Mechanical Behavior of CFRP Composites in Confined Concrete Columns

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Abstract

Fiber orientation is one of important parameters that affect strength and ductility of FRP-confined concrete columns. A number of studies have conducted on various fiber orientations and wrap thicknesses, but have not carried out a comprehensive study on tensile properties of FRP with various fiber orientations and their effects on confined concrete. In aerospace applications, significant researches have shown nonlinear behaviors in the off-axis direction in FRP structures. This paper presents the results of experimental studies about mechanical properties of high-strength carbon fiber reinforced polymer (CFRP) composites. In this study, 24 coupons of CFRP composites were tested in axial tension under displacement control mode. Eight ply configurations were prepared with fibers oriented at 0, ±45 and 90 from the axial direction and with 1, 2, 3 or 4 plies. It was found that stress-strain behavior is basically depended to fiber orientation. The behavior at pure longitudinal or matrix direction shows perfectly linear-elastic with brittle rupture, but at pure angle orientations is fully nonlinear and closed to elastic-perfect plastic with high ductility. At combination of longitudinal and angle orientations, the stress-strain curve shows a nonlinear behavior up to a maximum strength, and then down to a ductile failure with a nonlinear softening.

Keywords: Experimental study; CFRP; fiber orientation; strengthening; concrete column..

Introduction

In recent years, strengthening of reinforced concrete structures is a great challenge in civil engineering industry. For this subject the fiber reinforced polymer (FRP) composites are very suitable materials. These materials have high tensile strength, light weight, high modulus and corrosion resistance. Their flexibility allows them to be wrapped around several concrete elements with different geometries, especially column sections.

Previous researches have indicated that wrapping with FRP jackets or straps significantly increase the strength and ductility of poorly detailed columns [1-5]. This increasing emanate from the passive confinement pressure of FRP jackets [6]. Design of fiber-wrapped concrete has come a long way from the early applications of steel-based models such as that of Mander et al. [7] to recognize that such models fail to capture the true behavior of FRP-confined concrete [8]. This is mainly due to the unique dilation characteristics of concrete when confined by linear-elastic and non-yielding materials such as FRP [9]. The performance of unidirectional FRP laminates is highly dependent on fiber orientation with respect to applied load direction [10]. So fiber orientation is one of important parameters that affect strength and ductility of FRP-confined concrete columns [11].

A number of studies have conducted on various fiber orientations and wrap thicknesses in the civil engineering community. For example Mirmiran and Shahawy [8], Lam and Teng [12], Rochette and Labossiere [13], Pessiki et al. [14], Parvin and Jamwal [15, 16], Li et al. [17], Parvin and Wu [18], Xiao and Wu [19] and etc carried out many experiments on axially loaded concrete column confined by FRP. These researchers have mainly concentrated on behavior of confined concrete columns by FRP with various ply configurations.

Some of these researchers have considered properties of FRP in supplementary, but have not conducted a comprehensive study on tensile properties of FRP with various fiber orientations and their effects on confined concrete. For example Xiao and Wu [19] prepared three CFRP coupons with fiber oriented only at longitudinal direction (0o) and carried out axial tension test for determination of ultimate stress, ultimate strain and elastic modulus. In another study, Li et al [17] prepared 15 GFRP coupons with three fiber orientations 0, 45 and 90

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from the axial direction in one-ply and carried out axial tension test. In results, behavior of coupons with fibers oriented at 45o and 90o was classified such as pure resin without fibers. Lam and Teng [12] tested 35 CFRP coupons at longitudinal direction in order to comparison with rupture stress and strain of measured in tests on such FRP-confined concrete cylinders. They noted that experimental stress-strain responses of the CFRP coupons were found to deviate slightly from a perfectly linear relationship at the later stage of loading due to the gradual stiffening of the CFRP as a result of the straightening of the fibers. In a different approach, Yang et al [10] investigated degradation of strength and modulus of CFRP laminates from fiber misalignment using tensile coupon tests. The specimens consisted of one and two plies of unidirectional CFRP. The misalignment angles varied from 0 to 40 for the one-ply samples, and from 0 to 90 for one ply of the two-ply samples. It was concluded that misalignment affects strength more than elastic modulus. However, provided that mechanical parameters are related to the cross-sectional area of laminate with fibers continuous from end to end of the coupon, the degradation of strength can be accounted with a knock-down factor that is independent of misalignment angle.

On the other hand, and independently from the civil engineering community, significant researches have taken place since the 1970s in the aerospace applications to determine the source, and to assess the magnitude of, nonlinearity in the off-axis direction in FRP structures [20]. For example, Hahn and Tsai [21], Hahn [22], and Hu [23] reported that unidirectional FRP may exhibit severe nonlinearity in its in-plane shear stress–strain relation. Haj-Ali and Kilic [24] carried out several tension, compression, and shear tests on pultruded FRP coupons at different angles of 0, 15, 30, 45, 60, and 90. The overall linear elastic properties were identified along with the nonlinear stress–strain behavior under the in-plane multi-axial tension and compression loading.

