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EXPERIMENTAL STUDIES ON THE LONG-TERM TENSILE PROPERTIES OF FRP TENDONS

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Abstract
A fiber-reinforced plastic (FRP) is a composite material of fibrous reinforcement such as carbon fiber, aramid fiber or glass fiber combined with a plastic matrix, which is normally epoxy or vinyl ester resin. This new structural material has high strength, is light in weight, nonmagnetic, nonconductive and durable. Before using it as tendons for bridge strengthening, it is necessary to clarify its long-term basic properties, which are important factors in determining the critical tensile stress values. Creep rupture tests were conducted using tendons of carbon fiber-reinforced plastic (CFRP) and aramid fiber-reinforced plastic (AFRP). The correlation between creep rupture time and applied load was examined experimentally and design reference values were determined.
Key words: FRP tendon, creep rupture, load ratio

1 Introduction

The current research is part of a series to permit fiber-reinforced plastic (FRP) tendons to be used as external cable systems to strengthen existing prestressed concrete bridges, clarifying the basic properties that are essential to setting the limit values of tensile stress.

Unlike steel bars and PC tendons, FRP tendons can rupture under a constant continuous stress smaller than the static strength. It is known that their creep rupture strength depends on the magnitude of the applied continuous stress and the kind of fibers used. However, experimental results currently available are insufficient, so it is necessary to determine the tensile stress on the FRP tendons by conducting creep rupture tests.

Tendons of typical commercially-available carbon fiber reinforced plastic (hereinafter called CFRP) and aramid fiber reinforced plastic (hereinafter called AFRP) were used in the experiments (Figs. 1 and 2). Table 1 shows the main specifications of the test specimens. The values shown for nominal diameter, effective cross section and specified load are taken from the manufacturers' brochures.

2 Creep rupture

2.1 Experiment in outline

It would be most appropriate to conduct experiments using the FRP tendons that will be used in actual applications. However, it would take a long time with large-scale test equipment to conduct creep rupture tests on full-size FRP tendons. The authors, therefore, decided to use tendon specimens of reduced diameter and length for the test over

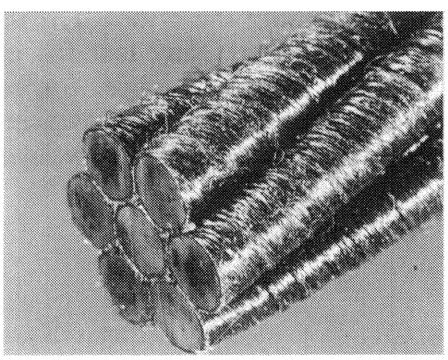

Fig. 1. CFRP

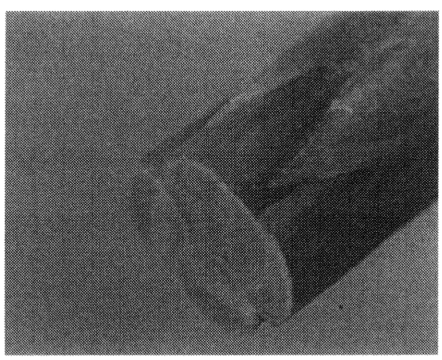

Fig. 2. AFRP

a low load range, reducing the scale of the test and enhancing testing efficiency.

In the high load range where creep rupture tests using large-capacity FRP tendons are possible, the creep rupture characteristics of two FRP tendons of different diameters are compared; and if (1) the shapes of their creep rupture probability distributions (survival probability) at an arbitrary load ratio are similar to each other, and (2) their relationships between creep rupture time and load ratio are also similar, the difference in the capacity of the material has little effect on their creep rupture characteristics. Two FRP tendons with different capacities, therefore, can be regarded as having similar creep rupture characteristics in the low load range. After verifying (1) and (2), it is possible to clarify long-term creep rupture by conducting tests using small-capacity FRP tendons over a low load range.

