Performance Evaluation of Fiber Reinforced Polymer Reinforcing Bar Featuring Ductility and Health Monitoring Capability

by A. Belarbi, K. Chandrashekhara, and S. E. Watkins

Synopsis:

The main objective of this study was to develop a new type of FRP rebar with focus on ductility and health-monitoring issues. One approach to provide ductility was the use of a hybrid FRP reinforcing bar consisting of different types of fibers, which fail at different strains during the load history of the rebar, thereby allowing a gradual failure of the rebar. The rebar was manufactured using pultrusion and filament winding techniques. These techniques have made it possible to embed fiber optic sensors within the reinforcement, for health monitoring, thus protecting the sensor from the harsh concrete environment. Pseudo-ductile behavior was validated through testing of coupon FRP rebar as well as RC beams. Testing of large-scale beams reinforced with the hybrid FRP rebar exhibited remarkable ductility behavior with ductility indices close to that of beams reinforced with steel rebar. Furthermore, the strain measured from the embedded fibers optics replicates the measurement of conventional LVDT and was reliable up to failure of the beams.

Keywords: composites; ductility; fiber reinforced polymers; flexure; reinforcing bars; sensors; structures

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INTRODUCTION

Limited service life and high maintenance costs are associated with corrosion, fatigue, and other degradations in concrete bridge and highway structures. Repair and replacement cost factors have led highway agencies and researchers to investigate new concepts applying advances in materials technology. Current efforts to improve transportation and civil engineering structures include the use of high-performance composite materials. Fiber reinforced polymer (FRP) rebars and tendons are being introduced at very slow rate in structural design because of issues such as insufficient bond resistance, poor bend-up capabilities, and nonexistent ductility which are fundamental requirements of rebar in RC structural design.

This current research has focused on developing a new type of FRP rebar for RC use which exhibit the mechanical properties of conventional rebar, such as strength, stiffness, ductility, fatigue, and bond capabilities. Furthermore, it would offer "smart" capability in which embedded sensors, e.g., fiber optic sensors provide sensing health monitoring and micro-damage assessment without destructive evaluation.

The research presented in this paper concentrated on manufacture of a final commercial FRP rebar product featuring pseudo-ductility, and the evaluation of its performance in bare conditions as well as inside concrete beams. Tensile testing of the proposed hybrid FRP rebars was performed, along with monotonic and repeated loading tests on hybrid FRP reinforced concrete beams. Finally, preliminary structural health monitoring using fiber optic sensors embedded in FRP reinforced beams was also performed.

PREVIOUS RELATED WORK

Many efforts have been made to incorporate ductility in FRP rebars. Because of the multiple manufacturing techniques available to FRP, many different approaches have been developed. The most common manufacturing techniques for FRP rebars are pultrusion, filament winding, and braiding techniques. Tamuzs and Tepfers [1] tested two different types of hybrid FRP rebars. The first type consisted of multiple fibers embedded in an epoxy resin matrix. An attempt was made to randomly mix the various fibers over the cross section. However, this was not possible due to various fiber sizes. These first efforts failed, since high stress concentrations at the location of fiber breakage damaged the surrounding fibers. It was concluded that the high stress concentrations were a result of the inability to randomly distribute fibers over the cross section. Their second attempt at a ductile FRP rebar consisted of braided FRP rebars with different core materials. As tension was applied, the braided FRP shell compressed the core material, thus causing a reorientation of the braided fibers. The reorientation of the fibers resulted in large deformations in the braided FRP rebar, but the cross section was reduced due to the compression of the core material.

Bakis, Nanni, and Terosky [2] also performed research on pseudo-ductile pultruded FRP rods. Rods using between two and three different fibers were designed using the rule of mixtures. These rods were then tested under tension, and the desired pseudo-ductile behavior was observed. However, premature failure of the hybrid rods occurred due to the local stress concentrations, similar behavior observed in Tamuzs study.

