FINAL REPORT
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HYBRID FRP-CONCRETE COLUMN

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EXECUTIVE SUMMARY

Problem Statement

In the last ten years, fiber reinforced polymers (FRP) have received considerable attention from the civil engineering community as a viable construction material for repair, rehabilitation, or new construction of the aging infrastructure in various states, especially those subjected to corrosive environments. A novel application in the form of concrete-filled FRP tubes (CFFT) was initially proposed by the author to the Florida Department of Transportation in 1993. Since then, the feasibility and short-term performance of CFFT piles and columns have been established. Most recently, piles made of precast CFFT were driven into the ground near Tallahassee, Florida to demonstrate the feasibility of the system. However, the long-term time-dependent behavior and the cyclic response of CFFT members have not yet received adequate attention. It is necessary to establish the time-dependent as well as lateral cyclic response of CFFT, if it is to be used as bridge pier columns or piles. The fundamental issues that need to be addressed are as follows:

- How does the presence of FRP tube affect shrinkage of concrete core?
- Does concrete core shrink away from the FRP tube over time?
- Since both concrete and FRP creep under sustained loads, how does the hybrid system creep over time?
- Is CFFT susceptible to creep rupture during its service life at levels of sustained load normally used for the design of buildings and bridges?
- Can CFFT piles and columns be designed with or without internal steel reinforcement to provide adequate ductility for a safe mode of failure under cyclic lateral loads?

Objective

The objectives of this research were as follows:

1. Developing an experimental database for creep and shrinkage of CFFT under axial and flexural loading conditions; and
2. Investigating the behavior of CFFT beam-columns, with different levels of fiber reinforcement, and with or without internal steel reinforcement, under constant axial loading and reverse cyclic loading in transverse direction.

Findings

A thorough analytical and experimental investigation was carried out into the long-term behavior of CFFT beams and columns under sustained loads. The study resulted in a number of findings as follows:

- Shrinkage of concrete core in FRP tube is in the order of 10%-20% of that of exposed concrete. For all practical purposes, concrete core in CFFT may be considered as sealed with quite negligible shrinkage strains. Moreover, the notion that concrete core may separate from the FRP tube under the effect of shrinkage is not warranted.

- The current models of the American Concrete Institute (ACI) grossly overestimate creep of concrete core in CFFT columns. The equivalent creep coefficients for concrete core in CFFT columns may be as low as 22% of that recommended by ACI for a sealed concrete of the same mix proportions and environmental conditions and for the same duration of loading.
- Effect of confinement on creep of concrete core is not as significant as the effect of sealing concrete and the stress re-distribution that occurs between concrete and FRP.
- Creep effects reduce the flexural stiffness of CFFT specimens. However, ultimate strength is not significantly altered.
- Slow rate of loading and short-term creep at 70% of static capacity may cause premature rupture of the FRP tube.
- Fiber analysis of CFFT beam-columns by discretizing the section into filled and hollow FRP tubes can adequately simulate the flexural creep behavior. Moreover, isochronous sustained stress - creep strain curves can be used as constitutive non-linear relationship for creep analysis in flexure.
- Creep rupture life expectancy of CFFT beam-columns with diameter to thickness (*D/t*) ratios of 40 or less is at least 50 years at transverse loads as high as 60% of the static capacity.
- CFFT columns with *D/t* ratios of less than 80 have a creep rupture life expectancy of 75 years at 70% of static capacity under concentric axial loads.

A thorough analytical and experimental investigation was carried out into the cyclic behavior of CFFT beam-columns under constant axial loads and cyclic lateral loads. The findings of the study can be summarized as follows:

- The two types of CFFT beam-columns tested under this study represented two different failure modes; a brittle compression failure for the over-reinforced specimens with thick FRP tube and majority of the fibers in the longitudinal direction, and a ductile tension failure for the under-reinforced specimens with thin FRP tubes and off-axis fibers. The FRP tubes with $\pm 55^{\circ}$ fiber orientation exhibited significant non-linearity and energy dissipation.
- A moderate amount of internal steel reinforcement in the range of 1%-2% may improve the cyclic response of CFFT members. The improvement is more significant for the under-reinforced FRP tubes. Adding internal steel, especially for members with thick FRP tubes, can be ineffective and may result in premature failure of the system. It is feasible to design CFFT columns with moderate steel reinforcement to be comparable to RC columns under cyclic loading.

Conclusions

The present study has clearly shown the feasibility of CFFT piles and columns not only under short-term static loading, but also under long-term sustained loading or dynamic and cyclic loading. The study emphasizes the importance of proper design of the FRP tube based on the type of applied loading.

CHAPTER 1
INTRODUCTION

1.1 Problem Statement

In recent years, fiber reinforced polymers (FRP) have received great attention from the civil engineering community as a viable construction material for repair, rehabilitation, or new construction of the aging infrastructure of the nation. A novel application in the form of concrete-filled FRP tubes (CFFT) was initially proposed to the Florida Department of Transportation in 1993. Since then, the author has worked with the Florida DOT and the National Science Foundation to study the feasibility and short-term performance of CFFT members. Two U.S. Patents (5,599,599 and 6,123,485) were obtained for this novel type of structure. Most recently, piles made of precast CFFT were driven into the ground near Tallahassee, Florida to demonstrate the feasibility of the system (Mirmiran and Shahawy, 2003). However, the long-term time-dependent behavior and the cyclic response of CFFT members have not yet received adequate attention. It is necessary to establish the time-dependent as well as lateral cyclic response of CFFT, if it is to be used as bridge pier columns or piles. The fundamental issues that need to be addressed are as follows:

- How does the presence of the FRP tube affect shrinkage of concrete core?
- Does concrete core shrink away from the FRP tube over time?
- Since both concrete and FRP creep under sustained loads, how does the hybrid system creep over time? and most importantly;
- Is CFFT susceptible to creep rupture during its service life at levels of sustained load normally used for the design of buildings and bridges?

Understanding the complex nature of a hybrid system with two time-dependent materials, i.e., concrete and FRP, it is essential to isolate the factors that can affect the behavior of the system. As such, one needs to consider the following issues in a CFFT member:

- Concrete core is essentially sealed from migration of any moisture due to presence of the tube. This causes considerably lower drying creep and shrinkage strains in CFFT.
- Confinement of concrete by the tube offers resistance to the lateral expansion of concrete. This multi-axial stress effect does not allow concrete to freely creep in the axial direction.
- Stress transfer between concrete core and the tube is possible in CFFT, resulting in stress relaxation of concrete, and further reducing its creep.
- As a result of stress relaxation in concrete, even though the total axial load on the column may be constant, stresses in each component (FRP and concrete) may vary significantly over time. This variation must be accounted for in the analysis.

Another area of concern is the low cycle fatigue response of CFFT systems under constant axial load and reverse lateral cyclic loading. FRP materials are well known for their linear elastic behavior until failure. This issue has design implications as to whether confinement alone can provide adequate ductility for this type of structural members, or they would need some internal steel reinforcement, particularly in the plastic hinge regions of the member. Also, some FRP structures may exhibit non-linearity due to their laminate architecture and inter-laminar shear. Another issue of great concern in FRP structures is the definitions of ductility. In reinforced concrete (RC) structures, ultimate displacements are measured against a reference displacement at the first yield of steel reinforcement. However, there is no such yield criteria for FRP-RC members. Therefore, one needs to develop a better understanding of the ductility measures that lend themselves to non-yielding materials such as FRP.

1.2 Research Objectives

The two main objectives of this research were as follows:

1. Develop an experimental database for creep and shrinkage of CFFT under axial and flexural loading conditions; and
2. Investigate the behavior of CFFT beam-columns, with different levels of fiber reinforcement, and with or without internal steel reinforcement, under constant axial loading and reverse cyclic transverse loading.

1.3 Report Outline

This report consists of five chapters besides this introductory chapter. Chapter 2 presents a literature review on the subject. Chapter 3 summarizes the experimental and analytical work on time-dependent behavior of CFFT. Chapter 4 presents the low-cycle fatigue behavior of CFFT. Finally, Chapter 5 summarizes the research, and provides concluding remarks in addition to recommendations for future research. A total of 8 papers, either published or in review, have been provided in the appendix to present the details of the two studies on the time-dependent and low-cycle fatigue behavior of CFFT.

