CREEP, STRESS RUPTURE, AND BEHAVIOR OF A DUCTILE HYBRID FIBER REINFORCED POLYMER (D-H-FRP) FOR CONCRETE STRUCTURES

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SUMMARY: Reinforced concrete (R/C) structures especially pavements and bridge decks that constitute vital elements of the infrastructure of all industrialized societies are deteriorating prematurely. Structural repair and upgrading of these structural elements has become a more economical option for constructed facilities especially in the United States and Canada.

The tensile strength, creep-rupture, and energy absorption capacity of a second generation ductile hybrid FRP reinforcement 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. The effects of similitude from fiber to braiding geometry were investigated for proper enlargement of the D-H-FRP bars. The D-H-FRP bar exhibits a bilinear stress-strain behavior, which shows significant material toughness for all bar sizes. The long-term viscoelastic effects (creep) show excellent life-cycle design capabilities. Finally, the D-H-FRP shows significant energy absorption under reverse cyclic loading, a crucial concern for reinforced concrete (RC) structures, especially those subjected to earthquake loading.

KEYWORDS: FRP, hybrid, ductility, reinforced concrete, translation efficiency, tensile strength, creep/stress rupture, energy absorption.

INTRODUCTION

Reinforced concrete (R/C) structures especially pavements and bridge decks that constitute vital elements of the infrastructure of all industrialized societies are deteriorating prematurely. Structural repair and upgrading of these structural elements has become a more economical option for constructed facilities especially in the United States and Canada.

This paper describes the scaling requirements, tensile strength, creep-rupture, and energy absorption capabilities of a second generation ductile hybrid FRP reinforcement developed in the form of a ductile hybrid bar (D-H-FRP) which simulates the stress-strain characteristics of conventional steel reinforcement [1,2]. 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 [3]. A combined experimental and analytical approach is taken to develop the architecture of the desired ductile hybrid fiber FRP reinforcement using advanced 2-D and 3-D braiding techniques pioneered in the Fibrous Materials Research Center of Drexel University [3].

Using a combination of high modulus carbon (Thornel P-55S) and aramid (Kevlar 49) fibers, 5 mm diameter bars 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 was obtained. 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 concrete beams 50 mm x 100 mm in section and 1.2 m long reinforced with ductile hybrid FRP bars developed which produced ductility indices that were essentially the same to those of a companion steel reinforced beam [2]. 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 [4] and [5].

An in-line braiding and pultrusion process was developed to produce high quality D-H-FRP bars up to 10 mm nominal diameter. Using the results from the tensile tests and fracture analysis, the stress-strain behavior of the D-H-FRP bars was fully characterized. The developed analytical model closely predicted the stress-strain behavior of D-H-FRP bars [5].

DESIGN CONCEPT OF THE DUCTILE HYBRID FRP (D-H-FRP)

Ductility is the ability of a material or structural member to undergo large inelastic deformations without distress. In the extreme event of a structure loaded to failure, it should be able to undergo large deflections at or near its maximum load carrying capacity. This will give forewarning of failure and prevent total collapse and may save lives. In statically indeterminate concrete structures, ductility of the members at the critical sections is necessary to allow moment redistribution to take place. 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. Taking advantage of the design flexibility and the wide availability of manufacturing capacity in the industry, braided structures were employed as the primary fiber architecture for the construction of the reported ductile hybrid FRP rebar system. The methodology of braiding, as detailed by Ko [6], 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 braided sleeve and the core structure, the load-deformation behavior of the braided fibrous assembly can be tailored (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 desired high stiffness. The rib effect, as commonly incorporated in steel rebars to increase the 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. The end product of this hybridization of material systems and fiber architecture is a *second generation* composite rebar which has high initial resistance to tensile deformation followed by a gradual failure process manifested by a gradual reduction in the slope of the stress-

