

CYCLIC BEHAVIOR OF A SECOND GENERATION DUCTILE HYBRID FIBER REINFORCED POLYMER (D-H-FRP) FOR EARTHQUAKE RESISTANT CONCRETE STRUCTURES

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SUMMARY

This paper describes the reversed cyclic characteristics of a second generation FRP composite reinforcement that has been demonstrated at Drexel University in the form of a ductile hybrid bar (D-H-FRP), which simulates the stress-strain characteristics of conventional steel reinforcement [Harris et al., 1997, 1998a,b]. The developed hybrid FRP bar possesses a ductile behavior, which is intrinsic to its hybrid fiber composition and the hybrid geometric architecture of its fibers [Ko et al., 1997].

Using the combination of high modulus carbon (Thornel P-55S) and aramid (Kevlar 49) fibers the writers have produced bars of up to 10 mm diameter with a Young's modulus of 202 GPa (same as that of steel reinforcement compared on a total fiber cross-section basis), a bi-linear stress-strain tensile curve with a definite yield, an ultimate strength higher than yield and an ultimate failure at between 2% and 3% strain. Excellent bond characteristics were obtained by integrating ribs into the braided jacket to increase the mechanical interaction at the bar to concrete interface. Results have been presented from beams 50 mm x 100 mm in section and 1.2 m long reinforced with the ductile hybrid FRP bars developed which produced ductility indices that were essentially the same to those of a companion steel reinforced beam [Huesgen, 1998]. The ductility indices were based on definitions of ductility according to displacement, rotation and energy considerations. The tensile strength, bond strength, and flexural interaction in concrete beams have been described by Somboonsong [1997] and Somboonsong et al. [1998].

The current paper describes test results on small beams representing portions of a rigid frame loaded with increasing cyclic horizontal load simulating the effect of an earthquake. Measured hysteretic behavior demonstrates the considerable energy absorbing capabilities of the D-H-FRP reinforcing bars.

INTRODUCTION

Replacement of the steel reinforcement in concrete structures with more corrosion resistant substitutes such as the various FRP's is rapidly becoming a more economical option for constructed facilities worldwide (ACI Report 440R-96), [Mufti et al., 1991], [Iyer and Sen, 1991], [Nanni and Dolan, 1993], [Basham 1994], [Saadatmanesh and Ehsani, 1996, 1998]. FRP of the bar type, because of its versatility, can be used in new or repaired reinforced concrete structures. In general, FRP systems (which usually consist of glass, aramid, or carbon fibers in a plastic matrix) have high strength, a range of moduli of elasticity and very low ultimate tensile strains as compared to steel. The stress-strain behavior of all of these fiber systems is linear up to failure, which makes it impossible to have significant hysteretic behavior based on material inelasticity. In spite of their superior light weight, corrosion resistance and non-magnetic properties, the lack of material ductility and energy absorbing capabilities is a severe limitation of all these fiber systems if they are to be considered for earthquake resistant applications.

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DESIGN CONCEPT FOR THE NEW DUCTILE HYBRID FRP (D-H-FRP)

In order to achieve ductility in reinforced concrete structures without using conventional steel rebar, a new design methodology was introduced by the authors to identify suitable fibrous composite materials that mimic the stress-strain characteristics of steel [Somboonsong et al., 1998]. The technology of braiding, as detailed by Ko [1989], is a well established technology which intertwines three or more strands of yarns to form a tubular structure with various combinations of linear or twisted core materials. By judicious selection of fiber materials and fiber architecture for the braid sleeve and the core structure, the load-deformation behavior of the braided fibrous assembly can be tailored. As illustrated in Fig. 1, the sleeve structure may be a tough aramid (e.g. Kevlar) filamentous structure for example whereas the core structure could be high modulus carbon fibers to provide the initial resistance to deformation. The rib effect, as commonly incorporated in steel rebars to increase bond strength between the rebar and concrete, can also be built into the sleeve structure during the braiding process. By proper combination of the braided fibrous assembly with a protective resin matrix system to form a composite material system, the stress transfer from the rebar structure to the fibers can be controlled.

