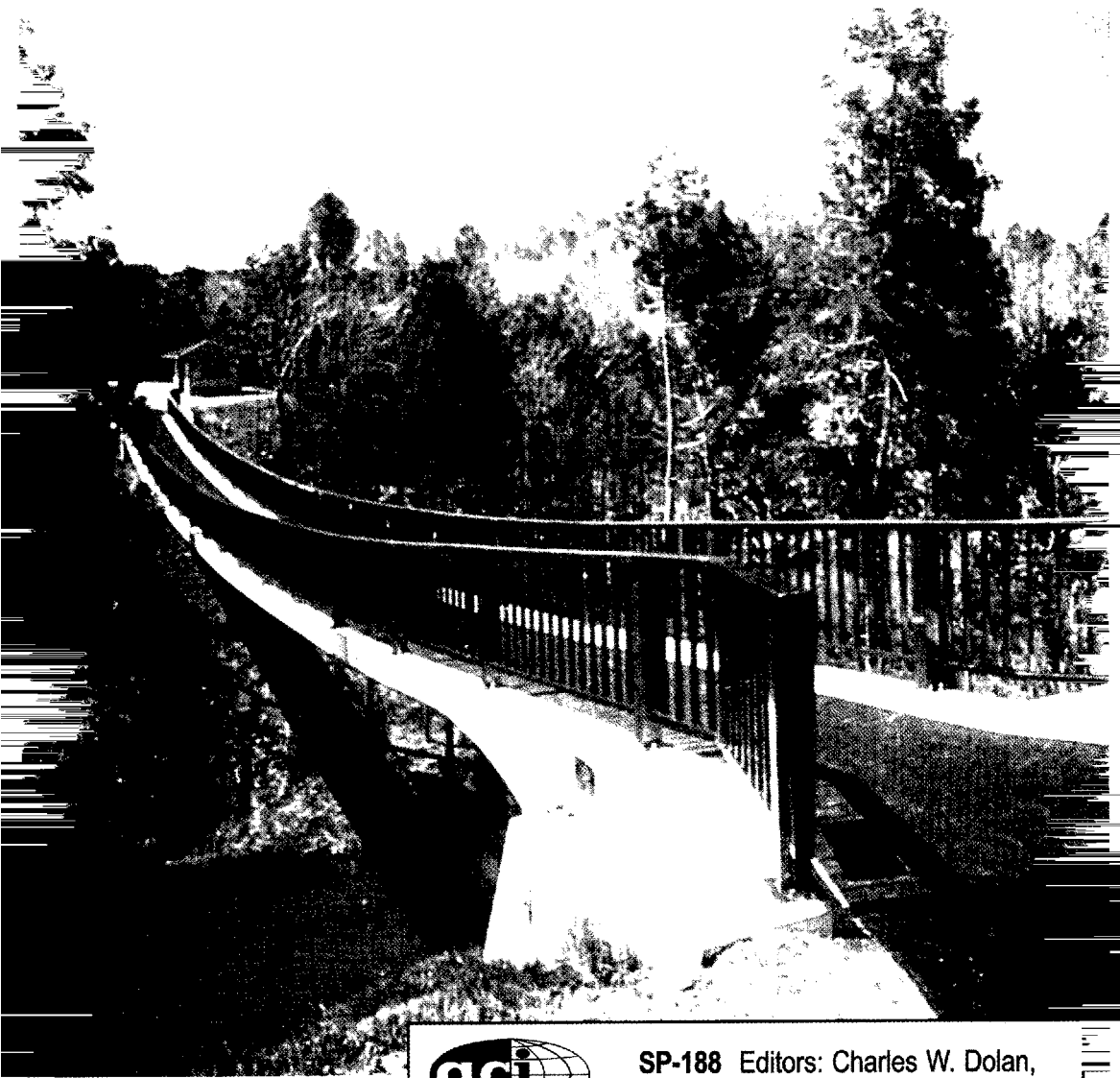


Fourth International Symposium

Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures



SP-188 Editors: Charles W. Dolan,
Sami H. Rizkalla, and Antonio Nanni



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Fourth International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures

Editors

Charles W. Dolan
Sami H. Rizkalla
Antonio Nanni



DISCUSSION of individual papers in this symposium may be submitted in accordance with general requirements of the ACI Publication Policy to ACI headquarters at the address given below. Closing date for submission of discussion is March 1, 2000. All discussion approved by the Technical Activities Committee along with closing remarks by the authors will be published in the July/August 2000 issue of either ACI Structural Journal or ACI Materials Journal depending on the subject emphasis of the individual paper.

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Cover photo: A durable and maintenance-free stress-ribbon pedestrian bridge constructed on a golf course in Ibaraki, Japan. CFRP rods were used for ground anchor tendons, AFRP flat bars were used for main slab cables, and CFRP strands with PVA short fibers were used for reinforcements of precast concrete forms. (Photo courtesy of Kajima Corp.)

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PREFACE

The American Concrete Institute sponsored the First International Symposium for Fiber Reinforced Polymer (FRP) Reinforcement for Reinforced Concrete Structures at the Spring 1993 ACI Conference in Vancouver, British Columbia, Canada. The international research community in attendance agreed to repeat this symposia every second year and rotate it to venues on different continents. The Second International Symposium was held in Ghent, Belgium, in 1995 and the Third International Symposium was in Sapporo, Japan, in 1997. This volume presents the papers of the Fourth International Symposium and represents a significant expansion in the state of knowledge that has occurred in the past 6 years. As in 1993, the five most important general topics for FRP reinforcement are:

1. FRP material properties;
2. FRP reinforcement for reinforced concrete structures;
3. FRP reinforcement for prestressed concrete structures;
4. Analysis and design;
5. Applications of FRP reinforcement.

While the general topics are the same as 6 years ago, the number of case studies presented in this volume is a marked increase from the first symposium. The economies of FRP and FRP performance in the construction marketplace are becoming more clearly understood and their usage is increasing.