CHAPTER 2
LITERATURE REVIEW

It is well known that confinement improves strength and ductility of concrete. The confinement in columns can be achieved by ties or stirrups or by encasing concrete in a steel or FRP tube. Also, steel and FRP jackets have been used for retrofit and strengthening of existing concrete columns. While considerable research has been carried out on the short-term static behavior of hybrid columns, very few have addressed their time-dependent behavior.

In 1993, Mirmiran proposed the concept of concrete-filled FRP tubes to address the corrosion problems for the Florida Department of Transportation. Cabrera (1996) conducted several shear tests on short beams with square sections. Half of the beams had shear connectors, while the other half had smooth internal surface. The beams were loaded to failure in a four-point loading test. Test results demonstrated that slippage between FRP and concrete could be completely arrested using shear connectors. She also conducted a study on the seismic performance of concrete-filled FRP tube based on a cyclic stress-strain model. Mirmiran et al. (1998) presented the design, fabrication and testing of the new hybrid column with internal shear connector ribs in the longitudinal and transverse directions. Based on the experimental interaction diagram for the proposed column, Mirmiran et al. (1999a) showed the new system to be equivalent to reinforced concrete (RC) columns with over 5% steel reinforcement.

Seible et al. (1996) studied the composite carbon shell systems for bridge columns under seismic loads. The new structural system was evaluated experimentally under simulated seismic loads using pilot test units which incorporated different design assumptions with the objective of matching or exceeding the performance of conventionally reinforced concrete columns. Consequently, a rational and comprehensive design procedure was developed to incorporate the mechanical characteristics of advanced composite materials into the design methodology conventional columns.

Mirmiran et al. (2000) further showed that off-the-shelf tubes with no surface preparation could be comparable to reinforced or prestressed concrete columns. The CFFT system, with an equivalent reinforcement ratio of only 1.4%, performed better than a 6% reinforced concrete section or a prestressed concrete section with 33% more concrete area. Fam and Rizkalla (2001) also studied the behavior of concrete-filled FRP tubes under axial/flexural loading conditions. The specimens ranged from 3.5 to 34 ft span length and from 3½ to 37 in diameter. Mirmiran et al. (1999b) investigated the enhancement of serviceability, strength and ductility of concrete-filled tubes under flexural loads by partial prestressing of the section. They recommended to keep the effective prestress within 10%-25% of the unconfined strength of concrete core, and to limit tendon location to the central kern area to avoid tensile stresses at the interface of the concrete core and the FRP tube, unless the tube is equipped with adequate ribs or shear connectors.

Davol et al. (2001) extended the studies of concrete-filled tubes to carbon FRP laminates. They tested two different laminate structures. The first shell with a lay-up of $[90^o, \pm10^o_2, 90^o, \pm10^o_2, 90^o]_{sym}$ experienced a compression failure due to local buckling at a longitudinal strain of 0.55%.

The second shell with a lay-up of [90^o_2, $\pm10^o_2$, 90^o, $\pm10^o_2$, 90^o, $\pm10^o$, 90^o_2, $\pm10^o$, 90^o_3] failed in compression at a much higher strain of 0.83%.

Fan et al. (2000) studied the seismic performance of reinforced concrete columns confined by FRP tube under low cycle reverse loading. The FRP tubes acted as formwork as well as lateral confining system. There was a 2 in gap between FRP tubes and the footing of columns. The experimental results showed that the FRP tube did not increase the capacity of the column, but it greatly enhanced its ductility ratio up to 10.

Yuan et al. (2002) proposed a novel hybrid GFRP tube filled with concrete. They reported that the FRP tube enhanced the strength of concrete by 2½ times. Fiber orientations in the tubes were ±45°. Coupons of the tube were cut and tested under monotonic tension and compression. Tests showed a bilinear response in tension and compression, with similar moduli of elasticity. However, the ultimate tensile strength was lower than the ultimate compressive strength.

Martin (1972) carried out experiments to study the long-term behavior of spirally pre-stressed confined concrete cylinders. He tested 18 such cylinders, where the pre-stressing wires provided an initial confinement pressure of 2100 psi. The specimens were subjected to sustained axial loads in the range of 17% to 83% of the static capacity. Test results showed that the reserved strength of confined concrete may be increased by as much as 19%. Also, he noted that the lateral strains developed due to creep continue to increase for a period of 60 to 90 days and then stabilize. Creep rupture of confined concrete occurs at sustained loads above 80% of the static capacity of the column.

Terrey et al. (1994) have considered the time-dependent behavior of concrete encased in a steel section as a gray area that needs further exploration. Their experimental study showed that moisture egress from encased concrete might be very small or eliminated totally. As a result, creep coefficients are expected to be in the order of 50%-60% of ordinary exposed concrete. The study further showed that shrinkage of concrete core in steel tubes might be safely neglected. Uy and Das (1997) studied time-dependent effects of creep and shrinkage of concrete in a fabricated steel box column typically used in tall building construction. The analysis used an age adjusted effective modulus method to simulate the construction of individual floor levels in a building.

Morino et al. (1997) reported on three sets of creep experiments for square concrete-filled steel columns, including: (a) six concentrically loaded stub specimens of square section with width to thickness (B/t) ratio between 23 and 47, and slenderness ratio (height to width (h/B) ratio) between 2:1 and 12:1; (b) one beam specimen with a B/t ratio of 33 and depth to span (B/L) ratio of 1/26; and (c) two eccentrically loaded column specimens both with B/t ratio of 33 and h/B ratio of 8:1. Although they did not make a conclusive statement regarding the length effect on the creep behavior of concrete-filled steel columns, they noted a clear reduction in the creep coefficients of concrete when inside a tube due mainly to the stress re-distribution that occurs between concrete and steel. They further questioned whether the creep coefficient is a function of the loading condition, and emphasized the need to develop a uniform method for the time-dependent analysis of concrete-filled steel tubes.

Li et al. (1999) analyzed shrinkage characteristics of expansive concrete in a steel tube. Cold shrinkage, creep and autogenous shrinkage were considered as the main reasons of causing contraction in concrete-filled steel tubes. The expansive agent not only compensates the shrinkage of the concrete core in early stages, but also makes the core expand according to the delayed expansion mechanism. As the result, the pre-stress loss may be reduced and expansive energy may be utilized effectively.

Pelvris and Triantafillou (1994) studied the time-dependent behavior of RC members strengthened with FRP laminates. The study addressed the time-dependent analysis of a hybrid section made of concrete, steel, and FRP sections based on two basic considerations: static equilibrium, and strain compatibility. They also assumed perfect bond between the RC section and the FRP laminate, and following the Euler-Bernoulli assumption of plane sections remain plane after bending. The model was based on the age adjusted effective modulus method for creep of concrete (Bazant 1972), and Findley's power law for creep of FRP (Findley 1960). The model utilized the relaxation and restoration techniques to account for time-dependent changes in strains, stresses, and curvature of the hybrid section. The study was accompanied by an experimental program to confirm the analysis and to assess the effect of different types of FRP laminates. The study showed that by increasing the area of the FRP laminate made of carbon or glass fibers the creep strains decrease without affecting the time-dependent curvature and the stress in the steel reinforcement or in the laminate.

Deskovic et al. (1995) studied the long-term behavior of hybrid beams made of glass fiber reinforced (GFRP) box section with a layer of concrete on the compression side and a carbon FRP laminate on the tension side. They proposed an analytical model based on the micro-mechanical properties of the components of the hybrid section and the classical laminate theory. The model was shown to agree favorably with the experimental results of large-scale creep tests. The study further showed that the new hybrid beams possess very good time-dependent response characteristics and that the exposure of the members to the environment is not likely to result in their rupture. However, reserved strength of the hybrid section was shown to decrease with the increase of the sustained load and its duration.

