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論 文

[1167] TRANSFER LENGTH OF BRAIDED ARAMID FIBER TENDONS

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1. INTRODUCTION

1.1 PROGRAM OBJECTIVE

High-strength aramid fiber (AF) can be braided and epoxy-impregnated to produce flexible and rigid rods for use as tendons in prestressed concrete members. These AF rods can replace conventional steel strands or reinforcing bars in applications where light weight, durability, electromagnetic fields, thin sections, and impact resistance are relevant [1,2]. As a part of a research project intended to evaluate the feasibility of AF flexible tendons in pretensioned prestressed concrete beams, the focus of this paper is on transfer length. Since the force in a pretensioned tendon is transferred to the concrete by bond in the end-region of the member, the determination of the distance within which this transfer occurs (i.e., transfer length) is necessary for both design and performance evaluation. Therefore, the objective of this research was to experimentally determine transfer length of AF tendons as compared to that of uncoated steel strand when varying tendon type, tendon size, tendon number, and concrete strength at time of release.

1.2 AF BRAIDED EPOXY-IMPREGNATED TENDONS

Braided epoxy-impregnated aramid fiber rods are available in different sizes with diameter varying between 3 and 20 mm [2]. Rod diameter is controlled by the number of strands woven: a rod is made with strands in multiples of 8. Each strand is composed of 1 to 10 yarns. Each yarn is a 6,000 denier industrial grade Kevlar-49. The gross cross section of a rod is approximately 60 percent Kevlar-49 and 40 percent epoxy resin. The stress-strain behavior of the composite after epoxy hardening is linear up to failure. Both the composite ultimate strength and elastic modulus are

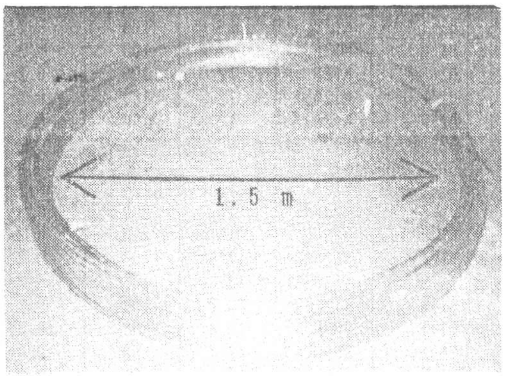

Fig.1 : Flexible AF Tendon (K128 type)

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practically 80 percent of values computed on the basis of the volume of Kevlar-49. By controlling the bond between strands, rigid or flexible rods can be manufactured. The latter is preferable for tendons for ease of shipment and workman-ship (see Fig. 1). Tendons used in this research are of the flexible type unless otherwise stated. Before epoxy hardening, silica sand can be adhered to the surface of rigid-type rods to improve the mechanical bond with concrete.

2. TEST PROGRAM

2.1 SPECIMENS AND MATERIALS

Nineteen beams as shown in Table 1 were fabricated. All samples had identical length (4 m) and cross section (12 by 21 cm) as shown in Fig. 2. According to tendon type and number, beams were subdivided into 5 groups A through E. The tendon type, nominal diameter, nominal area, modulus of elasticity, ultimate strength, number, nominal prestress force, and load release time for each beam is given in Table 1. Tendons were placed in all beams at a depth of 2/3 the section height. As indicated in Table 1, compression and shear reinforcement was also introduced in some specimens for additional tests to be conducted after transfer length determination. Compression reinforcement consisted of two deformed steel bars 13-mm diameter and shear reinforcement consisted of deformed steel stirrups 6-mm diameter, spaced at 75 mm, and with clear cover of 15 mm all-around. The concrete used for all specimens had the following proportions in kg/m^3: high-early strength portland cement 470, total water 174 (W/C ratio=0.37), sand 692, and gravel 957 (maximum aggregate size=10 mm). An air entraining agent and a plasticizer were used to produce air content of 5.5 percent and slump of 14.5 cm.