Perhaps the greatest change since 1993 is the enormous increase in the use of FRP as a rehabilitation material. A large number of the papers presented in this volume address the issue of bonded repair and rehabilitation applications. While engineers initially were attracted to the corrosion resistance and high strength of FRP, the ease of application in many repair situations has allowed the industry to focus on this unique aspect of FRP systems. Several technical sessions were devoted to the design and case studies of repair or rehabilitation using FRP systems.

Areas of concern identified in 1993, and still not completely resolved, are bond and long-term durability. The long-term performance of FRP reinforcement, whether embedded in the concrete or bonded to the concrete surface, remains a topic of active research. Professional engineers are still reluctant to accept these materials without standards for evaluation of long-term performance or successful histories of in-service performance. Sessions devoted to this topic address the research in progress, the demonstration projects and case studies of FRP repair, and their success and problems. As these case studies and demonstration projects are documented, the profession develops a body of knowledge that lends credibility to the use of these materials and identifies the difficulties associated with using them.

In reviewing the previous symposia volumes and the peer reviews for this volume, an increase in the level of sophistication of the research and the applications of FRP systems was starkly apparent. Those active in the field take for granted many assumptions and practices that were carefully documented or clarified in earlier volumes. Some of the more telling material came from the review comments of individuals not actively involved in FRP research and development. These reviewers very pointedly told the authors to clarify their

work for the general practitioner. The comments emphasize the gap that currently exists between the research community and the design and construction industry. These comments were invaluable in improving the quality of this work. This volume should help fill the void between research and practice.

ACKNOWLEDGMENTS

A work of this magnitude is not possible without the assistance of numerous volunteers and ACI staff members. The editorial committee received over 200 abstracts and papers for review. First and foremost, we wish to recognize those members of Joint ACI-ASCE Committee 423, Prestressed Concrete, and ACI Committee 440, Fiber Reinforced Polymer Reinforcement, and outside professionals who served as reviewers of the technical papers.

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Special thanks are due to Audrey Friesen of ISIS Canada, who diligently logged all the papers, comments, reviews, and correspondence. Her work single-handedly made this volume possible. The staff at ACI headquarters, especially Shirley Zarb and Jane Carroll, have worked tirelessly to complete this publication in time for the Fall ACI Baltimore Convention. W. N. Marianos, Chairman of Joint ACI-ASCE Committee 423, and Larry Bank served on the symposium editorial board. Lastly, we want to thank Luc Taerwe, of the University of Ghent, Belgium, and S. Morita, H. Okamura, and T. Uomoto of Japan, editors of the second and third symposia volumes and invaluable collaborators for maintaining the communications with our European and Japanese colleagues.

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Chapter 1

Properties of Fiber Reinforced Polymer Reinforcement

*Note: For additional information on this subject, please refer to page 1049.

SP 188-1

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 4FRP0.5. 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 $(W_{\text{tot}} / W_{\text{el}} + 1)/2$, 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.

ACKNOWLEDGEMENT

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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

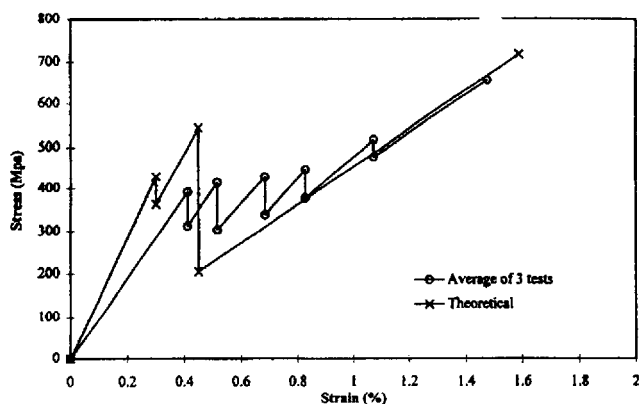


Fig. 1—Theoretical versus experimental stress-strain curves of hybrid FRP reinforcing bars.

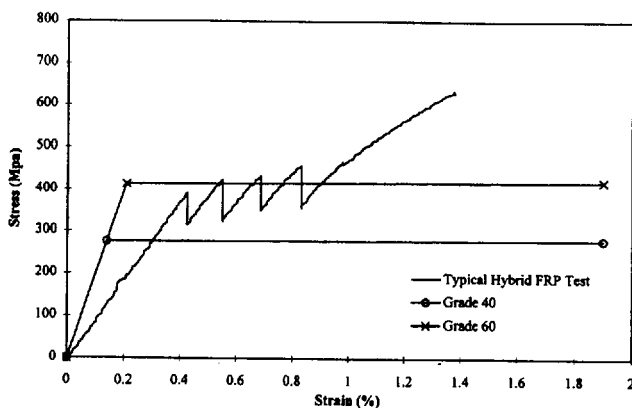


Fig. 2—Stress-strain curves of hybrid FRP reinforcing bars versus Grade 30/60 reinforcing bars.

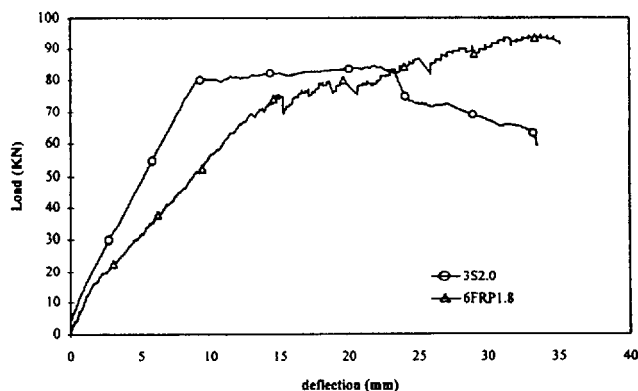


Fig. 3—Load-deflection curves—comparison of beams reinforced with hybrid FRP reinforcing bars and conventional FRP reinforcing bars.



Fig. 4—Beam 3FRP1.5 exhibiting large deflection as result of ductile FRP reinforcing bar.