Two basic techniques have been considered in the production of D-H-FRP: braiding and twisting. Processing parameters for producing samples using the first method include the braiding profile and the processing speed. A prototype manufacturing machine was designed incorporating these processing parameters. The manufacturing system consists of a braider and a puller, a resin applicator, a forming die and a curing chamber. A regular modulus carbon (T300) and aramid (Kevlar 49) fibers in a vinylester matrix was used for the 3 mm bar, whereas a high modulus carbon (Thornel P-55S) and aramid (Kevlar 49) fibers in an Epon 828 epoxy matrix was used for the 5 mm and 10mm bars.

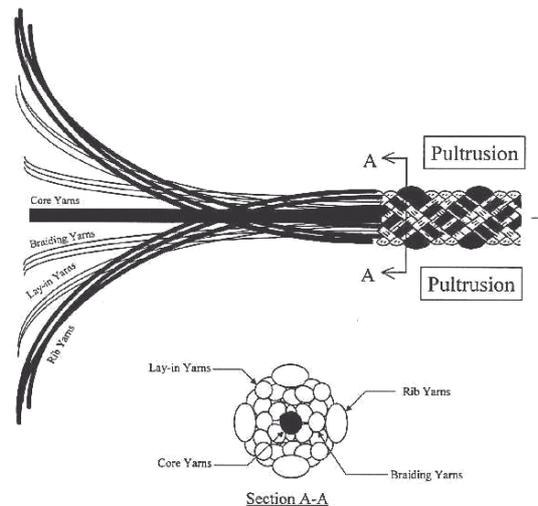


Figure 1: Composition of ductile hybrid FRP (D-H-FRP)

TENSILE STRENGTH CHARACTERIZATION

Tensile stress-strain characteristics have been obtained for all three sizes of rebars that have been produced in the laboratory. The monotonic stress-strain behavior of the 5 mm D-H-FRP bar is shown in Figure 2. It is of interest to note from Fig. 2 that the 5 mm. hybrid FRP bar achieved high initial modulus as well as a ductile failure mode characterized by a bi-linear stress-strain curve. The definite yield strength is achieved by the hybridization process and it's a manifestation of the fracture of the fibers with the lowest failure strain. The controlled nature of the failure process has been explained by Somboonsong et al. [1999]. A reduction in the stress fluctuations in the post yield region can be achieved by modifications to the fiber architecture in the FRP bar.

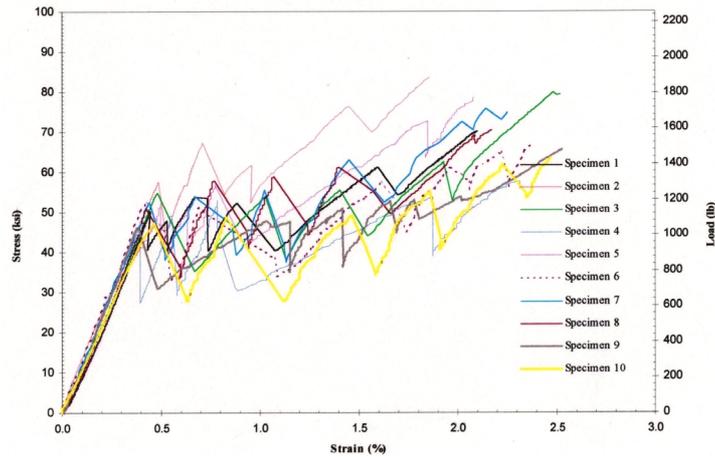


Figure 2: Stress-strain characteristics of D-H-FRP 5 mm diameter bars

BOND AND CRACKING CHARACTERISTICS

Bond characteristics between concrete and reinforcement significantly affect cracking, and in particular, the post-yield response of a structure. Since bond-slip reduces the flexural stiffness and the dissipation of energy in hysteretic behavior, a lack of bond similitude between model and prototype has a correspondingly negative effect on similitude in structural damageability and collapse limit state responses. Bond strength and bond-slip relationships for the developed D-H-FRP bars are studied using straight pull-out specimens and special beams in which both the concrete and the reinforcement are in tension. One of the major shortcomings of many presently available FRP rebars is their relatively low bond strength. The approach taken in the ongoing D-H-FRP research is to build into the bar a set of ribs during the braiding operation. This greatly increases the bond strength through a mechanical interlock between the composite rebar and the surrounding concrete. This improved bond strength has been demonstrated in 5 mm and 10mm bars that have been produced by the proposed method and tested in pull-out specimens. Average bond strength of the D-H-FRP bars is comparable to deformed steel bars of similar diameter.

