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STATIC STRENGTH AND ELASTIC MODULUS OF FRP RODS FOR CONCRETE REINFORCEMENT

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Taketo UOMOTO Tsugio NISHIMURA

ABSTRACT

This paper aims to clarify the fundamental properties of FRP rods for concrete reinforcements, such as static strength, elastic modulus and deformation characteristics. The rods are made of aramid fibers, glass fibers or carbon fibers, with the fiber content of 45%, 55% and 66% by volume. The tests were performed in accordance with the test method of JSCE (draft). The test results show that strength of CFRP rod may be affected by gripping chucks, strain measurement by plastic-wire-strain gauge may not be sufficient and it is also clarified that there are some points in the JSCE test method to be modified.

Key Words: FRP rod, static strength, strength distribution, elastic modulus, test method

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T. UOMOTO is a professor at the Institute of Industrial Science at the University of Tokyo, Tokyo, Japan. He received his Doctor of Engineering Degree from the University of Tokyo in 1981. He specializes in composite materials for construction, such as fiber-reinforced plastic, durability of concrete and application of nondestructive testing methods for concrete structures, he is a member of JSCE, JCI, ACI and JSNDI.

T. Nishimura is a technical engineer at the Institute of Industrial Science at the University of Tokyo, Tokyo, Japan. His research interests include fiber-reinforced plastic and steel-fiber-reinforced concrete. He is a member of JSCE and JCI.

1. Introduction

In recent years, the corrosion of high-strength tensile materials in many reinforced concrete structures, including prestressed structures, has become a problem in Japan as well as in other countries. In structures exposed to a marine environment such as at coastal and offshore sites, and also where large quantities of deicing salts are used, such deterioration results from the corrosion of steel due to salt penetration. Since 1980, Kobayashi et al.(1,2) have been carrying out research related to prestressed concrete structures subjected to severe corrosive environments. As a drastic solution to the corrosion problem, they used non-corrosive fiber reinforced plastics as prestressing strands; these offer a tensile strength equal to or greater than that of the prestressing steel used in conventional methods.

In a different area, studies related to the practicability of magnetic-field-driven linear motor transport have recently been in progress. The use of non-magnetic materials as reinforcing materials in the structure for such transport systems is essential instead of the conventional steel reinforcing and PC strands. Among the available non-magnetic materials, FRP rods are considered favorable for use in this type of structure.

Since FRP rods do not suffer from the above problems which plague conventional steel materials, studies regarding the practicability of these rods are required and are now in progress (2,3,4). Before future widespread adoption in concrete structures as reinforcement, the characteristics of these FRP rods have to be well understood. A great deal of research has been done to identify the characteristics of FRP rods, but the experiments vary widely and their results can not be compared. In April 1992, the Japan Society of Civil Engineers published basic regulations (tentative) for various experimental methods (4).

In the present study, tensile tests were carried out on various plastic rods containing Aramid fibers, glass fibers, and carbon fibers (abbreviated as AFRP, GFRP, and CFRP rods). Tensile tests were based on the tensile test methods for continuous fiber reinforcements as specified in the JSCE guidelines with the aim of clarifying the most important characteristics of FRP rods as regards their use as reinforcement in concrete structures. This paper presents the results of those tests and the analytical results obtained.

2. Outline of experiments:

Two series of experiments were carried. The main objective of the first series was to investigate the variations in the tensile strength and elastic modulus of FRP rods. The idea of the second series was to determine the deformation characteristics of FRP rods and methods of measuring them.

The reinforcing fibers tested in these experiments were as shown in Table 1, Aramid fibers, glass fibers and carbon fibers. The matrices of these FRP rods were vinyl resins as shown in

Tab.1 Characteristics of FRP rods

	Fiber type	aramid	glass	carbon
Dimensions (μm)	mean value	12.15	12.77	6.68
	S.D.	0.4141	0.6049	0.4441
	C.O.V.	0.0341	0.0474	0.0664
Strength (kgf/mm^2)	mean value	389	251	335
	S.D.	36	87	52
	C.O.V.	0.092	0.347	0.155
Elastic modulus (kgf/mm^2)	mean value	8355	8551	22730
	S.D.	1081	1629	2152
	C.O.V.	0.129	0.191	0.095

C.O.V. : coefficient of variation
S.D. : standard deviation

Tab.2 Characteristics of matrices of FRP rods

	matrix type	R ipoxy -R802	R ipoxy -H600
Tensile strength (kgf/mm^2)	mean value	8.49	6.70
	S.D.	0.115	0.496
	C.O.V.	0.01	0.07
Elastic modulus (kgf/mm^2)	mean value	311	400
	S.D.	3.7	3.9
	C.O.V.	0.01	0.01
Poisson's ratio (ν)	mean value	0.335	0.351
	S.D.	0.005	0.004
	C.O.V.	0.15	0.11
Extension at failure (%)	mean value	5.22	1.95
	S.D.	0.11	0.27
	C.O.V.	0.02	0.14

