

Durability of Aramid and Carbon FRP PC Beams under Tidal and Thermal Accelerated Exposure

Hiroshi Nakai, P.E.Jp

General Manager, MAEDA KOSEN CO., LTD., Tokyo, Japan

Hirofumi Watanabe, P.E.Jp

Manager, Kawada Construction Co., LTD., Tokyo, Japan

Tsuyoshi Enomoto

Manager, TOKYO ROPE MFG. CO., LTD., Tokyo, Japan

Taketo Uomoto, Dr.Eng.

Chief Executive, Public Works Research Institute, Japan

ABSTRACT

The authors present results from 300 cycles of accelerated drying and wetting exposure studied during six years to assess the effect of tide and temperature variation cycles on the durability. In this study, prestressed concrete (PC) beams were reinforced with Fiber Reinforced Polymer (FRP) and steel strand tendons. The FRP tendons considered in this study are aramid and carbon fiber polymer tendons. It is found that FRP tendons degraded due to the difference between thermal expansion coefficient of FRP tendons and concrete. Moreover, organic fibers and resins were hygroscopic materials which caused decomposition by reaction with water. The PC beams were placed in a circulating water tank which carried out under repeated temperature and humidity cycles for seven days.

The effect of drying and wetting exposure was evaluated from bending test conducted after 150 and 300 cycles. The effect of the exposure showed in deterioration of bond and decrease of effective prestressing force of the PC steel beams. Moreover, the envelope curves of the PC steel beams were deteriorated. The PC beams with FRP tendons showed better performance than that of PC beams reinforced with steel tendon regarding the effective prestressing force and flexural capacity.

KEYWORD

exposure test, tide, temperature, aramid, carbon

1. INTRODUCTION

During drying and wetting cycles, degradation in the bond between Fiber Reinforced Polymer (FRP) tendons and concrete is a potential problem due to the difference between the linear expansion coefficient of FRP tendons and concrete. Moreover, bonding resins and organic fibers are hygroscopic materials which have ability to attract water from surrounding environment. Therefore, the decomposition of these components occurs by reaction with water. This reaction is known as a hydrolytic degradation [1].

The objective of this study is to investigate the degradation over time of prestressed concrete (PC) beams reinforced with FRP or steel strand tendons and subjected to repeated drying and wetting cycles with varied temperature [2]. This paper reports the static loading test results after 150 and 300 cycles of the exposure.

2. SPECIMEN DATA

2.1 Materials

Table 1 shows the properties of the materials used as tendons. The aramid FRP was Technora®, and the carbon FRP was CFCC®. The coefficient of linear expansion of steel tendon is approximately the same as that of concrete, while the coefficient of linear expansion of FRP tendons is approximately zero or negative in some cases. Considering an approximate tensile strength of the tendon materials, a ratio of tensile strength of aramid, carbon and steel tendons is equal to 1:0.75:1, respectively. In addition, the ratio of Young's modulus is 1:2:4 for aramid, carbon and

steel tendons, respectively.

2.2 Dimensions, Loading Method and Various Capacities

The dimensions of the specimens used in the accelerated exposure test are 100 mm height, 100 mm width and 1,500 mm length. The tendon was placed at the sectional center of each specimen. The specimen cross section is shown in Fig. 1.

Static four point bending load were applied to the specimens with 0.4 m shear span length before and after the accelerated exposure test. Various capacities of the specimens and the values used for calculation are listed in Table 2.

The initial prestress for all specimens was 62% of their guaranteed tensile capacity. The effective prestress ratio was estimated using the apparent relaxation rate in each type of reinforcing tendon and shrinkage strain of specimens at the age of 44

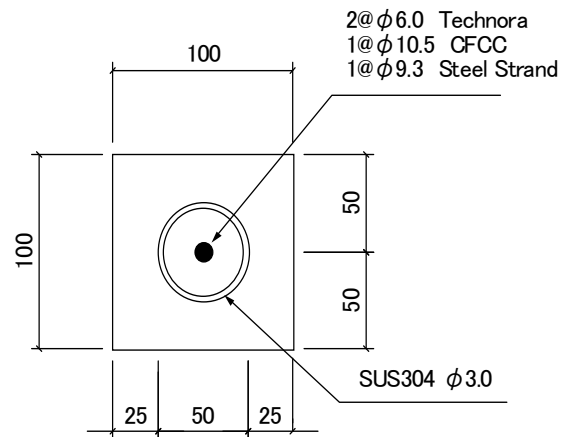


Fig.1 Specimen cross sections (mm)