Around the same time, 1995, Belarbi et al. [3], based their research on a hybrid system, but incorporated multiple manufacturing steps to further increase ductility in their proposed hybrid FRP rebars. They proposed combined pultrusion and filament winding techniques and the use of a hybrid system of fibers to produce the rebar. An inner core of various stiff carbon fibers was fabricated using the pultrusion process. The inner core was then placed in a filament-winding machine and wound with additional fibers. Under tension, it was theorized that the filament would give the additional elongation as they reorient themselves after rupture of the core. The work reported herein is the experimental investigation and proof of their original idea.

Most recently, a second generation ductile hybrid FRP rebar was developed and extensively tested by Harris, Somboonsong, Ko, and Huesgen [4]. Their manufacturing process also included two steps; braiding of various fibers was performed before the final pultrusion process cured the matrix. Their proposed system included stiff fibers located in the center of the rebar, with various aramid fibers braided around the stiff center fibers.

DEVELOPMENT OF SMART HYBRID FRP

Hybrid System

Current FRP rebars exhibits linear elastic behavior until failure in contrast to steel which has a definite yielding plateau. By definition, ductility is an increase in deformation without an increase in capacity. In traditional reinforced concrete structures, the yielding of longitudinal steel reinforcement provides ductility. In fiber composites, there is no definite yield point, since most fibers are linear elastic until failure. As a result, fiber composites exhibit brittle behavior, which if used in a reinforced concrete system, would give no warning of structural failure. One approach to incorporate ductility is to use a hybrid FRP reinforcing bar. The proposed hybrid rebar consists of different types of fibers, which fail at different strains during the load history of the rebar, thereby allowing a gradual failure of the rebar. In manufacturing the rebar, pultrusion and filament winding were used.

By combining two different manufacturing techniques, it was possible to symmetrically distribute different types of fibers over the cross section of a composite. Beginning with the pultrusion technique, a unidirectional core consisting of only one type of fiber was produced. Pultrusion is the most common technique for fabricating low cost composites. Once the core was produced, a filament winding was used to symmetrically place additional fibers around the core. Since symmetric fiber placement was desired in our proposed hybrid FRP rebar, parameters such as the diameter of the core and the wind angle were entered into the filament winding machine prior to winding. To achieve longitudinal strength and stiffness as required in FRP reinforcing, filament wound fibers were placed with a low wind angle with respect to the longitudinal axis of the core. The final proposed hybrid FRP rebar consisted of one type of fiber in the core, with two fibers symmetrically placed on the surface of the core, according to Table 1. To address the issue of bond, the proposed hybrid FRP rebar was sand coated directly after the filament winding process by applying sand to the uncured matrix.

Sensing System

Strain sensing in FRP structures and concrete structures has been done with in-situ fiber optic sensors. These sensors have found increasing applications in the development of smart structures because of advantages including compatibility with most materials and the ability to be multiplexed [5,6]. The technology allows the measurement of internal strains and has the potential for long-term monitoring. A smart FRP rebar can give quantitative assessment of internal loading and damage. In this study, fiber optic sensors were placed inside FRP rebars, which in turn were placed in concrete beams to monitor strain during load tests.

To incorporate fiber optic sensors inside the proposed hybrid FRP rebar, an intermediate step between pultrusion and filament winding was added. By securing the fiber optic sensor on the surface of the core at the desired location of measurement, the fiber optic sensor was covered by the filament winding process. Complete coverage of the sensor by the filament wound fibers protected the sensor from the harsh concrete environment. Extreme care was taken to ensure a reliable ingress/egress point of the fiber optic line.

FRP Rebar Tensile Test and Results

Tensile testing was performed on each batch of hybrid FRP rebars to account for slight variations in the manufacturing process. From each batch, three tensile coupons were selected. A gage length of about 600 mm was chosen to allow for a reliable average strain measurement over the coupon. Tensile tests were performed under displacement control of 1 mm/min. using an MTS Universal Testing Machine.

