論 文

[1212] Grip Effect on Failure Mode and Strength of FRP Rods

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1 INTRODUCTION

FRP tension elements are promising candidates for the future reinforcement of concrete; where lighter, stronger and more durable materials with good magnetic properties are needed. However, the customization of applying FRP as concrete reinforcement needs more understanding of their behavior that, consequently, leads to more reliable application.

The FRP rods have shown several phenomena that need interpretation. One of these is the variation of uniaxially reinforced FRP rods tensile strength versus fiber content (volume fraction V_f) [1]. The rods of three different materials do not show consistent strength increase with fiber content; where the high fiber contents give strength values less than expected.

In this research, the causes of this phenomenon are investigated. The approach depends on correlating the strength value and failure mode and studying the effect of the gripping system on the stress distribution inside the rod. First, the failure modes of the tested rods are categorized. Then, a reference failure mode under pure uniaxial tension is obtained experimentally. The effect of the used gripping system on the stresses is determined analytically. Comparing the failure modes in actual conditions with reference mode and in view of stress distributions, the governing failure mode at each fiber content is determined.

It should be understood that quantitative description of failure propagation inside the rod is not the target of this research, since the failure criteria like inter-laminar and cross-laminar shear strength are not available for the studied materials. Therefore, a qualitative description of the possible failure modes (in view of the resulting stress fields) is suggested and supported by the experimental observations on the studied materials and similar occurrence of such modes as found in the literature.

2 CHARACTERISTICS OF FRP RODS TENSILE STRENGTH

Three kinds of unidirectionally reinforced FRP rods were tested in axial tension. These are, AFRP, CFRP and GFRP. Rod diameter was 6 mm and length was 400 mm for all cases. Three fiber volume fractions were tested: 0.45, 0.55 and 0.66, that cover the practical range of fiber content. 100 rods from each material per volume fraction were tested in an Autograph testing machine of 10 ton capacity. Stroke rates were 2 mm/min for CFRP and 5 mm/min for AFRP and GFRP, in order to account for the difference in rods stiffness, where CFRP stiffness is about 2.5 times that of AFRP and GFRP. Further details can be found in reference [1].

Rods cumulative strength distributions are shown in Figure 1, for all cases. It is obvious that the strength is not linearly proportional to fiber (main strengthening element) content. The increase of strength with fiber content becomes smaller for higher volume fractions. Also, distribution standard deviation increases with fiber content, except for AFRP. One more interesting phenomenon is that observed for CFRP with $V_f = 0.66$. The distribution is divided into two distinct regions; the mean strength of the strong region is almost 50% above the mean of the weak region. Moreover, the weak region shows strength values as low as those observed for the

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weak CFRP rods with $V_f = 0.55$. This problem, obviously affects the feasibility of utilizing CFRP rods, where testing of small number of rods might lead to significantly misleading strength characterization.

The failure modes of the specimens could be divided into four categories. These categories are shown in Figure 2. The occurrence of these categories for different materials and fiber contents is shown in Table 1. From this table, one can realize that the failure mode is related to strength loss as it differs for the same material with fiber content.

3 DETERMINATION OF IDEAL (REFERENCE) FAILURE MODES

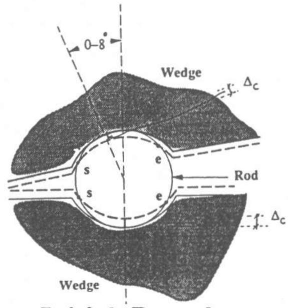
In order to decide the onset of failure mode change, in the tested cases, a reference mode is to be found. This mode is to be the ideal one obtained under pure uniaxial tensile state of stress. For determining the failure due to pure uniaxial tension, special specimens were prepared as shown in Figure 3. The rod has reduced central portion in order to force the failure to occur away from end grips and ensures the failure due to uniaxial tension. Ten specimens of each material, per volume fraction, were prepared for testing. The specimens were tested in conditions similar to those mentioned in the above section. Due to difficulties in machining the AFRP rods at $V_f = 0.66$, no experiments were conducted on them. The normalized mean tensile strengths are shown in Table 2 (coefficients of variation is about 3% for AFRP and 4% for both CFRP and GFRP). Failure mode, for each material, was independent of volume fraction. Ideal failure modes are shown in Figure 4 for the three materials.

