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EVALUATION OF TIME-DEPENDENT PROPERTIES OF FIBER-REINFORCED PLASTIC RODS

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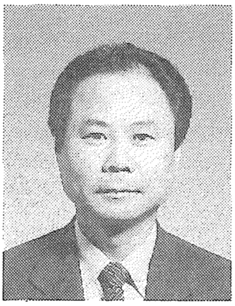
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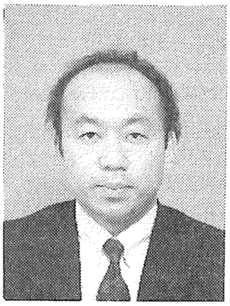
Hiroyuki OHGA

As a fundamental study on the applicability of fiber-reinforced plastic rods (FRP rods) to prestressing tendons, FRP rods reinforced with glass, aramid and carbon fibers were subjected to fatigue and creep tests, and the effect of mean stress, stress amplitude, and applied stress on fatigue and creep properties was investigated. The number of fatigue cycles to rupture fells with an increase in mean stress and stress amplitude in the case of GFRP rods, and could be estimated using these parameters. Failure time due to creep is reduced with rising applied stress. The ratio of applied stress to tensile strength is proportional to the logarithm of sustained time, and the threshold value of applied stress for a given service life could be estimated from this relationship.

Keywords : FRP rods, carbon fiber, aramid fiber, glass fiber, fatigue properties, creep properties

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1. INTRODUCTION

Toward the utilization of fiber-reinforced plastic rods (FRP rods) in construction, where their high tensile strength, non-corrosive, light weight, and non-magnetic properties promise considerable advantages, many investigations and examinations have been carried out. These have focused particularly on use as reinforcements or prestressing tendons in concrete structures1). The authors have already clarified certain properties of FRP rods containing various types of fibers: elasto-plasticity characteristics, failure properties, alkali resistance, fatigue properties, weather resistance, and others2)- 11). However, in order to apply FRP rods to actual structures, such time-dependent properties and durability characteristics as fatigue and creep must be examined by relating them to the characteristic of the various fibers.

In this paper, as a fundamental study on the applicability of FRP rods to prestressing tendons, fatigue and creep tests were performed for FRP rods reinforced with glass, aramid, and carbon fibers, and the time-dependent properties of these rods were evaluated.

2. OUTLINE OF EXPERIMENTS

2.1. MATERIALS

The FRP rods tested in the experiments were 6mm in diameter and 400mm in length. They were reinforced with carbon fibers (CFRP), aramid fibers (AFRP), and glass fibers (GFRP) aligned in one direction. The diameter, tensile strength, and elastic modulus of these fibers were as follows:

12.77 μm, 251 kgf/mm^2, 8551 kgf/mm^2	(glass fibers)
12.15 μm, 389 kgf/mm^2, 8355 kgf/mm^2	(aramid fibers)
6.68 μm, 335 kgf/mm^2, 22730 kgf/mm^2	(carbon fibers)

The fiber content of the FRP rods was 55% by volume in all cases, and vinyl resins were used as the matrix. The anchoring method was the split chucks developed by Kobayashi et al. 12), 13). These chucks were originally developed for the tensile testing of AFRP, and their applicability to the tensile testing of GFRP and CFRP has been confirmed11). On the assumption that there could be applied without problem, the same type of chucks were used for fatigue and creep tests. As with tensile tests, a protective coating was added to the anchoring surface by applying an unsaturated polyester resin as a bedding treatment and giving 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 in line with the experiments done by Kobayashi et al.14).

2.2. FATIGUE TESTS

A servo-pulsar loading machine (load control type with a capacity of 10 tons) was used for fatigue testing. The range of maximum stress (upper limit of stress) in these fatigue tests was varied from 20% to 100% of the average tensile strength of individual FRP rods. The average tensile strength as used here was defined as the tensile strength at 50% failure probability in static tensile tests carried on 100 of each type of FRP rod, with the same dimensions and fiber contents, as used for fatigue tests11). Average tensile strength and the standard deviation were as follows.