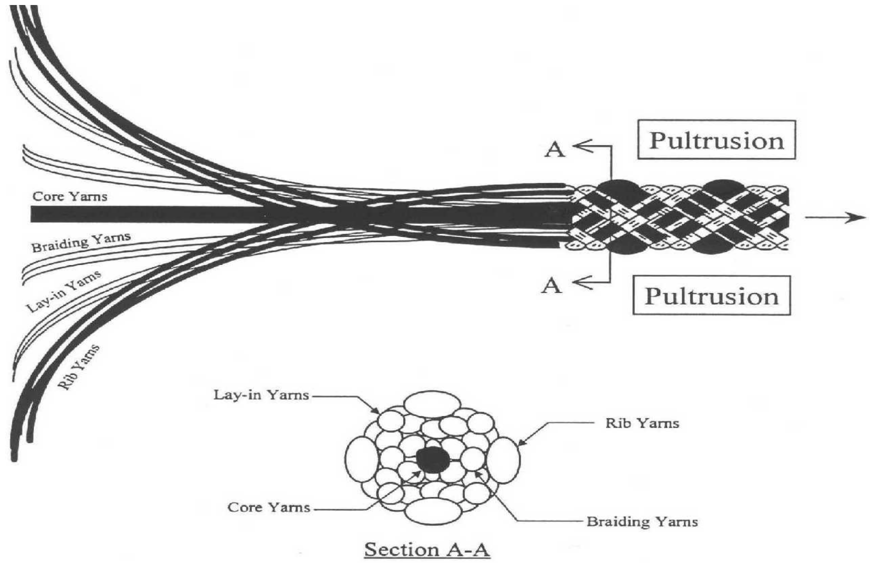


Fig. 1: Composition of Ductile Hybrid FRP (D-H-FRP)

strain curve before reaching a high level of ultimate strain. A mathematical model incorporating the effects of the hybrid architecture and statistical fiber strength can be used to design the FRP bar for any particular steel strength level desired. This methodology has been given in [5].

Processing parameters for producing samples of the hybrid FRP 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, a resin applicator, a forming die, a curing chamber, and a puller. This in-line braiding and pultrusion process, dubbed *braidtrusion*, was used to demonstrate the concept using D-H-FRP bars of 3 mm and 5 mm diameters. The manufacturing system is being modified to produce 10 mm diameter bars and eventually prototype bars.

BAR SCALING EFFECTS OF 10 mm DIAMETER BARS

There are two primary advantages to modeling. First is cost reduction. The materials comprising the D-H-FRP bar (Kevlar and Carbon) are expensive. The major cost is material cost. Using a model bar reduces this cost greatly compared with the material needed for the prototype bar. Second, modeling results in load reduction. For example, a concentrated load on a prototype bar is reduced in proportion to the square of the geometric scale factor of the model bar [7]. For example, for a 1/9 scale, a 100 kN prototype load is only a 1.23 kN model load, thereby reducing the need for large testing equipment and a reduction in testing time. Table 1 shows the scale factors for each bar and the reduction in load from the prototype to the model bar used in this study.

A major concern is the effect of translational efficiency of the D-H-FRP bars as they are scaled up from the 3 mm, 5 mm, and 10 mm sizes as compared to the prototype bar. The prototype bar is taken as a 25.4 mm bar (1 in diameter #8 bar). The design methodology of the D-H-FRP bars follows a structural hierarchy of fibrous assemblies [6] as shown in Fig. 2. This hierarchy includes various geometric levels to be studied including material properties, fiber and yarn packing and braid helix angle. Structural modeling techniques are used to model civil engineering systems following the principles of similitude [7]. These same techniques will be applied to the material system to quantify the effects of scaling the D-H-FRP bars. The following questions need to be answered. Do the geometric and material parameters at the fiber, yarn, and braid level obey the conditions of similitude? Can accurate predictions of strength be made for a prototype bar from these models? What is the effect of the interface between the fibers and matrix when scaling? Is the transfer properties equivalent for all diameter bars? Finally, is the ductility effected by larger bars with more fibers?