4 GRIPS EFFECT ON THE STATE OF STRESS INSIDE ROD SECTION

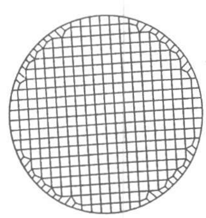
The gripping system used for the FRP rods studied in this research was developed by Kobayashi [2]. The grips made of steel, are shown in Figure 5. Due to the low transverse stiffness of the rods, grips can be considered rigid enough to cause forced uniform lateral displacement to rod surface during axial loading. The gripping mechanism can be described as follows. During loading, the inner wedges slide together with the rod inside the sleeve. Due to the tapered shape of the wedge/sleeve contact surface, the wedges push the rod laterally (to the position indicated by the broken lines shown in Figure 5) and result in a pressure sufficient to stop the sliding under the current load level. Sliding and lateral movement reoccur when the load level increases, in order to maintain equilibrium. Due to the lateral pressure, additional tensile stresses result in the axial direction at the ends of the grips. This effect is analogous to the case of uniform lateral pressure applied to a finite length of a cylinder and studied by Barton [3] and should result in failure initiation at the exit of the chucks in all cases. The additional axial stresses caused next-to-grip failure as observed for 0.45 CFRP rods, but do not interpret the two regions in CFRP strength distribution or slippage mode observed for AFRP and GFRP. Also, the values of these additional stresses are too small to cause a significant reduction in rods strength. Closer look to the gripping system in cross section as in Figure 6 shows that the grips do not press all the perimeter of the rod but only the portion in contact with the grips (the section of the wedge inner curved surface is a 2mm high part of a circle 7.5 mm in diameter.

Moreover, the wedges could assume parallel or inclined configuration, Figure 6.a & b respectively. The latter is expected to cause more stress concentration inside the rod section. Therefore, rod section was analyzed under the effect of forced displacement at the perimeter.

The FEM discretization of rod section is shown in the next figure where 348 four-node isoparametric elements are used. The origin is at the center of the mesh. The boundary conditions are the forced displacements of the surface nodes in the range between the points (s) and (e). Due to the rigidity of the wedges, all forced displacements are obtained given the central displacement (Δ_c).



Initial Boundary Conditions



FEM Mesh

The value of (Δ_c) is taken equal to 0.3 mm as measured experimentally [4]. The inclination of the two displaced portions is changed from 0 to 8 degrees (the possible range as determined from the geometry of the grips and for 6mm rods). A finite element analysis was conducted on the specified problem. Iterative procedure (based on the normal reaction at contact points) was employed for determining the contact length between the grips and the rod. In view of the big ratio of the gripped length to rod diameter, plane stress state was assumed. As the unidirectionally reinforced FRP is an orthotropic material, more than two parameters are needed for constitutive formulation. If the axial direction is considered as 1, and the other two perpendicular directions are 2 and 3 (rod section axes), E_1=15000 kg/mm^2,ν_{12}= .34, E_2=E_3=800 kg/mm^2, ν_{23}=ν_{32}= 0.55. These mechanical properties were determined based on previous measurements on CFRP only (performed by the producer). Therefore, the results will be shown in dimensionless form and qualitative conclusions will be drawn. This is done in absence of accurate values for all the materials.

The principal stresses were calculated, in addition to normal stresses at planes of maximum shear stresses. Sample of the results is shown in Figure 7-a to d. The stress contours for all inclinations were essentially similar with the exception that range of values increases for bigger inclination. The stresses are normalized as ($\sigma R/E_2\Delta_c$), where: E_2 is transverse Young's modulus, R is rod radius and Δ_c is the central lateral displacement (0.3 mm for the current case).

Collings [5] has reported the failure of CFRP blocks in shear mode (across the fibers) when the block is pressed in one of the directions perpendicular to the fibers and constrained in the other one. These conditions are satisfied inside rod section when the principal normal stresses are both compressive and the smaller is at least "Poisson's ratio" times the other. The elements inside the analyzed sections, that satisfy these conditions were determined for some chosen critical value and a comparison between two cases (of different wedges inclination) is shown in Figure 8. It is obvious that wedges inclination increases the potential for the cross-laminar shear failure mode.