Recently, Shao and Mirmiran [20] carried out an experimental investigation on coupons of two different types of laminated glass FRP tubes under tension and compression loading. W series tubes were made using centrifuge (spin) casting with 12.7 mm thickness and majority of the fibers in the longitudinal direction. The wall thickness in these tubes consisted of a 7.6 mm structural laminate with symmetric lay-up of 40 plies in the form of [0/0/+45/-45]10 from E-glass and epoxy resin, a 4.6 mm resin-rich inner layer, and a 0.5 mm gel coating on the exterior. Y series tubes were filament wound with 5 mm thickness and ±55 fiber orientation, also with E-glass and epoxy resin. However, these tubes did not have a resin layer or a gel coating. The two types of tubes represented two different failure modes; a brittle failure for W series with majority of the fibers in the longitudinal direction, and a ductile failure for the thin tubes with off-axis fibers. The nonlinearity and ductility in these types of structures stem from the off-axis response of the FRP tube.

According to previous researches on the subject; there are a number of issues that need to be addressed:

1. How is stress-strain behavior of CFRP composites?
2. What are effects of fiber orientation on stiffness and strength of CFRP?
3. How are nonlinearity, ductility, and failure mode of CFRP at various fiber orientations?
4. What are relations between confinement pressure and CFRP ply configuration in wrapped concrete columns?

The present study is an experimental investigation on tensile properties of CFRP composites in wrapped concrete columns. To response above questions, a number of CFRP coupons with different fiber orientations and various thicknesses were prepared. This experimental program is discussed in following section.

Experimental Program

Specimens Layout

A total of 24 coupon specimens of CFRP composites with a width of about 30 mm and a length of 250 mm were prepared and tested under axial tension loading. The main experimental parameters include fiber orientation and number of plies. The test program and coupon properties are summarized in Table 1. Eight coupon series (A to H) with different fiber orientations (0, 90, 0/90, 0/0, 0/0/0, ±45, +45/0/-45, and 0/±45/0) were used, also for each coupon series, three number of coupon were prepared. Figure 1 shows the typical geometry of coupon specimens. Gauge width, length, and thickness of every coupon were measured at three points and averages of them are summarized in Table 1.

Material Properties and Specimens Preparation

A unidirectional carbon fiber sheet was used to prepare the CFRP coupons. Table 2 provides the properties of carbon fibers as supplied by the manufacturer. The carbon fiber sheet was cut with scissor and impregnated with epoxy resin by the hand lay-up technique. The epoxy resin was consisted of two components, the main resin and the hardener. The mixing ratio of the components by weight was 100:15 and they were mixed for three minutes. The carbon fibers impregnated with epoxy resin and were configured as shown in Table 1. Epoxy resin should be cured in laboratory temperature (10 to 80 ^{o}C) for minimum seven days. Table 3 shows the properties of cured resin as supplied by the manufacturer. Both ends of the coupons were tabbed by 30 mm wide and 50 mm long

CFRP tabs attached by epoxy resin according to ASTM D3039/D3039M–95a standard [25] to avoid premature failure of the coupon ends. Figure 2 shows the total of 24 coupon specimens of CFRP composites.

Table 1- Test program and coupon properties

Coupon series (1)	Coupon number (2)	Number of plies (3)	Fiber orientation (4)	Gauge width (mm) (5)	Gauge length (mm) (6)	Gauge thickness (mm) (7)	Thickness per ply (mm) (8)
A	CP-A-1	1	0°	29.0	150	0.92	0.92
	CP-A-2			29.4	148	0.90	0.90
	CP-A-3			29.1	150	0.92	0.92
B	CP-B-1	1	90°	28.5	150	0.88	0.88
	CP-B-2			29.2	152	0.88	0.88
	CP-B-3			26.9	155	0.97	0.97
C	CP-C-1	2	0°/90°	30.7	150	1.85	0.93
	CP-C-2			29.2	152	1.83	0.91
	CP-C-3			28.9	150	1.83	0.91
D	CP-D-1	2	0°/0°	28.9	150	1.78	0.89
	CP-D-2			28.7	150	1.85	0.93
	CP-D-3			29.2	150	1.78	0.89
E	CP-E-1	3	0°/0°/0°	29.7	150	2.70	0.90
	CP-E-2			31.9	152	2.58	0.86
	CP-E-3			29.7	153	2.64	0.88
F	CP-F-1	2	±45°	29.6	146	1.58	0.79
	CP-F-2			25.8	150	1.68	0.84
	CP-F-3			30.0	152	1.60	0.80
G	CP-G-1	3	+45°/0°/-45°	31.4	150	2.43	0.81
	CP-G-2			34.0	150	2.43	0.81
	CP-G-3			32.4	150	2.40	0.80
H	CP-H-1	4	0°/±45°/0°	29.8	151	3.13	0.78
	CP-H-2			30.4	152	3.20	0.80
	CP-H-3			29.1	152	3.07	0.77