Table 1 : Beams and Tendons Characteristics

Sample Denom.	Tendon								Compr. Reinf. Type	Shear Reinf. Type (mm)
	Type	Nominal Diameter (mm)	Nominal Area (mm^2)	E ($10^5 \times kg/cm^2$)	fu (kg/cm^2)	Number	Nominal Prestress Force[%Pu]	Release Age (day)		
A2-1	K64	8	50	6.2	14080	2	25	7	N/A**	N/A
A2-2	K64	8	50	6.2	14080	2	25	14	N/A	N/A
A2-S	K64	8	50	6.2	14080	2	25	23	N/A	D6@75
B1-1	K128	12	100	6.2	13560	1	25	7	N/A	N/A
B1-2	K128	12	100	6.2	13560	1	25	14	N/A	N/A
B1-S	K128	12	100	6.2	13560	1	25	23	N/A	D6@75
B1-F-1	K128	12	100	6.2	13560	1	25	7	N/A	N/A
B1-F-2	K128	12	100	6.2	13560	1	25	14	N/A	N/A
B1-SF	K128	12	100	6.2	13560	1	25	23	N/A	D6@75
B2-S-1	K128	12	100	6.2	13560	2	25	7	D13-2	D6@75
B2-S-2	K128	12	100	6.2	13560	2	25	23	D13-2	D6@75
C1-S-2	K256	16	200	6.2	12960	1	50	7	D13-2	D6@75
C1-S-3	K256	16	200	6.2	12960	1	50	23	D13-2	D6@75
D1-1	K128SR*	13.5	100	6.2	13560	1	50	7	N/A	N/A
D1-2	K128SR*	13.5	100	6.2	13560	1	50	14	N/A	N/A
D1-S	K128SR*	13.5	100	6.2	13560	1	50	23	N/A	D6@75
E1-1	SWPR7A	12.4	93	19.0	21200	1	75	7	N/A	N/A
E1-2	SWPR7A	12.4	93	19.0	21200	1	75	14	N/A	N/A
E1-S	SWPR7A	12.4	93	19.0	21200	1	75	23	N/A	D6@75

Note: * Rigid type with adhered sand, ** N/A = Not Applicable   100 kg/cm^2 = 9.81 MPa

2.2 FABRICATION AND MEASUREMENTS

Tendons were stretched at the preset level three days prior to casting and re-stretched immediately before casting in order to recover initial

Table 2 : Measured Stress and Strain Values

Beam Group	Initial Stress (kg/cm^2)	Tendon Strain (x10^{-6})	Strain Change (x10^{-6}) Beyond Transfer Length: Tendon 7-day	Tendon 14-day	Tendon 23-day	Concrete 7-day	Concrete 14-day	Concrete 23-day
A2	3207	5591	68	—	—	67	71	66
B1	3204	4448	67	63	—	83	77	69
B2	3202	— *	—	—	—	145	—	135
C1	6402	9228	—	—	235	296	—	281
D1	6400	—	—	—	—	138	149	134
E1	13523	—	—	—	—	258	256	268

Note : 100kg/cm^2 = 9.81MPa   * — = Data not available

relaxation losses. For AF tendons, the stress level was monitored with a load cell and strain gages positioned along the tendon. For steel strands, only load cells were used. Conventional wedge anchors were employed for the steel strands, whereas a resin injection-type anchor was used in the case of AF tendons. This anchoring system consists of a cone (made of epoxy resin and silica sand) molded around each tendon-end and encased in a threaded high-strength steel pipe. After the tendon is released and cut, the pipe is removed for multiple applications. For specimens with two tendons, pretensioning was attained simultaneously with an appositely designed device which allowed for the adjustment of the force in each tendon. AF tendons were stretched at 25 and 50 percent of their ultimate nominal capacity. The upper number is below the conservative estimate of the stress-rupture value of AF tendons for a 100-year life span [3]. For the 7-wire steel strand, the prestress force was 75 percent of the ultimate guaranteed capacity as common in practical applications. Stress and strain in tendons as measured at the time of concrete casting from load cells and strain gages, respectively, are shown in the first two columns of Table 2.