CHAPTER 3
TIME-DEPENDENT BEHAVIOR

An extensive experimental program was carried out into the long-term behavior of concrete-filled fiber reinforced polymer (FRP) tubes (CFFT). Table 3.1 provides a summary of the specimen test matrix. Four types of tests were conducted; axial loading, flexural loading, shrinkage and push-out. Three types of specimens were prepared; concrete-filled FRP tube (CFFT), hollow FRP tube, and fiber-wrapped concrete cylinders (FWCC). Creep investigations included static tests of virgin specimens to determine their capacity, creep at different levels of sustained load and for different load durations, creep recovery upon unloading, and static tests of specimens after creep recovery for their reserved strength. Since application of CFFT or FWCC is mostly in bridge pier columns, sustained loads may be in the range of 6% to 20% of the column capacity.

Figures 3.1 and 3.2 show the self-reacting frames for the axial and flexural creep testing of the CFFT specimens. Table 3.2 shows the shrinkage strains in CFFT specimens at the time of creep loading. Table 3.3 shows test results for the creep specimens in comparison with the ACI 209.

The creep analysis followed the rate of flow method and the double power law for concrete, and the Findley's power law function for FRP. The model adhered to geometric compatibility and static equilibrium, and considered the effects of sealed concrete, multi-axial state of stresses, creep Poisson's ratio, stress re-distribution, variable creep stress history, and creep rupture of the column. For flexural creep analysis, average stress-creep strain isochronous curves were used as non-linear constitutive relation. The creep models were verified against previous tests for bonded and unbonded concrete-filled steel tubes (CFST), and the experiments of the present study on FWCC and CFFT columns and beams. A parametric study was carried out for creep rupture and creep under service loads.

The study showed that concrete core in CFFT has negligible shrinkage strains, similar to that of sealed concrete. Bond strength at the interface of concrete and FRP is lower than that of steel and concrete, but it is still large enough to prevent concrete from shrinking away from the tube. The existing models are shown to grossly overestimate creep of hybrid columns. The creep behavior of FWCC and unbonded CFST is very close to that of sealed concrete of the same mix. The effect of confinement on creep of concrete is generally not very significant. Bonded CFST and CFFT columns creep much less than their unbonded counterparts, mainly due to axial stress re-distribution. As the stiffness of the tube increases relative to concrete core, a larger stress re-distribution takes place, and a much lower creep develops. There is a threshold, beyond which, stiffer tubes would not significantly lower creep of concrete. Creep behavior of CFFT beam-columns is much better than CFFT beams, due mainly to the presence of axial load in the section, as it tends to retard cracking of concrete and growth of its curvature. Creep rupture life expectancy of CFFT columns and beam-columns is shown to be within acceptable range.

Details of the experimental and analytical work on this subject have been summarized in four papers that are presented in the appendix to this report. Details can also be found in Naguib (2001).

Table 3.1 Specimen Test Matrix

Test No.	Type of Test	Type of Specimen	Test Objective	Test Duration	No. of Specimens	Specimen Size
1	Axial Loading	CFFT	Virgin Strength	Instantaneous	1	6” diameter, 36” height
			Creep	6 months	4	
			Creep Recovery	1 month	4	
2		FRP Tube	Virgin Strength	Instantaneous	2	6” diameter, 6”&12” height
			Creep	6 months	2	
			Creep Recovery	1 month	2	
			Reserved Strength	Instantaneous	2	
3		FWCC	Virgin Strength	Instantaneous	1	6” diameter, 12” height
			Creep	3 month	2	
			Creep Recovery	3 weeks	2	
			Reserved Strength	Instantaneous	2	
4	Flexural Loading	CFFT	Virgin Strength	Instantaneous	1	6” diameter, 84” length
			Creep	6 months	2	
			Creep Recovery	1 month	2	
			Creep Rupture	4 hours	1	
			Reserved Strength	Instantaneous	2	
5	Shrinkage	CFFT	Free Shrinkage	1 year	1	6” diameter, 36” height
6	Push-out	CFFT	Bond Strength	Instantaneous	4	6” diameter, 6 &12” height

Table **Error! No text of specified style in document.**.2 Shrinkage Strains for CFFT Specimens at the Time of Loading

Specimens name	Age at loading (Days)	Shrinkage strains at loading (με)	ACI-209 shrinkage strains at loading (με)	
			Unsealed	Sealed
Specimen A	550	75	733	219
Specimen B	64	100	504	148
Specimen C	276	75	692	203
Specimen D	56	85	480	141
Flexure I	176	75	651	191
Flexure II	365	75	712	209

Table 3.3 Test Results for Axial Creep Specimens

Specimen Name	Age at Loading (days)	Elastic Strain	Total Strain after 6 Months	Experimental creep Coefficient after 6 Months	ACI-209 Creep Coefficients after 6 Months	
					Unsealed	Sealed
A	556	0.00044	0.00054	0.22	0.86	0.58
B	64	0.00381	0.00428	0.125	1.28	0.86
C	276	0.00228	0.00268	0.18	1.15	0.77
D	53	0.00178	0.00218	0.22	1.31	0.88

Table 3.4 Test Results for Flexural Creep Specimens

Specimen name	Age at loading (days)	Applied loads (kips)	Initial (elastic) deflection (in)	Deflection at 180 days (in)
Virgin Specimen	137	51	3.5*	----
Flexure I	165	20	1.3	1.6
Flexure II	371	13	1.1	1.3

* Ultimate deflection at failure.