Table 1 shows the FRP tendons used in the experiment. The 12.5 mm-dia. CFRP and 15 mm-dia. AFRP specimens are each component strands of an FRP multiple tendon that could be used on an actual bridge. The 5 mm-dia. CFRP and AFRP specimens were used to reduce the scale of the creep rupture test. The test specimens were held by a friction-type anchorage with a steel casing grouted by expansive cement mortar, the structure of which was the same as that used to determine the specified rupture load. The loading level was represented by the ratio of the applied stress to the mean static tensile strength of each test specimen, called the "load ratio" here. Ten specimens were used for each load ratio. The "Creep rupture test method for FRP tendons (tentative)" with modifications was adopted and the creep rupture time was measured at each load ratio at room temperature. Figure 3 shows a view of the creep rupture test.

Table 1. Main specifications of FRP tendons used in the test

Tendon	CFRP		AFRP	
Fibers	PAN-based carbon fiber		Para-type aramid fiber	
Matrix	Modified epoxy resin		Bisphenol epoxy resin	
Shape	Twisted		Braided	
Nominal diameter	12.5 mm	5 mm	15 mm	5 mm
Nominal cross section	76.0 mm^2	10.1 mm^2	170.0 mm^2	21.0 mm^2
Specified rupture load	142.1 kN	17.6 kN	235.2 kN	31.4 kN

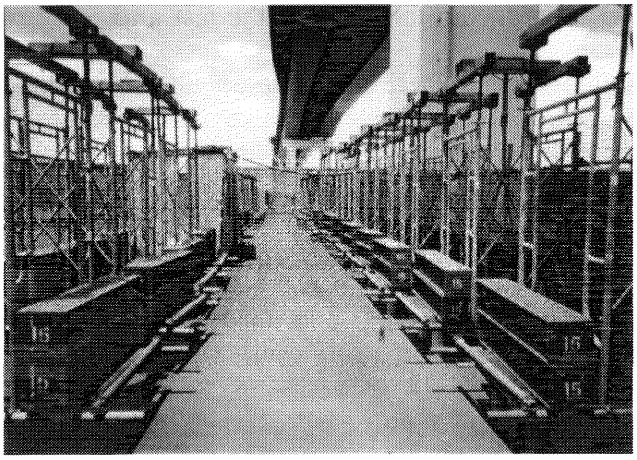

Fig. 3 View of creep rupture test

2.2 Experimental results and discussion

2.2.1 Experimental results

Experimental data ordered by the diameter of the FRP tendons and the load ratio is shown in Tables 2 and 3. "Instantaneous failure" means that a test specimen broke while the load was being initially applied, indicating that that specimen had a small static tensile strength and was not subjected to creep rupture. "Failure to rupture" means that a test-specimen did not break during the experiment due to its long creep rupture time and so did not yield time data.

Table 2. Creep rupture test results for part of the AFRP specimens

Load ratio	Time to rupture (h)	Remarks	Load ratio	Time to rupture (h)	Remarks
	1.63	Ruptured		0.40	Ruptured
0.89	4.70	Ruptured	0.93	2.23	Ruptured
	6.05	Ruptured		6.23	Ruptured
	10.50	Ruptured		6.40	Ruptured
	11.50	Ruptured		7.75	Ruptured
	12.55	Ruptured		8.19	Ruptured
	24.00	Failure to rupture		9.50	Ruptured
				10.70	Ruptured
	24.00	Failure to rupture		15.56	Ruptured
	24.00	Failure to rupture			

Table 3. Load ratio and number of test specimens

	Nominal diameter	Load Ratio	Number of test specimens		
			Instantaneous failure	Ruptured	Failure to rupture
CFRP	12.5 mm	0.92	0	4	0
		0.91	0	3	0
		0.90	0	4	0
	5 mm	1.04	13	7	0
		1.03	10	10	0
		1.01	8	8	4
		0.91	0	0	(14) In progress
AFRP	15 mm	0.93	0	9	0
		0.91	0	10	2
		0.89	0	9	3
	5 mm	0.94	0	11	0
		0.91	0	12	0
		0.89	0	9	2
		0.83	0	15	0
		0.77	0	0	(14) In progress