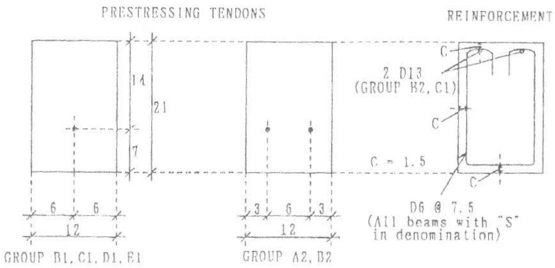

Fig. 2 : Typical Specimen Cross-Section

After concrete casting, specimens were allowed to cure for one day. Upon removal of the forms, contact points were glued with epoxy resin along one side of the beam at both ends. Forty-eight contact points per beam with AF tendons (72 per beam with steel strand) were placed at the depth of the tendon and intervals of 5 cm. A Whittemore-type extensometer was used to measure the distance between contact points over a 10-cm gage length (see Fig. 3). The extensometer readings had a precision of 5x10-4 mm. Tendons were released at 7, 14, and 23 days when the compressive strength of air-cured concrete was 297, 325, and 353 kg/cm^2 (29.1, 31.9, and 34.6

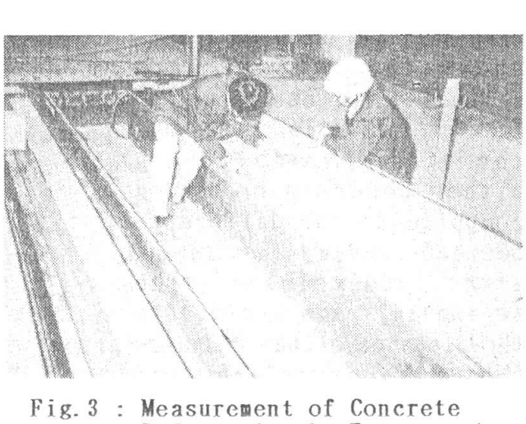

Fig. 3 : Measurement of Concrete Deformation by Extensometer

MPa), respectively. The target minimum compressive strength for load release was set at 300 kg/cm^2 (29.1 MPa) as it corresponds to a low-end value in practical applications. The maximum compressive stress in concrete due to prestressing was not to exceed 1/3 of the concrete compressive strength at time of load release. Tendons were slowly released (2 to 3 minutes) by means of a jack attached to one of the tendon ends (jack-end). After releasing the jack-end, no residual load at the opposite tendon anchor (fixed-end) was present since the bottom form was covered with a plastic sheet to act as a bond breaker. The measurement of strain (length) change in concrete using the Whittemore-type extensometer was taken as the average of two successive readings. The average difference between first and second reading was 6.6 x 10^{-4} mm with a standard deviation of 5.8 x 10^{-5} over a readings range of 100.5 ± 0.5 mm.

3. RESULTS AND DISCUSSION

Fig. 4 (relative to beam A2-1 released at 7-day) shows the typical data collected for one specimen. The vertical axis represents the strain variation in either concrete or tendon computed as the difference between readings before and after load release. The horizontal axis represents the distance of the measurement place from the beam end. Two curves are relative to strain change in concrete for the jack-end

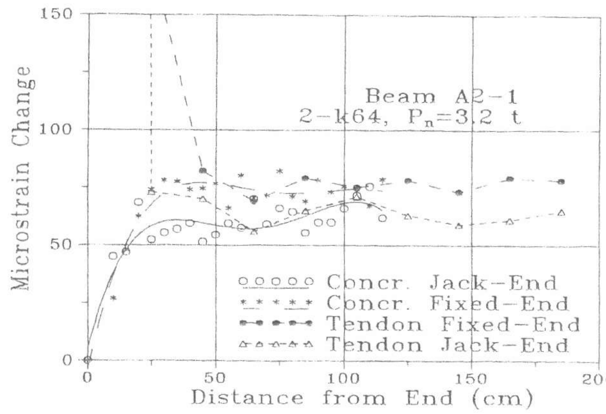

Fig. 4 : Microstrain Change vs. Position Along Beam (A2-1)