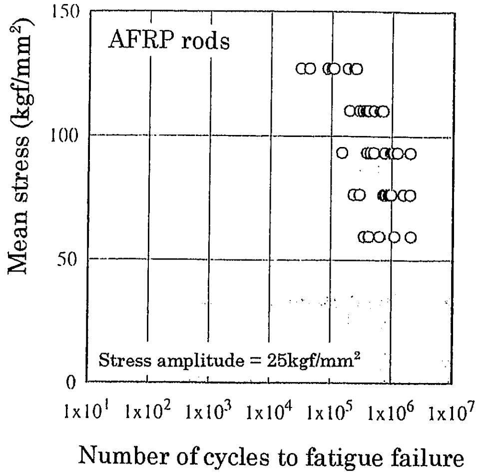


Fig.1 Results of fatigue tests on FRP rods

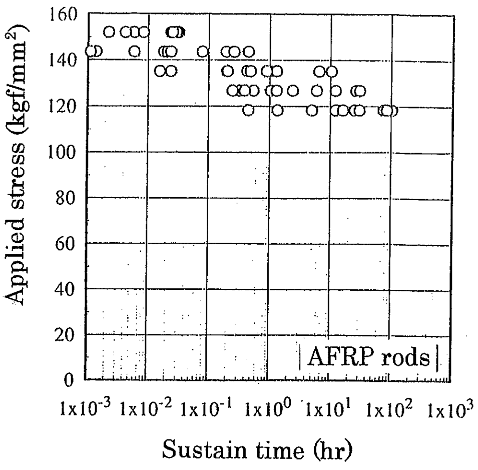


Fig.2 Results of creep tests on FRP rods

GFRP rods :	169 kgf/mm²,	8.5 kgf/mm²
AFRP rods :	169 kgf/mm²,	14.8 kgf/mm²
CFRP rods :	134 kgf/mm²,	11.2 kgf/mm²

Five different stress amplitudes of fatigue loading were applied, 5, 10, 25, 40, and 50 kgf/mm², and the frequency was varied from 1 to 10 Hz. For each condition, from 5 to 10 rods were fatigue tested.

The experimental fatigue test results for the case of AFRP rods are shown in Fig.1. Though there is wide scatter in the number of fatigue cycles to failure even for identical mean stress (the mean value of the minimum stress and maximum stress), the number of cycles to fatigue failure for each loading condition is defined as the failure cycle at 50% failure probability. The tests were performed at room temperature which was maintained in the range 20 ± 3°C.

2.3. CREEP TESTS

A servo-pulsar loading machine (load control type with a capacity of 10 tons) was also used for creep testing. The creep stress applied to GFRP, AFRP, and CFRP was varied 66.7% to 94.5%, 70% to 90%, and 96.4% to 101.2%, respectively, of each static tensile strength. Failure modes included perfect ruptures, fissure failure, slipping out of one of end grips, cutting at the exit of one of the grips. However, all were considered fractures whatever the failure mode. Since ruptures caused by stress concentration in the chuck occurred in only a few cases, the chuck design used in these experiments is considered suitable for not only static tensile strength tests, but also fatigue and creep tests.

3. FATIGUE PROPERTIES OF FRP RODS

Figure 3 shows that relationship between stress amplitude and fatigue failure cycle in the case of GFRP. The fatigue upper limit stress was set from 20% (33.8kgf/mm²) to 80% (135.2kgf/mm²) of the static tensile strength (169kgf/mm²) at increment of 10%, varying the

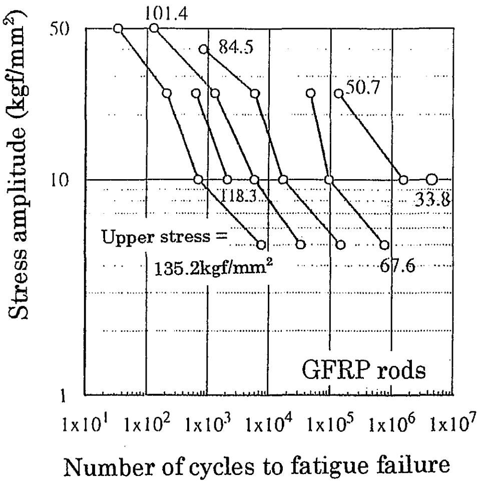


Fig.3 Relationship between stress amplitude and fatigue failure cycle (GFRP)

