論 文

[1169] EXPERIMENTAL MODEL FOR IDEAL TENSILE FAILURE OF FRP RODS

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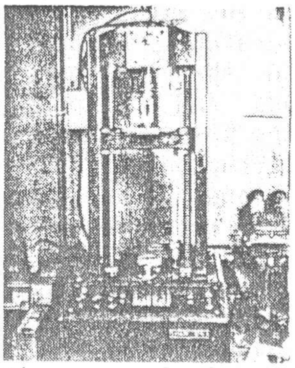
1. INTRODUCTION

FRP rods, with continuous fibers, have come into use as prestressing tendons for concrete due to their merits such as high strength, light weight and durability. However, there are still many uncertainties concerning their behaviours under different cases of loading encountered in practice. The properties of the rods are direct consequence of their components properties and the components interaction. Hence, investigation of the single component behaviour under different cases of loading seems one basic approach to provide interpretation on the rods behaviour. The role played by each component differs depending on its sensitivity to the loading case in question. In practice, the rods might be subjected to static, dynamic and cyclic tensile loading. This research considers only the monotonic increasing static loading of the rods. The study aims at developing ideal stress-strain curve for the rods by testing single fibers of three different materials commonly used (aramid, carbon& glass). Due to the minute matrix participation (about 2%) to the rod strength, matrix strength is neglected in formulation and ideal relevant properties are assumed in order to establish the intended model.

2. SPECIMENS PREPARATION AND TESTING PROCEDURE

Single fibers were separated from different locations along the fiber rolls. The fibers were attached to pieces of paper with standard dimensions (JIS R-7601/1986) using instant adhesive. Fig.1 shows the standard specimen and photograph for the experiment arrangement. The paper pieces were punched near both ends to ease mounting them in the machine chucks. Testing machine has capacity of 300 grams and can provide a variety of cross-head speeds through a gearbox. In



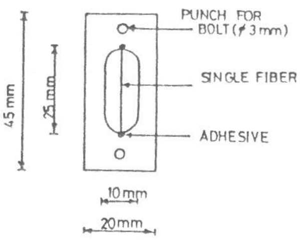


Fig.1 Standard Specimen and Experiment Arrangement

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order to investigate the effect of loading rate, three strain rates, .016, .04 and .132/min were used. Almost 500 specimens of all fibers were tested. The specimen is mounted into the chucks using bolts; then the chucks are fitted into the machine. The paper is cut on both sides of the fiber leaving it as the only connection between the two chucks. The machine is connected to a plotter that monitors the load develoment upon the machine operation. The resulting load-time curve is transformed into stress-strain curve by considering fiber length, cross-head speed, chart speed and fiber diameter.

Fibers diameters were measured using scanning electronic microscope (SEM). Diameters of different fibers at different sections were measured resulting in 100 pieces of data for each kind of fiber. This data was statistically analysed and the main characteristics are shown in Table 1. The uniformity of the fibers were concluded due to the low scattering of the data (low standard deviation) and confirmed by the SEM photographs. This low scattering allows the use of mean diameter values for the strength analysis.

Table 1 Statistical Characteristics of Fibers Tensile Parameters and Diameters

Material		Diameter (μm)	Strength (MPa)	Max. Strain (x10^{-6})	Young's Modulus (GPa)
Aramid	Mean (conf. 99%)	12.15 ± .11	3815 ± 78	44116 ± 3100	82 ± 4
HFY-T240	Std. Devn.	.4141	350	8475	11
	C.O.V.	.0341	.092	.192	.129
(154)	Weibull Modulus	—	13.2	—	—
Carbon	Mean (conf. 99%)	6.68 ± .12	3290 ± 110	13882 ± 725	223 ± 5
Pan	Std. Devn.	.4441	510	3147	21
T-300	C.O.V.	.0664	.155	.228	.095
(150)	Weibull Modulus	—	7.5	—	—
Glass	Mean (conf. 99%)	12.77 ± .16	2460 ± 175	28871 ± 2600	84 ± 4.6
RST110	Std. Devn.	.6049	850	9032	16
PA-535	C.O.V.	.0474	.347	.313	191
(155)	Weibull Modulus	—	3.2	—	—

3. EXPERIMENTAL RESULTS, STATISTICAL ANALYSIS AND DISCUSSION

Samples of the resulting load-time curves are shown in Fig.2 for different loading rates. Carbon fibers have neat and sharp linear curves whereas glass and aramid fibers, although having some linear curves, show many interrupted curves. The yield-like portions in the curves, for all fibers, occurred at the load range of 13-15 grams. Therefore, they were attributed to the common part among all the specimens (i.e. holding paper) as its bearing failure around the chuck bolt. Drops reported in some curves were attributed to the slip of the paper edges on the bolt teeth. Testing, by mistake, of more than one fiber at a time, as a possible cause of the drops, was disregarded because of the drops values and curves slopes.