Table 1: Scale and load reduction effects

Bar Size (mm)	Scale Factor	Load reduction (%) Prototype load : Model load (% difference)
3	1/9	100 kN : 1.23 kN (98.7%)
5	1/5	100 kN : 4.0 kN (96%)
10	1/3	100 kN : 11.1 kN (88.9%)

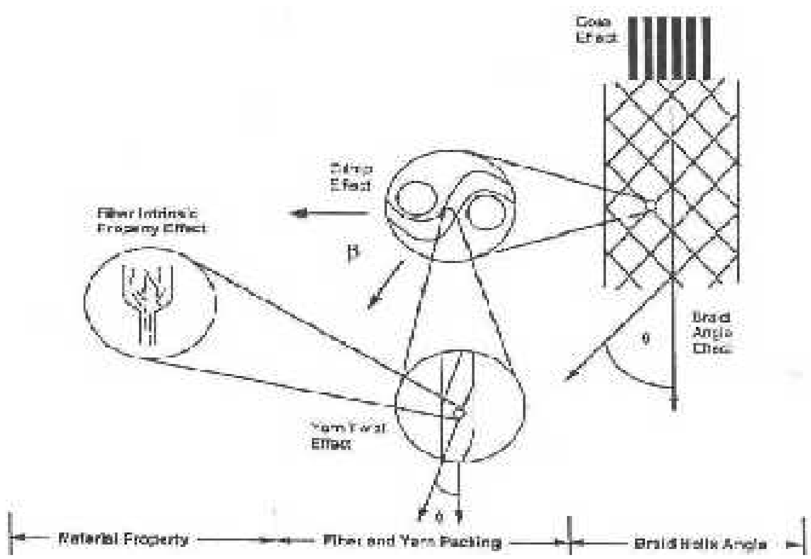


Fig. 2: Structural Hierarchy of Fibrous Assemblies (Ko, [6])

The most important problem presented here is to quantify the transfer properties of the various levels of geometry for the different bar sizes.

At the fiber level the most important parameters are bond (the volume fraction of bonds), crystallinity, and orientation. The fiber modulus is as

$$E = \frac{l\cos\alpha}{A}\left[\frac{\cos^2\alpha}{k_1} + \frac{\sin^2\alpha}{4k_p}\right]^{-1} \tag{1}$$

where α is the bond angle, l is the bond length, A is the area of the unit cell and k_1 and k_p are constants depending on bond type.

At the yarn level, the important geometric parameters are orientation, attenuation, and integration. Integration involves twisting of the yarns. The transfer properties for the yarn are given as

$$E_y = E_f \cos^2\theta\left(\frac{TM}{5}\right) \tag{2}$$

$$\varepsilon_y = \frac{\varepsilon_f}{\cos^2 \theta} \tag{3}$$

where θ is the angle of twist and the twist multiplier *TM* can be viewed as a scale factor. The primary observation here is that as the bar sizes increases two, three, or four times, does the angle of twist remains the same. If not, the yarn modulus will change thereby affecting the transfer properties to the braid level.

At the braid level, the volume fraction is given by

$$V_f = K + \frac{2w^2 \cos^2 \theta}{x^2} \tag{4}$$

$$x = \frac{2\pi R_c}{N} \tag{5}$$

where *K* is the fractional area covered by the fibers in a braided structure, *w* and *x* are the width and length of a unit cell (respectively), *N* is the number of carriers on the braiding machine, and R_c is the radius of the core fibers. The resulting braid angle is given as

$$\beta = \cos^{-1}\left(\frac{\left(1 + \sqrt{1-K}\right)Nw}{2\pi K R_c} \right) \tag{6}$$

Therefore, the braid angle is a function of the radius of the core fiber. Does R_c scale up directly form the smallest model bar to the prototype? This will effect the initial bar strength since the unidirectional core fibers take the initial stress when loaded.

For optimum strength, the properties of the D-H-FRP bar must be transferred from the various geometric levels: the fiber level, the yarn level, and the braid level. The orientation and the volume fraction at each level are most important, and at each level effect the modulus of fiber, yarn, and braid structure. At the yarn level, the amount of twist put into the yarn structure may vary as the bar diameter increases. This could significantly change the yarn modulus thereby reducing the transfer strength to the braided geometry. The amount of crimp in the yarn could also effect the overall structural strength. As the number of yarns increase, the amount of crimp may also increase, allowing for more elongation and therefore more ductility. A more ductile bar could have a lower yield value and a lower modulus but greater toughness. Therefore crimp must be investigated for transfer effects. The bond between the fibers and matrix is of great importance when testing the bar structure. As the volume of fibers increase, so does the wetting surface that the matrix has to cover. There is probably not a direct scale up for all bar sizes of the interface strength. This bond is crucial for stress transfer from the carbon fibers which fracture first to the Kevlar fibers. These all require a complete dimensional analysis.