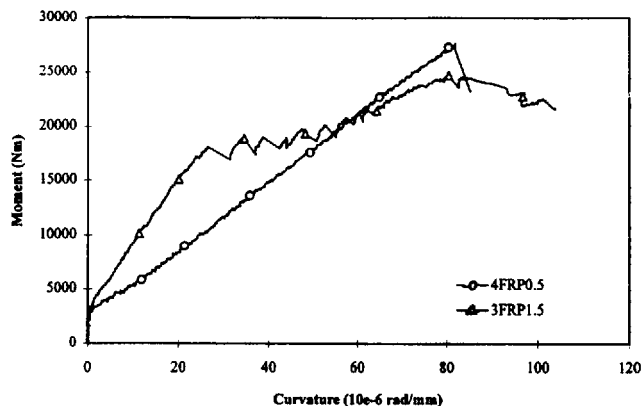


Fig. 5—Load-deflection curves—comparison of beams reinforced with hybrid FRP reinforcing bars and conventional FRP reinforcing bars.

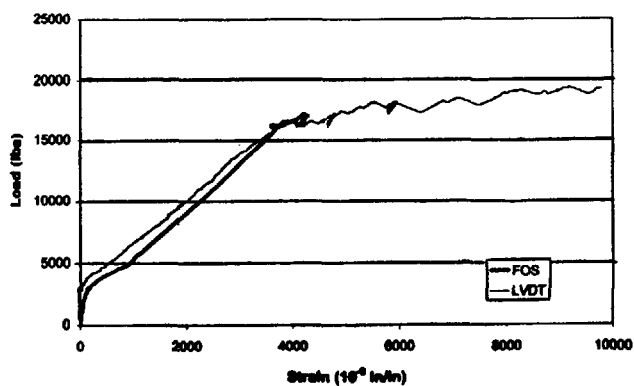


Fig. 6—Comparison of beam surface strain measured from LVDT and fiber optic sensors (FOS).

SP 188-2

Development of Continuous Fiber Flexible Reinforcement

**by T. Sugiyama, S. Tomita, S. Kouzaki, Y. Sato, T. Ueda,
and A. Kobayashi**

Synopsis:

The authors have developed a continuous fiber flexible reinforcement (CFFR) which has good workability and can be used as a reinforcement in concrete. It consists of a plastic tube containing continuous fiber bundles and resin. The salient feature of this new material is that it can be easily formed at the construction site. The authors have conducted a study of fabrication methods of the material and an evaluation of its mechanical properties. This paper introduces the material and fabrication methods, and details the tensile strength of a member formed from this material. A member bent into a U shape was subjected to a load test to examine its basic properties. As a result, it was found that even when the material was bent, the applied tensile load was transmitted through it. Also, the load-deflection characteristic of the material and the stress concentration due to bending were influenced by the wall thickness of the plastic tube.

Keywords: carbon; fibers; reinforced polymer

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INTRODUCTION

Today, in order to secure sufficient seismic capacity for reinforced concrete structures, great importance is attached to increasing the structural ductility. Therefore, the latest design standard stipulates that a reinforced concrete structure shall be provided with sufficient amounts of stirrups and intermediate stirrups and that they shall be securely anchored at the ends with suitable hooks. In actual construction work, however, there are cases where it is extremely difficult to densely arrange stirrups and intermediate stirrups and anchor them with sharp-angle hooks. Under these conditions, a more effective hoop method is needed.

Starting with a concept of a highly flexible alternative reinforcing material, the authors have developed a flexible tube containing continuous fiber and a method of fabricating with the new material.

This paper describes the method of fabricating the new material and mechanical properties of resulting fiber-reinforced polymer (FRP). It also describes the results of a load test of an FRP member bent into a U shape. The test was conducted assuming that the FRP member would be used as stirrups or intermediate stirrups of a square RC structural member.

STRUCTURE AND FEATURES OF CONTINUOUS FIBER FLEXIBLE REINFORCEMENT

The Continuous Fiber Flexible Reinforcement (CFFR) is a tubular material consisting of a bundle of unidirectional, high-performance fiber, such as carbon fiber, covered with a plastic material as shown in Fig.1. It is intended primarily as a confinement for RC structures. A suitable clearance is provided between the reinforcing fiber bundle and the plastic covering. As liquid resins is injected into the clearance and harden, the material becomes a unidirectional fiber-reinforced polymer.

Before resin injection, CFFR is so flexible that it can be made into any desired shape. Since CFFR can be easily wound at the construction site even in a complicated pattern as shown in Fig.2, it can be expected that CFFR will not only facilitate bar arrangement but will also increase the freedom of bar arrangement.

Since CFFR is embedded in the concrete with the reinforcing fiber covered

with plastic material, it does not adhere directly to the concrete. Therefore, when an RC structure which uses CFFR together with conventional reinforcement is subjected to an external force, it is expected that the RC structure will show a deformation characteristic different from that of an RC structure using only conventional reinforcement.

FABRICATION METHOD

Fabrication procedure

The fabrication procedure of CFFR is similar to the method of Resin Transfer Molding, and the steps are listed below:

- +Cutting CFFR to a suitable length
- +Winding of CFFR at a prescribed place
- +Fitting of attachments to resin injector
- +Producing a vacuum inside of CFFR
- +Injection of resin
- +Cure

As a rule, resin is injected into the tube after the CFFR is wound. However, the CFFR may be wound around the reinforcement after the resin is injected as long as the resin working time has not expired.

Impregnation resin

In order to impregnate the bundle of reinforcing fiber with resin by the pressure of resin injection alone, the resin must have a low viscosity. As the injected resin flows through the tube, the pressure drop will increase gradually. As the distance to be injected increases, the time required for injection increases exponentially. Therefore the resin needs to have a longer working time. The authors have developed a suitable composition of resin which has a low viscosity (100 to 250 [mPa-s]) and a long working time. Table 1 shows the typical composition and working time of the resin that is now used for CFFR impregnation. It has been confirmed that the working time can be prolonged to a maximum of about seven hours as shown in the Table 1. At present, it is possible to inject the resin into a 20 m long CFFR tube in about an hour at room temperature (23°C).