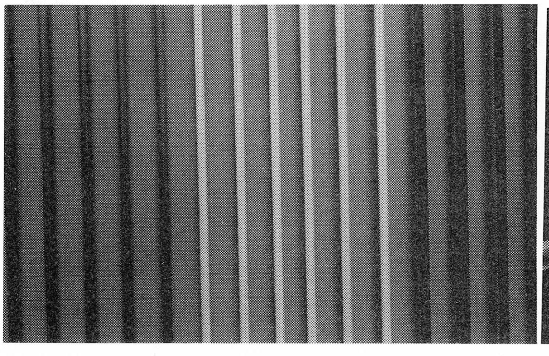

Photo-1 Fibers used in the experiments

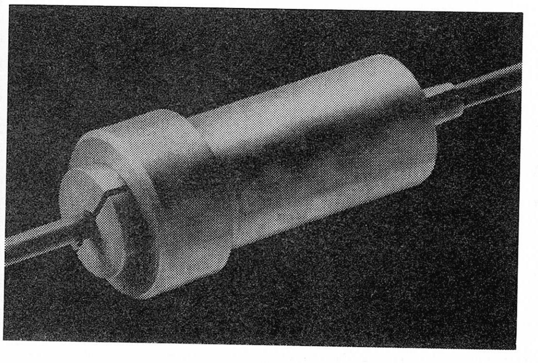

Photo-2 Split chuck used at the anchorage

Table 2. The matrices for AFRP and GFRP were ripoxy-R802, while that for CFRP rods was ripoxy-H600. All FRP rods were 6 mm diameter round bars (as shown in Photo 1) aligned in one direction and with fiber volume fractions of 45%, 55%, and 66%. Dimensions, strengths, and elastic moduli of the fibers shown in Table 1 were obtained in the experiments carried out by Hodhod et al. on more than 100 monofilaments (6).

Tensile tests on FRP rods were carried out according to the tensile test methods specified for continuous fiber reinforcements (JSCE). Anchoring method was the split chucks (shown in Photo 2) developed by Kobayashi et al.(1,7). These chucks were originally developed for the testing of AFRP rods. Since the shape and measurements are the same for GFRP and CFRP, assuming that there are no problems in application of these, the same type of chucks were used for GFRP and CFRP. A protective coating was added to the anchoring surface by first applying unsaturated polyester resin as a bedding treatment and then a uniform coating of a mixture of unsaturated polyester resin and iron powder (300 mesh) with a weight ratio of 1:1.8. The thickness of this protective coating was made about 300 μm according to the experiments done by Kobayashi et al.(8).

Tests were carried out on 40 cm long AFRP, GFRP, and CFRP rods and for each fiber volume fraction. Twenty rods of the same type were tested per day. After testing 100 rods, tensile tests were carried out in the same way on different type of rods. The testing machine, an Autograph, is a displacement control type with a capacity of 10 tons. Loading rate was maintained at 5 mm/min. Tensile strength values in each experiment were obtained by dividing the maximum load by the cross sectional area over which the load was applied (the average diameter was 6 mm). Strain was measured using an ordinary wire strain gauge (2 mm in length, referred to as normal gauge). Tests were performed at room temperature (which was maintained within the range $20\pm5^{o}c$).

In the second series of experiments, tests of deformation characteristics were carried out on three types of FRP specimens of 80 cm in length. A Servo-Pulsar loading machine (load control type) was used in these experiments, and the rate of loading was maintained at 20-22 kgf/sec. The measurements taken were as follows:

1) Stress-strain curve for monotonic loading conditions
2) Stress-strain relationship after subjecting a specimen to static cyclic loading (at intervals of 500 kgf)
3) Stress-strain relationship and secant modulus after 20 cyclic loadings (the lower limit for each FRP rod was kept at 25% of the average tensile strength and the upper stress levels were varied between 50%, 75%, and 85% of the average tensile strength.)

Strain of the rods was measured keeping extensometer (EDP-5A-50, length of extensometer as 50mm, an error of 0.03% for 5mm deflection measurements of cyclic loadings) as the base measurement and comparison was made with the measurements of normal wire strain gauges (length 2mm and hereinafter referred to as normal wire gauges) and plastic-wire-strain gauges (length 5mm and hereinafter referred to as plasticity gauges). Two strain gauges of each type were pasted symmetrically on the center of rod surface.

3. Tensile strength of rods

3.1 Static tensile strength and its variation

The tensile strength and elastic modulus of each type of FRP rod, as well as the standard deviation and coefficient of variation of strength are indicated in Table 3. Figures 1(a)-1(c) show the relationship between tensile strength and failure probability of rods as the fiber volume fraction, Vf, of each type of FRP rod is varied from 45% to 66%. According to the results for AFRP rods (case (a)), the change in variation of strength was more or less the same and a linear increase in strength was shown as Vf was increased. In case (b), GFRP rods behaved similarly to AFRP rods when Vf was 45% and 55%. There was little strength when Vf was increased to 66%. This tendency was different in the case of CFRP rods (case (c)) where the variation in strength was large and little increase in tensile strength was exhibited even when Vf was increased.