Figure 3.1 Axial Creep Test Rig

Figure 3.2 Flexural Creep Test Rig

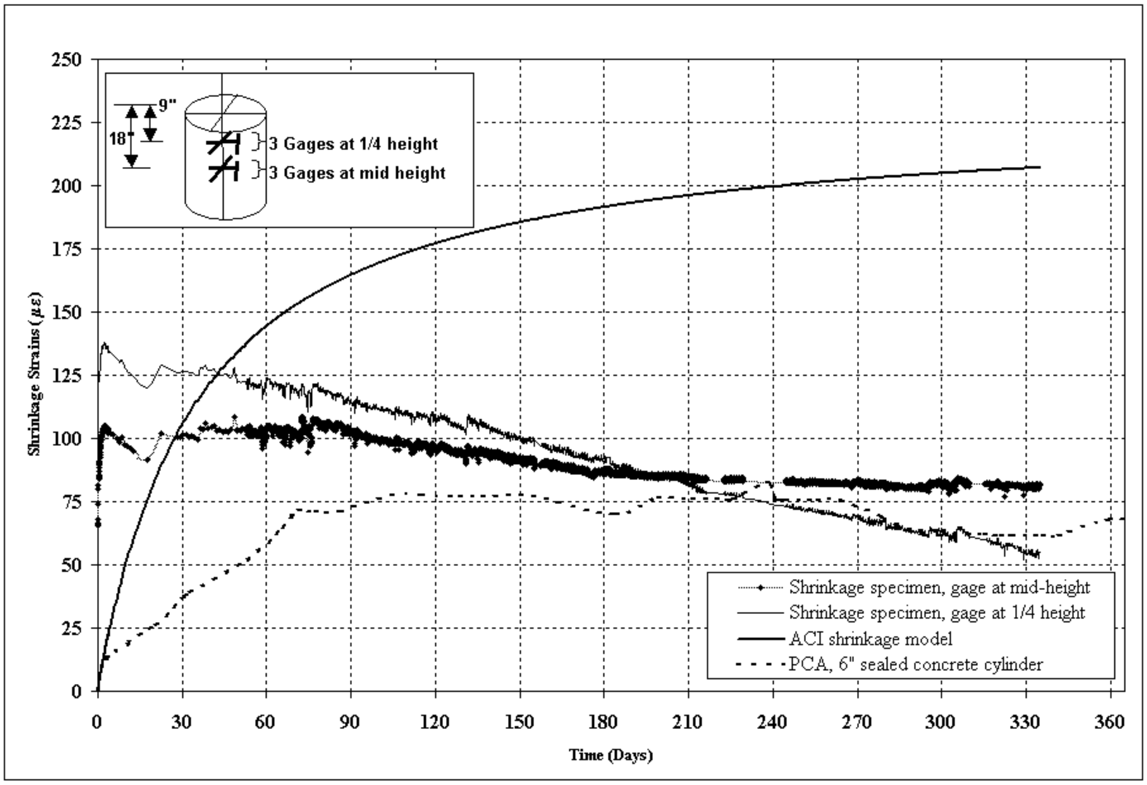

Figure 3.3 Shrinkage Strains Compared to Sealed Concrete and ACI-209

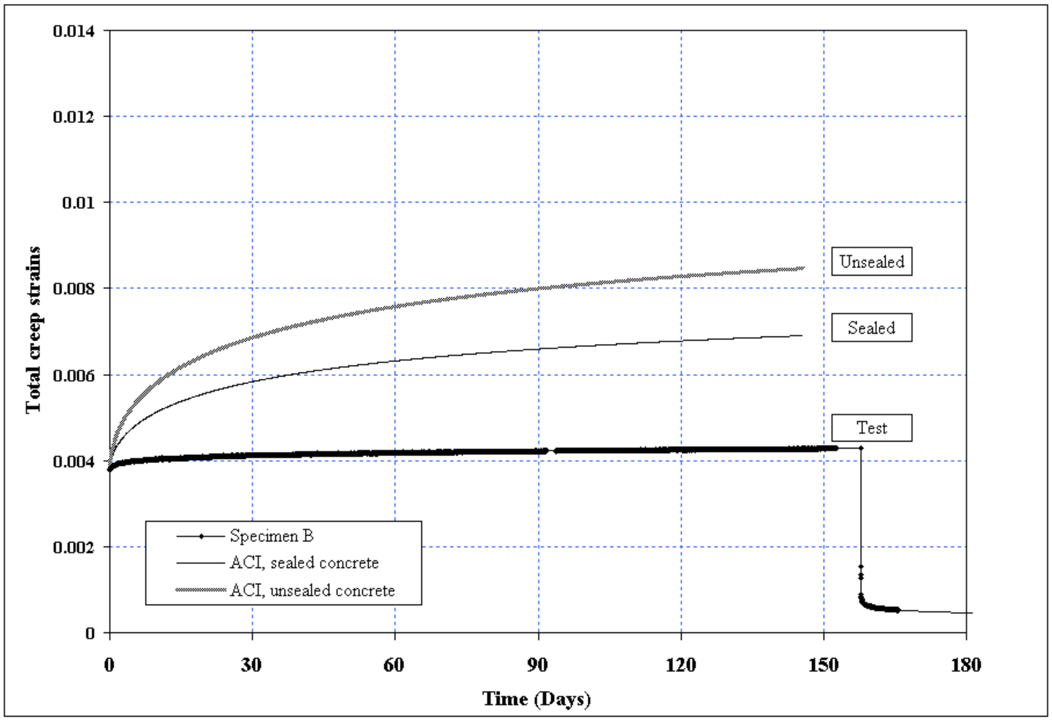

Figure 3.4 Axial Creep Strains in CFFT Compared to Sealed Concrete and ACI-209

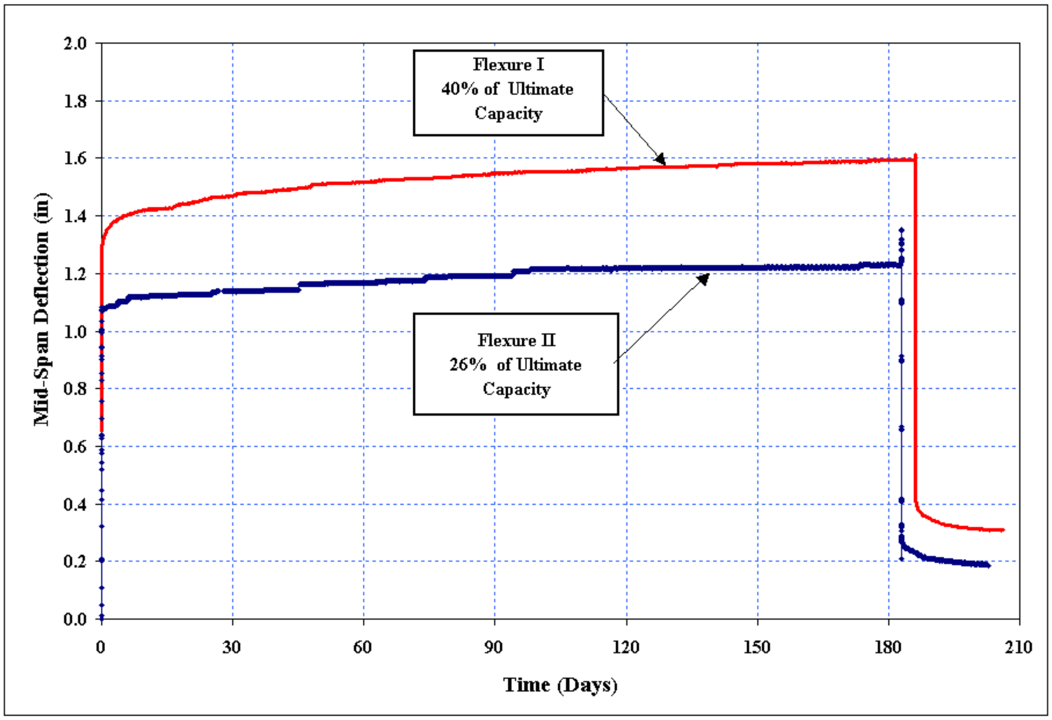

Figure 3.5 Mid-Span Deflections of CFFT Beams under Creep Loading

CHAPTER 4
LOW-CYCLE FATIGUE BEHAVIOR

An extensive experimental and analytical program was carried out into the cyclic behavior of concrete-filled fiber reinforced polymer (FRP) tubes (CFFT). The experimental component of the program comprised of the following:

- Beam-column tests: Six (6) large-scale CFFTs with two different types of FRP tubes and three different levels of internal steel reinforcement were tested under constant axial compression loading and reversed cycles of transverse loading in four-point flexure. The objective of these tests was to establish the cyclic response of hybrid FRP-concrete columns with and without steel reinforcement. Table 4.1 shows the test matrix for the beam-columns. Figure 4.1 shows a section of each one of the two types of tubes used in this study. Table 4.2 shows a comparison in properties of the two tube types of tubes. These are the same two tube types that were tested at the Florida DOT Structures Laboratory in late 1990's under Phase 3 of the Hybrid FRP-Concrete Pile Project. Figure 4.2 shows the beam-column test setup. Figure 4.3 shows one of the yellow specimens under the application of the loads. Figure 4.4 shows typical modes of failure for the white and yellow specimens.
- Stub tests: Twenty-four (24) short stubs of FRP-wrapped concrete were tested under cycles of loading and unloading in uniaxial compression. The objective of these tests was to develop the cyclic model for concrete confined with different amounts of FRP.
- FRP coupons: Twenty-five (25) coupons cut from the two types of FRP tubes were tested under cycles of loading and unloading in uniaxial tension or compression, as well as reverse cyclic loading in tension and compression. The objective of these tests was to establish the material models for the FRP tubes. Table 4.3 shows the average results of tension and compression coupon tests. Figures 4.5 and 4.6 show the failure modes of the white and yellow coupons in tension and compression, respectively.

The analytical component of the program comprised of the following:

- Modeling cyclic behavior of FRP-confined concrete in compression;
- Modeling cyclic behavior of linear and non-linear FRP materials in tension and compression;
- Employing a fiber element model to predict the cyclic behavior of CFFT beam-columns;
- Carrying out a parametric study on the cyclic response of CFFT beam-columns, and evaluating their hysteretic performance measures including cumulative energy dissipation, ductility and pinching effect; and
- Comparison of the hysteretic response of CFFT beam-columns with those of reinforced concrete and concrete-filled steel tubes.

Figures 4.7-4.12 show comparisons of the experimental load-deflection hysteretic response of the six beam-columns specimens with the analytical prediction model. Good agreement is noted in all cases. This study has resulted in a number of findings, as outlined below:

- Cyclic response of the FRP-confined concrete depends on the level of unloading in comparison to the bend point in the envelope curve. Unloading prior to the bend point is characterized as linear elastic, whereas unloading after the bend point is represented by a parabolic curve with a distinct plastic or residual strain.