The primary objective of the tensile testing program was to determine if the theoretical stress-strain curve of the proposed hybrid rebar could be reproduced through experimental testing. It was believed that the rule of mixtures would not accurately predict the actual behavior of the proposed hybrid rebar for one main reason. Since the rebars were produced using two manufacturing techniques, it was believed that the components of the proposed rebar (i.e., the core and the shell) would not follow the behavior of the rule of mixtures due to shear interface between these two components. This explanation proved to be true, according to the experimental results. Figure 1 compares the theoretical stress-strain curve from the rule of mixtures with the experimental stress-strain curve for a typical tensile test coupon fabricated following Table 1. Under tension, the rebar coupons experienced successive cracking of the filament wound shell as the fibers in the shell reached their failure strains. Each crack typically corresponded with a drop in load, as shown in Figure 1. Furthermore, these cracks were spread out evenly across the gage length of the coupon at a crack spacing of 100-130 mm. It was also observed that the load increased after the occurrence of each crack in all tensile tests. Finally, the core ruptured at a strain comparable to that of the carbon fibers used in the core.

It is quite evident that the theoretical curve based on rule of mixtures does not predict the behavior of the proposed hybrid rebar. The experimental results shows five peaks typically occurred during the load history of the coupon using only three different types of fibers. This contradicts the rule of mixtures in that only three peaks should occur if the composite contains three types of fibers. It is believed this difference in behavior can be explained using the analogy of "tension stiffening," in RC elements where the shell is equivalent to surrounding concrete and the core is equivalent to steel reinforcing embedded in concrete [7]. In RC, concrete has lower tensile stress as compared to steel and therefore, under tension a reinforced concrete element exhibits multiple crack patterns before the yielding of the reinforcement.

Figure 2 compares the stress strain curves of the proposed hybrid FRP with conventional Grade 40 and 60 mild steel rebars. Many deficiencies are evident, beginning with the stiffness of the hybrid FRP. The initial stiffness of the hybrid FRP is approximately half that of conventional steel rebars. This indicates a hybrid FRP reinforced structure will have larger service deflections as compared to a steel reinforced structure. Another deficiency is that the pseudo-yielding plateau of the proposed hybrid FRP is shorter and exhibits small ultimate strain. With future research and selection of other fiber types and volume fractions, it is believed that the engineering properties of steel can be reached through the proposed technique.

BEAM FLEXURE TESTS

Test Setup and Beam Specimen

To investigate the ductile behavior of the proposed hybrid FRP rebars embedded in concrete, a flexural testing program was performed. The study consisted of nine reinforced concrete beams having different types of reinforcement. Three control beams with different percentages of Grade 40 steel reinforcing were designed, while five beams were designed using the proposed hybrid FRP rebars.

All hybrid-reinforced beams used the three-fiber hybrid FRP rebars developed at UMR. The engineering properties of the hybrid rebars were determined from the tensile tests and used in the design of the hybrid FRP reinforced beams. In addition, two of the five hybrid FRP reinforced beams were also instrumented with fiber optic sensors within the rebars. A final beam was designed using a single fiber unidirectional FRP reinforcing. The results of this beam test would show the difference in behavior between current FRP and hybrid FRP. Table 2 contains pertinent information on all test beams including reinforcement ratio, concrete compressive strength, and ductility indices. Beams designated with an "R" signify a repeated loading test, while all other beams underwent monotonic loading until failure. As shown in Table 2, the beams are labeled such that the first number refers to the number of the beam, the abbreviation refers to steel "S" or FRP and the last number refers to the percentage of reinforcement. Beams 3FRP1.5 and 4FRP0.5 were designed with the same reinforcement index, except beam 3FRP1.5 was made with hybrid FRP rebars and beam 4FRP0.5 was made with rebars manufactured with one type of stiff fibers. All tested beams measured 2000 mm in length by 120 mm wide by 200 mm deep.

The objective of the testing program was to compare the behavior of different types and percentages of reinforcing under flexure. For this reason, ample shear reinforcing was provided from Grade 40 reinforcing steel and placed every 100 millimeters. Compressive strain, tensile strain, and midspan deflection measurements were made for each test beam. Comparisons were then made between different types of reinforced beams. Furthermore, fiber optic sensors located within hybrid FRP rebars were used to monitor the flexural performance of beams during test. All beams were tested using a MTS Universal Testing Machine. Load was applied at quarter points along the test beam using pin and roller supports. All monotonic and cyclic tests were performed under displacement control at a rate of 1.0 mm/min. The data collection was made using six linear variable differential transformers (LVDT), an MTS internal load cell, two dial gages, and a sophisticated data acquisition system. In addition to traditional data collection, two hybrid FRP reinforced beams (5FRP1.8 and 6FRP1.8) featured 2 Fabry-Perot fiber optic sensors within the reinforcing of each beam.