5 DISCUSSION

As shown in Figure 4, AFRP and GFRP rods fail under pure axial tension in a bundle-like mode as if there were no binding matrix (combined breakage, debonding and pullout modes). The reason for this mode is attributed to the relative properties of the two phases (fiber and matrix) and is discussed in reference [6]. The case of CFRP, however, shows failure similar to homogeneous materials where plane failure surface can be seen (resulting from fibers and matrix breakage without debonding). Hence, for the mode "S" for AFRP and GFRP and mode "B" for CFRP grip effect not axial loading is dominant. The mean tensile strength values obtained for these ideal cases are plotted as the broken lines in Figure 1. Referring to Table 1, one can see that the grip effect-dominant modes caused the weak parts of strength distributions. A strength reduction is observed for all cases. However, According to Barton [3], due to the transverse pressure, additional axial tensile stresses results near the chuck of about .50 the transverse pressure If we consider the case of CFRP representative to all composites, the equivalent uniform pressure as calculated from the above mentioned analysis is about 200 MPa. Hence, the reduction of rods strength should be within 100 MPa if the ideal modes are maintained. This is obviously the case for all FRP rods with v_f= .45 and for AFRP and GFRP with v_f= .55 (where the ideal modes are maintained). It remains to interpret the non-ideal modes of failure (and consequently strength reduction) for the high V_f values.

The additional stresses from the grips have some characteristics that could lead to some additional failure modes. As shown in Figure 7, maximum shear stresses occur in the central portion of rod section although this portion possesses the lowest shear resistance due to the low compressive stresses on planes of maximum shear. Therefore, inter-laminar shear failure might start from the center of the section and propagates to the surface, within the potential area hatched in Figure 9. This leads to splitting of rod end that results (due to the relative movement of the splitted portions) in loose grips and slippage of the rod at loads lower than the actual tensile capacity. This interprets the reduction of rods strength (from the ideal ones) in case of AFRP and GFRP where slippage modes were observed. From Figure 1, AFRP shows lower scattering for high fiber content where GFRP shows bigger scattering. This is acceptable as the former case shows only one mode of failure (slippage) while the latter shows combination of two modes. The occurrence of more than failure mode at the same V_f is a result of the inclination of wedges (as mentioned in section 4, this increases the stress concentration in rod section). A limited number of tensile testing on AFRP and GFRP rods was conducted to confirm the cause of slippage. End splitting could be observed in the slipped rods as shown in Figure 10.

Another mode of failure (that is aggravated by wedges inclination) is the shear failure across the fibers (cross-laminar shear failure) of surface portions subjected to confined state of stress, as shown in Figure 8. This failure is followed by separation of the surface layers of the rod due to debonding. Effective cross-sectional area, consequently, decreases (for the case in Figure 8, 16% reduction occurs at 6°) and so does the ultimate load. Such failure mode causes drops in the load-displacement relationship of the rods and is reported by the authors in [4]. The confined lateral compressive state that leads to the cross-laminar shear failure is, also, aggravated by the axial tensile stresses existing in actual conditions of tensile testing. The inherent debonding of this failure mode results in a bundle-like failure of CFRP rods as shown in Table 1. The effect of wedge inclination on changing the failure mode and strength is most obvious in the two regions of the distribution of CFRP rods with $V_f = 0.66$ although it has affected CFRP at $V_f = 0.55$. Hence, the distributions in Figure 1 characterize the tensile and cross-laminar shear strengths of CFRP. This makes the large scattering of distributions reasonable for high fiber content. In case of AFRP and GFRP, the distributions characterize both tensile and inter-laminar shear strengths. In case of GFRP, it is also possible that cross-laminar shear failure has occurred at V_f =0.66 and results in a bundle-like failure at the weak portion of the distribution.