MECHANICAL PROPERTIES OF CFFR

In order to clarify the mechanical properties of CFFR after the resin was impregnated and cured, the CFFR was subjected to a tensile test according to JSCE-E 531-1995⁽¹⁾. The specifications of the CFFR used and the test results are shown in Table 2. As shown, the member developed approximately 80% of the strand strength of reinforcing fiber.

TENSILE TEST OF U-SHAPED SPECIMENS

When the CFFR is to be used as reinforcement for a RC member of rectangular cross section, it is bent into a U shape. In this case, depending on the compressive stiffness of the covering tube, the round cross section of the CFFR is

deformed into an ovoid at the bent part. Then the soft covering tube acts an inter-layer between the FRP and the concrete.

It is necessary to understand how an external load is transmitted through the CFFR and how CFFR is deformed. Therefore, the authors subjected U-shaped CFFR members with different covering tube wall thickness to a load test to study the deformation, the load transmission mechanism, and the strength of the bent section of CFFR.

U-shaped members were prepared using three types of CFFR which were the same in cross-sectional area of the carbon fiber bundle (16.9 mm^2) but were different in wall thickness of the covering tube—2.5 mm, 1 mm, and 0.5 mm (U2510, U1010, U0510, respectively). The inside radius of the bent section of each member was 10 mm. After the resin was injected and hardened, the covering tube of each member, except for the inside of the bend, was peeled and strain gauges were attached to the exposed part. The ends of the member were then fitted into the steel anchor (Fig.2) to form the test specimen.

Experimental procedure

In the present experiment, each specimen was subjected to a tensile load via a loading plate having a loading point chamfered to $R = 10 \text{ mm}$ at either end as shown in Fig.2. Transducers were attached to the loading plate and to each specimen to measure the amounts of deformation of the specimen and covering tube under load. Strains at various parts were measured by strain gauges shown in Fig.2.

Experimental results and discussions

Load-displacement characteristic—The load-displacement curves obtained with the specimens are shown in Fig.3. As shown, in the early stages of loading, each specimen showed a nonlinear relationship between load and displacement. As the load was increased, the load-displacement relationship showed tendency to become linear. As it is evident from the relationship between load and tube deformation shown in Fig.3, the reason for this is that the compressive stiffness of the tube approaches infinity as the load continues to be increased. It can be seen from the figure that the smaller the tube wall thickness, the more linear the load-displacement relationship becomes.

The experimental results are shown in Table 3. The specimen U2510 and U0510 ruptured at the bends. The specimen U1010 did not rupture because the CFFR slipped out of the anchors under a certain load. With specimen U0510, the displacement exceeded the full scale of the transducer when the amount of deformation reached 4.6 mm during load application. Therefore, the subsequent displacements of that specimen until its rupture could not be measured. However, it is estimated that the displacement continued to increase linearly until the specimen ruptured.

The amount of tube deformation right before rupture was 1.6 mm (0.64 in terms of strain) for specimen U2510 and 0.17 mm (0.34 in terms of strain) for specimen U0510.

The ultimate loads of the ruptured specimens, U2510 and U0510, were decreased to 40% and 78% respectively of the average tensile load measured in uniaxial tension.

Load-strain characteristic of straight section—Fig.4 shows the relation between applied load and average strain measured at the top (A 06/B06-A08/B/08) of the specimen. In this figure, strains are normalized by the average value of right side (A00/B00-A05/B05) and left side (A09/B09-A14/B14).

Since the tensions applied at both sides were transmitted to the top as can be seen from the figures, it was confirmed that the decrease in tension due to the formation of a U-shape by bending CFFR at right angles was small and that the applied tensions were transmitted through the CFFR beyond the bent section. The rate of load transmission to the top of the specimen was approximately 85% to 95%.

Strain distribution the specimens—Strain distributions in the specimens showed tendency to change markedly at the bent sections. As an example, the strain distribution measured on the outside of each specimen under a load of 10 kN is shown in Fig.5. From this figure, it can be seen that a local flexural deformation occurred in each of the bent sections (A05-A06, A08-A09) and that the maximum strain was measured at the top of each specimen. The larger the tube wall thickness, the more noticeable was this tendency. With specimen U2510, a wide range of strain fluctuation from -6000μ to 8000μ was observed locally. As described above, when a thin-walled tube is bent, the cross section of the CFFR is easily deformed flat because of the low compressive stiffness of the tube, and the CFRP of the bent section decreases in thickness. As a result, the difference in strain between the outside and inside of the CFRP becomes smaller than when a thinner-walled tube is bent. This explains why the fluctuation of strain in the specimen having a thin-walled tube was small.

Table 4 shows the maximum and minimum strain values measured at the bent section of each specimen under the maximum load. For the specimens that ruptured (U2510, U0510), the maximum strain was nearly equal to the maximum strain measured in a uniaxial tensile test (16000μ).

CONCLUSIONS

The authors have developed a continuous fiber flexible reinforcement (CFFR) system consisting of a plastic tube into which a bundle of continuous fiber is inserted, and a fabrication method for this new material. Basic mechanical properties of the material were tested.

- (1) A new impregnating resin having a low viscosity and a long working time was developed. This resin has made it possible to fabricate CFFR into an FRP material, which can be bent into desired shapes.
- (2) It was confirmed that CFFR, after resin impregnation, develops satisfactory strength.
- (3) When a load is applied to U-shaped CFFR via covering tube, the load-displacement characteristic depends heavily on the covering tube thickness of CFFR.

(4) When a tensile load is applied to one side of CFFR bent at right angles, a wide fluctuation of strain occurs at the bent section. However, the tensile load is transmitted through the CFFR beyond the bent section. In this case, the maximum tensile strain occurs at the side to which the tensile load is transmitted.

(5) When CFFR is bent, its apparent strength declines due to stress concentration.

(6) It was confirmed that the stress concentration in CFFR is influenced by the flatness of its bent section and that the smaller the tube wall thickness, the smaller the stress concentration becomes because the thinner tube wall makes the CFFR flat easily.

ACKNOWLEDGMENTS

The authors wish to express their heartfelt thanks to Prof. Yoshio Kakuta at Hokkaido University for his extensive cooperation in the present research and development efforts.