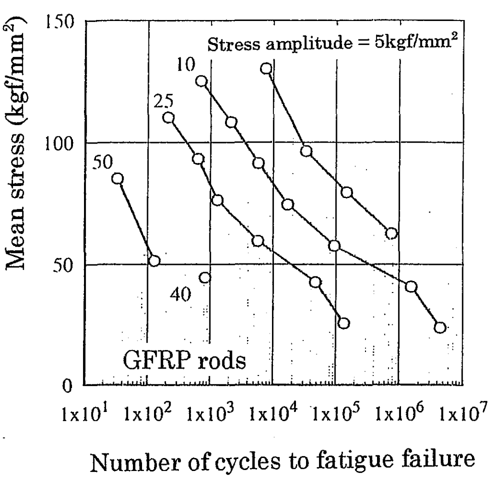


Fig.4 Relationship between mean stress and fatigue failure cycle (GFRP)

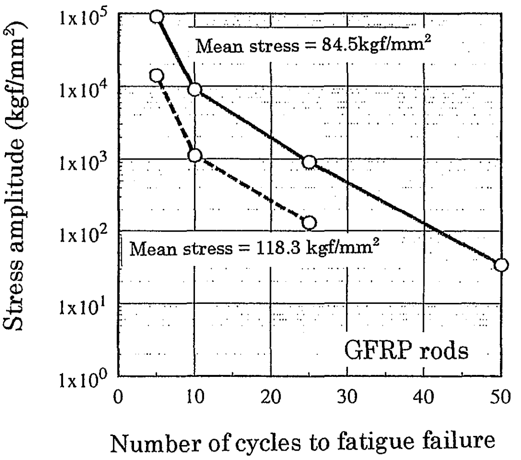


Fig.5 Effect of stress amplitude on fatigue properties (GFRP)

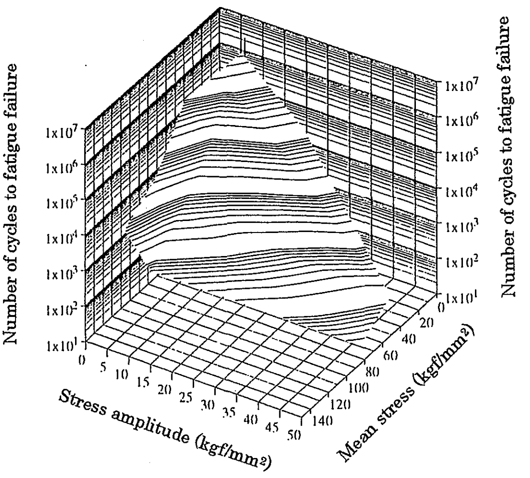


Fig.6 Effect of stress amplitude and mean stress on fatigue properties (GFRP)

amplitude from 5kgf/mm^2 to 50kgf/mm^2 for each upper limit stress. The numbers in Fig.3 represent the value of upper fatigue stress. The number of cycles to fatigue failure decreases with increasing upper stress. Furthermore, it decreases with the increasing stress amplitude.

Figure 4 shows the relationship between mean stress and fatigue failure cycles of GFRP rods at each amplitude. The number of cycles to fatigue failure decreases almost in inverse proportion to the mean stress in the fatigue tests. With decreasing stress amplitude, the number of cycles to failure tends to rise.

Now, extracting the fatigue failure cycle with the stress ratio (a ratio of the mean stress to static tensile strength) at 50% and 70% (84.5kgf/mm^2 and 118.3kgf/mm^2 as mean stress) from Fig.4, the relationship between the fatigue failure cycle and stress amplitude can be obtained as shown in Fig.5. The number of cycles to fatigue failure decreases with increasing stress amplitude, and the difference in fatigue failure cycle between 50% and 70% is within one order of magnitude.

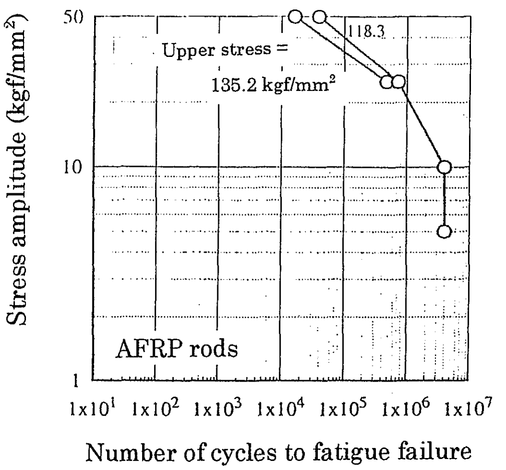


Fig.7 Relationship between stress amplitude and fatigue failure cycle (AFRP)