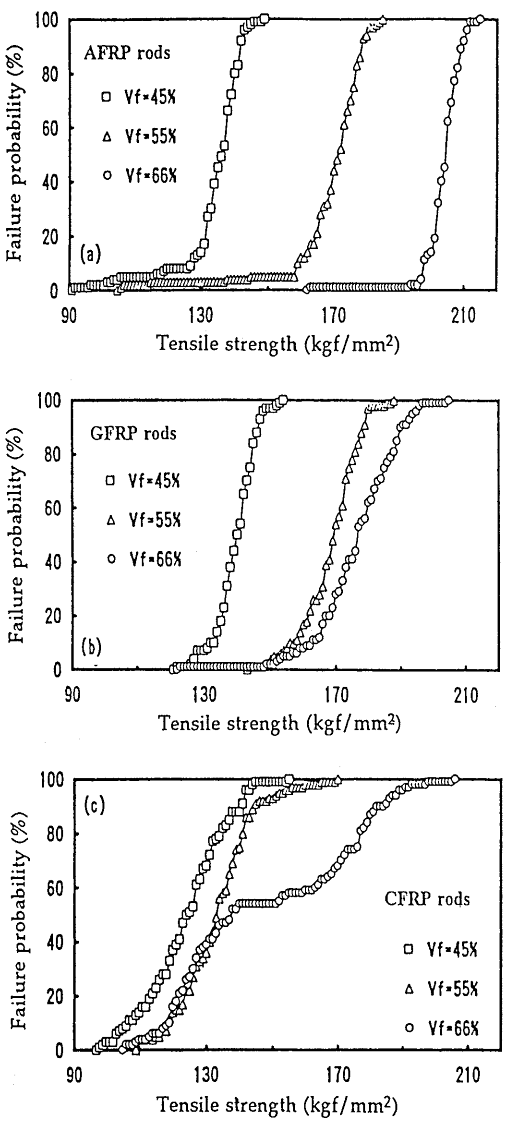

Fig.1 Relationship of tensile strength and failure probability of FRP rods

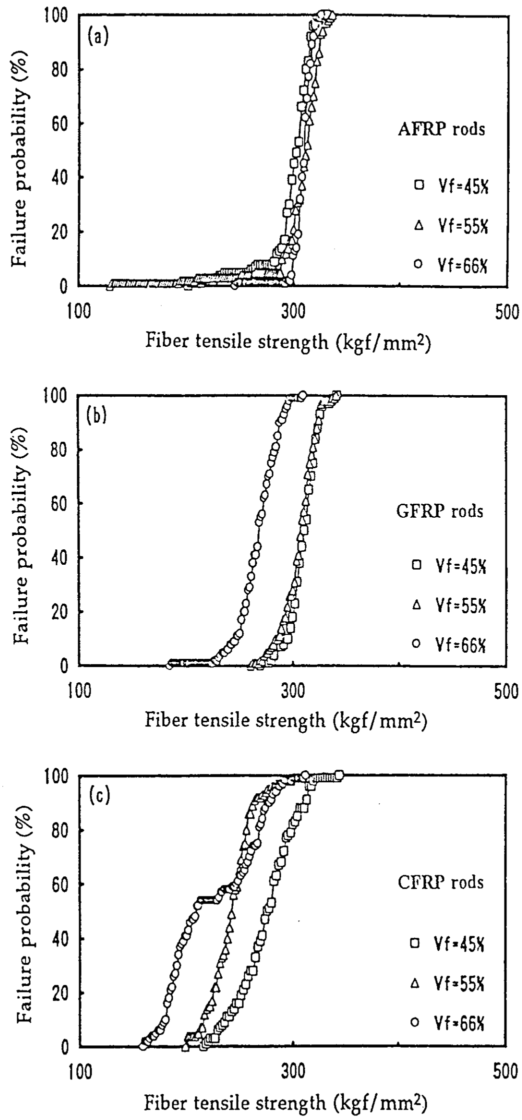

Fig.2 Relationship of tensile strength and failure probability of FRP rods

Figures 2(a)-2(c) give the relationships for tensile strength divided by the fiber volume fraction. That is, they represent fiber tensile strength without considering the effects of the fiber volume content and failure probabilities. According to Fig. 2(a), for AFRP rods, the strength distribution is almost the same whatever the fiber volume fraction, and the average tensile strength is 308 kgf/mm^2. For GFRP rods, shown in Figure 2(b), the strength distribution is almost the same for Vf values of 45% and 55% and the average fiber tensile strength for all fiber fractions is about 310 kgf/mm^2. However, when Vf reaches 66%, the average tensile strength decreases to 270 kgf/mm^2. On the other hand, CFRP rods (shown in Figure 2(c)), show a

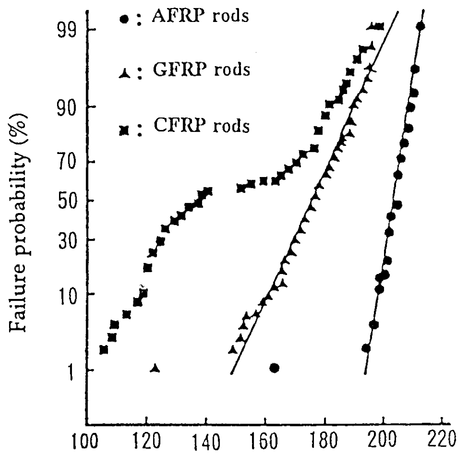

Fig.3 Relationship of tensile strength and failure probability of FRP rods where Vf is 66% (plotted on a log normal paper)

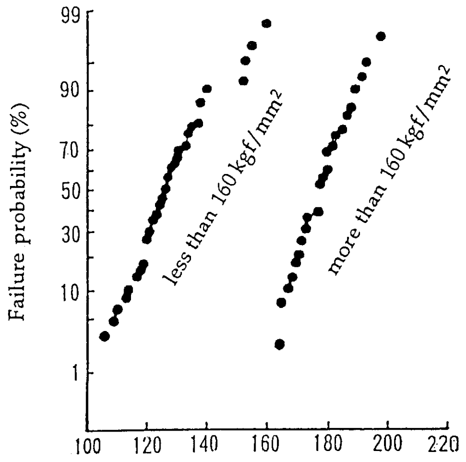

Fig.4 Relationship of tensile strength and failure probability of CFRP rods where Vf is 66% (plotted on a log normal paper)

different kind of behavior, where not only does the strength distribution differ according to fiber volume fraction, but the average fiber tensile strength also changes - it is 276, 243 and 224 kgf/mm^2 for Vf values 45%, 55% and 66% respectively. That is to say, the lower the fiber volume fraction, the higher the average fiber tensile strength.

In order to determine how the strength of FRP rods is distributed, the strength of FRP rods obtained from the tests was plotted on a Gaussian distribution axis. With the 66% fiber fraction rods as an example, the results are shown in Figure 3.

As can be seen from this figure, in the case of AFRP and GFRP rods, the failure probabilities show almost a linear behavior. In the case of AFRP rods, the variation seems to be small (standard deviation: 5.7 kgf/mm^2) and that of GFRP rods is large compared with AFRP rods (standard deviation:12.2 kgf/mm^2). However, in the case of CFRP rods, the behavior is non-linear. Instead, the curve can be classified into three stages, corresponding to stress, intermediate stress, and low stress. CFRP rods not only exhibit a larger variation than the other two types, but also have a very low average tensile strength of 148 kgf/mm^2. Judging from the fiber strength alone, however, one might expect a higher strength. To discover the reason for this unusual behavior, the following investigations were carried out.