The dimensional analysis and similitude requirements are very powerful for many structural levels, both micro and macroscopic. Similitude requirements have been studied in detail on the macrostructural level, however, less work has been done at the microstructure level of braided composite materials. Full similitude studies should be conducted to quantify the transfer properties of the braided D-H-FRP bar. This geometrically based effects the final strength of the bar. For a full understanding of the material, geometric, and strength characteristics of the D-H-FRP bar (model and prototype), a complete parametric study must be completed at the micro level.

Shown in Fig. 3 is the manufacturing process for the production of the scaled up 10 mm nominal diameter D-H-FRP bars. The process includes a 12-carrier braider, a resin applicator, a heated die for proper cure and a heated chamber for continued post-cure. Four carriers are used for rib yarns and the other eight are used for braiding and lay-in yarns. These form a braided sleeve of Kevlar fibers. The core fibers are laid-in and consist of unidirectional carbon fibers. The polymer resin is poured over the fibers prior to braiding to wet the fiber surfaces. This process consisting of both braiding and pultrusion is named 'braidtrusion'.

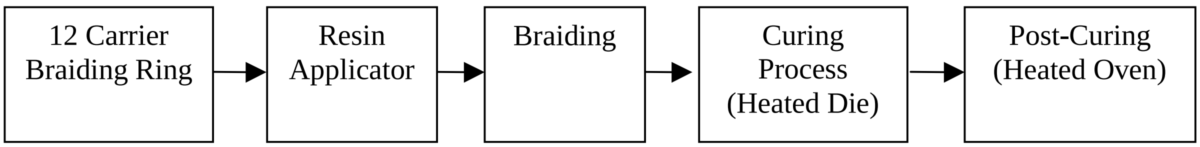


Fig. 3: Manufacturing Process for 10 mm Dia. D-H-FRP Bars

RESULTS OF 10 mm DIAMETER D-H-FRP BARS UNDER UNIAXIAL TENSION

Tests were conducted to obtain the tensile strength of 10 mm D-H-FRP bars. The core (Thornel P-55S) provides initial stiffness while the yielding of the braided aramid fibers provides ductility [4].

A Tinius Olsen 50 kN (10000 lb) capacity universal test machine was used in conjunction with a System 4000 data acquisition system. Two Linear Variable Differential Transformers (LVDT) gauges were attached to measure extension. Two series of tests were conducted, one on 5 mm diameter bars and the other on 10 mm diameter bars. The load was then plotted versus strain. The specimens had end tabs to prevent material crushing and stress concentrations at the supports. The end tabs for the 5 mm specimens were a chopped fiber composite with glass fibers and epoxy resin. The 10 mm diameter specimens were embedded in 76.2 mm by 152.4 mm concrete cylinders, confined by a plastic sleeve and steel rings. This provided enough lateral confining pressure to prevent failure at the supports.

Shown in Fig. 4 is the load versus strain for both the 5 mm and the 10 mm diameter specimens. All of the specimens, both 5 and 10 mm diameters, show a ductile mode of failure with a bilinear (trilinear) load-strain curve. The linear (elastic) portion of the curve was repeatable for all specimens, with the 10 mm diameter specimens having a slightly higher initial modulus. As shown, however, the transfer efficiency is not 100 % from the 5 mm bar to the 10 mm bar. A first level approximation for the transfer properties from the 5 to 10 mm bar is four. This is based on the bar area which is proportional to the square of the diameter. However, the ultimate load was fairly high (15.66 to 20.69 kN) for the 10 mm bar compared with the 5 mm bar and the ultimate strain was between 1.5 % and 3.0 %. These curves show a significant amount of toughness for a composite material, which results in energy absorption. The 10 mm bar has increased toughness due to the larger fiber content which increases the crimp in the yarn geometry [6].