RESULTS OF BEAM TESTS

A series of appropriately sized simple beams of 50 mm x 100 mm cross-section and 1.2 m long were tested in four point bending to study the flexural behavior of the 5 mm D-H-FRP rebar developed. The beams were designed to have the same ultimate moment in all beams irrespective of type of reinforcement based on nominal strength properties. Steel wire stirrups were used in both steel and FRP reinforced beams, which were cast simultaneously using a properly sized model concrete [Harris and Sabnis, 1999]. One steel reinforced and three D-H-FRP reinforced beams were cast at the same time. Testing was performed using a 44.5 kN capacity displacement and computer controlled Tinius-Olsen universal testing machine. Load-deflection and moment-curvature relationships were theoretically and experimentally determined.

A comparison of the load-deflection behavior of the steel reinforced and the ductile hybrid FRP reinforced beams is shown in Fig. 3a. Note from Fig. 3a that the D-H-FRP reinforced beams had very repeatable behavior with a high initial stiffness (identical to the companion steel reinforced beam) up to the cracking load. The precracking behavior of all three D-H-FRP beams was identical to that of the steel reinforced beam. The post cracking behavior of all three D-H-FRP reinforced beams was very similar and all had a bilinear load-deflection curve up to the yield point.

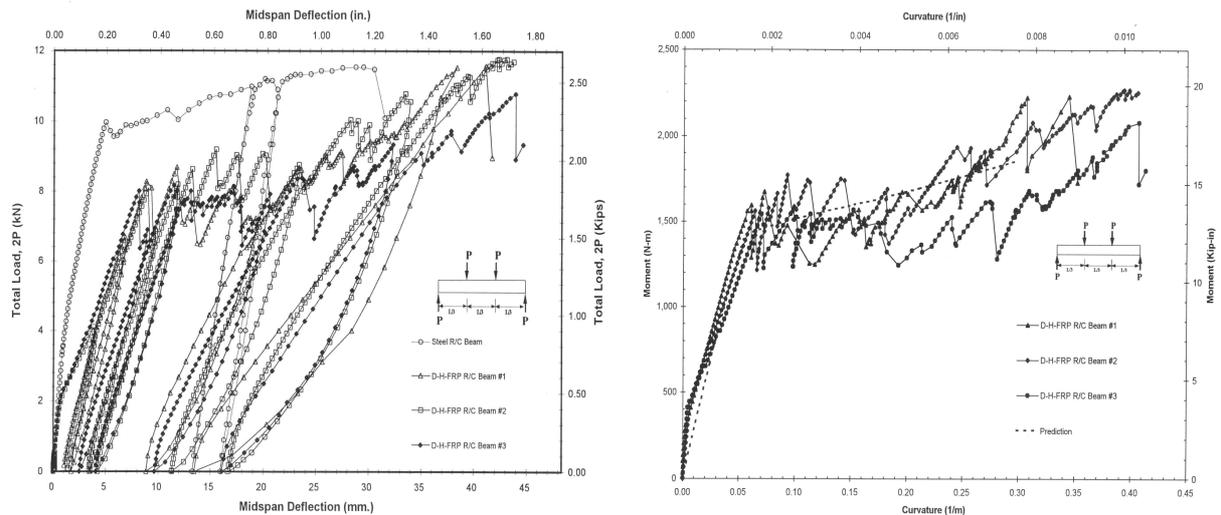


Figure 3: (a.) Load versus Deflection and (b.) Moment versus Curvature for beams with 5 mm diameter D-H-FRP bars