6 CONCLUSIONS

The tensile strength variation of unidirectionally reinforced FRP rods versus fiber volume fraction, is studied for three different materials. The approach for clarifying the phenomena observed depends on the correlation between the strength and failure mode. The failure modes were characterized for the tested specimens and the ideal failure modes and strength values, under pure axial tension, were determined experimentally. The ideal behavior was found independent of the fiber content, unlike the practical cases. The effect of lateral grips on the state of stress inside the rod was determined analytically and the possible modifications of the failure modes were found to be through shear failure modes. Correlation between these concluded modifications and the experimental observations was successful. The effect of the grips on reducing the strength FRP rods, with unidirectionally aligned fibers, is found to be serious for the cases of high fiber content, specially for CFRP. From the manufacturer side, the efficiency of the rods can be increased by utilizing different matrix that provide higher inter-laminar shear strength for AFRP and GFRP. For CFRP, however, the source of inefficiency is the cross-laminar shear strength that is dependent on the fiber not the matrix. Therefore, replacement of the current gripping system by less aggressive one is the way to efficient utilization of the rods. A proposal for reducing grips lateral pressure, and consequently strength loss, is suggested based on changing the taper angle of the grips and is explained in reference [6].

ACKNOWLEDGMENT

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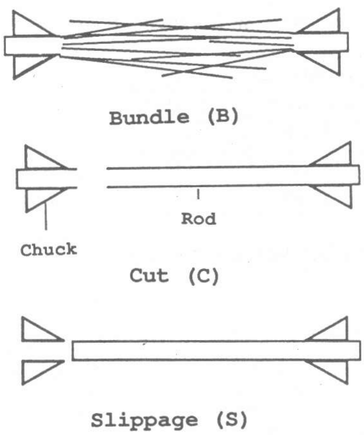

Fig.2 Observed Failure Modes of FRP Rods

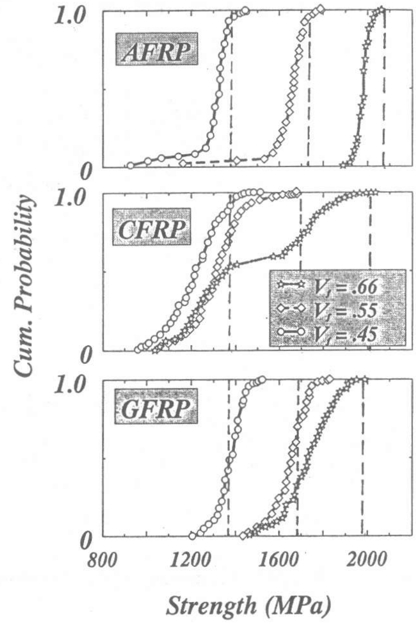

Fig.1 Tensile Strength Distributions of FRP Rods with Different Fiber Contents

Table 1: Location of Different FRP Rods Failure Modes

Material	Fiber Volume Fraction V_f		
	V_f=0.45	V_f=0.55	V_f=0.66
AFRP	B	S B	S
CFRP	C	C B	C B
GFRP	B	B	S B

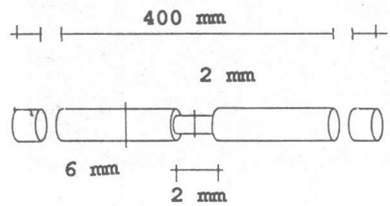

Fig.3 Idealized FRP Rod Specimen

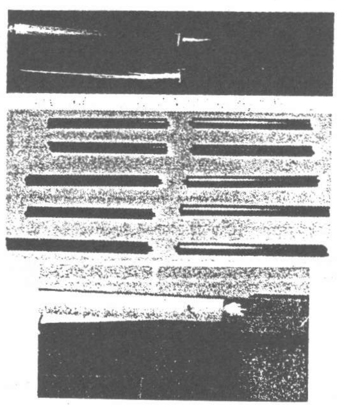

Fig.4 Failure Modes of Idealized FRP Rods Downwards: AFRP, CFRP and GFRP

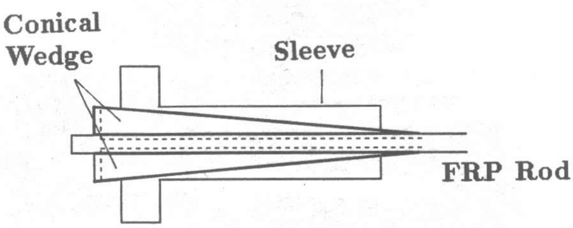

Fig.5 FRP Rods Gripping System

Table 2: Normalized Mean Tensile Strength Values for Idealized Rods

Material	Number* of Specimens	Tensile Strength $(MPa)/V_f$		
		V_f=0.45	V_f=0.55	V_f=0.66
AFRP	10/10/-	3313	3014	—
CFRP	10/10/10	2930	3085	3100
GFRP	10/10/10	3030	2930	2980

* Numbers are arranged according to fiber volume fraction.