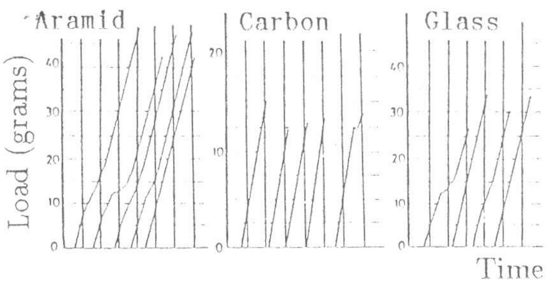

Fig.2 Samples of Fibers (load-time) Curves

The mean strength for all fibers at all loading rates was calculated and the results are plotted in Fig.3. It is obvious that strength has no strain rate dependence. Hence, all data, regardless of loading rate, is used for the statistical analysis of tensile parameters (strength, Young's modulus E and maximum strain). Statistical characteristics of the tensile parameters, together with the number of tested fibers in parentheses, are shown in Table 1. Fig.4 shows correlations between the strength and both E and maximum strain. Weibull moduli (calculated using [1,4] and [pp.211,2]) shown in Table 1 agree with the relative brittleness of the three materials, because it possesses the lowest value for glass, the highest for aramid and intermediate for carbon. The confidence range of the results is also given for 99% confidence and it shows that the most reliable mean is that of the most ductile material (aramid).

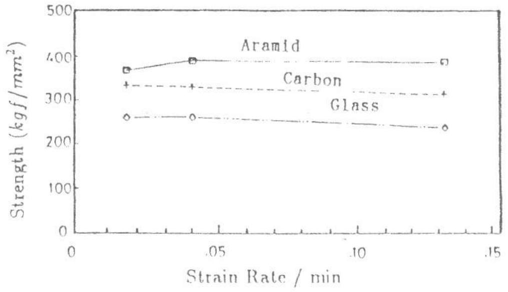

Fig.3 Varaition of Fibers Strength Mean Values with Strain Rate

As shown in Fig.4, all the distributions of E values show low scattering and this is confirmed by the linear correlation between strength and maximum strain and the correlation absence between strength and E values. The linear correlation between strength and maximum strain assures, also, the linear stress-strain relationships of the fibers.
The results of different statistical parameters and also the correlations assure the reliability of the experimental data as basis for rods behaviour prediction.