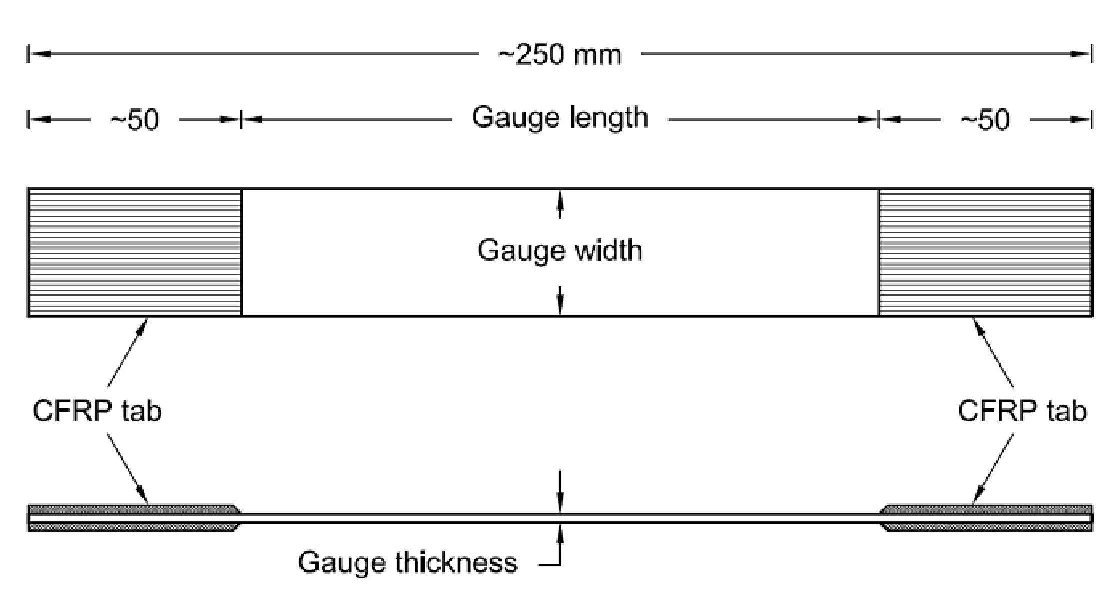
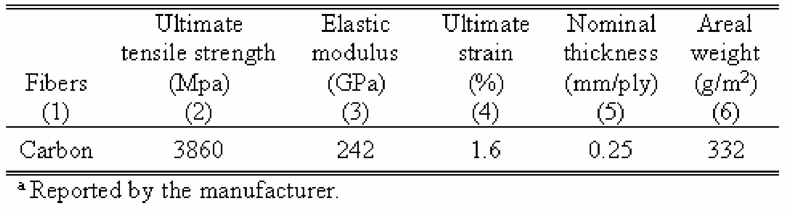


Figure 1– Typical geometry of coupon specimen

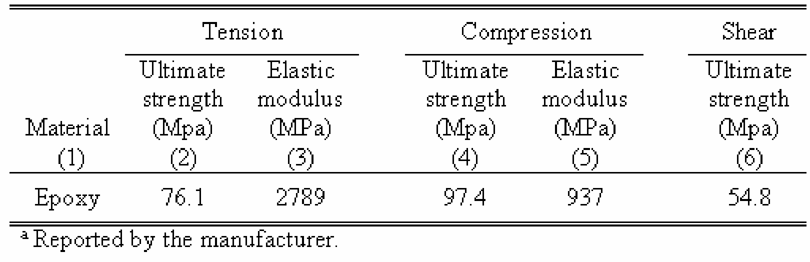
Table 2- Properties [a] of unidirectional carbon fiber sheets



Fibers (1)	Ultimate tensile strength (Mpa) (2)	Elastic modulus (GPa) (3)	Ultimate strain (%) (4)	Nominal thickness (mm/ply) (5)	Areal weight (g/m^2) (6)
Carbon	3860	242	1.6	0.25	332

[a] Reported by the manufacturer.

Table 3- Properties [a] of unidirectional carbon fiber sheets



	Tension		Compression		Shear
Material (1)	Ultimate strength (Mpa) (2)	Elastic modulus (MPa) (3)	Ultimate strength (Mpa) (4)	Elastic modulus (MPa) (5)	Ultimate strength (Mpa) (6)
Epoxy	76.1	2789	97.4	937	54.8

[a] Reported by the manufacturer.