A maximum of five load/unload cycles were performed on each of the tested D-H-FRP reinforced beams in the cracked and post yield ranges to study the nature of their inelastic behavior. As can be seen from Fig. 3a, the new ductile hybrid FRP has significant energy absorbing capabilities very similar to those of the steel reinforcing bars. This behavior is not found to this extent in any existing FRP that has linearly elastic characteristics up to failure but is only possible to materials such as the D-H-FRP bar, which has a definite yield point. Unloading from the yielded condition produced significant permanent deformation (and hence warping) as seen in Fig. 3. The steadily increasing load carrying capacity of the beam shown in Fig.3 is a direct result of an ultimate strength in the new FRP bar that is higher than its yield (Fig. 2).

Moment-curvature relationships of all three D-H-FRP reinforced beams were computed numerically from the equally spaced deflection measurements at the mid-span and are shown in Fig. 3b. As can be seen, a ductile behavior was obtained for all three D-H-FRP reinforced beams with good reproducibility. The predicted moment-curvature relation, based on the bilinear lower bound stress-strain curve is plotted in Fig. 3b and shows very close agreement with the experimental results. It should be noted that the bi-linear moment-curvature behavior of the new D-H-FRP is made possible only by the fact that, through its special design, it possesses a definite yield point, an equivalent bilinear stress-strain curve, and an ultimate strength higher than the yield.

Ductility indexes for the three D-H-FRP reinforced beams, were in the range from 4.6 to 5.4 based on deflection measurements (Fig. 3a) and compare well with the 6.1 of the companion steel reinforced beam. Ductility indexes based on measured curvature (Fig. 3b) ranged from 5.7 to 6.3 for the D-H-FRP beams as compared to 12 for the companion steel reinforced beam. Ductility indexes computed on the basis of energy considerations as given by Naaman and Jeong [1995] ranged from 3.4 to 3.8 for the D-H-FRP beams and compare to 4.3 for the companion steel reinforced beam. Thus it can be concluded that based on direct comparison, the ductility indexes of the D-H-FRP reinforced and steel reinforced beams are very similar.

HYSTERETIC BEHAVIOR OF FLEXURAL MEMBERS

Specimen Description and Materials

The test specimens used for cyclic characterization were idealized flexural specimens that can be interpreted as half a beam length in a rigid frame structure. The reversing transverse load applied at the end of the beam simulates the force at the inflection point of a beam in a frame carrying reversing lateral loads. The test specimen was anchored to a very substantial reinforced concrete base, oriented in a horizontal position and loaded at its end by the loading head of a 44.5 kN universal testing machine.

The model beams were designed to be approximate 1/12 scale models of a hypothetical prototype beam and their dimensions were greatly simplified (Fig. 4).

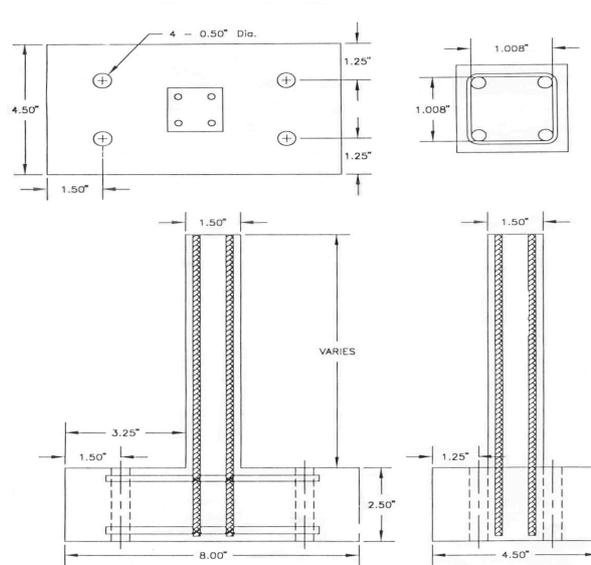


Figure 4: Dimensions of beam specimens under reverse cyclic loading.

The base foundation was designed to so that cracking would be minimal. This was accomplished by providing the equivalent of #10 bars for the prototype and 2.65 mm deformed steel bars for the model. In addition, the base foundation was externally post-tensioned to the supporting base with steel clamps.