3.2 Variation in tensile strength and failure mode of CFRP rods

FRP rods in general exhibit several modes of failure including failure of the fibers, cracking of the matrix, partial interfacial adhesion failure, failure between fiber and matrix, longitudinal cracking, etc,. The reason for the unusual distribution shown in Fig.3 is believed to be the difference in failure mode according to the situation. In fact, observing the area of

Tab.3 Tensile strength and elastic modulus of FRP rods

	Vf	Fiber type	AFRP	GFRP	CFRP
Strength (kgf/mm^2)	45%	mean value	135	140	124
		S.D.	9.49	5.83	11.8
		C.O.V.	0.0703	0.0416	0.0952
	55%	mean value	169	169	134
		S.D.	14.8	8.53	11.2
		C.O.V.	0.0876	0.0505	0.0836
	66%	mean value	204	177	148
		S.D.	5.73	12.2	27
		C.O.V.	0.0281	0.0689	0.1824
Elastic modulus (kgf/mm^2)	45%	mean value	3748	4274	11202
		S.D.	216.1	52.2	259.5
		C.O.V.	0.0576	0.0122	0.0232
	55%	mean value	4570	5211	13530
		S.D.	194.5	47.6	236.3
		C.O.V.	0.0426	0.0091	0.0175
	66%	mean value	5460	6024	15714
		S.D.	241.2	101.2	379.4
		C.O.V.	0.0442	0.0168	0.0241

the failure, it is evident that AFRP and GFRP rods have similar failure patterns irrespective of their strength, and failure of both the fiber and anchorage of these two types of rod seems to occur at the same time. Depending on the conditions, however the failure mode of a CFRP rod can be divided into three categories:

1. fiber pullout and simultaneous failure at anchorage and partial failure nearby
2. fan-type failure
3. a mix of failures of 1 and 2

Accordingly, the data for CFRP rods were divided into failures at above 160 kgf/mm^2 (as in 1) and those at less than 160 kgf/mm^2 (as in 2). These were plotted on a Gaussian distribution axis as shown in Figure 4. The results are two straight lines.

This analysis indicates that the strength characteristics of CFRP do in fact fall into three categories according to stress (low, intermediate and high stress). The reasons for failure of the rods can be broadly categorized into two types, as follows:

1. failure due to stress concentration
2. fiber matrix failure

The third failure mode is assumed to be due to both of these occurring simultaneously. If 1 and 2 are considered two independent events, each one has its own failure distribution pattern. However, overall failure of the rod is considered to result from a mixture of failures 1 and 2.

Considering the results of Fig.3, and assuming that failures 1 and 2 occur in a normal distribution and the fraction of failures occurring due to 1 is p1 and that due to 2 is p2, then the failure probability density function f(x) for the rod itself can

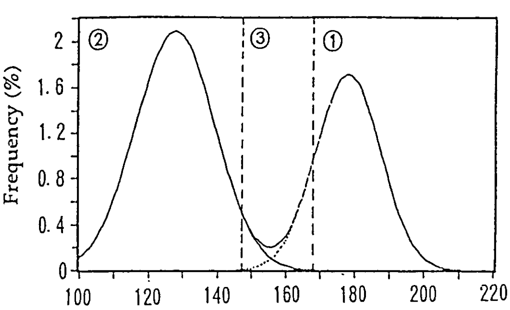

Fig.5 Frequency distribution of tensile strength of CFRP rods (calculated values)

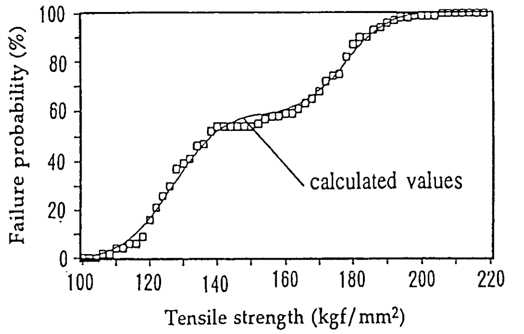

Fig.6 Comparison of calculated and observed values of frequency

be written as follows.

$$f(x)=p1.f1(x)+p2.f2(x)\ldots\ldots\ldots\ldots(1)$$

here, $p1+p2=1$

$$f_1(x)=\frac{1}{\sigma_1\sqrt{2\pi}}\cdot\exp\left[-\frac{(x-\mu_1)^2}{2\sigma_1}\right]$$

$$f_2(x)=\frac{1}{\sigma_2\sqrt{2\pi}}\cdot\exp\left[-\frac{(x-\mu_2)^2}{2\sigma_2}\right]$$

$\mu 1, \mu 2$: average stresses
$\sigma 1, \sigma 2$: standard deviations

Considering the equation(1), data shown in Fig.3 can be classified into two; the strength values higher and lower than a limiting value of 160 kgf/mm^2. The resulting values for p1 and p2 are 0.4 and 0.6 respectively. The following can be concluded from these observations:

For tensile strength more than 160 kgf/mm^2,
average value $\mu 1$ = 178.1 kgf/mm^2
standard deviation $\sigma 1$ = 9.3 kgf/mm^2
For tensile strength less than 160 kgf/mm^2,
average value $\mu 2$ = 127.7 kgf/mm^2
standard deviation $\sigma 2$ = 11.5kgf/mm^2

Using these results, the tensile strength frequency distribution can be calculated from equation 1. It is illustrated in Fig.5, with three regions of distribution.