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TABLE 1—TYPICAL COMPOSITIONS OF IMPREGNATION RESIN VERSUS WORKING TIME.

	Mixing ratio by Weight		
Resin	100	100	100
Hardener	1	1	1
Catalyst	0.5	0.5	0.5
Retarder	2	3	4
Setting time ,minutes			
@23°C (73 °F)	120	340	More than 420
@31°C (88 °F)	60	150	240

TABLE 2—COMPONENTS AND MECHANICAL PROPERTIES OF CFFR.

Component	Tube	Material	PVC
		Thickness mm	2.5
	Reinforcement	Material	HT-Carbon fiber
		Number of strands	19
		Cross-sectional area of Reinforcement mm ²	16.9
		Tensile strength of strand GPa	5.00
Mechanical properties (After resin impregnation)		Modulus GPa	265
		Tensile strength GPa	4.14
		Elongation %	1.6

TABLE 3—EXPERIMENTAL RESULTS.

Specimen	U2510	U1010	U0510
Wall thickness of tube t_u , mm	2.5	1.0	0.5
Maximum deformation of Tube U_{tu} , mm	1.84	0.75	0.18
$\Delta u_{tu} / u_{tu}$	0.74	0.0.75	0.36
Ultimate load P, kN	27.9	24.5	54.3
Failure mode	Rupture at bent portion	Slipping out of anchorage	Rupture at bent portion

TABLE 4—MAXIMUM STRAIN MEASURED IN BENT SECTION.

Specimen		U2510	U1010	U0510
Maximum strain $\epsilon_{\max}$, μ		15260	11272	16155
Measured point		E4	C7	C7
Minimum strain $\epsilon_{\max}$, μ		-9252	-3462	-11451
Measured point		C2	C9	C1

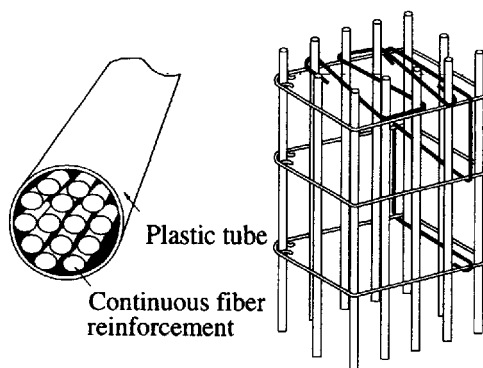


Fig. 1—Schematic view of CFRP.

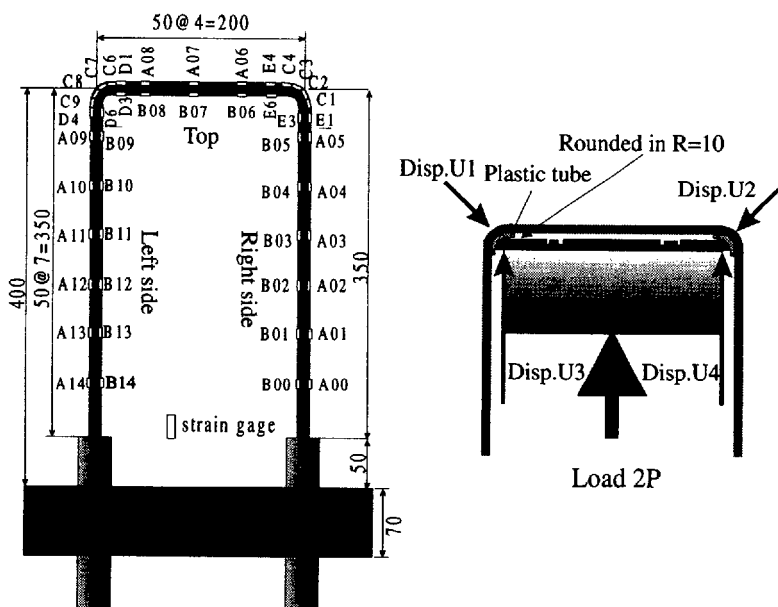


Fig. 2—U-shaped specimen and loading condition.

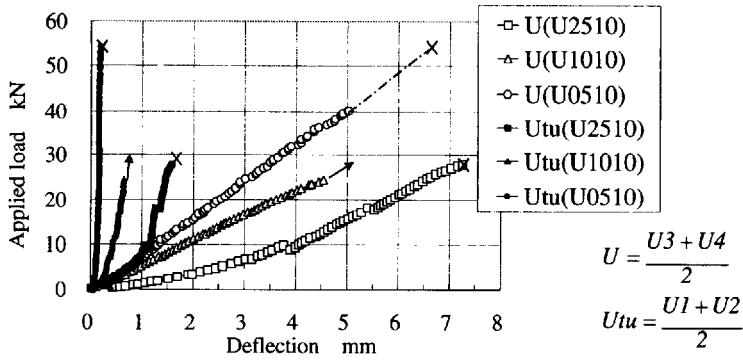


Fig. 3—Applied load versus deflection and tube deformation.

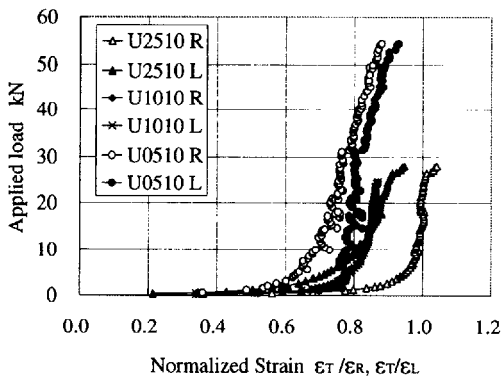


Fig. 4—Load versus normalized strain at top of specimen.