Table 1 Properties of tendons

Material	Aramid	Carbon	Steel
Designation	Technora φ6.0	CFCC φ10.5	SWPR-7A φ9.3
Nominal cross section area (mm ²)	32.5	79.1	51.6
Nominal diameter (mm)	6.4	10.0	9.3
Guaranteed capacity (kN)	56.9	104	88.8
Tensile Capacity (kN)	62.5	114	103
Young's modulus (kN/mm ²)	46	104	197
Elongation (%)	3.8	1.2	7.1
Thermal expansion coefficient (x10 ⁻⁶ /°C)	-3	0.6	12

months after prestressing. The estimated rate of apparent relaxation in each type of tendon is 15%, 1.75% and 1.5% for aramid, carbon, and steel tendons, respectively. Regarding a shrinkage strain, the measured value (approximately 900 μ) of the exposed specimens for natural outdoor exposure test was used although exposure conditions such as environment, dimension, and prestress level are different[2].

Flexural cracking capacity is calculated by using the values of effective prestress ratio and flexural cracking strength. Crack reopening capacity refers to the load which produces bending moment required for suppressing the compressive stress which is generated by effective prestress at the tension edge. For flexural capacity, the bending moment at which the upper edge compressive strain reaches 3,500 μ is calculated based on the concrete compressive strength of 80 MPa.

3. TEST METHOD

3.1 Test Equipment

A circulating water tank with controlled temperature and water levels was used for the accelerated exposure test. The specimens placed in the tank are subjected to a weekly cycle of repeated temperature and humidity as shown in Fig. 2. The water tank was heated up to 60°C and after that its temperature was lowered to the room temperature by spontaneous heat release. This heating and cooling cycle is automatically repeated.

The loading force was applied to accelerate the degradation of the bond between prestressed concrete and FRP tendon due to the difference in linear expansion coefficient between components as well as hydrolytic degradation.

Table 2 Effective prestress and calculated capacity of the specimens

Material of specimens	Jacking force (kN)	Prestressing stress (MPa)	Effective stress (MPa)	Effective prestress ratio	Compressive stress due to prestressing (MPa)	Flex. tensile strength of con. (MPa)	Cracking moment (kN m)	Cracking capacity (kN)	Visible crack load (kN)	Decompression moment (kN m)	Crack reopening capacity (kN)	Ultimate capacity $f_{ctk}=80\text{MPa}$ (kN)
Aramid	68.5	1053.8	854.4	0.811	5.55	5.59	1.86	9.3	10.90	0.93	4.6	21.0
Carbon	61.6	778.8	671.5	0.862	5.31	5.59	1.82	9.1	10.20	0.89	4.4	23.9
Steel	59.2	1147.3	952.8	0.830	4.92	5.59	1.75	8.7	10.00	0.82	4.1	25.0

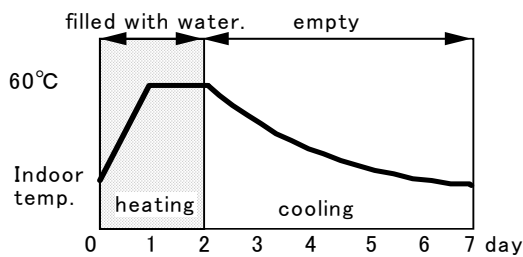


Fig. 2 Tank temperature and humidity profile over a weekly cycle



Fig. 3 The accelerated exposure situation at the water tank

Table 3 Parameter of exposure

Name of specimen	Initial loading	150 cycles exposure	2nd loading	Destructive test	Total 300cycles exposure	3rd loading	Destructive test	Quantity
A[A,C,S]Control			yes	yes				3
A[A,C,S]1	yes	yes	yes	yes				3
A[A,C,S][2,3]*	yes	yes	yes		yes	yes	yes	5

Initial letter designates type of exposure: A = Accelerated.

[A,C,S] describes the tendon: A = Aramid; C = Carbon; S = Steel.

*: AS is 2 only

3.2 Exposure Cycles and Evaluation Method

Table 3 shows the parameters used for the accelerated exposure test. In the table, the initial letter A denotes an accelerated exposure. Specimens with [A,C,S] and [Control,1,2,3] indicate tendon type and the number of exposure cycles, respectively. The first, second and third static loading tests were conducted according to the number of exposure cycles. Specimens denoted as A[A,C,S] Control were placed under natural exposure at an inland site in Chiba Prefecture to the age of 44 months.