- FRP tubes with fiber architecture, such as the $\pm 55^{\circ}$ in the yellow tubes tested for this research, exhibit significant non-linearity with considerable energy dissipation.
- The two types of CFFT beam-columns tested under this study represented two different failure modes; a brittle compression failure for the over-reinforced white tube specimens with thick FRP tube and with majority of the fibers in the longitudinal direction, and a ductile tension failure for the under-reinforced yellow tube specimens with thin FRP tubes and off-axis fibers.
- A moderate amount of internal steel reinforcement in the range of 1%-2% may improve the cyclic response of CFFT members. The improvement is more significant for the under-reinforced FRP tubes. Adding internal steel, especially for members with thick FRP tubes, can be ineffective and may result in premature failure.
- Both displacement-based ductility and energy-based ductility measured could be used to assess the hysteretic response of CFFT members. A minimum ductility factor in the range of 4-5 is recommended for CFFT members.
- The pinching effect in CFFT members depends mainly on the amount of internal steel reinforcement, rather than the type of FRP tube.
- Hysteretic performance measures of CFFT members, including energy dissipation capacity and pinching effect, are greatly enhanced at higher levels of axial load, primarily due to the confinement effects.
- Slender CFFT members have less capacity than their short stocky counterparts. However, they are less susceptible to pinching effect and premature shear failure.
- It is feasible to design CFFT beam-columns with moderate amount of internal steel reinforcement to have comparable hysteretic performance to that of RC members.
- Hysteretic response of CFFT members, irrespective of the type of FRP tube or the amount of internal steel reinforcement, may not measure up to their CFST counterparts. However, selection of CFFT members may lie in their superior durability and lower weight.

Details of the experimental and analytical work on this subject have been summarized in four papers that are presented in the appendix to this report. Details can also be found in Shao (2003).

Table 4.1 Test Matrix of FRP-Concrete Beam-Column Specimens

FRP Type	White Specimens			Yellow Specimens		
Specimen Name	W1	W2	W3	Y1	Y2	Y3
Test Location	UC	UC	NCSU	NCSU	NCSU	NCSU
Span Length, *L* (in)	96	96	108	108	108	108
Core Diameter, *D* (in)	11.00	11.00	11.00	12.28	12.28	12.28
Tube Thickness, *t* (in)	0.5	0.5	0.5	0.2	0.2	0.2
Steel Reinforcement	None	8#4	8#5	None	4#4+4#5	4#5+4#6
Steel Reinforcement Ratio, ρ_s (%)	0.0	1.65	2.58	0.0	1.70	2.53
L/D Ratio	8.7	8.7	9.8	8.8	8.8	8.8
D/t Ratio	22.0	22.0	22.0	61.4	61.4	61.4
Reinforcement Index, ω	3.29	3.59	3.19	0.17	0.43	0.56

Table 4.2 Comparison of White and Yellow Tubes

Description	White Tubes	Yellow Tubes
Thickness	0.5 in	0.2 in
Axial Tensile Strength	57.9 ksi	10.3 ksi
Tensile Modulus of Elasticity	2256 ksi	1820 ksi
Axial Compressive Strength	55.7 ksi	33.3 ksi
Compressive Modulus of Elasticity	3373 ksi	1260 ksi
Flexural Strength	81 ksi	25 ksi
Flexural Modulus of Elasticity	3564 ksi	1179 ksi
Fiber Architecture	$(0^\circ, 0^\circ, \pm 45^\circ)_{10}$	$(\pm 55^\circ)$, Total = 17
Fabrication Method	Spin Casting	Filament Winding
Glass Content	51.2%	75.5%

Table 4.3 Average Results of Tension and Compression Coupon Tests

FRP Type	White Tube		Yellow Tube	
Source	Tension	Compression	Tension	Compression
Ultimate Strength (ksi)	75.0	60.0	6.5	23.0
Ultimate Strain (in/in)	0.0230	0.023	0.0045	0.0044
Initial Modulus of Elasticity (ksi)	6,800	2,900	4,000	750
Secant Modulus of Elasticity (ksi)	3,250	2,900	1,500	563