CREEP-RUPTURE TEST

Data on the creep-rupture capacity of materials is needed for proper life-cycle design of structures. The creep-rupture strength and behavior is well known for materials such as steel, but is less defined for newly manufactured composite materials. For steel, a sustained tensile load of

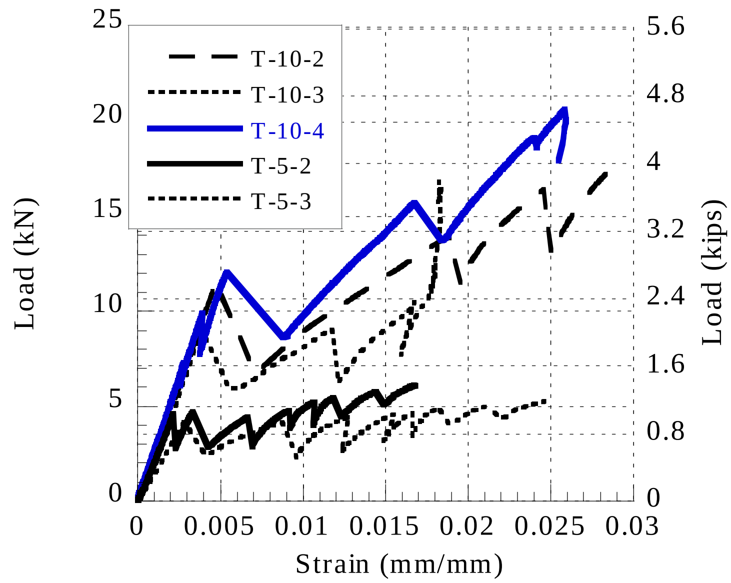
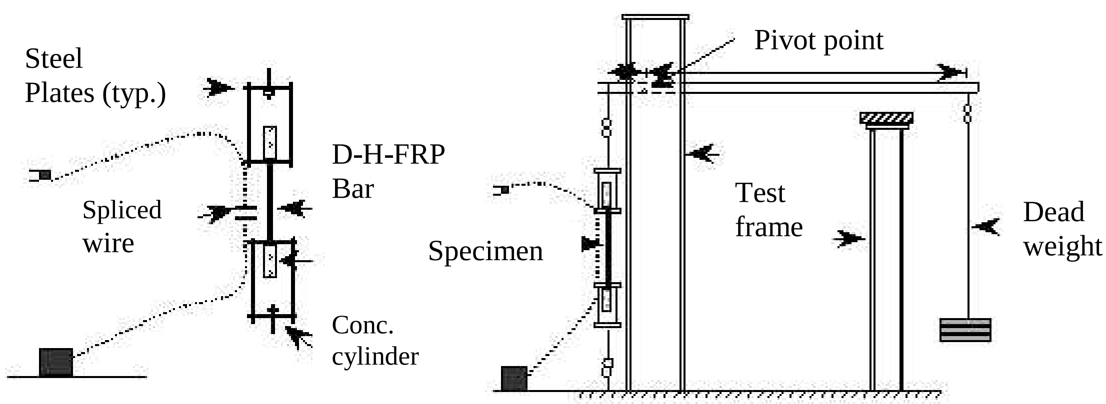


Fig. 4: Comparison of 5 mm and 10 mm Diameter D-H-FRP

75% or lower of the ultimate load is considered safe for creep rupture failure [4]. For the proper life-cycle design of reinforced-concrete structures with D-H-FRP reinforcing, it is mandatory to know the creep-rupture strength for the 50-year design life of the structure.

Creep is a viscoelastic effect that is manifested as a polymer deforms under constant load. For steel, this effect occurs at elevated temperatures, but for polymers, creep can occur at room temperature. Since the D-H-FRP is designed with life-cycle costs in mind, the long-term time dependent properties of the material must be fully quantified. A test was conducted to determine the creep-rupture behavior of 5 mm diameter D-H FRP bars. The bars were mounted in the test machine and subjected to a sustained static load until failure (Fig. 5). The load to weight ratio is 1:10. The ends of the bar were embedded in 50.8 mm by 101.6 mm (2" by 4") concrete cylinders.