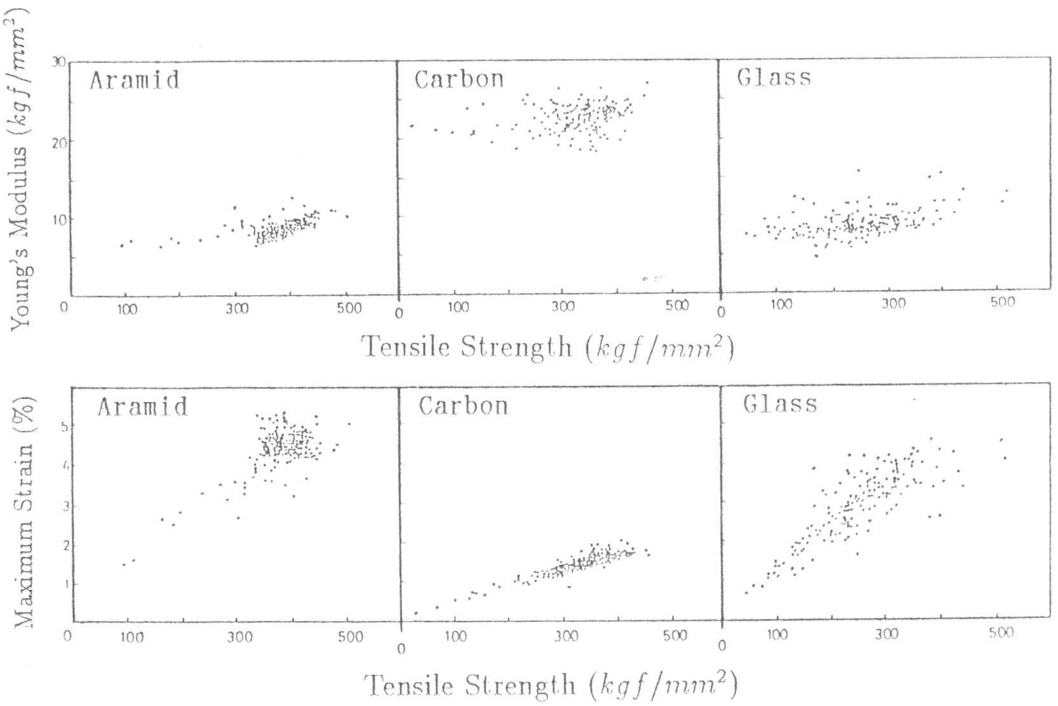

Fig.4 Maximum strain-Strength and Young's Modulus-Strength Correlation

4. IDEAL MODEL FOR ROD BEHAVIOUR UNDER TENSILE LOADING

In order to predict the behaviour of FRP rods in the ideal case, some assumptions concerning the matrix properties and the matrix-fiber interaction should be set. These assumptions are as follows:
1) The matrix maximum strain is much more than that of the fibers and there exists perfect bond between them at all strain levels.
2) The ductility of the matrix can absorb the stress concentration resulting from fiber fracture with no matrix failure or debonding.
3) The percentage of cut fibers during rod manufacturing is too low to affect the overall performance.
4) Matrix strength is negligible with respect to that of fibers.
5) Fibers are uniformly distributed inside the rod.

When the rods are loaded both fibers and matrix undergo the same strain ϵ . The resulting stress is proportional to Young's modulus and hence the total load carried by rod, containing n fibers, is

$$P = \sum_{i=1}^{n} E_{fi} A_f \epsilon = \epsilon A_f \sum_{i=1}^{n} E_{fi} \tag{1}$$

where E_{fi} = Young's modulus of i th fiber
A_f = mean cross-sectional area of single fiber

If σ denotes the nominal rod stress, A is its cross-sectional area and E_c is its Young's modulus, then

$$P = \sigma A = E_c \epsilon A = \epsilon A_f \sum_{i=1}^{n} E_{fi} \tag{2}$$

$$E_c = \frac{A_f}{A} \sum_{i=1}^{n} E_{fi} = \frac{nA_f}{nA} \sum_{i=1}^{n} E_{fi}$$

$$= V_f \bar{E}_f \tag{3}$$

where V_f = fiber volume fraction

This implies that Young's modulus of the rod is proportional to the mean Young's modulus of the fibers and hence the response is also linear.
When fiber fails in tension, it will act as discontinuous fiber and cause disturbed zone around the cut section. This zone has the dimensions required to support fiber anchorage. The dimensions of this zone are estimated, roughly, as follows;
Following the analysis made by Jayatilaca [4], the transfer length (l_c) of fiber can be estimated from the following formula

$$\frac{l_c}{r} = \frac{\sigma_f}{2\tau} \tag{4}$$

where r = fiber radius
τ = matrix shear strength
σ_f = fiber tensile strength

The matrix shear strength is almost half of its tensile strength [4] and the fiber mean strength is usually 45-50 times higher than that of the matrix. At low stress levels (about half the mean value of fibers) the transfer length is about 25 times the fiber radius. The separation caused by fiber failure can be approximated to a crack and the stress distribution along it follows the formula derived by Westergaard [7]

$$\sigma_y = \frac{p}{\sqrt{1-(\frac{\alpha}{x})^2}} \tag{5}$$

where α = semi crack width
p = applied uniform stress
x = distance, from the crack center, along crack axis

In order to correct the stress singularity at the crack tip, the equivalent crack concept is used [5]. The perfect plastic matrix will provide the yielded zone around the virtual crack and hence the value of α is substituted by r/V_f (considering the uniform distribution of the fibers in the section). From equation (5), the disturbance in stress almost vanishes at $x = 3a$. This means that the radius of disturbed zone is about 7 times the fiber radius for practical cases (V_f above 40%).
Hence, the disturbed zone due to fiber failure can be considered as cylinder with diameter of $100\mu m$ and height of $350\mu m$. This implies that the effect of fiber breakage is limited to small zone around the fiber.