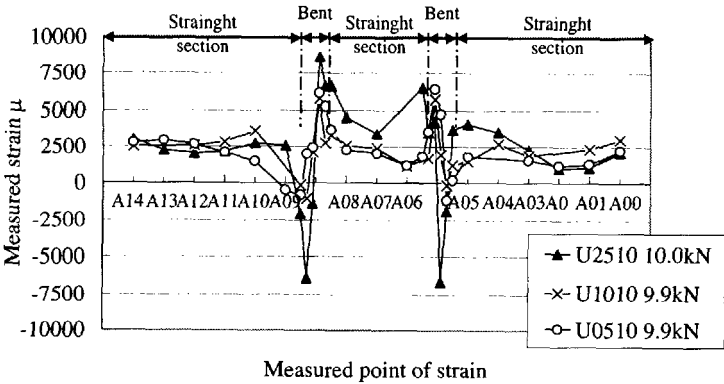


Fig. 5—Strain distributions outside of U-shaped specimen.

SP 188-3

Creep Rupture of Fiber Reinforced Polymer Prestressing Tendons under Curvature

by G. S. Kaski and C. W. Dolan

Synopsis:

The long-term durability of FRP prestressing tendons in a harped configuration or in flexure under short radius bends has not been extensively investigated. Creep-rupture data for straight uniaxial tension testing may not be representative of the material behavior in a prestressing application requiring curvature of the tendon. The FRP response in a harped or bent configuration may be compromised due to a lack of ductility in the outer fibers of the tendon. Long-term creep-rupture experiments conducted on harped Carbon FRP tendons are reported. The tests are conducted in a bend test so outer fibers are stressed up to 88 percent of the uniaxial strength. All tests are conducted in air at nominal room temperature. This paper presents design information concerning the long-term performance of harped FRP tendons and coiled storage of FRP tendons.

Keywords: buckling; creep; curve; durability; prestress; relaxation; resin; rupture; strain; stress; tendon

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INTRODUCTION

Creep is the time dependent inelastic strain of a material subjected to a sustained load. At high stress levels, creep in fiber reinforced polymer (FRP) composites generates progressive rupture of fibers and failure of the tendon. Creep-rupture testing is conducted to evaluate the material behavior under a sustained load with environmental influences considered (1,6). Creep-rupture testing is typically performed at much higher stress levels than the sustained design load. Testing at high stress levels allows development of time to failure curves needed for design. Additional factors influence creep-rupture of FRP prestressing tendons. The combined axial tension forces and the bending moment induced on the FRP prestressing material creates stresses on the tendons that magnify the effects of creep-rupture. The FRP tendon creep-rupture response when placed under a small curvature, as occurs at a harp point, at a wobble point or general radius in a post-tensioned tendon, or even the curvature on a storage coil, is evaluated in this study.

Manufacturers and suppliers transport FRP material in wound spools that may create a long-term creep-rupture phenomenon due to pure bending. The bending of the FRP tendons weakens the materials overall strength, which lowers the creep-rupture time to failure. Failure, which can best be described as creep-buckling, may occur in addition to the tensile creep-rupture. Analysis of buckling and creep-rupture on spooled FRP tendon materials are discussed.

TEST METHODOLOGY

American Society for Testing and Materials describes the procedure for creep-rupture testing of plastics (2). Straight tension tests were conducted to analyze the FRP tendons short-term and long-term creep-rupture strength using various testing frames. The CFRP testing program included:

- Axially loading the FRP to determine ultimate static strength
 - Recording stress and strain data over time
 - Conducting short-term straight tension tests in lever advantage and spring loaded test frames
 - Conducting long-term straight tension tests and long-term harped tension tests in spring loaded frames
 - Determining long-term creep-rupture in pure bending
- Assessing anchorage methods
- Designing test frames to induce short radius curvature in the FRP tendons.

Two types of anchors were used in gripping the specimens: Epoxy-socketed tapered anchors were used in the original tests and expansive cement anchors

were used on residual strength tests and later tests. Anchor selection is summarized in Table 1. The expansive cement anchors were used in place of the epoxy anchors due to their lower coefficient of variation and increased reliability. Expansive cement anchors provide a more distinguishable difference between the three modes of failure: bond, shear, and tensile.

Direct tension creep-rupture tests were conducted at 100, 95, and 85 percent of the ultimate uniaxial stress. Creep-rupture bend tests were conducted by axially loading tendons to 100, 85, and 75 percent of the ultimate load in a fixed-radius direct-tension bend test fixture. Ultimate strength was determined by loading the CFRP straight tension samples to failure. The long-term creep-rupture straight tension samples were 3 mm (1/8 in) diameter and 3 m (6 ft.) in length between expansive cement anchors. The bend test is conducted on a segment of the straight tension test sample with a fixed radius curvature superimposed on the axial load. The fixed radius jig was made with a 25 mm x 19 mm x 305 mm (1 in x 3/4 in x 12 in) aluminum block, Figure 1. A 3.3 mm x 5.1 mm (0.13 in x 0.2 in) groove was cut into the block having outer radius of 610 mm (24 in) and an interior radius of 508 mm (20 in).

SHORT-TERM TENSILE STRENGTH

Short-term tensile strength testing used 3 mm (1/8 in) diameter circular rods. Two different machines and two different anchoring techniques were used for comparison purposes. The testing machines were a Tinius-Olsen universal testing machine and an Instron 1332. The data acquisition method used Labview and recorded data at a sampling rate of 2 Hz. The strain measurements were taken using 2-250 mm (10 in) linear extensometers placed back-to-back and the load was determined by using a calibrated pressure transducer. The strains from each extensometer were averaged to eliminate any bending effects. The results of the ultimate strength tests for Carbon T-600 and Carbon T-300 (65% volume fraction) can be found in Tables 2 and 3, respectively. The static strength results for Carbon T-300 bent specimen are in Table 4.

CREEP-RUPTURE IN BEND

Introduction

Two conditions were investigated. First, the tendon under a sustained load and bent over a fixed harp point was investigated. Second, the bend effects caused by spooling were evaluated.

Long-Term Effects in Bends

The bend tests were conducted using 3 mm diameter Carbon T-300 FRP rods. Straight tensile material properties were obtained with static strength tests using anchorage methods listed in Table 1.