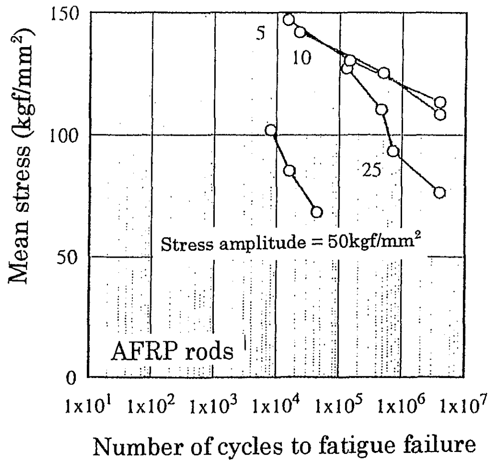


Fig.8 Relationship between mean stress and fatigue failure cycle (AFRP)

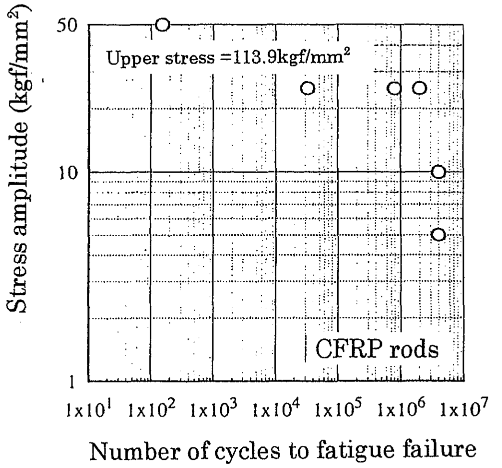


Fig.9 Relationship between stress amplitude and fatigue failure cycle (CFRP)

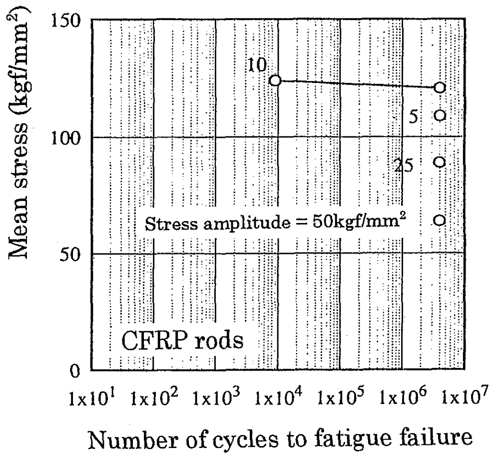


Fig.10 Relationship between mean stress and fatigue failure cycle (CFRP)

Figure 6 summaries the relationship between fatigue failure cycle and both stress amplitude and mean stress in the case of GFRP. Since the number of cycles to fatigue failure linearly decreases with increasing stress amplitude and mean stress, as mentioned above, the relationship can be shown as an essentially plane surface.

Figure 7 shows the effect of stress amplitude on the fatigue failure cycle of AFRP when the upper limit stress is 118.3kgf/mm^2 and 135.2kgf/mm^2 (70% and 80% stress ratio). For a particular upper limit stress, the number of cycles to fatigue failure increases with falling stress amplitude. Over 4 million cycles is achieved with an upper limit stress of 118.3kgf/mm^2 (70% stress ratio) and a stress amplitude under 10kgf/mm^2. Figure 8 shows the relationship between fatigue failure cycle and mean stress in the case of AFRP. The number of cycles to fatigue failure linearly decreases with increasing stress amplitude and mean stress, just as with GFRP. However, with a stress amplitude under 10 kgf/mm^2 or over 25 kgf/mm^2, somewhat different trends can be seen in the relationship between fatigue failure cycle and mean stress. When the stress amplitude is over 25 kgf/mm^2, the rate of increase in the number of cycles to fatigue failure with falling mean stress is lower than when the stress amplitude is