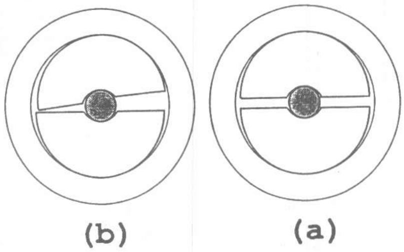

Fig.6 Possible Gripping Configurations of FRP Rods

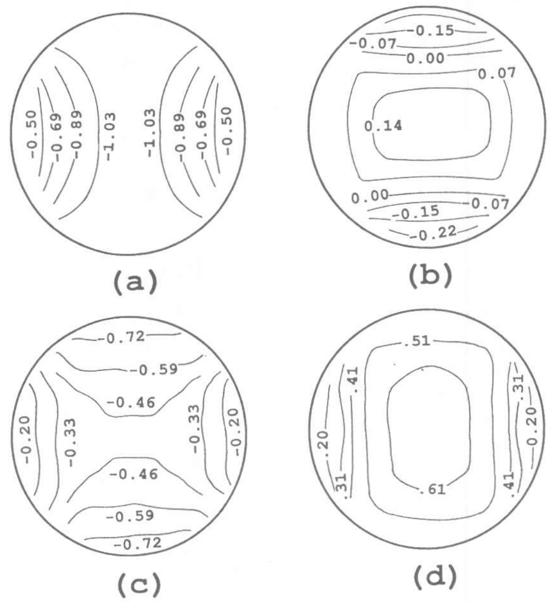

Fig.7 Contour Lines of Normalized Principle Stresses Due to Gripping Pressure: a) min. Normal b) max. Normal c)Normal at max shear Planes d) max. Shear.

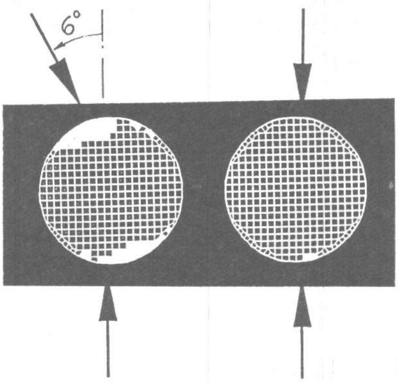

Fig.8 Confined Elements Inside Rod Section at Two Wedges Inclination and Same Lateral Displacement.

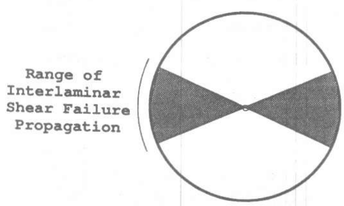

Fig.9 Weak (Potential) Area for Interlaminar Shear Failure.

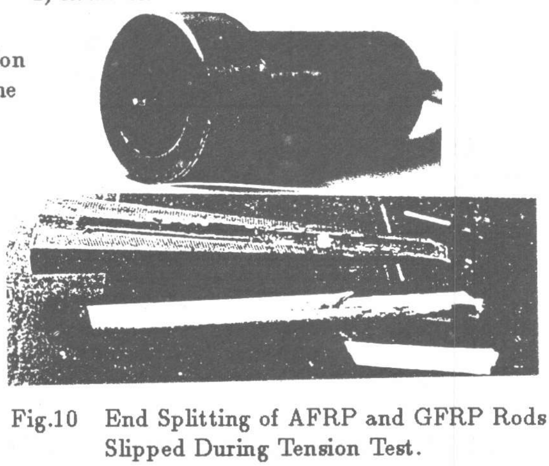

Fig.10 End Splitting of AFRP and GFRP Rods Slipped During Tension Test.