2.2.2 Survival probability and creep rupture time

Correlations between survival probability and creep rupture time that were drawn by the normal distribution of order statistics are shown in Figs. 4 and 5 for CFRP tendons and Figs. 6 and 7 for the AFRP. The survival probability is expressed in relation to the creep rupture time. The gradient of each straight line in the graphs represents the time variable of survival probability, i.e., the failure ratio.

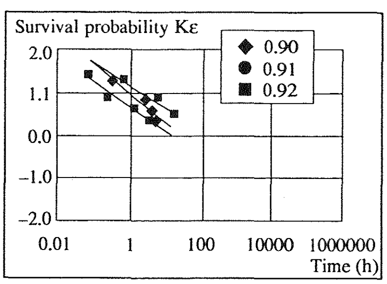

Fig. 4. Survival probability of 12.5 mm dia. CFRP

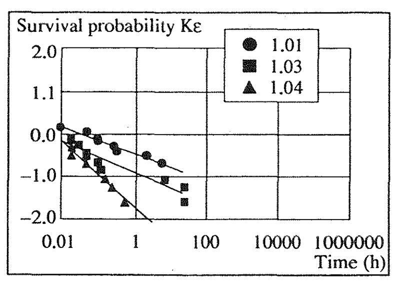

Fig. 5. Survival probability of 5 mm dia. CFRP

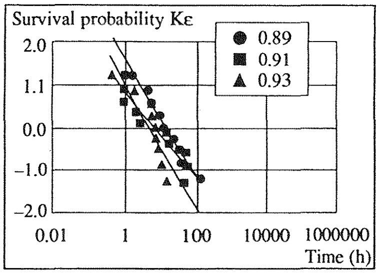

Fig. 6. Survival probability of 15 mm dia. AFRP

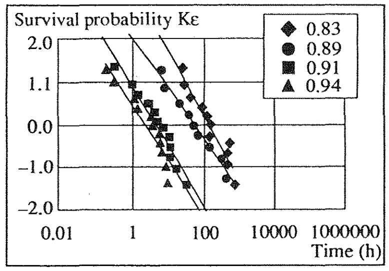

Fig. 7. Survival probability of 5 mm dia. AFRP

As the relationship between survival probability and the logarithm of creep rupture time can be approximated by a straight line for both CFRP and AFRP, it can be safely said that the distribution of creep rupture time on the logarithmic time axis is normal. The gradient of the approximated straight line is almost constant regardless of the difference in load ratio and diameter of the strand. Further, the approximate straight lines of the load ratios are arranged on the logarithmic time axis in descending order in proportion to the load ratios, which indicates that the logarithm of creep rupture time and load ratio are proportional to each other. When data of different diameters are compared, their approximate straight lines almost overlap each other at the same load ratio. According to this finding, the effect of the strand diameter on the creep rupture characteristics can be assumed to be small. Figure 8 summarizes the relationships between survival probability and creep rupture time.

Tests are still to be carried out to obtain more experimental data at lower load ratios, because the experimental results above showed an excessively wide distribution of creep rupture time in relation to the actual service life of bridges, and that the load ratios were set too close to each other and at too high a level in the test.