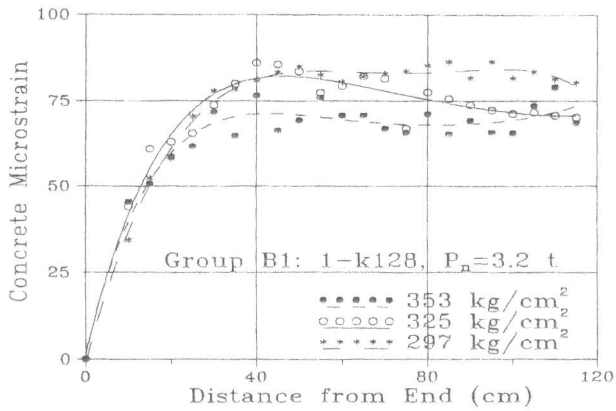

Fig. 5 : Microstrain Change vs. Position Along Beam (Group B1)

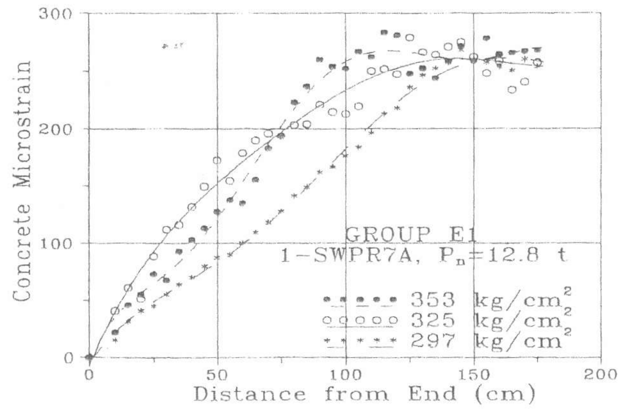

Fig 6 : Microstrain Change vs. Position Along Beam (Group E1) (circle symbols) and the fixed-end (asterisk symbols), respectively. These curves are similar and show that strain increases very rapidly from 0 to an average of 67 microstrains. Correspondingly, the curves relative to strain variation in the tendons (triangle symbols=jack-end, filled-circle symbols=fixed-end) show that strain drop starts from the initial value of 5591 microstrains and rapidly reaches a constant average value of 68 microstrains. Given the similarity of the results at the two beam ends, the average strain change in concrete can be computed and plotted as a function of the distance from the beam end for each specimen group. As an example, Fig. 5 shows the data relative to the six beams of Group B1 with load released at each of the three release dates. The figure shows that data-points are slightly influenced by concrete strength at time of force release. It was assumed that transfer length would correspond to the cross section "i" where the measured strain ε_i had the following characteristics:

$$\varepsilon_i > \varepsilon_{i+1} \quad \text{and} \quad \varepsilon_i > [(\sum_{i+1}^{n} \varepsilon_j) / (n-i)]$$

That is, the next data-point and the average of all following data-points were lower. Columns 2 to 4 in Table 3 show the transfer length computed under this criterion for all specimens. Considering the results of all groups (with exception of Group C1 where split cracking occurred), it appears that transfer length decreases with increasing concrete strength at time of force release. This is particularly evident for the case of Group E1 (see Fig. 6) where the pretensioning stress was the highest. The values of the average strain change in tendons and concrete as measured beyond transfer length are shown in columns 4 to 9 of Table 2 for all groups. The values obtained for concrete with the Whittemore-type extensometer favorably compare with those obtained directly from the strain gages on the tendons, as well as with analytically derived values. The strain change in concrete beyond transfer length was analytically computed as follows: 1) given beam cross-section geometry, assume elastic stress distribution in concrete resulting from prestress force release; and 2) given concrete modulus of elasticity and tendon mechanical properties, compute concrete elastic strain at tendon level allowing for tendon relaxation losses and beam elastic shortening. For the case of Group B1 released at 23-day, the expected concrete strain is 66 microstrains. The loss of strain in the tendon from the time of concrete casting is within the range of 5.4 to 10.8 percent of the initial strain and may depend on tendon size, prestress force, and release time (concrete shrinkage).