From Fig.6, it is evident that there is good agreement between calculated values and observed values, so it can be said that the theory described above fits well with the actual behavior of rod failure. In other words, the reason for the strength distribution of CFRP rods shown in Fig.3 is that there are two failure modes which can exist independently. These two different failures are assumed to be caused by the following:

1. The failure of the fiber itself due to stress concentration at the anchorage (when the stress is greater than 160 kgf/mm^2)

2. Failure at the interface between fiber and matrix (when the stress is less than 160 kgf/mm^2)

It can be assumed for CFRP rods that the stress concentration at the anchorage influences failure when the fiber strain is as less as 1%. Moreover, the average fiber tensile strength obtained from the distribution curve of failure mode 1 is,

$178/0.66 = 270\ kgf/mm^2$

This value is close to the fiber strength when the fiber volume fraction is 45%.

3.4 Tensile strength and number of test specimens

Figures 7(a)-7(c) are graphs drawn of tensile strengths for 100 bars of each FRP type described previously. In each graph, the ratio of maximum and minimum tensile strength for "n" number of specimens where "n" varies from 3 to 90, and the average strength of 100 rods are plotted against number of specimens "n". It is evident from these figures that the results vary depending on the fiber volume fraction. Even for average strength of 100 rods, the smallest deviation was shown by GFRP while CFRP showing the maximum. For example, when the number of test specimens is 10, the results for AFRP rods show a deviation of about 5-9% whereas GFRP rods show 4-8% and CFRP 12-17%.

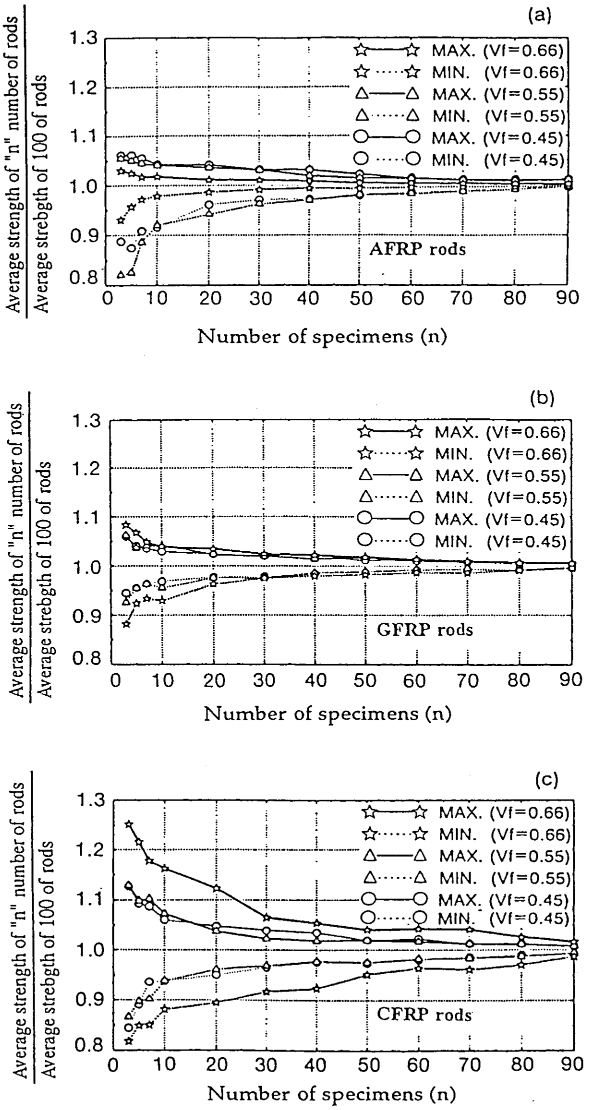

Fig.7 Relationship of average strength ratio and number of specimens

Tab.4 Number of specimens required to evaluate the mean value of population (critical factor,10%)

Fiber volume fraction (Vf)	CFRP	AFRP	GFRP
45%	7	9	10
55%	7	13	8
66%	12	10	11

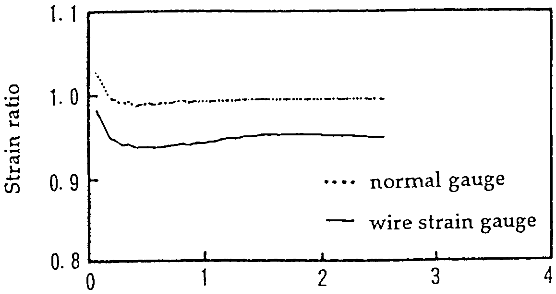

Fig.8 Ratio of normal and wire strain gauge readings based on extensometer values (GFRP)

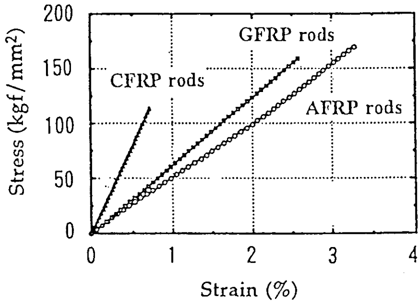

Fig.9 Stress-strain relationship of FRP rods during monotonous loading

On the other hand, the experimental results are used to calculate the number of test pieces needed to estimate the mean value of the lot with a risk of 10%. This required number of test pieces is obtained as shown in Table 4, assuming the mean value of 100 test pieces is equivalent to that of the lot. According to this table, the number of rods required to estimate the lot depends on the type of fiber and the fiber volume fraction, and varies from 7-13 rods. This means, for the FRP rods used in the precast experiments (in which Vf was 45%-66%) and considering the effect of anchorage and the 10% critical factor, more than 13 rods are required for AFRP, more than 11 for GFRP and more than 12 for CFRP. According to JSCE (Testing methods for continuous fiber reinforced materials - a tentative report), the number of test specimens must be more than 5, but the results of this study, indicate that when the number of test specimens is 5 for all types of fiber (AFRP, GFRP and CFRP), the risk may exceed 10%.