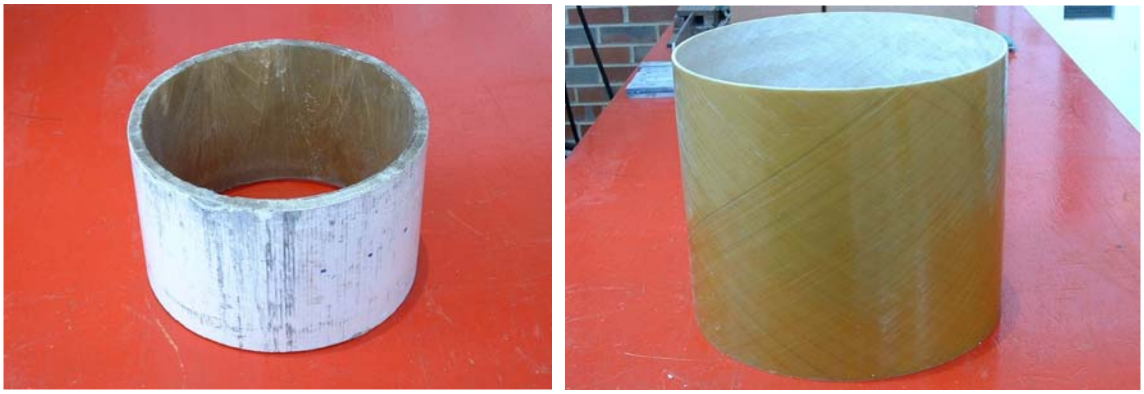

Figure 4.1 White and Yellow Tubes

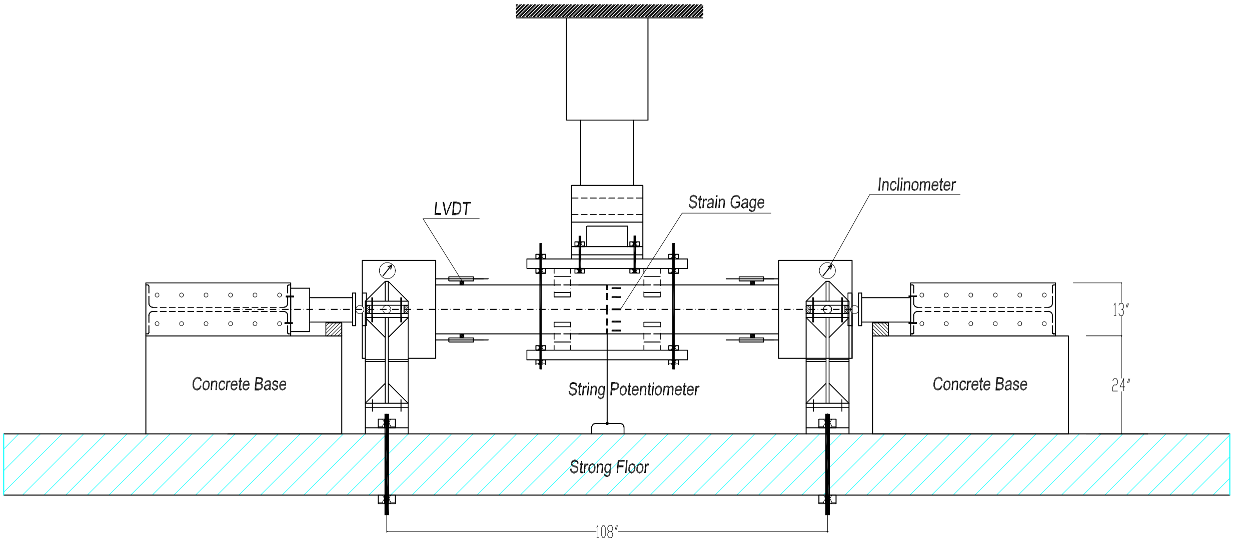

Figure 4.2 Test Setup

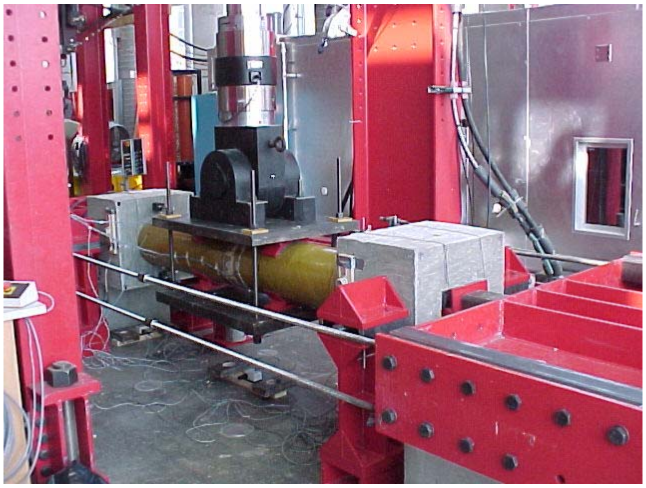

Figure 4.3 Yellow Specimen under Load

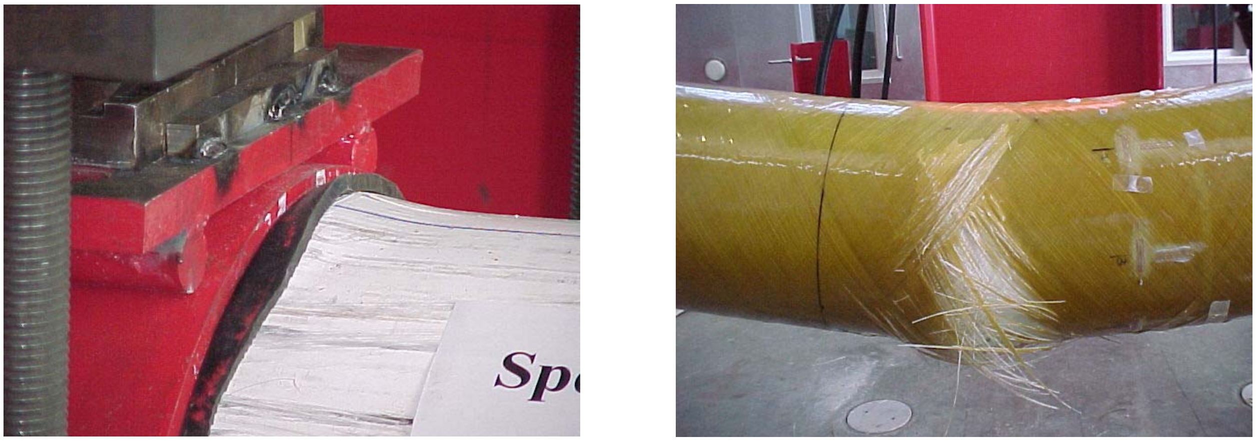

Figure 4.4 Failure Modes of White and Yellow Tubes

Figure 4.5 Failure Modes of White and Yellow Coupons in Tension

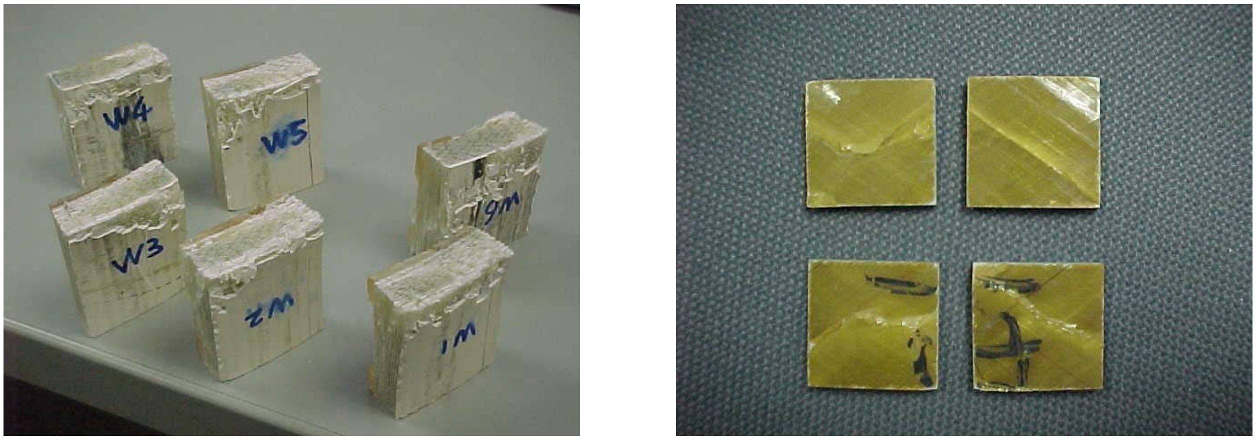

Figure 4.6 Failure Modes of White and Yellow Coupons in Compression

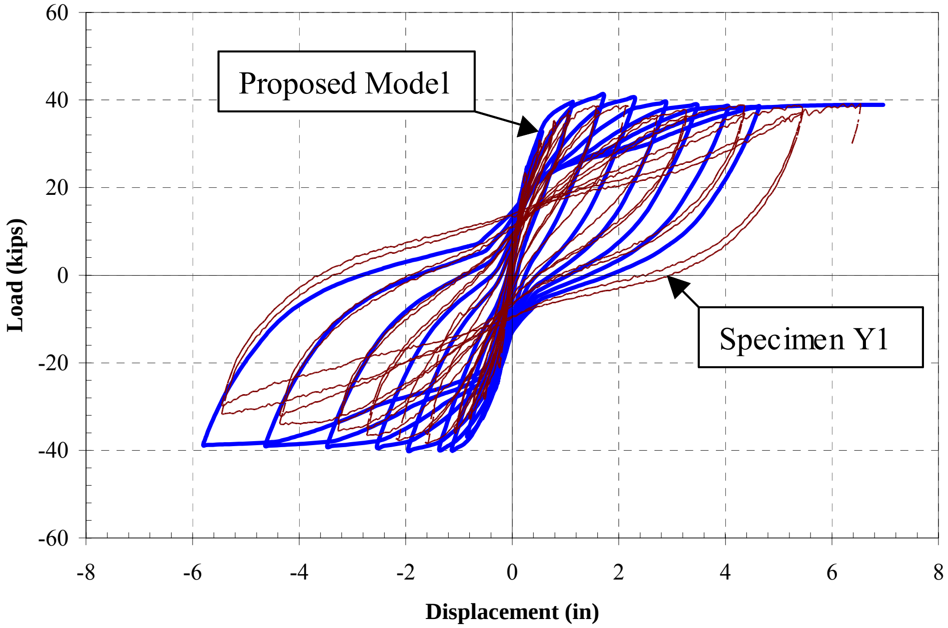

Figure 4.7 Comparison of Specimen Y1 with Proposed Model

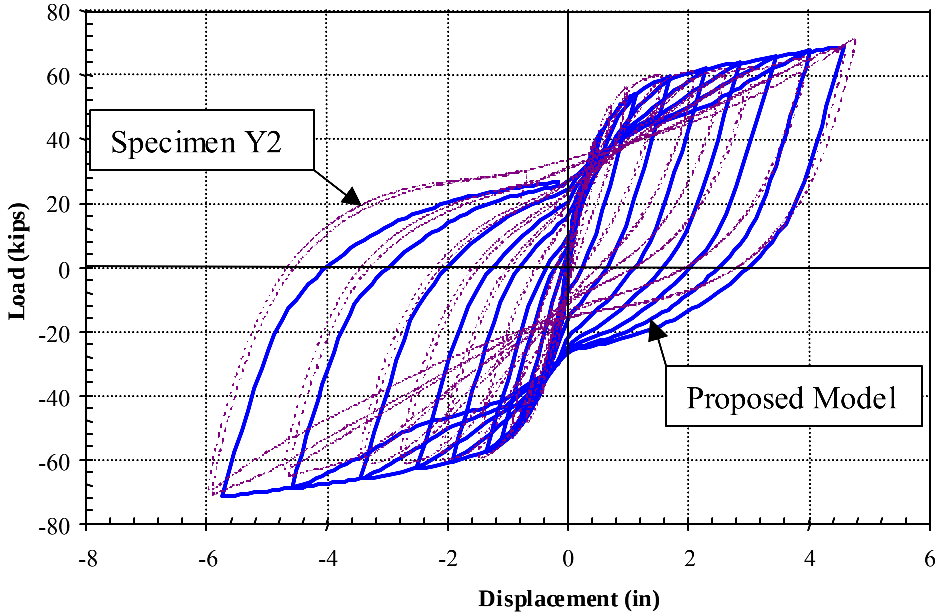

Figure 4.8 Comparison of Specimen Y2 with Proposed Model

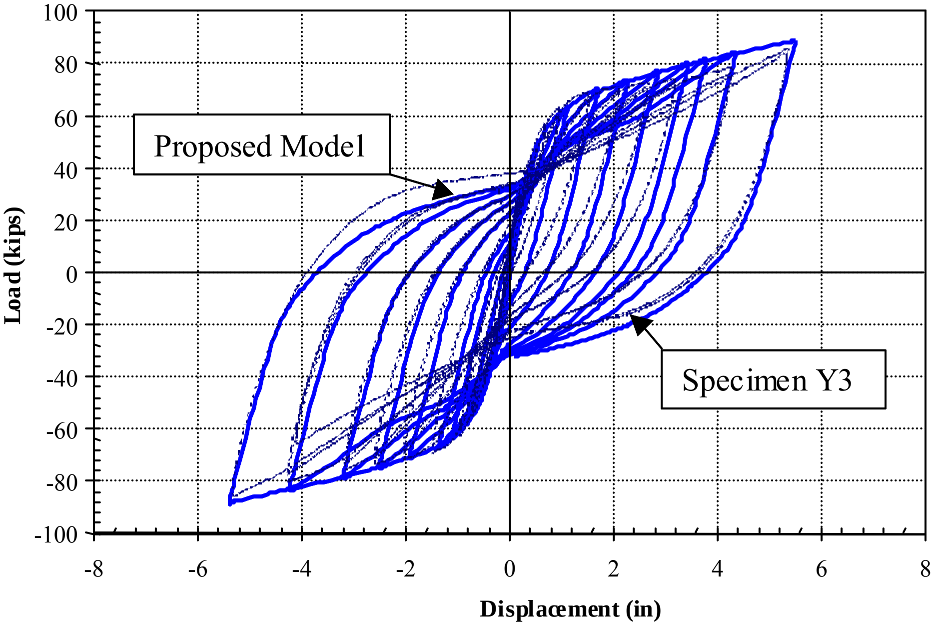

Figure 4.9 Comparison of Specimen Y3 with Proposed Model

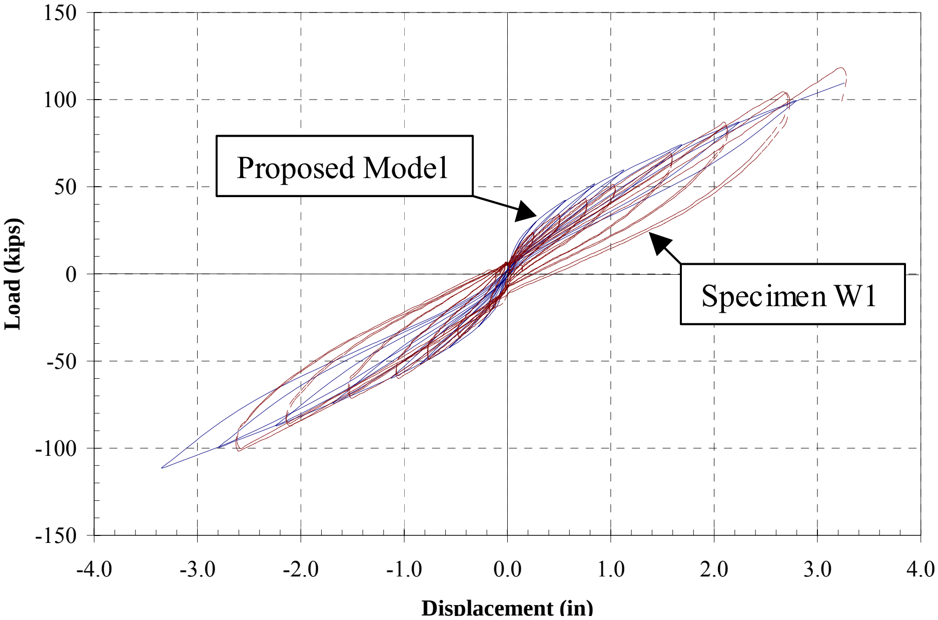

Figure 4.10 Comparison of Specimen W1 with Proposed Model

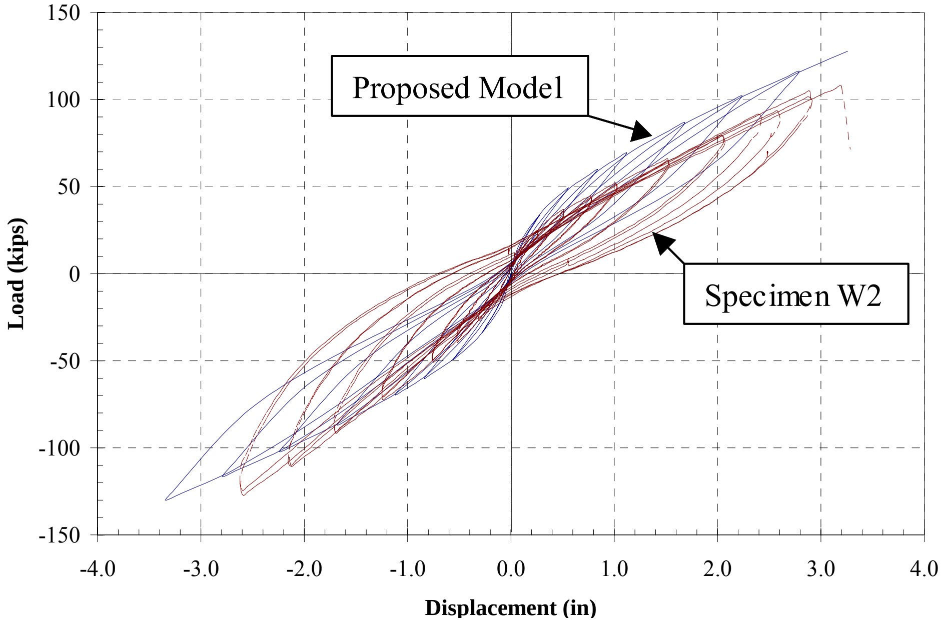

Figure 4.11 Comparison of Specimen W2 with Proposed Model

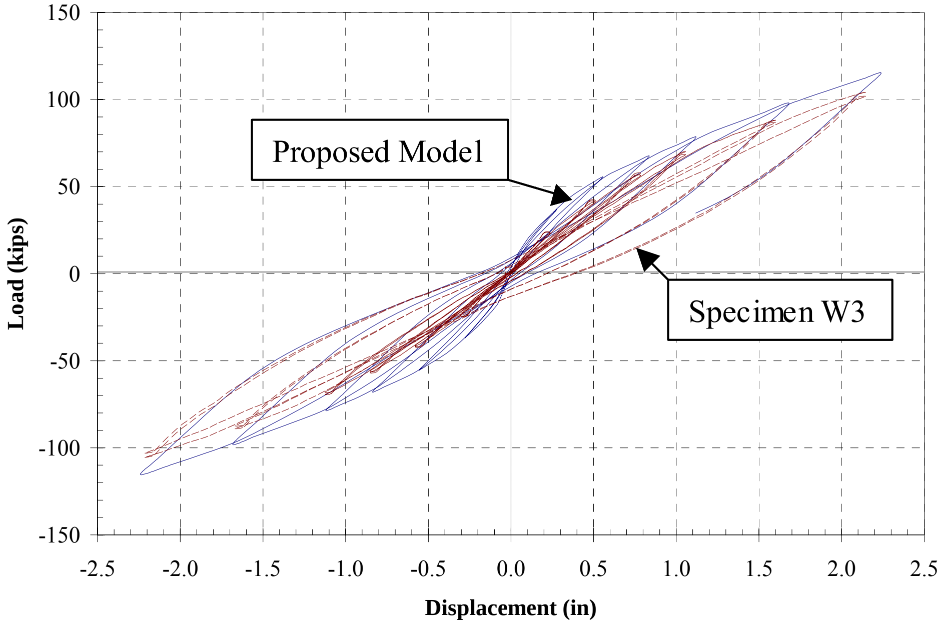

Figure 4.12 Comparison of Specimen W3 with Proposed Model

CHAPTER 5
CONCLUSIONS

Since 1993, when the author proposed to the Florida Department of Transportation the use of concrete-filled FRP tubes (CFFT) as piles and pier columns, significant research has been carried out by the author and other investigators who have followed his work. The two areas that have received least attention, however, are the long-term time-dependent behavior and the cyclic response of CFFT members. The issues of concern include the effect of FRP tube on shrinkage of concrete core, creep of FRP tube and concrete core together, potential creep rupture of the hybrid system, and the need for internal reinforcement in CFFT columns and piles to provide adequate ductility under cyclic lateral loads.

The present study was carried out with two major objectives: (a) to develop an understanding of the time-dependent creep and shrinkage behavior of CFFT, and (b) to assess the cyclic response of CFFT with and without internal steel reinforcement.

A thorough analytical and experimental investigation was carried out into the long-term behavior of CFFT beams and columns under sustained loads. The study resulted in a number of findings as follows:

- Shrinkage of concrete core in FRP tube is in the order of 10%-20% of that of exposed concrete. For all practical purposes, concrete core may be considered as sealed with quite negligible shrinkage strains. Moreover, the notion that concrete core may separate from the tube under the effect of shrinkage is not warranted.
- The current ACI models grossly overestimate creep of concrete core in CFFT columns. The equivalent creep coefficients for concrete core in CFFT columns may be as low as 22% of that recommended by ACI for a sealed concrete of the same mix proportions and environmental conditions and for the same duration of loading.