The bend curvature was selected to provide a 10-15% decrease in the net axial capacity. The maximum stress at failure could be found by the addition of P/A and Mr/I stresses. P was recorded at failure. M was found using the strain relationship, $M=EI/R$, Figure 2. The maximum bending stress in the curve is equal to

$E/r/R$, where E is the gross modulus of elasticity, r is the tendon radius, and R is the radius of curvature. The average uniaxial stress at failure in a bent section is less than the ultimate stress at failure of a straight sample, however, the combined bending and axial stress in the bent portion of the tendon is 130% of the failure stress of the direct tension ultimate tests. The failure always occurred in the bent section.

In summary, three conclusions result from the bend testing. First, the static stress values must include the bending effect, $E/r/R$. Second, the bend test method provides an indication of the tensile capacity of FRP strands independent of the anchorage. Third, high-stress creep-rupture tests in curvature are needed to evaluate the time to failure in this condition.

Long-Term Effects on Spooled FRP

FRP tendons are transported from the manufacturer to the consumer wound on spools. Consequently, the CFRP material was subject to creep due to pure bending throughout the entire time it was spooled. There were two indications of creep-rupture effects on the CFRP T-600 material. First, it was noticed while unwinding the T-600 from the spool that the material was broken in varying lengths ranging from 6 m (20 ft.) to 0.6 m (2 ft.). Second, tests indicated that the ultimate strength of the unbroken sections of the CFRP was reduced up to 10% over a 2-3 year period. The maximum stress due to curvature on the inner and outer fibers was 20% of the ultimate static stress of the tendon, well below recognized creep-rupture limits.

Close inspection of the tendon revealed that micro buckling of the inner fibers caused the tendon to break. The buckled section of the tendon was approximately 1 mm (0.04 in) in length. Slight crinkles throughout the length of unbroken sections indicated a progressive creep-buckling failure, Figure 3.

This particular creep phenomenon can be modeled as the buckling of a bar on an elastic foundation between fixed supports, Figure 4. The critical buckling load of the column can be computed but is dependent upon the modulus sub-grade reaction, k (4,6). Lateral support of the column is provided by the foundation through the resin medium. As the resin relaxes the fibers buckle laterally. The interior fibers buckle toward the center of curvature, the only direction open to them. Eventually, a separation takes place between the buckled section and the rest of the tendon. Relaxation of the resin continues until, k , is decreased to the point where it is no longer effective in providing lateral support to the buckling section.

The modulus of sub-grade reaction is the effective modulus of elasticity of the resin, and is initially on the order of 3,450 MPa (500,000 psi). The epoxy resin creeps so that the lateral resin force decreases over time, and buckling occurs when the effective modulus of the foundation, k , decreases to a critical amount. The effective modulus becomes a function of time directly related to the lateral force applied to the portion buckling. The effective modulus decay over time is represented at any time, t , with Eq. 1, where β , is a coefficient determined from boundary conditions.

$$k(t) = k_o e^{-\beta(t-t_o)} \quad (1)$$

The effective modulus of the foundation decays at a rate illustrated by Figure 5. The plot demonstrates a typical exponential relaxation response of matrix material. While this figure shows a decay of 30,000 hours, the time is variable, and resin relaxation under normal and axial load occurs in as little as 48-60 hours. If a tendon is coiled immediately after fabrication, the resin will have a much smaller modulus and be more susceptible to relaxation. Figure 5 represents the longest decay time based on the sample storage history. Buckling possibly could have occurred prior to our observations.

The buckling load is found by multiplying the bending stress acting at the centroid of the cross-sectional area of the section being buckled by the area of that section, Figure 6. The section was analyzed by varying the center angle, α , of a circular segment between 0 and 20 degrees. A center angle ranging between 14 to 15 degrees results in the greatest magnitude of the elastic modulus, k , allowed for buckling to occur. Thus, without considering material flaws or other defects, the buckled section area would be a maximum at a center angle equal to 15 degrees (6). When the center angle exceeds 15 degrees, the cross-sectional area is great enough that buckling will not take place regardless of whether or not lateral support is provided from the elastic foundation.

In conclusion, micro buckling may be prevented with the use of a larger spool radius. A radius must be obtained that will keep the flexural compressive stresses lower than 20% of the maximum bending stress of the strand during shipping and storage of solid circular tendons.

CONCLUSION AND RECOMMENDATIONS

Creep-rupture times decrease when the element is subjected to combined loading, axial tension and bending. Therefore, bending effects must be included in design calculations to account for the increased stress affecting creep-rupture.

Designs using FRP should consider actual and accidental bend effects of post-tensioned tendons in ducts.

Creep-buckling becomes a problem when compressive stresses are induced in a section of the FRP tendon. FRP materials shipped and packaged in tightly wound spools are influenced by creep-buckling by inducing relaxation in the matrix from the instant they are wrapped on the spool. FRP should be shipped in such a way that would eliminate creep-buckling of the strand. Bending stresses as low as 20% of the strand ultimate strength is sufficient to cause buckling.

Anchors used to test FRP specimens produce some stress concentration at the anchor/tendon interface that result in lower ultimate failure of the tendon. Tension testing done on a curved fixed radius sample provides ultimate strength data at the peak fiber stress and simultaneously provides a method of determining anchor efficiency.

ACKNOWLEDGEMENTS

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TABLE 1—ANCHOR SELECTION.

Anchor Selection				
Test	Percent	Anchor Type	Number of Tests (Exp. Cement/ Epoxy)	
Condition	Loading	(T-300/T-600)	Stress-Strain	Strength only
Long-term Creep-rupture	50-80	Exp. Cement/Epoxy	NA	18/67
Residual Strength	100	NA/Both*	NA	33/17
Bend Tests	85+	Exp. Cement/NA	NA	10/0
Coiled Tendon Tension	100	Exp. Cement/NA	10/0	NA
Static Strength	100	Both/Both	40/15	0/10
Short-term Creep-rupture	85+	Both/Epoxy	0/12	NA

* Environmentally exposed portions of each specimen were tested with expansive cement anchors on each end of the sample. The portions exposed to the air were tested with an epoxy anchor on one end of the sample and an expansive cement anchor on the other.

TABLE 2—CARBON T-600 STATIC STRENGTH RESULTS (3).