The rod response is the integration of infinitesimal responses along the rod

$$\epsilon = \int_l d\epsilon = \int_l \frac{\sigma}{E} dl/l \tag{6}$$

and the disturbed length and the additional load spilled from the cut fiber are too small to affect the value of the response. Hence, the individual fiber failures scattered along the rod will not affect the overall response of the rod. At high stress levels, the number of failed fibers will, statistically, increase. However, the probability of having one fiber broken at many sections or having many fibers broken at the same section is small. Hence, a few number of severly damaged sections of high strains will exist, where failure initiation is likely. At these sections the transfer zone is still small in length and hence the rod response remains linear. The failure propagation in the severely damaged sections is dependent on the strength of the fibers surrounding the damage. This is completely random and hence the maximum strain at which the rod fails is also random. However, as the cumulative strength distribution of the fibers is steep around the mean value, any incremental stress at this region will drive additional fibers broken. Hence, it is the most probable point of damaged section instability. Therefore, it could be a good estimation for the mean value of net rod strength (fibers area only considered). A mean nominal rod strength follows the equation

$$\sigma = \sigma_f V_f \quad \text{where } \sigma_f = \text{fiber mean strength} \tag{7}$$

This model was compared with the actual stress-strain curves of FRP rods reinforced with the three kinds of fibers and fiber volume fraction 0.66. Linear behaviour was confirmed for all the three types of FRP rods and the slope agrees well with the proposed model as shown in Fig.5. However, the strength of CFRP rods was much below the value predicted by equation (7). There exist several reasons, concerning the failure mode of the rods, the real properties of the matrix, and also the loading system caused this deviation and will be discussed later elsewhere.

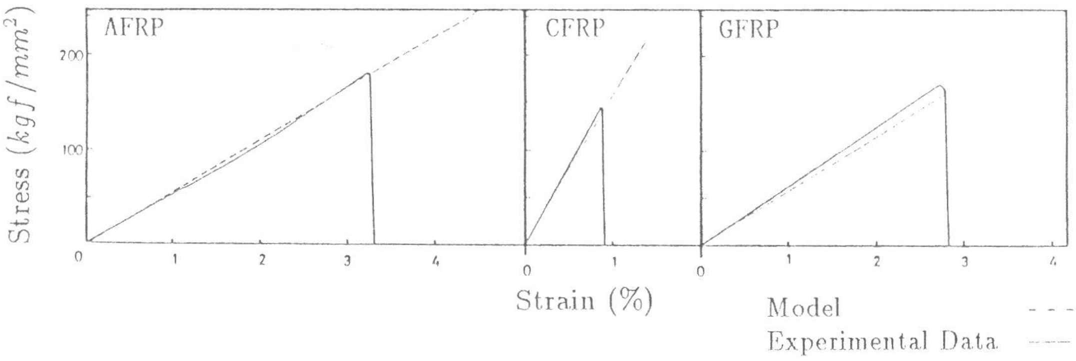

Fig.5 The Agreement of Actual FRP Rods Behaviour and the Proposed Model

5. CONCLUSIONS

1. The stress- strain relationships for the three tested fibers are linear up to failure and all fibers have uniform geometry. Also, there is no strain rate dependence of the strength.
2. For further investigation of fibers behaviours through testing, the fiber holding material should be carefully chosen to account for the stress concentration at the chuck bolt.
3. Stress-strain relationships for FRP rods, under the ideal conditions of matrix plasticity and perfect bond, are linear up to failure.
4. The ideal properties assumed for matrix have hardly any effect on the linearity of the actual rod behaviour (that is also linear up to failure) for high fiber volume fraction.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude twards Prof. KAGAWA (University of Tokyo, IIS, 4th devision) and his laboratory staff for providing the fiber testing machine and many useful advices during experiments. The authors are, also, quite grateful to TEIJIN company, the fibers manufacturer, for providing the fibers tested.

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