2.2.3 Load ratio and creep rupture time

The correlation between the load ratio and creep rupture time of CFRP is shown in Fig. 9 and that of AFRP in Fig. 10. These figures are drawn by plotting mean and mean-3σ values of creep rupture time at each load ratio. The results for the two FRP tendons of different capacities approximate the same straight line. This indicates that the effect of the difference in capacities on creep rupture time is small for both FRP tendons. The test results show that the creep rupture time distribution of CFRP ranges from instantaneous to one million hours at a given load ratio, which is much wider than AFRP; and that many

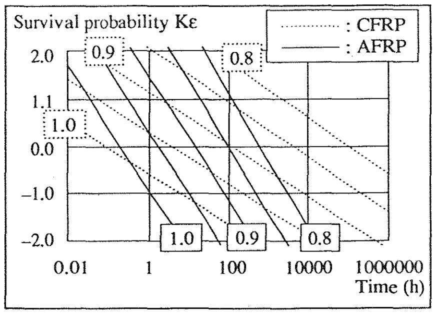

Fig. 8. Schematic diagram of survival probabilities

CFRP specimens broke instantaneously at high load ratios of 0.9 Pu and above. It is difficult, therefore, to discuss long-term creep rupture based only on these test results.

Meanwhile, the data on the right side of the symbol (■→) in Figs. 9 and 10 show the results of the test that is currently in progress at the lower load ratios. Fourteen specimens each of CFRP and AFRP are being tested. These data made it possible to verify that these approximate straight lines stay on the safe side, and indicate that the estimated values of creep rupture strength are reasonable.

2.2.4 Creep rupture strength

The above results allow the authors to estimate the critical value of creep rupture strength, one of the elements to be used to determine the design reference values of the tensile strength of tendons. Based on the approximate straight line made by the load ratio and creep rupture time, creep rupture strengths of the respective FRP tendons after fifty years at the end of the structure's service life, would be 0.66 Pu (survival probability: 50%) for the AFRP tendons and 0.79 Pu (survival probability: 50%) for CFRP, where Pu is the mean static rupture load.

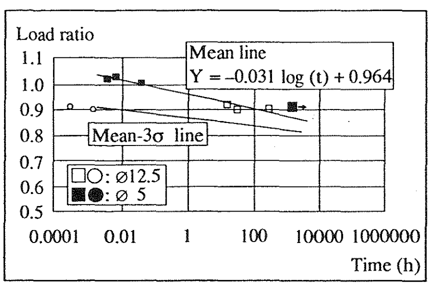

Fig. 9. Load ratio and creep fracture time of CFRP

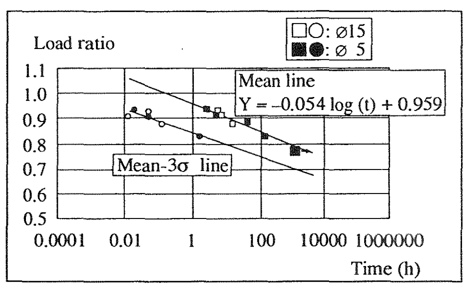

Fig. 10. Load ratio and creep fracture time of AFRP

2.2.5 Creep strain

The relationship between time and creep strain under load is shown by the curve in Fig. 11. The creep speed gradually drops during primary or transient creep, levels during secondary or steady state creep, and then accelerates during tertiary or accelerating creep, leading to eventual failure of the structure.

Creep strain was measured using the small-scale specimens used in the creep rupture test and a π-shaped gauge or a strain gauge which was attached directly to the surface of the fiber. Measurements were carried out automatically every 2 hours immediately after applying load and every 12 hours from the 7th day on. Table 4 shows the measurement conditions.

The relationship between the loading time and creep strain found in the test is shown in Fig. 12 for CFRP and in Figs. 13 and 14 for AFRP. Due to measurement intervals, primary and tertiary creep strains may not have been measured. The focus is placed mainly on the increase in the creep strain in these diagrams.