The 1/12 scale models are 38 mm square sections of varying length and are reinforced with four 5 mm diameter D-H-FRP rebars. Due to the lack of composite D-H-FRP stirrups, steel ties were used in both types of models. The average yield load for the 5 mm D-H-FRP used for design was 4.45 kN. A model concrete was chosen for design to have an f'_c of 31 MPa.

Fabrication and Casting

Fabrication and casting techniques as described in Harris and Sabnis [1999] were used to make the model specimens. Fig. 5 shows the column reinforcement cage prior to casting. The casting was carried out in a two-stage process. First the footing was cast in an open wooden mold (Fig.5b) and then the column form was attached to the top of the footing mold by means of eight 44.5 mm wood screws. The column cage was held in place as the model concrete was introduced into the mold using a vibrating table and hand rodding. The model and its control specimens were removed from the molds 24 hours after casting and introduced into a moist room for curing until testing after 28 days.



Figure 5: (a.) Fabricated cage of cyclic specimen and (b.) casting procedure for footing

Test Set-Up

The testing set-up is shown schematically in Fig. 6. As shown in Fig. 6a, the beam is tested in a horizontal position with the cyclic loading applied by the cross-head of the Tinius-Olsen testing machine (Fig. 6b). A photo of the test apparatus is shown in Fig. 7. The load-transferring device, which is critical to the properly applied load from the testing machine to the center of the test specimen, is shown in Fig. 8. This was fabricated from a series of plates and when assembled in line with the load cell allowed rotation of the specimen during testing.

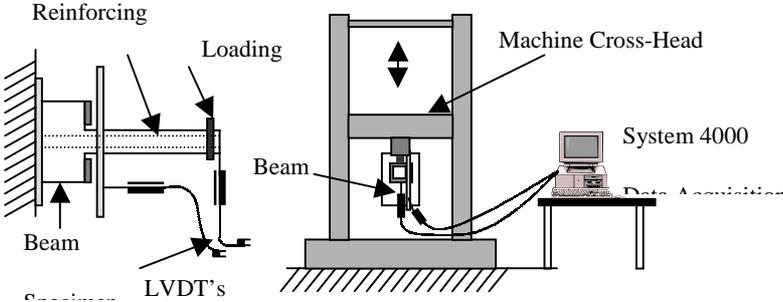


Figure 6: Beam test setup showing (a.) side view and (b.) front view in Tinius Olsen machine

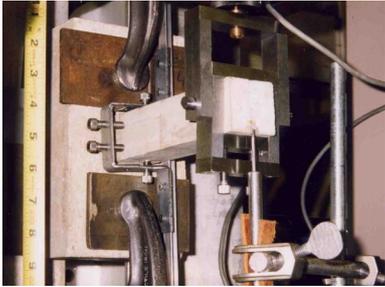


Figure 7: Instrumented beam test setup.

Instrumentation and Test Procedure

Three parameters were measured for each specimen: applied load, displacement at the top of the specimen, and rotation at its base. Linear Variable Differential Transformers (LVDT's) with a gage length of 50 mm and an accuracy of ± 0.0127 mm were used for displacement measurements. Since considerable damage was expected at the bottom of the specimen, the base rotation was measured at a distance equal to a half of the effective depth above the base foundation. At this point, a steel bar was attached to all four sides of the section by turning the screws as shown in Fig. 8b. LVDT's mounted at the ends of the attached arms measured the rotation of the section. A Measurements Group System 4000 data acquisition system was used to record continuously the load and displacement readings throughout the test. Reversing cyclic loads were applied in a displacement control mode. Displacement cycles were steadily increased in magnitude starting with $0.1 \Delta y$ for the first cycle. Subsequent cycles had peak displacements which were: $0.2 \Delta y$, $0.4 \Delta y$, $0.5 \Delta y$, $2\Delta y$, $3 \Delta y$, $4 \Delta y$, $6\Delta y$, and $8\Delta y$.