4. Consideration of deformation characteristics of test specimens

4.1 Stress-strain relationship of FRP rods in monotonous loading and elastic modulus

Figure 8 is produced from the stress-strain results taken during monotonous loading of GFRP rods. Here, the strain ratio obtained from normal gauge and plasticity gauge strain values divided by the extensometer value which is kept as the base value is plotted against the strain value. Table 5 shows the ratio of strain for each type of FRP rod as obtained using both the normal and plasticity gauges based on extensometer values.
Prior to these tests, eight types of adhesive were used and these adhesives performed well under deflection conditions.

According to the results of static monotonous loading tests, normal gauges were able to measure strain with an error of less than 5% keeping extensometer value as the base value. However, it should be noted that when using plasticity gauges, as in AFRP rod measurements, an error of 10% is indicated. This may be because plasticity gauges are generally used to measure large strain values of the order of 5-15%. However, in these tests,

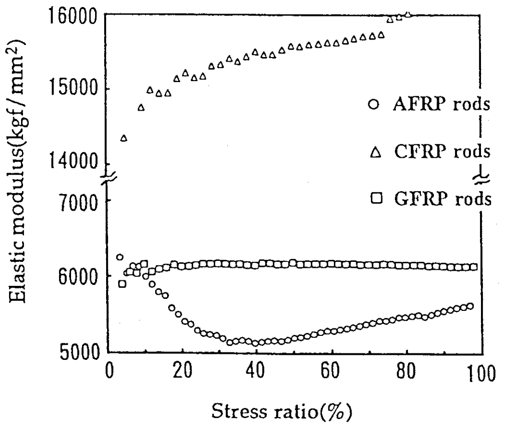

Fig.10 Relationship of stress ratio and secant modulus during monotonous loading

the strains recorded were in the order of 0-5%. Given the results of these experiments, it can be said that smaller maximum strains under monotonic loading conditions, such as in CFRP rods are best measured using extensometers and normal gauges. Moreover, use of normal gauges is preferable considering the risk of damage to extensometers at maximum strain levels. (According to the manufacturers, analysis of these experiments has enabled them to improve their plasticity gauges, and they can now measure even smaller strain values quite accurately.)

Figure 9 shows the stress-strain relationship for FRP rods during monotonous loading (stress ratio of 85%). In the case of CFRP rods, it was feared that failure would occur at a 65% stress level and therefore the extensometers were removed. According to the figure, the stress-strain relationship of FRP rods can be approximated by straight lines if small differences are neglected. However, closer analysis of GFRP rods shows linear behavior, whereas AFRP and CFRP deviate from linearity. In other words, AFRP rods have the tendency towards a large increase in stress ratio for small stresses, while at the higher stress range, it becomes smaller. In the case of CFRP, even though there is a small difference at the beginning, strain becomes smaller at higher stress levels. From this behavior, it can be observed that for both AFRP and CFRP rods, the elastic modulus value at higher stress levels is much larger than that of lower levels. This phenomenon has to be considered in design and analysis.

Figure 10 shows the results of secant modulus of elasticity obtained from the stress-strain results shown in Figure 9. Here the load at 200 kg (7 kgf/mm^2) is taken as the base point and measurements were taken at every 100 kg until failure occurred. As can be seen from the figure, for GFRP, the secant modulus of elasticity remains the same even when the load is increased. But in the case of CFRP, the secant modulus increases linearly with loading, for AFRP, the modulus first falls but then rises later as the load increases. The stress-strain curve for GFRP rods can

Tab.6 Comparison of elastic modulus values

Fiber volume fraction (Vf)	Item	AFRP	GFRP	CFRP
45%	(1) experimental value	3760	3848	10229
	(2) value obtained from CEA	3391	4220	11292
	(2)/(1)	0. 90	1. 10	1. 10
	(3) calculated value	3748	4274	11202
	(1)/(3)	1. 00	0. 90	0. 91
	(2)/(3)	0. 90	0. 99	1. 01
55%	(1) experimental value	4595	4703	12502
	(2) value obtained from CEA	4363	5209	13541
	(2)/(1)	0. 95	1. 11	1. 08
	(3) calculated value	4570	5211	13530
	(1)/(3)	1. 01	0. 90	0. 92
	(2)/(3)	0. 95	1. 00	1. 00
66%	experimental value (1)	554	5644	15002
	value obtained from CEA (2)	50.43	59.86	159.68
	(2)/(1)	0. 91	1. 06	1. 06
	calculated value (3)	5460	6024	15714
	(1)/(3)	1. 01	0. 94	0. 95
	(2)/(3)	0. 92	0. 99	1.02

Units of (1), (2) and (3) are kgf/mm^2

Tab.5 Strain ratio during monotonous loading (maximum stress at 85%)

	AFRP	GFRP	CFRP
Wire strain gauge	0.908	0.960	0.993
Normal gauge	0.958	1.023	1.009

be approximated by a linear curve. That of CFRP rods is a secondary curve and for AFRP it can be approximated by a tertiary curve. Furthermore, when the stress-strain curve for CFRP rods is approximated by a straight line, the maximum error in the elastic modulus becomes 7% while in the case of AFRP it tends to give an error of 13%.

These results show that elastic modulus for monotonous loading of GFRP rods remains roughly constant. In the case of CFRP and AFRP rods, the variation in strain due to incremental stress varies depending on the load level, and the elastic modulus does not remain constant. However, according to the recommendations of JSCE (Tensile test methods for continuous fiber reinforcements - a tentative report), elastic modulus should be obtained by two points at 10% and 50% of the guaranteed load level. In the case of CFRP and AFRP rods, this would result in a smaller value of elastic modulus near the failure point.