To produce pre-cracks before the exposure, the initial load was applied under a load equivalent which is approximately 1-1/2 times of the flexural cracking capacity (13.5 kN).

After 150 cycles of accelerated exposure, the second loading was carried out for all specimens including the control specimen. For pre-crack loading, all specimens were preloaded up to 13.5 kN and then followed by a load equivalent to 80% of calculated flexural capacity. Finally, the A[A,C,S] Control specimen and A[A,C,S]1

specimen of each tendon material were loaded to failure. The remaining specimens (A[A,C,S][2,3]) were unloaded and returned to the exposure site for continued accelerated exposure.

The third loading was conducted in the similar way of three stages after completion of total 300 cycles of accelerated exposure. Two specimens with FRP tendons and one specimen with steel tendon were preloaded with 13.5 kN and followed by a load equivalent to 80% of the calculated flexural capacity. Finally, they were loaded to failure.

4. TEST RESULTS AND EVALUATION

4.1 Appearance and the Inside of Specimens after Exposure Test

There was no observable damage to the appearance of the specimens caused by bond splitting at the tendon anchor part by accelerated exposure. Moreover, no corrosion was observed in the steel strands which were broken down and examined after the static loading test. It is able to conclude that the high temperature load and

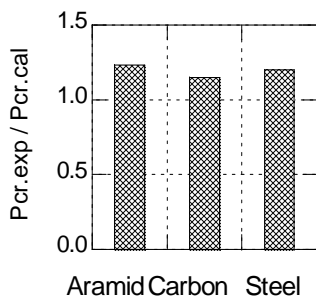


Fig. 4 Actual flexural cracking load compared with the calculated values

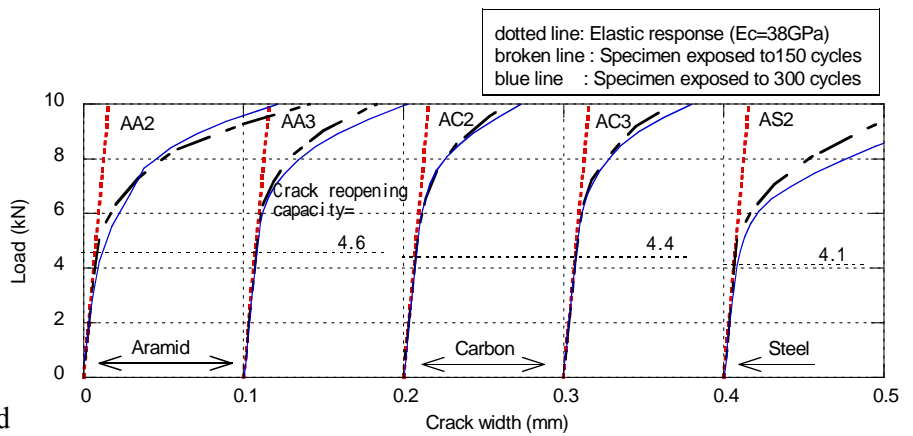


Fig. 5 Variations of crack reopening load of exposed specimens

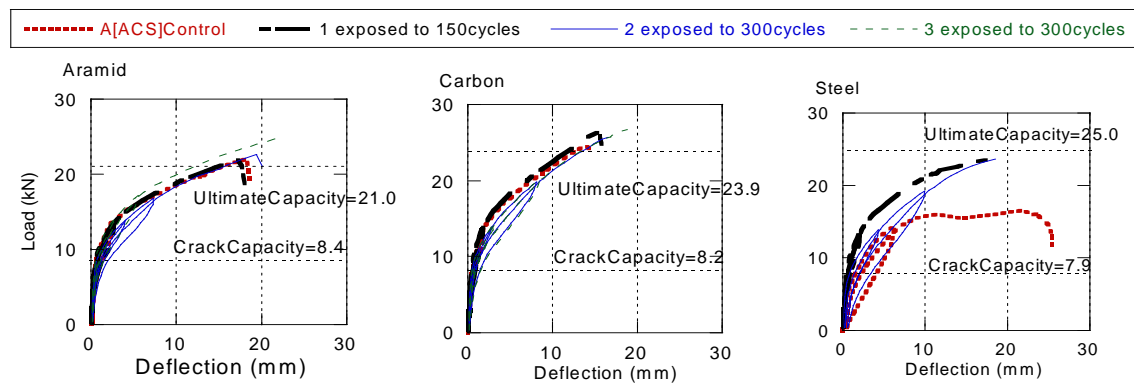


Fig. 6 Load-displacement relation by tendon material

repeated drying and wetting cycles loaded under this accelerated exposure test did not cause damage to concrete and steels.