The load was based on a percentage of the average ultimate tensile load, P_{ult}. The maximum sustained load and time to failure were then recorded for each specimen.



5a: Specimen Detail 5b: Creep Test Apparatus

Fig. 5: Creep-rupture Experimental Setup for 5 mm Diameter D-H-FRP Bars

Fig. 6 shows a plot of the load ratio $P_{rupture}/P_{ult}$ (rupture load to ultimate load ratio) versus time until failure. Four load levels were used in the test based on percentages of the ultimate strength of the material. From tension tests, the ultimate strength of the material is 5.34 kN (1.2 kips). The load levels chosen were 3.56, 4.00, 4.23, 4.45 kN (0.8, 0.9, 0.95, 1.0 kip); these values correspond to 67 %, 75 %, 79%, and 83 % of the ultimate tensile load, respectively. To initially get the system in horizontal equilibrium, an additional 0.31 kN of preload was added.

The characteristic endurance line generated from the test data is given by the logarithmic function,

$$Y = 0.863 - 0.035 \log x \tag{7}$$

As expected, the data shows decreasing load ratio with increased failure time. Two specific failure times are noted in Fig. 6. First, failure at 50 years is shown. The load ratio value at this time is 0.69or 69 % of the ultimate load. The load ratio value at 10^6 hours is 0.61 or 61 % of the ultimate. These values are very promising when compared to other results from creep tests. Budelmann and Rostasy [8] found that sustained stress is limited to 60% of the short-term ultimate strength for GFRP. Also, Anigol [9] and Khubchandani [10] reported no loss in

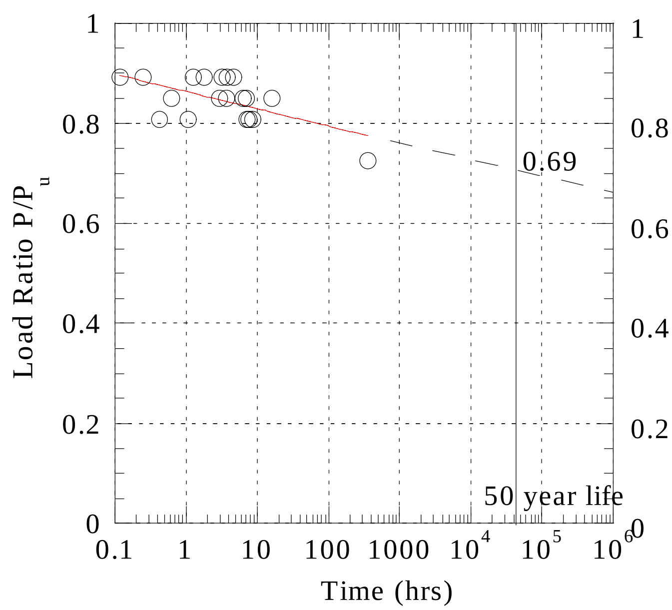


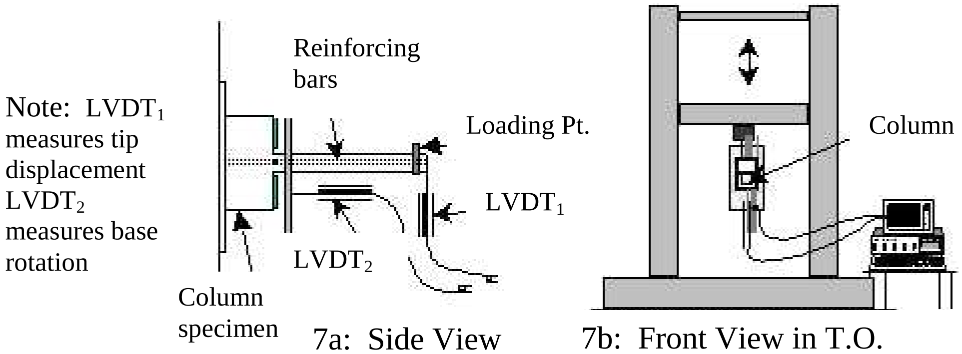
Fig. 6: Creep-rupture for 5 mm Diameter D-H-FRP

strength for 50% of the ultimate for CFRP and GFRP. Therefore, the obtained results are in line with other FRP materials.