To experimentally determine the curvature of the test beams, a compressive strain and tensile strain measurement provided by the LVDTs and the known distance between them were used to compute an experimental moment curvature diagram for each test beam. Sufficient gage length was selected to measure the tensile and compressive strain measurements within the constant moment region of a quarter point flexure test and to ensure an adequate average strain value reading. Midspan deflection was measured using two LVDTs.

Flexural Test Results

To understand the results of the beam tests, one must understand the theory behind the design of the test specimens. For example, beams 3S2.0, 5FRP1.8, and 6FRP1.8 were designed with approximately the same reinforcement ratio. Since the engineering properties (specifically the pseudo-yield stress) of the hybrid FRP rebars fall within the range of conventional mild steel rebars, it was theorized that the proposed hybrid FRP could replace traditional reinforcing without developing a new design methodology. More importantly, the ultimate load and deflection should be similar, regardless of the load path taken. This observation is evident in the load deflection curves of 3S2.0 and 6FRP1.8 shown in Figure 3. The embedded hybrid FRP rebars behaved in much the same way as the tensile test results had predicted. Furthermore, both beams exhibited ductile failure with the concrete crushing before rupture of the reinforcing. Figure 4 shows Beam 3FRP1.5 with the excessive deformation resulting from the ductile FRP rebars.

Figure 5 compares the experimental moment curvature diagrams for beams 3FRP1.5 (made of hybrid FRP rebars) and 4FRP0.5 (made of single type of fibers rebars). A pseudo-ductile region is observed in beam 3FRP1.5 while no ductility is observed in beam 4FRP0. This pseudo-ductile region allows the hybrid FRP beam to fail in the desired gradual manner as opposed to the sudden, catastrophic failure observed in the conventional FRP beam. Furthermore, beam 4FRP0.5 exhibited a smaller flexural rigidity as compared to the other beam with the same capacity.

Since ductility is measured beyond the yield (or pseudo-yield) point of reinforcing in a concrete structure, energy methods can be useful to help describe the behavior of the structure. In this study, the ductility is evaluated based on energy and deflection methods using the load-deflection curves of the test beams. Naaman and Jeong [8] define a ductility index based on the energy computed from load deflection curves as $(W_{tot} / W_{el} + 1)/2$, where W_{tot} is the energy computed up to failure, and W_{el} is the energy computed for the elastic portion of the load deflection curve. This allows direct comparisons of ductility between test beams regardless of their material and geometric properties. In addition to ductility based on energy, another measure of ductility can be computed from the load deflection curves. The deflection ductility can be calculated as deflection at ultimate divided by deflection at yield. A summary of the ductility indices for the test beams is shown in Table 2. From the table, the lack of ductility in beams reinforced with conventional (single-type fibers) FRP rebar is evident, since no post yielding behavior is observed in contrast, the steel reinforced beams exhibit high ductility indices, due to the large yielding plateau of steel. Finally, the ductility indices of the hybrid FRP reinforced beams demonstrate their effectiveness in providing pseudo-ductility to a concrete structure. With modifications to the engineering properties of the proposed hybrid FRP rebars in the future, ductility comparable to that of steel will be possible.

With regards to fiber optic sensors, EFPI fiber optic sensors were placed inside FRP rebars and used to measure localized strain during load tests of concrete beams. These sensors provided comparable strain measurement to that of the LVDT as shown in Figure 6. Furthermore, The EFPI optical strain sensors survived the rebar and beam fabrication steps and operated during most of the load tests. The optical sensors did not fail until severe cracking of the concrete beam and the FRP rebar. The sensor data reliably indicated the occurrence of cracks and the subsequent straining in the RC beam up to the occurrence of the pseudo-yield of the FRP rebars. The fiber optic could have reached the ultimate strain if they were embedded inside the core of the FRP rebar rather than at the interface of the core and the shell, because the fiber optic broke during the first crack of the shell. As a matter of fact, this will be the new direction of future rebar manufacturing. The study demonstrated the usefulness of fiber optic sensors for monitoring internal strain in reinforced concrete subject to large deformation.