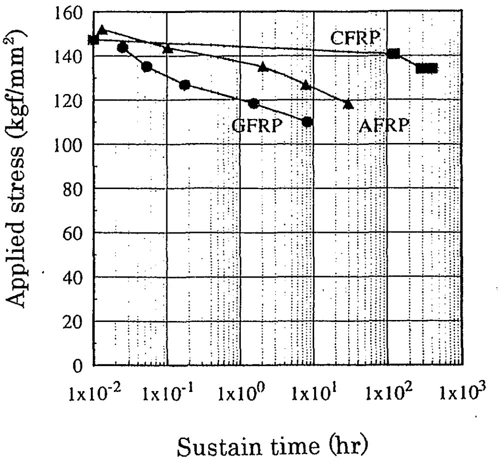


Fig.11 Results of creep tests

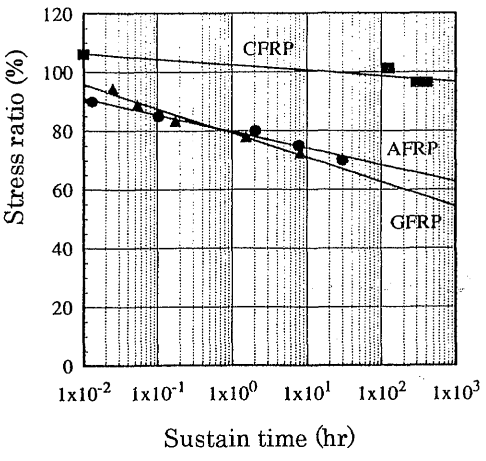


Fig.12 Relationship between stress ratio and creep sustain time

under 10 kgf/mm^2. Furthermore, with a stress amplitude under 10 kgf/mm^2, stress amplitude has little influence on fatigue failure cycle, whereas at stress amplitudes over 25kgf/mm^2, the number of cycles to fatigue failure decreases rapidly with increasing stress amplitude.

In the case of CFRP, with on 113.9 kgf/mm^2 upper limit stress (85% stress ratio), the relationships between stress amplitude and fatigue failure cycle, and between mean stress and fatigue failure cycle are shown respectively in Fig.9 and Fig.10. In contract with GFRP and AFRP, over 4 million cycles are reached under most fatigue conditions. However, CFRP rods have several failure modes in fatigue tests as in static tensile tests, and fatigue properties may change with only small differences in applied fatigue stresses[11)]. The failure modes observed in fatigue tests included perfect ruptures, fissure failure, slipping out of one of end grips, and cutting at the exit of one of the grips due to stress concentration in the chuck.

4. CREEP PROPERTIES OF FRP RODS

Figure 11 shows the relationships between loading stress and failure time in creep tests. The creep properties of FRP rods depend on type of fiber used, and with the same applied stress, creep failure time is longer in the order CFRP, AFRP, and GFRP. Though the creep properties of FRP depend on the tensile strength and creep properties of the fiber itself, the relationship between creep failure time and the stress ratio, which is the ratio of applied stress to the tensile strength, is shown in Fig.12. From the viewpoint of stress ratio, AFRP rods and GFRP rods have quite similar creep properties, but CFRP rods sustain the stress longer than other types of rods at the same stress ratio. In the case of CFRP rods, even at a 95% stress ratio, creep failure does not occur until 400 hours.

By applying the least squares method to these results, the relationship between creep failure time and stress ratio can be obtained as follows:

$\sigma_{\text{applied}} / \sigma_{\text{tensile}}$
$= 79.2 - 8.29 * \text{LogT}$ for GFRP rods (1)
$= 79.8 - 5.67 * \text{LogT}$ for AFRP rods (2)
$= 102 - 1.91 * \text{LogT}$ for CFRP rods (3)

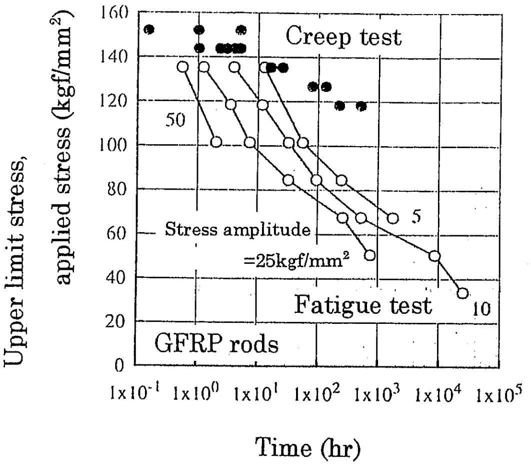


Fig.13 Relationship between results of fatigue and creep tests (GFRP)

