause a definite shear failure of the beam.

Table 2 Mechanical properties of prestressing steel

Type	Area (mm^2)	Yield load (kN)	Breaking load (kN)	Elastic Modulus (MPa)
SWPR7A 1T9.3mm	51.61	87	96	192300
SWPR7A 1T12.4mm	92.9	159	174	192300
PC bar ϕ 23 mm	415.5	462	492	203700

2.2 LOADING METHOD AND INSTRUMENTATION

Static two point symmetrical loading with a distance between loading points of 1.50 m, giving a shear span-to-total depth ratio (*a/h*) of 3.33, was adopted as the loading method. During loading, measurements of deflections at midspan and loading points, concrete and nonprestressed strains of concrete and nonprestressed steel at a section near loading points were made. Force in external tendon was monitored by using load cells at the end of beams as well as strains from the electrical resistance strain gages attached to the external tendon along the beam length.

3. TEST RESULTS AND DISSCUSSION

The effect of tendon configuration on shear strength of PC beams with large eccentricity was studied by comparing the test results as summarized in Table 3. Discussion is made on crack pattern and failure mode, load-deflection response, force in external tendon, respectively.

Table 3 Summary of experimental results

Beam	Cracking Load (kN)		Ultimate Load (kN)	Deflection (mm)		Force in External Tendon F_{ps} (kN)			Failure Mode
	Flexure	Shear		Initial	Ultimate	Effective	Ultimate	ΔF_{ps}	
A-1	36.8	171.7	193.3	- 0.34	21.7	9.5	33.0	23.5	Diagonal tension
A-2	34.3	186.4	229.7	- 0.42	27.1	10.3	61.3	51.0	Shear compression
A-3	34.3	186.4	189.3	- 0.54	18.6	6.8	34.8	28.0	Diagonal tension
A-4	34.3	181.5	249.0	- 0.86	24.7	24.8	73.5	48.7	Shear compression

3.1 CRACK PATTERNS AND FAILURE MODE

Crack patterns and location of failure are shown in Fig. 2. In all the beams, flexural cracks started to develop in the entire midspan region between two loading points and subsequently in the shear span regions where diagonal tension cracks occurred. As load was increased, diagonal cracks propagated rapidly towards the concrete compression zone under loading points, but with slightly different inclination. The inclination of such diagonal cracks in beams with smaller tendon area (A-1 and A-3) was approximately 30°, while it was about 25° in beams with larger tendon area (A-2 and A-4). At the ultimate state, the mode of failure was also different, that is a tied arch mechanism was developed in beams with larger tendon area (A-2 and A-4) after the appearance of diagonal crack, leading to further load carrying capacity and eventually failed by crushing of concrete at regions

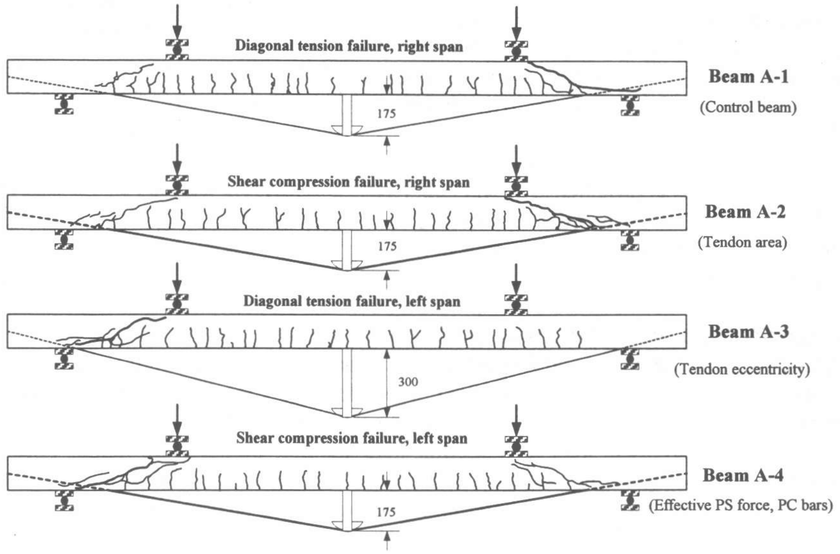

Fig.2 Crack patterns and failure mode

under loading points (*shear-compression failure*), whereas beam A-1 and A-3, having smaller tendon area, failed immediately after the formation of diagonal cracks (*diagonal tension failure*).

3.2 LOAD-DEFLECTION RESPONSE

Comparison of the applied load-midspan deflection response of all specimens is shown in Fig. 3. It can be seen that all the beams exhibited nearly similar behavior up to the occurrence of flexure crack (about 35 kN). Beyond that, however, beams with larger tendon area (A-2 and A-4) registered higher stiffness than beam with smaller tendon area (A-1). Similarly, the same characteristic was also observed in beam A-3, in which the tendon eccentricity was higher than beam A-1 (375 mm and 250 mm, respectively). This is mainly due to the difference of tendon force increase, where beam A-1 showed the lowest amount of force increase compared with other beams due to the effect of tendon eccentricity and tendon area. Comparing beam A-2 with beam A-4 (see Fig. 3), the influence of effective prestressing force could be obtained. Beam A-4 with higher effective prestress force (25 kN) registered higher stiffness after the occurrence of flexural cracks compared with beam A-2 (10 kN). However, it should be noted that this difference was partly attributed to the different area of internal reinforcement (154.8 mm^2 and 166.2 mm^2 for beam A-2 and A-4, respectively). A slight drop of loading near the ultimate state in beams A-2 and A-4 was due to the appearance of large diagonal cracks. But, beyond that, beams still carried further load by forming a tied arch mechanism, leading to the development of diagonal crack in the other span and, finally, failed in shear-compression mode. Considering

