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論 文

[2217] Experimental Investigation of External Prestressed Concrete Beams

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1. INTRODUCTION

External prestressed concrete beams have been extensively developed for the new trends of construction during the past ten years, especially in Europe, due to some advantages of PC beam using external cable system such as, 1)dead load of structures can be reduced by making web thickness smaller, 2)old or damaged cables can be easily replaced and/or re-prestressed, 3)loss due to friction of tendon can be reduced, etc. To determine the ultimate bending capacity of external PC beam, the stresses in cable at ultimate have to be computed. An accurate calculation for the stress in cable of unbonded members at ultimate state is more difficult than for that of bonded ones. A lot of previous analytical and experimental studies have been undertaken to investigate the stresses in the cable of PC beams. These studies implied that an external PC beam can be treated as an unbonded member due to non-bonding between concrete and cables.

The purposes of this paper are, 1)to study the ultimate behavior of PC beam using different materials for external cables, which were prestressing steel (SWPR7B/12.7 mm), AF-rope (Aramid Fiber rope without resin) and CFRP/17.8 mm(Carbon Fiber Reinforced Plastics tendon combined with resin), 2)to review the existing prediction equations for the cable stress at ultimate state proposed by the previous investigators, so that the equations with good accuracy can be determined, and 3)to compare the test results obtained in this study with the value computed by the selected equations. In addition, the applicability of the prediction equation to PC beam using new materials as external cable was checked.

2. REVIEW OF PREVIOUS STUDIES

In the following sections, the existing studies of prediction equation for stress in cable, fps, are reviewed and compared with the available experimental results so that the prediction equation with good accuracy can be obtained.

The most common approach and analytical method to predict the stress in the prestressing cable at ultimate (fps) for unbonded members are shown in the following expression;

$$fps = fpe + \triangle fps \qquad \text{...... (1)}$$

where fpe is the effective prestressing stress and $\triangle$fps is the stress increase due to additional load leading to ultimate stage. It is noted that the effective prestress is defined as the stress in prestressing cable under the effect of the dead load moment. In this study, the existing prediction equation proposed by many investigators were reviewed as follows;

Initially, ACI Building Code 318-63 suggested the prediction equation of stress in cable at ultimate as;

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$$fps = fpe + 105 \quad \text{(MPa)} \qquad \text{.... (2)}$$

Existing Proposed Equations

1. Worwaruk, Sozen, and Siess[4]:

$$fps = fpe + (207 + \frac{\rho_{ps} x 10^{12}}{f'c}) \quad \text{(MPa)} \qquad \text{..... (3)}$$

$$fpe \leqq 0.60fpu$$

where ρ_{ps} is the prestressing steel ratio, f'c is the compressive concrete strength and fpu is the ultimate strength of a cable.

2. Mattock, Yamazaki, and Kattuala[4]:

$$fps = fpe + 700 + 1.4f'c/\rho_{ps} \quad \text{(MPa)} \qquad \text{..... (4)}$$

where ρ_{ps} is the prestressing steel ratio, f'c is the compressive concrete strength.

3. Pannell and Tam[6]:

$$fps = fpe + \gamma_s(1\text{-}c/dp) \quad \text{(MPa)} \qquad \text{..... (5)}$$

$$c = \frac{\mu_p Aps+Asfy-A'sfy-Cf}{0.85\beta_1 f'cbw+ \gamma_s Aps/dp}$$

$$Cf = 0.85f'c(b\text{-}bw)hf$$

if $\beta_{1c} < hf$; $Cf = 0$, $bw = b$

$$\gamma_s = 10.5Eps\,\varepsilon_{cu}/(S/dp)$$

$$\mu_p = fpe + \gamma_s$$

where Eps is Young's Modulus of a prestressing steel, S/dp is the span-to-depth ratio, b is width and hf is flange thickness of a beam, Aps is an area of prestressing steel, As and A's are the area of tension and compression steels respectively.

4. Du and Tao[4]:

$$fps = fpe + 786 - 1920\frac{(Asfy + Apsfpe)}{bdsf'c} \quad \text{(MPa)} \qquad \text{..... (6)}$$

provided that (Asfy + Apsfpe)/bdsf'c $\leqq$ 0.30, 0.55fpy $\leqq$ fpe $\leqq$ 0.65fpy, fps $\leqq$ fpy
where fpy, fy are the yield stress of the prestressing steel and nonprestresing tensile steel respectively, ds is the distance from the extreme concrete compressive fiber to centroid of the nonprestressing tensile steel.