Table 6 shows values of elastic modulus (2) obtained according to the methods established by the Civil Engineering association, average secant modulus values up to failure (1), and their ratio (2)/(1). This indicates that there is an error of up to 10% depending on the method adopted to obtain the elastic modulus. In the case of AFRP rods, unlike the other FRP rods, the tendency is toward lower values of elastic modulus when taken from 10% and 50% of maximum load value.

These observations indicate that the elastic modulus of FRP rods differs depending on the stress level. The method recommended by JSCE does not mention this behavior. In order to obtain the relevant elastic modulus, the actual stress levels have to be considered.

4.2 Stress-strain relationship and elastic modulus of FRP rods subjected to static cyclic loading

Stress-strain relationships were obtained in repeated loading tests for AFRP and GFRP at 85% of stress ratio and for CFRP at 65%. The tests consisted of 20 repeated cycles were performed for AFRP and GFRP rods, with the lower stress level at 25% of the stress ratio keeping the maximum stress ratios at 50% and 75%. The fiber volume fraction of the rods in each test was 66%.

Figure 11 shows stress-strain relationships for each type of FRP rod where the strain was measured using an extensometer (with load increment steps of 500 kgf). Table 7 shows the strain ratios of measurements taken using normal gauges and plasticity gauges. (Here, the strain ratios were obtained assuming extensometer value as base value)

From this figure, it is evident that in the case of CFRP and GFRP rods, even though they were subjected to static cyclic loading under increasing load, there is no residual deformation and stress-strain relationships were almost the same as those in the initial static loading test. However, in the case of AFRP rods although the behavior at the initial loading seems to be almost the same as in the monotonous loading test, the relationship during lowering and reloading showed a different behavior, tracing almost a second-order curve. The remaining strain after unloading the CFRP and GFRP rods was 2-3% of the maximum strain. This was much larger for AFRP rods, which showed a value of 18%. As a result, the elastic modulus of AFRP rods after the first cycle of cyclic loading is higher than in the case of initial monotonous loading. When obtaining the secant modulus keeping the zero stress point as the base point, and when the stress ratio was less than 20%, the above mentioned difference became less than 5%. When the stress level was 85%, the difference was more than 20%.

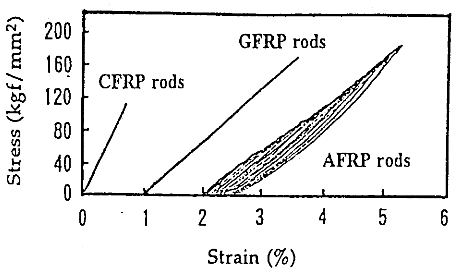

Fig.11 Stress-strain relationship of FRP rods during cyclic loading

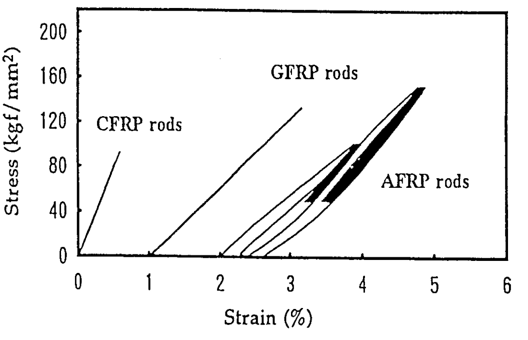

Fig.12 Stress-strain relationship of FRP rods subjected to 20 cyclic loadings

Tab.7 Residual strain ratio during cyclic loading

	AFRP	GFRP	CFRP
Wire strain gauge	1.207	4.263	0.408
Normal gauge	1.182	3.245	0.310

(based on extensometer values)

Tab.8 Residual strain ratio after 20 cycles of cyclic loading

	AFRP	GFRP	CFRP
Wire strain gauge	1.528	15.563	0.548
Normal gauge	1.223	9.372	0.303

(based on extensometer values)

Figure 12 shows the stress-strain relationship for each type of FRP rod after 20 cyclic loadings. Strain was measured using extensometers, as in the first cyclic loading test. Table 8 shows the ratio of residual deformation obtained using normal and plasticity gauges, keeping values obtained from extensometers as base values.

According to this figure, CFRP and GFRP rods show a residual strain of 1.5-2.5% of maximum strain after unloading, as in the first cyclic loading. Also, the elastic modulus did not show any variation. However in the case of AFRP rods, residual strain developed to about 18% of the maximum strain. Also, at all stress levels, there was a big difference in stress-strain relationship in initial loading and cyclic loading. The elastic modulus was higher in cyclic loading compared to virgin loading. For the 25-50% and 25-85% stress levels shown in this figure, the elastic modulus was 1.53 and 1.47 times that of virgin loading.

According to the results given in Figures 11 and 12 for GFRP and CFRP rods, there is neither a change in elastic modulus nor any residual strain. When AFRP rods were subjected to cyclic loading, they had residual strain as well as a large variation in elastic modulus. It can be concluded that this phenomenon for AFRP is due to the characteristics of the fibers and not due to the measuring method. The main reason for this may be the presence of fiber materials of varying stiffness within the fiber structure of Aramid. Further investigations are necessary on this matter. Considering this phenomenon, attention should be paid in obtaining the elastic modulus for AFRP rods subjected to certain conditions, such as the monotonic loading described in section 4.1. When considering structures subjected to cyclic loading, it is necessary to obtain the elastic modulus after applying several cycles of loading up to the service load. In this case, care must also be taken regarding the residual strain.

As indicated in Tables 7 and 8, when cyclic loading is carried out on AFRP and GFRP rods, the residual strain measured using normal and plastic-wire-strain gauges is large compared with the extensometer values. Especially in the case of GFRP rods, the residual strain measured after the first cycle of loading is more than 3-4 times the extensometer reading, whereas after 20 cycles, this becomes 9-15.5 times. These values appear large since the residual strain obtained by the extensometer is almost zero. In the case of CFRP rods, extensometer readings showed higher values whichever method was used, and the residual strains were of the order of 10-30x10-6.