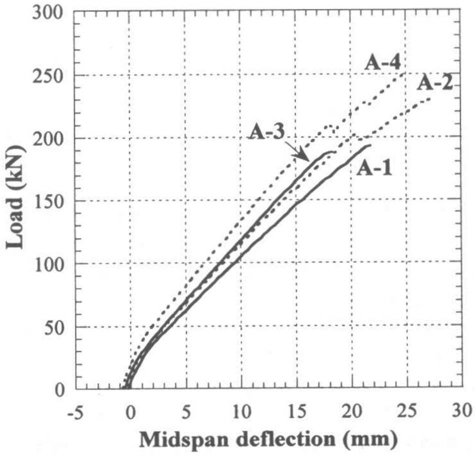

Fig. 3 Load-deflection response

the ultimate load, it can be seen from Table 3 that beams A-2 and A-4 registered higher ultimate shear strength (229.7 kN and 249.0 kN, respectively) than beam A-1 (193.3 kN), which is the control beam with lower tendon area. This clearly indicates the effect of tendon area on increasing the ultimate shear strength. However, by comparing beam A-3 (P_u=188.4 kN) with A-1 (P_u=193.3 kN), it was found that tendon eccentricity had no large influence on the ultimate shear strength. This may be attributed to the fact that the ultimate tendon forces, which play an important role on the ultimate load, were nearly the same in those two beams (33.0 kN and 34.8 kN for beam A-1 and A-3, respectively).

3.3 FORCE IN EXTERNAL TENDON

The amount of stress increase in external tendon beyond the effective prestress is an important characteristic, which depends mainly on the overall structural behavior. Fig. 4 shows the relation between stress increase in external tendon and midspan deflection. It can be seen that all the beams exhibited nearly a linear relationship, implying that stress increase in external tendon is largely dependent on the midspan deflection at any step of loading up to the ultimate state. The effect of tendon eccentricity is clearly observed by comparing beam A-3 with other beams. Beam A-3, having larger tendon eccentricity (375 mm), exhibited the greatest rate of stress increase of 28.5 MPa/mm, while it was about 20.0 MPa/mm in all other beams. However, when comparing force in external tendon (see Fig. 5), beam A-2 and A-4 showed very high value at the ultimate. This is because of the effect of large tendon area in such beams, which resulted in greater ultimate shear strength as well as the different failure mode as previously described. Surprisingly, comparing beam A-1 with A-3 (larger tendon eccentricity), it can be seen that the ultimate tendon forces were nearly the same. The reasons may be the different initial prestress force as well as the comparatively low tendon force increase as a result of small deflection observed in diagonal tension failure.

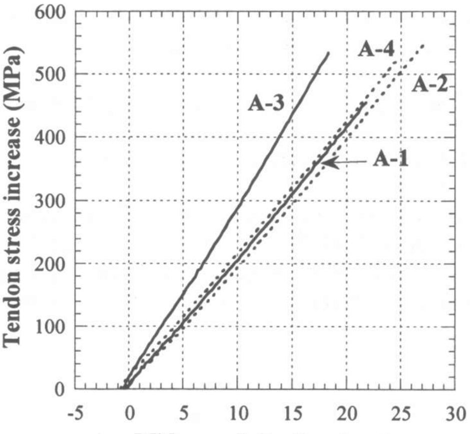

Fig. 4 Stress increase in external tendon

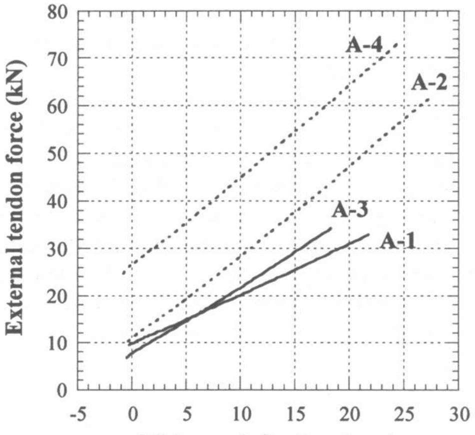

Fig. 5 Force in external tendon

4. CONCLUSIONS

This study presents the investigation of the effect of tendon configuration on the ultimate shear strength of externally PC beams with large eccentricity without web reinforcement. The following conclusions may be drawn from this study:

1) By using larger external tendon area, the ultimate shear strength was substantially increased. The mode of failure was also changed, that is a tied-arch mechanism was developed in beams with larger tendon area after the occurrence of diagonal crack in the shear span, leading to higher load-carrying capacity and eventually failed by shear-compression mode.
2) The effect of tendon eccentricity on the ultimate shear strength of beams used in this test is insignificant. On the other hand, it was found that beam with larger tendon eccentricity registered slightly lower ultimate load compared to that with smaller eccentricity. This is because the ultimate tendon forces were nearly the same due to the different initial prestress force as well as the low increase of tendon force, resulting from small deflection in diagonal tension failure.
3) By introducing more effective prestress, force in external tendon at the ultimate state was higher, resulting in greater ultimate shear strength.
4) Stress increase in external tendon has a linear relationship with the deflection at midspan, where the strut deviator was provided. The amount of stress increase was higher in beam with larger tendon eccentricity.

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