5. Harajli and Kanj[6]:

$$fps = fpe + \gamma_o fpu(1.0 + 3.0[\frac{Apsfpe + Asfy}{bdpf'c}]) \quad \text{(MPa)} \qquad \text{..... (7)}$$

$$\gamma_o = \frac{L1}{L2}(0.12 + \frac{2.5}{(L/dps)})$$

where $[\frac{Apsfpe + Asfy}{bdpf'c}]$ is not more than 0.23, and L1 is loaded span length, L2 is total length of beam, and L/dps is the span-to-depth ratio.

6. Naaman and Alkhairi[5]:

$$fps = fpe + \Omega u Eps\, \varepsilon_{cu}(dps/c-1) \quad \text{..... (8)}$$

$$c = \frac{(-B1 + \sqrt{(B1^2 - 4A1C1)})}{2A1} \quad \text{..... (9)}$$

$$A1 = 0.85f'cbw\,\beta 1$$

$$B1 = Aps(\Omega u Eps\, \varepsilon_{cu}(L1/L2)-fpe) + A'sf'y - Asfy + 0.85f'c(b-bw)hf$$

$$C1 = -Aps\,\Omega u Eps\, \varepsilon_{cu} dps(L1/L2)$$

$$\Omega u = \frac{2.6}{(L/dps)} \quad \text{; for one-point loading} \quad \text{..... (10)}$$

$$= \frac{5.4}{(L/dps)} \quad \text{; for third-point or uniform loading}$$

where b = bw, for rectangular sections or rectangular section behavior of flanged sections, ε_{cu} is the concrete strain at ultimate, Ωu is strain reductioin factor for unbonded member, b and bw are width of flange and web of beam respectively, c is depth from the extreme compression fiber to the neutral axis at ultimate, and L/dps is span-to-depth ratio.

Comparison of Accuracy of fps in Different Studies

In this study, the existing test results conducted by Harajli were utilized to compute the stress in cable by the different prediction equations so that comparison of accuracy of the different models could be made. The calculations of stress in cable of PC beams and coefficient of correlation were summarized in Table 1.

From Table 1 and Fig.1, it can be seen that the equations proposed by Naaman gave better correlation than any of the other equations. In the discussion of test results, the proposed equation of Naaman, Harajli and Pannell were used to checked the applicability to the test results of PC beam using different types of materials for cables.

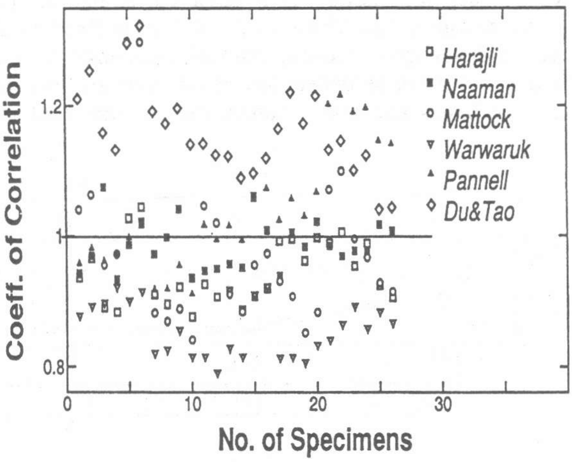

Figure 1. Correlation Coefficient of different Models

Table 1 : Comparison of accuracy of different models

Source of Studies	Correlation Coefficients		
	Avg Coef. of Correlation	Standard Deviation(STD)	Avg/STD (%)
Naaman's	0.985	0.037	3.77%
Harajli's	0.943	0.047	4.97%
Pannell's	1.088	0.103	9.45%
Mattock's	0.979	0.115	11.76%
Warwaruk's	0.858	0.040	4.70%
Du&Tao's	1.158	0.067	5.78%

Note :
- *from Harajli's study, the effective prestressing (fpe) were 60% of ultimate strength of cable.*
- *the value of ε_{cu} used in calculation is 0.0035*
- *total number of test specimens used for calculation is 26*

3. OUTLINE OF EXPERIMENT

3.1 MATERIAL FOR EXTERNAL CABLE

Fiber Reinforced Plastics (FRP) is a new interesting material in the construction field. Some advantageous properties in using FRP as external cable for PC beam are high tensile strength, non-corrosion, non-magnetization and very low relaxation. To investigate the ultimate behavior under flexure of PC beam using new kind of material as external cable, two types of FRP, which are AF-rope and CFRP/17.8 mm, were used in two specimens. The third specimen using prestressing steel (SWPR7B/12.7 mm) as external cable was tested as the indicator to compare the test results and characteristic of bending resistance.