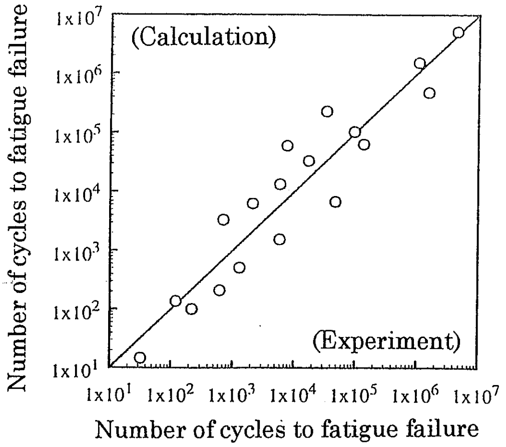


Fig.14 Estimation of number of cycles to fatigue failure

where, σ_{applied} : applied stress (kgf/mm^2)
σ_{tensile} : static tensile stress (kgf/mm^2)
T : creep rupture time (hr)

Correlation coefficients between experimental values and estimates made using the above equation are as follows, with each type of FRP rod indicating good correlation:

-0.984	for GFRP rods
-0.987	for AFRP rods
-0.913	for CFRP rods

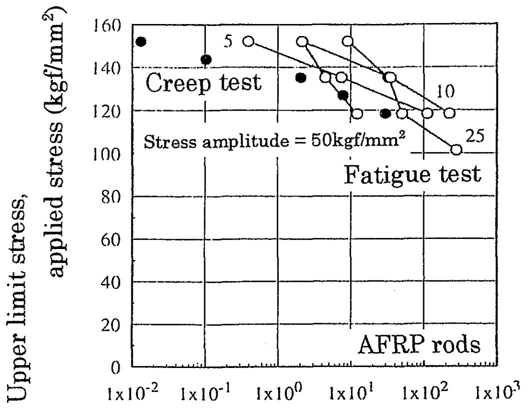
Under creep-dominant conditions, the service life of FRP rods can be estimated using the above equations. If a 100-year service life is assumed, the limit applied stress for each type of FRP rod can be estimated as follows:

45.6 kgf/mm^2 (30.0% stress ratio)	for GFRP rods
77.9 kgf/mm^2 (46.1% stress ratio)	for AFRP rods
127 kgf/mm^2 (91.1% stress ratio)	for CFRP rods

It is thus found that the limit applied stress (limit stress ratio) for this service life is quite different for each FRP rod type

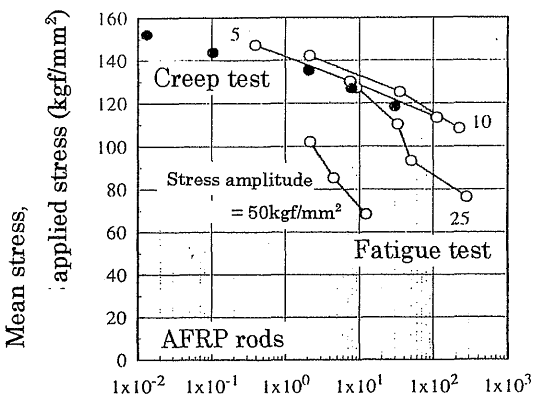
5. EVALUATION OF TIME-DEPENDENT PROPERTIES

The relationship between applied stress and creep failure time in the case of GFRP is shown in Fig.13 by the ● marks. Also, the relationship between upper limit applied stress and time (as converted from the failure cycle using the frequency (failure cycle / frequency)), obtained from the fatigue tests, is shown in the same figure by the ○ marks. The failure time decreases with increasing loading stress in creep tests, but the rate of failure time decreases in creep tests is greater than that in fatigue tests. The failure time in creep tests is longer in comparison with that fatigue tests for identical applied stress (upper limit stress). This difference is particularly remarkable when the stress amplitude is large. That is to say, fatigue



Time (hr)

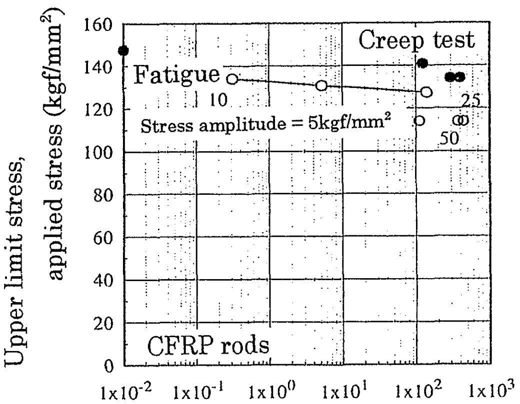
Fig.15 Evaluation of fatigue tests by upper limit stress (AFRP)