- Effect of confinement on creep of concrete core is not as significant as the effect of sealing concrete and the stress re-distribution that occurs between concrete and FRP.
- Creep effects reduce the flexural stiffness of CFFT specimens. However, ultimate strength is not significantly altered.
- Slow rate of loading and short-term creep at 70% of static capacity may cause premature rupture of the tube.
- Fiber analysis of CFFT beam-columns by discretizing the section into filled and hollow FRP tubes can adequately simulate the flexural creep behavior. Moreover, isochronous sustained stress - creep strain curves can be used as constitutive non-linear relationship for creep analysis in flexure.
- Creep rupture life expectancy of CFFT beam-columns with diameter to thickness (*D/t*) ratios of 40 or less is at least 50 years at transverse loads as high as 60% of the static capacity. CFFT columns with *D/t* ratios of less than 80 have a creep rupture life expectancy of 75 years at 70% of static capacity under concentric axial loading.

A thorough analytical and experimental investigation was carried out into the cyclic behavior of CFFT beam-columns under constant axial loads and cyclic lateral loads. Findings of the study can be summarized as follows:

- The two types of CFFT beam-columns tested under this study represented two different failure modes; a brittle compression failure for the over-reinforced specimens with thick FRP tube and with majority of the fibers in the longitudinal direction, and a ductile tension failure for the under-reinforced specimens with thin FRP tubes and off-axis fibers. The thin FRP tubes with $\underline{+}55^{o}$ exhibited significant non-linearity with considerable energy dissipation.
- A moderate amount of internal steel reinforcement in the range of 1%-2% may improve the cyclic response of CFFT members. The improvement is more significant for the under-reinforced FRP tubes. Adding internal steel, especially for members with thick FRP tubes, can be ineffective and may result in premature failure. It is feasible to design CFFT columns with moderate steel reinforcement to be comparable to RC columns under cyclic loading.

In summary, the present study has clearly shown the feasibility of CFFT piles and columns not only under short-term static loading, but also under long-term sustained loading or dynamic and cyclic loading. The study emphasizes the importance of proper design of the FRP tube based on the type of applied loading.

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APPENDIX
DISSEMINATED PAPERS

The following four papers on the subject of time-dependent behavior of CFFT have either been published or are in press:

1. Naguib, W., and Mirmiran, A., "Time-Dependent Behavior of FRP-Confined Concrete Columns," *Structural Journal*, American Concrete Institute (ACI), Vol. 99, No. 2, pp. 142-148, 2002.
2. Naguib, W., and Mirmiran, A., "Flexural Creep Tests and Modeling of Concrete-Filled FRP Tubes," *Journal of Composites for Construction*, ASCE, Vol. 6, No. 4, 272-279, 2002.
3. Naguib, W., and Mirmiran, A., "Creep Analysis of Axially Loaded FRP-Confined Concrete Columns," *Journal of Engineering Mechanics*, ASCE, Vol. 129, No. 11, Scheduled for November 2003.
4. Naguib, W., and Mirmiran, A., "Creep Modeling of Concrete-Filled Steel Tubes," *Journal of Constructional Steel Research*, Elsevier, in press.

The following four papers on the subject of cyclic behavior of CFFT are under review:

5. Shao, Y., and Mirmiran, A., "Experimental Investigation of Cyclic Behavior of Concrete-Filled FRP Tubes," *Structural Journal*, American Concrete Institute (ACI), in review.
6. Shao, Y., and Mirmiran, A. "Modeling of FRP-Confined Concrete under Cyclic Loading," *Journal of Engineering Mechanics*, ASCE, in review.
7. Shao, Y., and Mirmiran, A. "Nonlinear Cyclic Response of Laminated Glass FRP Tubes Filled with Concrete," *Composite Structures*, Elsevier Science Ltd., in review.
8. Shao, Y., Aval, A., and Mirmiran, A. "Fiber Element Model for Cyclic Analysis of Concrete-Filled FRP Tubes," *Journal of Structural Engineering*, ASCE, in review.

In the following pages, copies of these papers are presented.

Paper 1

TIME-DEPENDENT BEHAVIOR OF FRP-CONFINED CONCRETE COLUMNS

Naguib, W., and Mirmiran, A.

Structural Journal, American Concrete Institute (ACI), Vol. 99, No. 2, pp. 142-148, 2002

Paper 2

FLEXURAL CREEP TESTS AND MODELING OF CONCRETE-FILLED FRP TUBES

Naguib, W., and Mirmiran, A.

Journal of Composites for Construction, ASCE, Vol. 6, No. 4, 272-279, 2002

Paper 3

CREEP ANALYSIS OF AXIALLY LOADED FRP-CONFINED CONCRETE COLUMNS

Naguib, W., and Mirmiran, A.

Journal of Engineering Mechanics, ASCE, Vol. 129, No. 11, Scheduled for November 2003

Paper 4

CREEP MODELING OF CONCRETE-FILLED STEEL TUBES

Naguib, W., and Mirmiran, A.

Journal of Constructional Steel Research, Elsevier, in press.

Paper 5

EXPERIMENTAL INVESTIGATION OF CYCLIC BEHAVIOR OF CONCRETE-FILLED FRP TUBES

Shao, Y., and Mirmiran, A.

Journal of Structural Engineering, ASCE, in review

Paper 6

MODELING OF FRP-CONFINED CONCRETE UNDER CYCLIC LOADING

Shao, Y., and Mirmiran, A.

Journal of Engineering Mechanics, ASCE, in review

Paper 7

NONLINEAR CYCLIC RESPONSE OF LAMINATED GLASS FRP TUBES FILLED WITH CONCRETE

Shao, Y., and Mirmiran, A.

Composite Structures, Elsevier Science Ltd., in review

Paper 8

FIBER ELEMENT MODEL FOR CYCLIC ANALYSIS OF CONCRETE-FILLED FRP TUBES

Shao, Y., Aval, A., and Mirmiran, A.

Journal of Structural Engineering, ASCE, in review