3.2 TEST SPECIMENS

All test specimens were T-shaped section, simply supported with a span length of 2.5 m. The details of the test beams were shown in Fig 2. Two cables were symmetrically installed on both sides of the beam and deflected at two-pointed concrete deviator, which were extended from flange of T-section. The deformed steel bars having diameter of 10 mm (grade SD35 with yield strength of 356 MPa) was used for bonded tensile reinforcement with a ratio of 0.41%. Electrical-resistance strain gauges (PL-type and π -gauge) were attached to reinforcement, external cables and concrete surface to monitor the strains at critical location such as midspan, 0.45 m from the midspan, etc. Three load cells were fixed at the end of cables to checked the cable forces. To investigate load-displacement relationships of an external PC beam, three transducers were fixed to measure deflections at midspan and two-point deviators. The material properties of test specimens and test variables were summarized in Table 2.

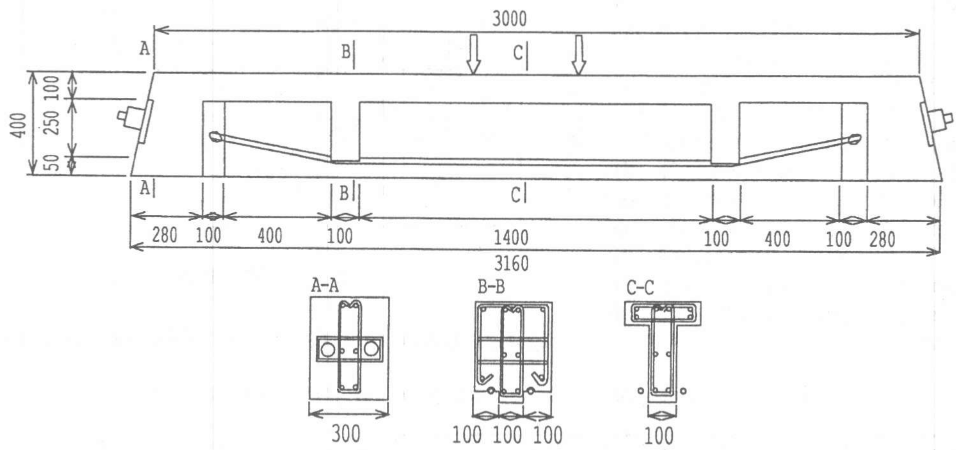

Figure 2. Details of Test Specimen (mm)

3.3 TEST PROCEDURE

Firstly, the initial prestressing forces were introduced simultaneously by hydraulic jacks at one end of the beam before loading was applied. Two-point loads were applied monotonically through a spreader beam at 0.20 m from center of beam (see Fig 2). Loads were applied with a specific interval in two cycles. The maximum load on the first cycle was fixed when the first visible cracks were observed. Afterwards, specimen was unloaded to zero, and then the final cycle load was applied until the beam failed. All data were recorded and stored automatically by computerized system at each step of load. The failure mode of test specimens at ultimate were observed as well.

Table 2: Materials Properties and Test Variables

Specimen No.	Type of Cable	Sectional Area Aps(cm^2)	Nominal Tensile Strength of Cable (kN)	Introduced prestress (per cable) Force(kN)	Introduced prestress (per cable) %of fpu	Young's Modulus Eps(MPa)	Concrete Strength f'c(MPa)
1	AFRP-rope	0.764	147.15	58.86	40%	$1.27x10^5$	31.39
2	SWPR7B/12.7	0.987	183.00	56.27	31%	$1.95x10^5$	35.22
3	CFRP/17.8	1.528 (0.991)	271.60	60.33	22%	$1.37x10^5$ ($2.16x10^5$)	29.23

Note : - The span-to-depth ratio of all specimen is fixed at 7.14
- The values in ( ) are effective area and Young's Modulus of CFRP excluding resin.

4. TEST RESULTS AND DISCUSSION

4.1 TEST RESULTS

The relationships between load and deflection and load and tensile force in cable of all specimens were shown in Fig 3 and 4 respectively. From the load-deflection curve, all specimen's results gave elastic behavior before cracking stage, and presented the sign of yielding before failure. Yielding of PC beams occurred due to the nonprestressed reinforcing bars at tension zone. Two or three fine cracks were appeared and propagated mainly between the flexural span, and then developed upward to the compression zone. Due to the minimum requirement (0.4%) of ordinary bonded reinforcements in tension zone, no single concentrated crack was observed, as had been described in the previous studies[5,6].