Table 3 : Transfer Length Summary

Beam Group	Transfer Length* (cm) from Concrete 7-day	14-day	23-day	from Tendon 7-day	14-day	Initial Stress** Normal	Bond
A2	20	30	20	35	—	σ_B	$0.67\tau_B$
B1	50	40	30	45	45	σ_B	τ_B
B2	40	—	40	—	—	σ_B	τ_B
C1	Split Crack	—	Split Crack	—	—	$2.0\sigma_B$	$2.67\tau_B$
D1	25	15	20	—	—	$2.0\sigma_B$	$2.0\tau_B$
E1	145	125	115	—	—	$4.2\sigma_B$	$4.3\tau_B$

Note : * At different load release ages
** Initial stress with reference to the case of Group B1
- Data not available

The summary of transfer length results based on concrete and tendon strain change as shown in Table 3 allows for some observations with respect to beam groups. For clarity, the last two columns of Table 3 show the nominal tensile stress in the tendon and the corresponding ideal bond stress at the concrete-tendon interface by taking Group B1 values as reference. The nominal values of σ_B and τ_B for Group B1 represent: 1) the initial prestress force divided by the tendon cross-section area; and 2) the initial prestress force divided by the tendon lateral surface area per unit length of tendon.

- (B1 vs. B2). Given the same tendon diameter and same initial stress, there is no experimental evidence to support the existence of a different transfer length between the case of one versus two tendons.
- (A2 vs. B2). Given the same number of tendons and the same initial stress, tendons with larger diameter require longer transfer length.
- (A2 vs. B1). Given the same total prestress force, the use of two smaller diameter tendons requires a transfer length smaller than in the case of one large tendon.
- (B1 vs. D1). Given the same AF tendon cross section, the transfer length of adhered-sand tendon is significantly smaller than that of smooth tendon even for an initial prestress twice as large.
- (C1). Unreinforced concrete with up to 353 kg/cm^2 (34.6 MPa) strength and minimum clear cover of 5.2 cm around the tendon, cannot resist the split tension resulting from a force of 12.8 t (125.6 kN). Approximately eighty-five percent of the force could be released before cracking.
- (E1 vs. B1 and D1). Transfer length in steel strands is higher than in AF tendons of similar diameter even when allowing for different initial stress. The shorter transfer length in AF tendons may result from three major factors: tendon deformed surface resulting from the braiding process, presence of adhered-sand on the tendon surface, and wedging effect due to high Poisson's ratio. A reliable procedure for the determination of the Poisson's ratio for fiber-made rods is not available; however, it is estimated that a value close to 0.5 is appropriate for tendons such as those used in this project.

4. CONCLUSIONS

Laboratory determination of tendon transfer length in pretensioned prestressed concrete beams using different tendons was successfully obtained by measuring concrete displacement along the length of the member at the level of the tendon. It was shown that transfer length is affected by: 1) tendon type (adhered-sand AF tendon has shorter transfer length than smooth AF tendon and steel strand); 2) tendon size (AF tendon with larger diameter shows longer transfer length); and 3) concrete strength (the higher the concrete strength the shorter the transfer length). Transfer length of braided epoxy-impregnated aramid fiber tendons is shorter than that of conventional steel strands. This feature can be advantageous in a number of practical applications. The mechanism of load transfer in AF tendons may be substantially affected by tendon surface configuration, adhered-sand, and wedging due to a relatively high Poisson's ratio. Research on transfer length of AF tendons is to be continued to include various prestress levels and large diameter rods.

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