From these results, it is seen that CFRP rods do not suffer from any measuring problems. However, AFRP and GFRP rods suffer from the problem of larger residual strain indications than the actual values when measured up to the order of 3% strain under cyclic loading using normal and plasticity gauges. This shows that strain gauges, and especially plasticity gauges, themselves undergo plastic deformation. Considering these factors, it is preferable to use extensometers to measure residual strain accurately.

5.0 Elastic modulus and the rule of mixture

In general, the rule of mixture can be applied to composite materials such as FRP; considering the strength of the fibers and the matrix and their elastic moduli separately, the strength of an FRP rod and its elastic modulus can be calculated. From the rule of mixture, the strength, , and elastic modulus, E, are obtained on the basis of the following assumptions.

1. The fiber and matrix are assumed to be perfectly elastic materials
2. There exists a perfect bond between fiber and matrix
3. During strain, failure of fibers and matrix occur simultaneously

$$E = E1\,Vf + E2(1 - Vf) \qquad (2)$$
$$\sigma = \varepsilon E = \sigma 1 Vf + \sigma 2(1 - Vf) \qquad (3)$$

Where E : elastic modulus of the composite material
E1 : elastic modulus of fiber
E2 : elastic modulus of matrix
σ : strength of the composite material
$\sigma 1$: strength of fiber
$\sigma 2$: strength of matrix
Vf : fiber volume fraction

Moreover, the following approximations can be made assuming that the strength and elastic modulus of fibers are much higher than that of the matrix:

$$E \fallingdotseq E1Vf \qquad (4)$$
$$\sigma \fallingdotseq \sigma_1 Vf \qquad (5)$$

Tab.9 Comparison of calculated and experimental values of tensile strength using mixture rule

Fiber volume fraction (Vf)	Item	AFRP	GFRP	CFRP
45%	(1) experimental value	134.5	140.1	124.4
	(2) calculated value	175.1	113.0	150.8
	(1)/(2)	0.77	1.24	0.83
55%	(1) experimental value	168.9	168.9	133.5
	(2) calculated value	214.0	138.1	184.3
	(1)/(2)	0.79	1.22	0.72
66%	(1) experimental value	204.2	176.9	148.4
	(2) calculated value	256.7	165.7	221.1
	(1)/(2)	0.80	1.07	0.67 0.81 *

Units of (1) and (2) are kgf/mm^2

* Denotes the mean experimental value divided by calculated value when σ is more than 160 kgf/mm^2

Tables 6 and 9 show the ratios of experimental and calculated values (experimental value/calculated value) for each type of FRP rod. The values of fiber strength and elastic modulus used in the calculations were obtained from Table 1 and the elastic modulus is the average obtained up to the failure point.

From this table, it can be seen that the experimental values of elastic modulus are within the range of 0.9-1.02 times the calculated values. For strength, however, they are in the range of 0.67-1.24. These results show that the elastic modulus values obtained using the rule of mixture agrees well with the experimental values. However the strength values do not always agree well. The reasons for this may be as discussed by H. Hodhod et al., (9,10): although the bond between the matrix and fibers is perfect, the strength of the fibers varies greatly and the average value of strength is not meaningful. In the case of CFRP rods, where the extension at failure is small, the effect of stress concentration at the anchorage is prominent. As for AFRP rods, during fiber failure extension occurs in the failure neighborhood without the transmission of strength to the matrix.

6. Conclusions

The conclusions drawn from this study are as follows.

1) Tensile strength tests for AFRP and GFRP rods show a linear rise as the fiber volume content increases in the range 45-66% and 45-55%, respectively. In the case of CFRP rods, this type of linear increase is not seen even if the fiber content is increased.
2) The strength of AFRP and GFRP rods has a normal distribution with a coefficient of variation of less than 10%.
3) Tensile tests of CFRP rods indicate a failure at the anchorage, and this is considered to be due to stress concentration. Thus the expected increase is not seen even if the fiber content is increased.
4) In order to estimate the mean values of the tensile strength of FRP rods, considering variations of strengths, including the anchorage system, keeping the risk less than 10%, the number of rods required for AFRP was more than 13, for GFRP more than 11 and for CFRP more than 12. If the number of test specimens are selected, which is more than 5, as specified by JSCE (Method for tensile strength - a tentative report), the risk may exceed 10%.
5) In observing the stress-strain relationships of the rods, GFRP can be approximated by a linear curve, CFRP by a secondary curve, and AFRP by a tertiary curve.
6) The elastic modulus of rods shows almost a linear variation with fiber content. According to the method given by the JSCE, elastic modulus is obtained by considering the load range of 10-50% of the maximum load, and this would give AFRP rods a value 10% less and CFRP rods a value 10% higher than the average value of elastic modulus in the range up to failure.
7) In the case of AFRP rods, the elastic modulus obtained in cyclic loading tests is a higher value than that in initial loading tests, and therefore in obtaining an elastic modulus value for design purposes, it is necessary to consider the actual conditions.

8) Cyclic loading tests performed on GFRP and CFRP rods show a residual strain value of less than 2% of the maximum strain. This value was as much as 18% for AFRP rods.
9) In measuring the deflection of rods subjected to static monotonous loading tests, it is desirable to use normal wire strain gauges and extensometers. However when plastic-wire-strain gauges are used, it is necessary to use gauges that give errors no more than 5%. If it is required to measure large deflections under cyclic loading, it is desirable to use extensometers. Normal and plastic-wire-strain gauges themselves undergo plastic deformation and give erroneous results.
10) The strength of a rod cannot be calculated correctly using the rule of mixture. However, the value of elastic modulus can be calculated with an error of less than 10%.

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