4.2 Cracking Load during Initial Loading

Fig. 4 shows the rate of actual cracking loads during the initial load application before the accelerated exposure loading in comparison with the calculated cracking capacities. As shown in the figure, the actual experimental results correspond to 115 to 124% of those calculated results. It indicates that each of these materials satisfied the required performance level according to the design. In other words, it proves that prestress effectively worked for all the materials in the cracking capacity level.

4.3 Exposure Cycles and Crack Reopening Load

As mentioned previously, it is important for prestressed concrete beams to maintain prestress level in a stable way. In this section, the authors attempted to evaluate the effective permanent prestress based on the calculated crack reopening load and the load-crack width relationship obtained during the static loading test.

Fig. 5 shows the relationship between load and crack width of A[ACS][2,3] specimens subjected to the second and third loadings. The red dotted line in Fig.5 is the first crack reopening load corresponding to the elastic displacement. In the elastic range, it is assumed that Young's modulus of concrete at the lower edge of these beams to 50-mm span pi-gauges is equal to 38 GPa. Moreover, fig. 5 also shows the crack reopening capacity which suppresses the calculated effective prestress.

Crack opening displacement of FRP-reinforced specimens is proportional to the stiffness corresponding to the elastic displacement until crack opening load is higher than the calculated crack reopening load. In addition, the change point and decrease level of stiffness of the crack opening displacement, caused by the increase of exposure cycles, are also identical. As a result, deterioration due to the increase of exposure cycles was not observed.

On the other hand, the AS2 specimen with steel tendon began to crack nearly from calculated loading level. It is obvious that specimen prestressed with steel tendon is inferior to specimens prestressed with FRP tendon. Additionally, when specimen was exposed to 300 cycles, its crack reopening load substantially

declines causing a sharp increase of crack width. This is most probably attributable to damaged bond by the effect of second loading resulting in a decrease of its effective prestress.

4.4 Relationship between Exposure Cycles and Load Displacement

In Fig. 6, the load-displacement relationships of all specimens loaded to failure were expressed. The calculated flexural cracking capacity and ultimate capacity were also included.

It can be seen that the FRP prestressed specimens satisfied the critical requirements in each stage, while those prestressed with steel strands did not satisfy the required ultimate load. It should be also noted that no deterioration was observed in the load-displacement relationship of FRP prestressed specimens even after they were exposed to the accelerated loading. However, the decrease of stiffness in the load-displacement relationships of those specimens reinforced with steel strands were observed depending on loading or non-loading of accelerated exposure as the number of cycles increases. This is attributable to the slippage of steel strands due to deterioration in bond between steel strands and concrete.

5. CONCLUSIONS

The following conclusions have been drawn from the test results:

- (1) The flexural cracking load of the beams was superior to the design value.
- (2) The post-flexural-cracking properties of concrete beams reinforced with FRP tendons are superior to those of beams reinforced with steel strands, regardless of application or non-application of accelerated exposure.
- (3) It has been shown by the accelerated exposure loading test that beams reinforced with FRP tendons provide a stable prestress, while prestress decreased in beams reinforced with steel strands.
- (4) During this accelerated exposure test, there was no observable deterioration in bond between the pretensioned concrete beams and their FRP tendons. This is due to the relative low linear expansion coefficient of FRP and hydrolytic degradation of bonding resins and organic fibers.

ACKNOWLEDGMENT

This study was undertaken by the Institute of Industrial Science, the University of Tokyo through funding from the Association for Advanced Composite Technology on Construction Field (ACC).

REFERENCES

- [1] Rajan Sen, Mohsen Shahawy, Josas Rosas and Satya Sukumar: "Durability of Aramid Fiber Reinforced Plastic Pretensioned Elements under Tidal/ThermalCycles", ACI Structural Journal No.90-S11, Jan./Feb.1999, pp.95-104
- [2] Hiroshi Nakai, Hiroshi Sakai, Tsugio Nishimura, Taketo Uomoto: Durability of aramid and carbon FRP PC beams under natural and accelerated exposure, FRPRCS-6, July 2003