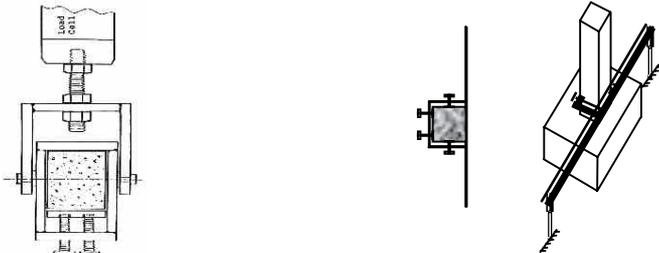


Figure 8: Column attachment setup (a.) Front view and (b.) Attachment to measure base rotation

TEST RESULTS

The hysteretic load-displacement is of primary importance in the evaluation of the D-H-FRP reinforcement since it gives an overall basis for evaluating the beam specimen, including degradation rates and energy absorption, and with less emphasis on local response characteristics such as cracking and bond-slip. A summary of the test results is given in Table 1. Typical hysteretic load-deflection results for specimen C-1 are shown in Fig. 9a. This specimen showed significant ductility and energy absorption capability. The final loading to failure of specimen C-1 achieved a ductility factor of 10.9.

The moment-rotation response of the D-H-FRP reinforcement was also plotted for each specimen. The moment-rotation is influenced by local behavior of the model and the contribution of cracking and bond-slip in the hinging region. As can be seen by the response of specimen C-1 shown in Fig. 9b, no apparent deterioration was evident in this specimen until the higher ductility ratios were reached.

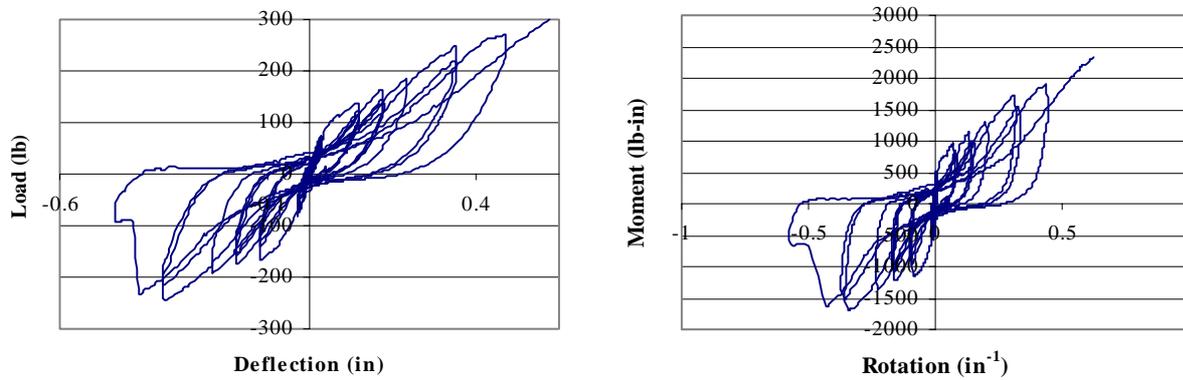


Figure 9: (a.) Load-Deflection and (b.) Moment-Rotation for beam specimen under reverse cyclic loading.

Table 1: Summary of Cyclic Tests

Specimen	Max Load (kN)	Max Deflection (mm)	Min. Load (kN)	Min. Deflect. (mm)	Max. Moment (kN-mm)	Max. Rotation (mm ⁻¹)	Min. Moment (kN-mm)	Min. Rotation (mm ⁻¹)
C1	1.21	11.94	-1.08	-11.94	211.95	0.017	-192.97	-0.015
C2	0.81	13.21	-0.85	-10.92	140.66	0.010	-157.61	-0.005
C3	0.67	16.51	-1.15	-16.256	134.22	0.020	-240.53	-0.013

CONCLUSIONS

Results have been presented of the cyclic flexural behavior of a new ductile hybrid FRP (D-H-FRP) reinforcing bar for earthquake resistant concrete structures. Load-deflection and moment-curvature relations from small beams show that the D-H-FRP rebar can achieve a ductile behavior with ductility indexes similar to those of mild steel reinforcement.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the funding and support of the National Science Foundation for this study.

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