Time (hr)

Fig.16 Evaluation of fatigue tests by mean stress (AFRP)

failure properties converge on creep failure properties, at smaller stress amplitudes. From these results, it appears that the fatigue failures described in section3 were caused by a combination of damage accumulated by both sustained loading and repetitive loading. Further, by reducing the stress amplitude in fatigue tests, the damage caused by the sustained loading seems to become a more dominant factor in failure.



Time (hr)

Fig.17 Relationship between results of fatigue and creep tests (CFRP)

Since the fatigue failure properties of FRP rods are affected by mean stress, stress amplitude, and number of fatigue cycles, as found from the examination in section3, the relationship between mean stress, stress amplitude, and number of fatigue cycles in fatigue tests is assumed empirically to be:

$$\sigma m \cdot \Delta\sigma = a \cdot N^b \qquad (4)$$

where, σm : mean stress (kgf/mm^2)
$\Delta\sigma$: stress amplitude (kgf/mm^2)
N : number of fatigue cycles to failure
a,b : constant

In the case of GFRP, the constant coefficients are calculated by the least squares method to be a = 4.83, and b = -0.226, and the correlation coefficient = -0.943. A comparison of calculated values and experimental values using the above equation is given in Fig.14. Since the calculated and experimental values show good correlation, the number of fatigue cycles to failure can be estimated using this equation from the mean stress and stress amplitude.

The relationship between applied stress and creep failure time in the case of AFRP is shown in Fig.15 and Fig.16 by the ● marks. Further, the relationship between both upper limit loading stress and mean stress and time (as converted from the failure cycles using the frequency (failure cycle / frequency)), obtained from the fatigue tests, is shown in Fig.15 and Fig.16, respectively, by the ○ marks.

In the case of AFRP rods, the failure time in creep tests is sooner compared with that in fatigue tests for identical loading stress (upper limit stress). On the other hand, from the viewpoint of mean stress, at stress amplitudes under 10kgf/mm^2, the relationship between loading stress (mean stress) and time in the fatigue tests is almost the same as in the creep tests. However, at stress amplitudes over 25kgf/mm^2, as in the case of GFRP, the reduction in time to failure with increasing applied stress is less than in the case of the creep tests. These differences in failure properties may originate from different fracture mechanisms of the fibers themselves, and further examination of this issue is considered necessary[15)].

The relationship between applied stress and creep failure time for CFRP is shown in Fig.17 by the ● marks. Further, relationship between upper limit applied stress and time (as converted from the failure cycle using frequency (failure cycle / frequency)), obtained from fatigue test, is shown in the same figure by the ○ marks. As with GFRP, the failure time in creep tests is extended in comparison with that in the fatigue tests for identical loading stress (upper limit stress). However, CFRP rods have several failure modes in creep tests as described in section2.3, so their creep properties may change with small differences in loading stress. As a general tendency of CFRP rods, creep failure times are longer than fatigue failure times.

6. CONCLUSIONS

In order to evaluate the time-dependent properties of FRP rods, this research focused on the effects of mean stress and stress amplitude on fatigue properties, as well as the effect of applied stress on creep properties. The types of FRP rods examined experimentally included glass, aramid, and carbon fibers. The results ca be summarized as follows.

(1) Since the fracture mode of FRP rods in fatigue and creep differs by specimen, considerable scatter is present in the results even where identical stress was applied.

(2) The number of fatigue failure of FRP rods is affected by the mean stress and stress amplitude in the fatigue tests. In the case of GFRP rods, the logarithm of the failure cycle falls in proportion to increasing mean stress and stress amplitude.

(3) For GFRP rods, the number of cycles to fatigue failure can be estimated using an empirical formula based on mean stress and stress amplitude.

(4) The logarithm of creep sustain time falls in proportion to increasing applied creep stress.

(5) Though the logarithm of creep sustain time is proportioned to stress ratio in the creep tests, the gradient depends on the type of used fiber.

(6) The critical creep stress of an FRP rod can be estimated using the proportional relationship between stress ratio and the logarithm of creep failure time as obtained in creep tests.

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