For the observed failure mode, all specimens exhibited ductile behavior before failure. The test beam using prestressing steel as external cable failed by the crushing of concrete at the compression zone. Meanwhile, the test beams using AF-rope and CFRP failed by breaking of cable itself. The failure of AF-rope was due to the breaking in fiber at anchorage grip. And CFRP failed by breaking of cable at deviators due to bending, which were the weak points for high tension. Therefore, the use of CFRP as external cables should be carefully considered if arranged in curve or sharp bend. The detail of experimental results were shown in Table 3.

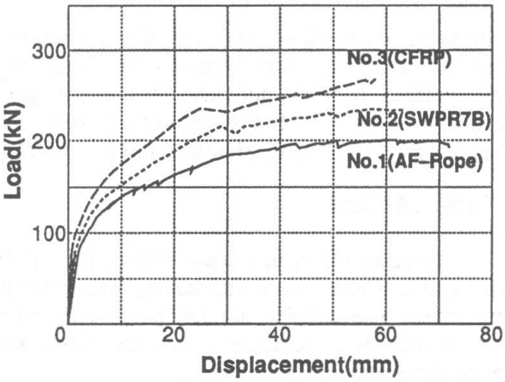

Figure 3. Load-Deflection Curves.

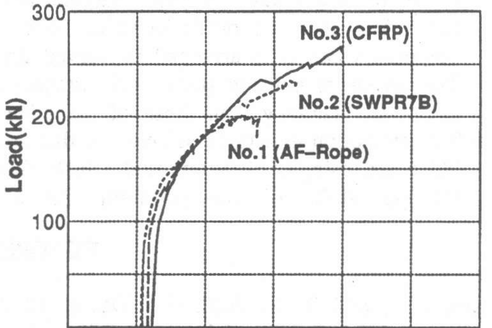

Figure 4. Load-Tensile force in Cables Curves.

4.2 DISCUSSION ON STRESS IN THE PRESTRESSING CABLES

First of all, the test result of specimen No.2, using prestressing steel as external cable, is discussed and compared with values computed by the selected proposed equations for stress in cable (fps). The coefficients of correlation obtained from Naaman's, Harajli's and Pannell's equation based on in this test data, which were 1.420, 1.332 and 1.253 respectively, were not so good as those based on Harajli's experiments. It is possibly due to the effect of effective

Table 3: Experimental results and Analytical Calculations

Specimen No. /Cable type	Observed Failure Mode	Experimental Results			Analytical Results					
		Flexural Strength	Tensile in Cable		Naaman's		Harajli's		Pannell's	
		(Applied Load) (kN)	Force/cable (kN)	fps (MPa)	fps (MPa)	Cal/Exp	fps (MPa)	Cal/exp	fps (MPa)	Cal/Exp
1) AFRP-rope	Breaking in external cable	189.33	110.07	1440	1810	1.257	1536	1.066	1215	0.843
2)SWPR7B/12.7	Concrete failed by compression	176.68	96.14	974	1383	1.420	1297	1.332	1218	1.253
3) CFRP/17.8	Breaking in external cable	235.15	139.00	897 1402*	1660 2674*	1.850 1.907*	1079 1720*	1.202 1.226*	794 1243*	0.884 0.886*

Note : - (*) are the calculated values using effective area of CFRP excluding resin.
- the ultimate strength is defined when the concrete strain at compression surface reached 0.0035

prestressing stress (fpe). Because the assumption in those proposed equations and controlled parameter in experiments were on the basis that the effective prestress of cables should be approximately 60% of ultimate tensile strength of cables. For specimens No.1 and 3, the acceptable accuracy of fps calculated from selected equations also could not be obtained [Naaman's (1.257,1.850), Harajli's (1.066, 1.202) and Pannell's (0.843, 0.884)].

5. CONCLUSION

External PC beams using various kind of materials as external cables were experimentally investigated. Three specimens having prestressing steel, AF-rope and CFRP as external cables were tested. The existing studies were reviewed in order to obtain the prediction equations for stress in cable with acceptable accuracy. From the test results and study reviews, the conclusions can be drawn as the following ;

- From load-deflection curves, test specimens having different material as external cables give almost the same ultimate flexural behavior.
- It can be noted that the new materials are acceptable for use as external cables for PC beam. However, the brittle material, such as CFRP, must be carefully used for the design purposes when it is arranged in curved line or sharp bend.
- The review of existing studies (six studies) disclosed that Naaman's proposed equation gave the better accuracy than those of the other studies.
- The prediction equations selected in this study gave a poor accuracy of predicted value for PC beam using AFRP-rope and CFRP cable as the external cables. However, to confirm the applicability of those equations, further studies should be done.

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