Carbon T-600-Static Test Results							
Test	Load at Failure		Max. Stress at Failure		Max. Strain	Elastic Modulus	
#	(kN)	(lbs)	(MPa)	(ksi)		(GPa)	(ksi)
1	21	4707	2779	403	0.0163	170990	24800
2	24	5303	3130	454	0.0182	171679	24900
3	20	4473	2641	383	0.0174	151685	22000
4	27	6155	3634	527	0.0232	156511	22700
5	23	5268	3110	451	0.0202	153753	22300
6	20	4567	2696	391	0.0227	118590	17200
7	21	4719	2785	404	0.0179	155822	22600
8	22	4836	2854	414	0.0199	143411	20800
9	17	3738	2206	320	0.0187	117900	17100
10	20	4462	2634	382	0.0161	164785	23900
Average =	21	4823	2847	413	0.019	150513	21830
Std. Dev =	3	643	380	55	0.002	19091	2769
Coef. Var =	0.13	0.13	0.13	0.13	0.13	0.13	0.13

TABLE 3—CARBON T-300 STATIC STRENGTH RESULTS.

Carbon T-300- Static Test Results							
Test	Load at Failure		Max. Stress at Failure		Max. Strain	Elastic Modulus	
#	(kN)	(lbs)	(MPa)	(ksi)		(GPa)	(ksi)
1	13	3031	1723	250	0.0061	262282	38041
2	13	2921	1660	241	0.0070	197214	28603
3	14	3093	1758	255	0.0067	249243	36150
4	13	3013	1712	248	0.0076	217757	31583
5	12	2706	1538	223	0.0078	163110	23657
6	13	3007	1709	248	0.0071	235324	34131
7	13	2902	1650	239	0.0086	177575	25755
8	12	2737	1555	226	0.0074	181959	26391
9	13	2970	1688	245	0.0080	183534	26619
Average =	13	2931	1666	242	0.0074	207555	30103
Std. Dev =	0.6	132	75	11	0.001	35038	5082
Coef. Var =	0.05	0.05	0.05	0.05	0.10	0.17	0.17

TABLE 4—CARBON T-300 STATIC STRENGTH RESULTS IN BEND.

Carbon T-300-100% Creep w/Curve								
Test	Load at Failure		P/A Stress		Computed Mr/I Stress		Max. Stress at Failure	
#	(kN)	(lbs)	(MPa)	(ksi)	(MPa)	(ksi)	(MPa)	(ksi)
1	11343	2550	1449	210	633	92	2082	302
2	11454	2575	1464	212	633	92	2096	304
3	11454	2575	1464	212	633	92	2096	304
4	10787	2425	1378	200	633	92	2011	292
5	11009	2475	1407	204	633	92	2039	296
6	10609	2385	1356	197	633	92	1988	288
Average =	11109	2498	1420	206	633	92	2052	298
Std. Dev =	362	81	46	7	0	0	46	7
Coef. Var =	0.03	0.03	0.03	0.03	0.00	0.00	0.02	0.02

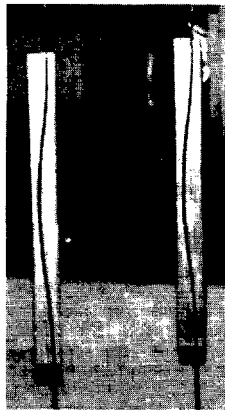


Fig. 1—Curves-in-place on T-300 tendon.

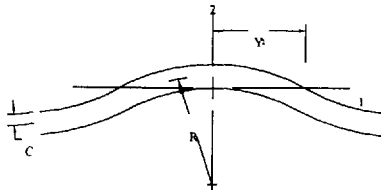


Fig. 2—Bent configuration of T-300 harped samples (5,6).

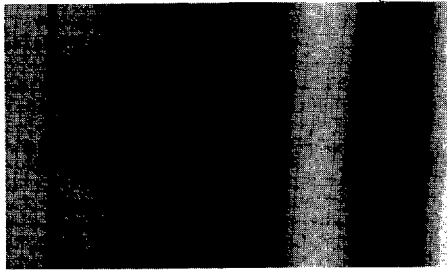


Fig. 3—Buckled carbon T-600 3 mm (1/8 in.) spooled tendon.

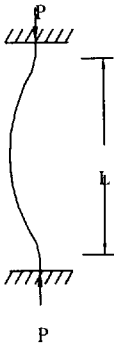


Fig. 4—Column with elastic supports (4,6).

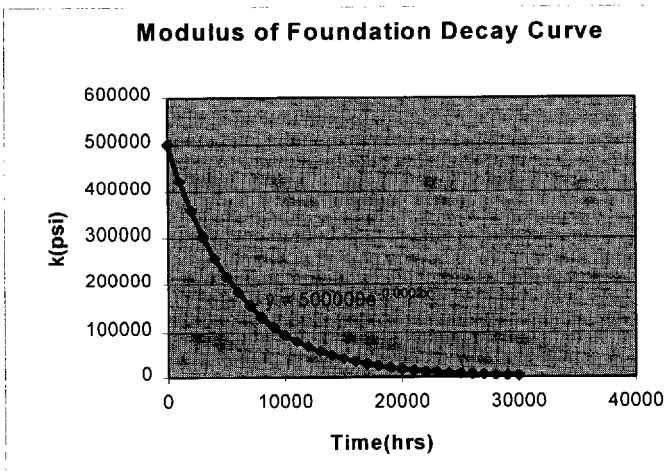


Fig. 5—Decay curve of effective modulus of foundation.

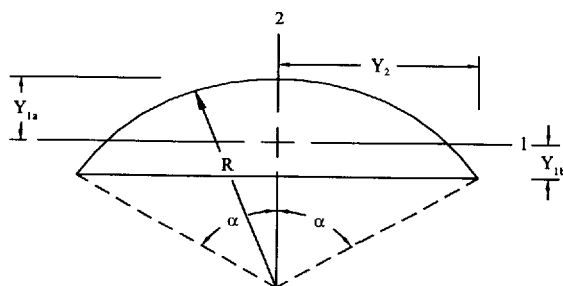


Fig. 6—Cross section of buckled section (5,6).