ENERGY ABSORPTION CAPACITY OF 5-mm DIAMETER D-H-FRP

It is crucial for a structure to be able to be able to absorb energy, especially during an earthquake event. Therefore, a ductile reinforcing material is needed for reinforced concrete structures. Steel provides this ductility for R/C elements, but many FRP's are linear elastic to failure and do not possess significant energy absorption capacity under reverse cyclic loading. Contrary to this, however, the D-H-FRP developed shows significant energy absorption capacity.

Shown in Fig. 7 is the test setup for the determination of the energy absorption capacity of the D-H-FRP bars. The bars were embedded in square concrete columns of lengths 3150 and 3937 mm.



7a: Side View 7b: Front View in T.O.

Fig. 7: Setup for Reverse Cyclic Load Test, 5 mm Diameter Bars

Four D-H-FRP bars were placed as the longitudinal reinforcing. These were confined with hoop reinforcement called stirrups which prevented buckling of the longitudinal reinforcing and provided shear reinforcement. The column was loaded at its tip and was cycled through both tensile and compressive loads. Both tip deflection and base rotation was measured.

Shown in Fig. 8 is the result of a reverse cyclic load test. As seen in the load cycles, the energy absorption capacity of the D-H-FRP material is significant. The hysteresis loops illustrate two key points. First, the D-H-FRP bars show energy absorption capability, unique when compared with most composite materials. Second, the ductility of the D-H-FRP is further quantified by this energy absorption capacity. This is particularly valuable in design and retrofit of reinforced concrete structures in regions of high seismicity.

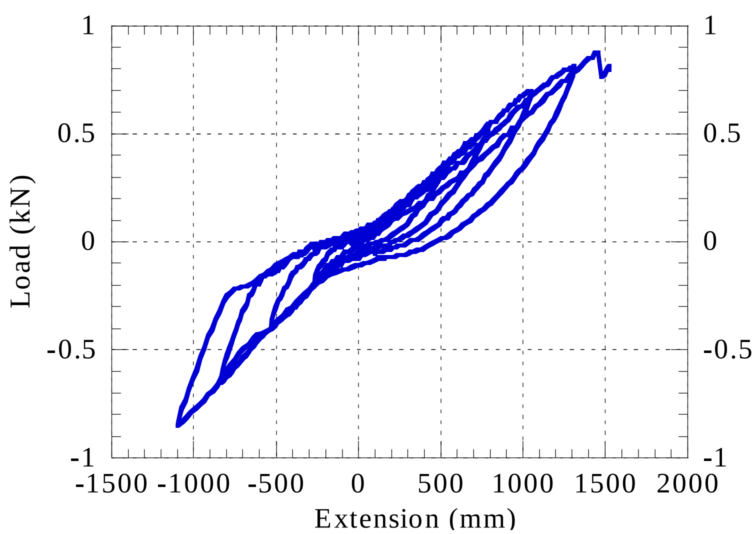


Fig. 8: Reverse Cyclic Loading of Column Specimens, 5 mm Diameter D-H-FRP Bars

CONCLUSIONS

The Ductile Hybrid Fiber Reinforced Polymer (D-H-FRP) bar shows much promise in the design of new reinforced concrete structures and retrofitting existing structures, especially in areas of moderate to high seismicity. The bar has been successfully scaled up to the 10 mm nominal diameter size, the equivalent to a conventional steel number 3 bar. These larger D-H-FRP bars show good tensile properties, and a bilinear load-strain curve, with significant post-elastic deformations. The energy absorption capacity of the D-H-FRP bars is significant, with a large amount of hysteresis. The long-term mechanical properties also show significant promise, specifically the creep-rupture properties. The D-H-FRP is adequate for the life-cycle design of a structure.

ACKNOWLEDGEMENTS

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