CONCLUSIONS

The overall already known benefits of FRP are noncorrosive, electromagnetic immunity, and lightweight. In addition to these benefits, the hybrid FRP rebars developed at UMR exhibit pseudo-ductile engineering properties that can be used in conventional reinforced concrete design. These unique engineering properties were achieved through the combined pultrusion / filament-winding techniques discussed earlier. Furthermore, the beam-testing program has proven that ductility can be achieved through the use of the hybrid FRP rebars. Traditional design methods were used in the hybrid FRP reinforced beams. Furthermore, the advantages of structural health monitoring by using fiber optic sensors embedded within the hybrid FRP rebars has been demonstrated through the preliminary fiber optic sensor testing program.

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TABLE 1—VOLUME FRACTIONS FOR HYBRID FRP REINFORCING.

Fiber	Type	Volume Fraction %	Young's Modulus Gpa	Failure Strain	Wind Angle (degrees)
1	Mitsubishi K137HG	5	905	0.003	20
2	Mitsubishi K13710	12.5	649	0.0045	20
3	Zoltek Panex-33	19	228	0.0159	0
Matrix	Shell Epon 9500	63.5	3.1	0.113	N/A

TABLE 2—SUMMARY OF TEST BEAMS.

Beam	Reinforcing Type	f'c Mpa	A_s cm^2	ρ %	μ_w	μ_Δ
1S1.0	Steel	37.9	2.13	1.0	6.10	6.72
2S1.7R	Steel	37.9	3.55	1.7	4.43	5.10
3S2.0	Steel	31.0	4.26	2.0	2.81	2.75
1FRP1.0	Hybrid FRP	37.9	1.86	0.9	3.31	3.05
2FRP1.0R	Hybrid FRP	37.9	1.86	0.9	3.93	3.85
3FRP1.5	Hybrid FRP	35.1	3.10	1.5	3.02	3.10
4FRP0.5	Unidirectional FRP	37.9	1.07	0.5	1.00	1.00
5FRP1.8	FOS Hybrid FRP	31.0	3.72	1.8	2.40	2.20
6FRP1.8	FOS Hybrid FRP	31.0	3.72	1.8	2.62	2.33

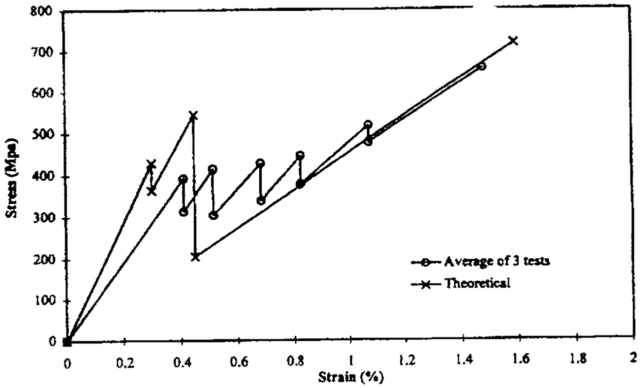

Fig. 1—Theoretical versus experimental stress-strain curves of hybrid FRP reinforcing bars.

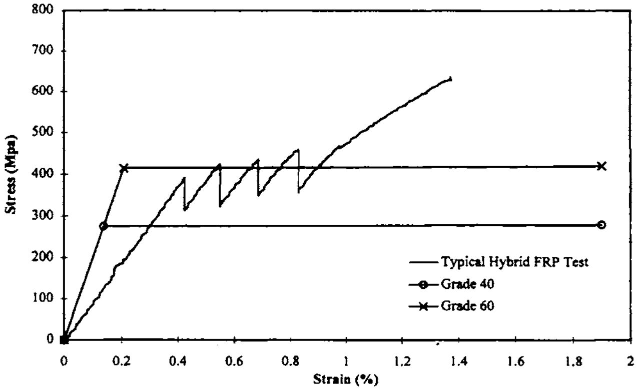

Fig. 2—Stress-strain curves of hybrid FRP reinforcing bars versus Grade 30/60 reinforcing bars.