The creep strain in both CFRP and AFRP increases with time at a rate which suggests that individual FRPs have intrinsic creep strain

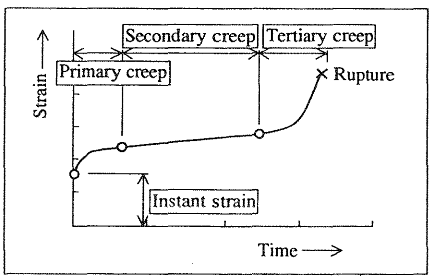

Fig. 11. Creep strain model diagram

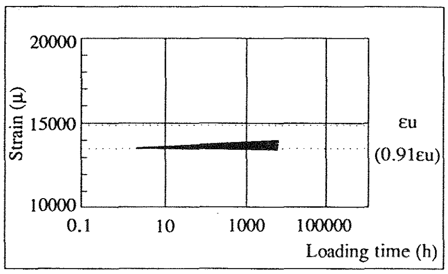

Fig. 12. Creep strain of CFRP

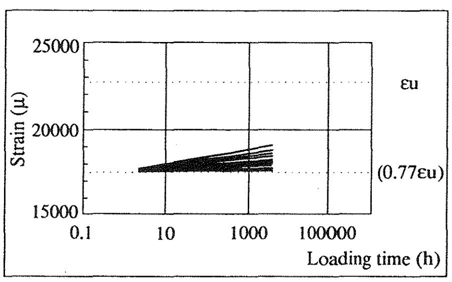

Fig. 13. Creep strain of AFRP case 1

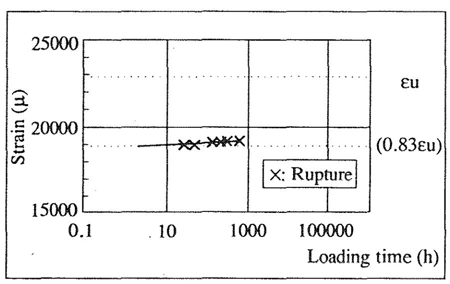

Fig. 14. Creep strain of AFRP case 2

Table 4. Test conditions

	CFRP	AFRP Case 1	AFRP Case 2
Load	0.91 Pu	0.77 Pu	0.83 Pu
Tool	π gauge	Strain gauge	π gauge
No. specimens	13	8	6
Measurement time	6418 to 6442 h Failure to rupture	3742 to 3921 h Failure to rupture	26 to 597 h All ruptured

speeds. The gradients of AFRP Case 1 varied remarkably as compared with the other cases. It is highly likely that the measurement was very topical because the strain gauge was attached directly to the surface of the fiber. AFRP Case 2 ruptured during the measurement period probably because of tertiary creep immediately before rupture.

These results suggest that CFRP and AFRP have intrinsic characteristics in their development of creep strain, which is almost proportional to the logarithms of the load time.

2.3 Summary

The main findings concerning creep rupture from this study are as follows:

1. FRP tendons were subjected to creep rupture during tests conducted in this research. The time to failure varied extremely widely, which would require a stochastic method to handle these data.
2. The rate of time variance for survival probability (i.e. failure rate) follows almost the same logarithmic normal distribution, regardless of the diameter of the tendon and the load ratio.
3. The difference in the capacities of the tendons does not have any effect on the creep rupture time; and the load ratio and the logarithm of creep rupture time are proportional to each other.
4. The creep strain increased in proportion with the logarithm of time.
5. It will be necessary to employ different load ratios to accumulate more data for long-term creep rupture that are experimentally feasible time-wise and which present a better spread of ratios compared with the test results above.

3 Concluding remarks

Intrinsically the tensile strength of FRP tendons when they are employed in an actual structure is reduced gradually by relaxation and therefore creep rupture and relaxation occur at the same time in them. In addition to creep rupture, fatigue and delayed rupture also proceed with time: it would be necessary to determine the design rupture strength of an FRP tendon by taking all of these elements into consideration. So far almost no tests have been conducted which distinguish strictly between these rupture modes or analyze interactions between multiple rupture modes. It is necessary to clarify the differences and similarities among the various rupture modes, and their interactions.

4 Acknowledgements

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