Test Setup and Loading

A hydraulic testing machine was used with hydraulic wedge grip assemblies in the Structure Laboratory of the Amirkabir University of Technology. Top grip assembly of the machine is vertical adjustable and it is attached to an actuator, while the bottom assembly is fixed. The coupons were first aligned with the centerline of the bottom grip. Each top and bottom grip-area of the coupon was 50 mm that were griped by a pressure of 30 MPa. The coupons were tested in axial tension loading under displacement control mode with a rate of 0.5 mm/min. The force and displacement data were obtained by data collecting system of the machine during the test and were filed by computer software. The test set-up is shown in Figure 3.

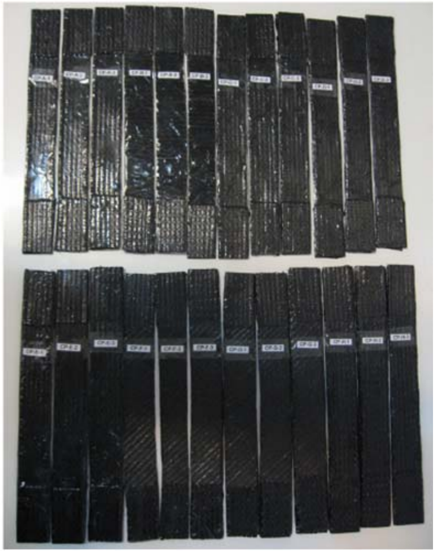


Figure 2– Total of coupons

Figure 3– Tension test set-up

Experimental Results and Discussions

Experimental load-elongation curves of series A (0), D (0/0), and E (0/0/0) are shown in Figure 4. Each curve is an average of three tested coupons with the same properties. The load-elongation curves show linear-elastic behavior up to the rupturing. With addition number of layers, stiffness and maximum load increase while maximum elongations do not change too much.

Stress and strain in coupons were calculated with gauge thickness and gauge length of every coupon (see Table 1). The nominal thickness of carbon fiber sheet was 0.25 mm/ply, which was increased to 0.77 to 0.97

mm/ply when impregnated with epoxy resin. Figure 5 shows experimental stress-strain curve of series A (0), B (90), and C (0/90). The stress-strain curve of series D (0/0) and E (0/0/0) were closed to serie A (0), the fiber orientation of these series is noted as longitudinal direction. The tensile strength of CFRP composites in longitudinal direction was established to be approximately 303 MPa based on the fiber content corresponding to 0.92 mm/ply. This observation was found to be in agreement with the 3860 MPa fiber strength reported by the manufacturer (see Table 2). The maximum tensile strain of 1.6% specified by the manufacturer was also in agreement with the average ultimate strain 0.74% recorded in coupon tests. The above mentioned values translate into an elastic modulus of 41GPa for the composite material, which is in line with 242 GPa reported for the modulus of elasticity of carbon fibers alone. Recent study by Ozbakkaloglu1 and Saatcioglu [26] has shown a similar result. Fiber orientations of series B (90) and C (0/90) are noted as matrix direction and orthotropic orientation in sequence. The stress-strain curve of matrix direction shows linear-elastic behavior up to the rupturing and for orthotropic orientation shows linear-elastic behavior up to the maximum strength and then softening behavior down to the ultimate strain. Failure mode of longitudinal and matrix directions are completely brittle rupture but orthotropic orientation has a brittle rupture with slightly softening.

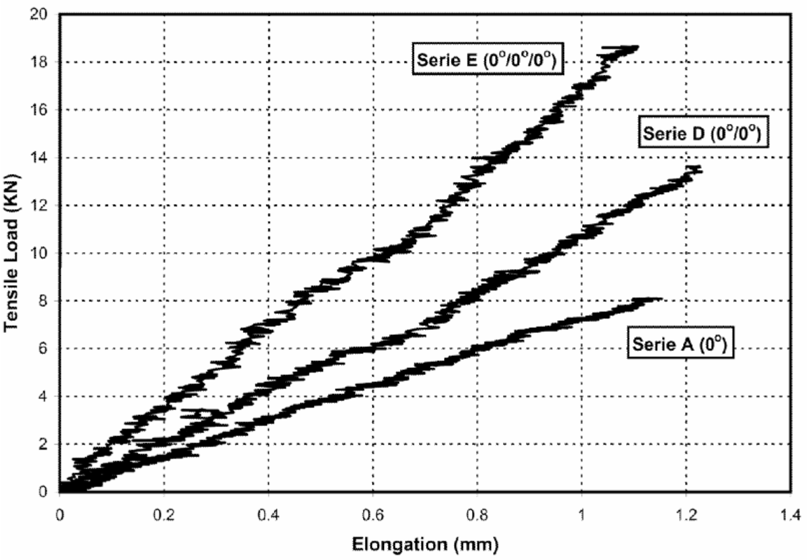


Figure 4– Experimental load-elongation curves of series A, D, and E

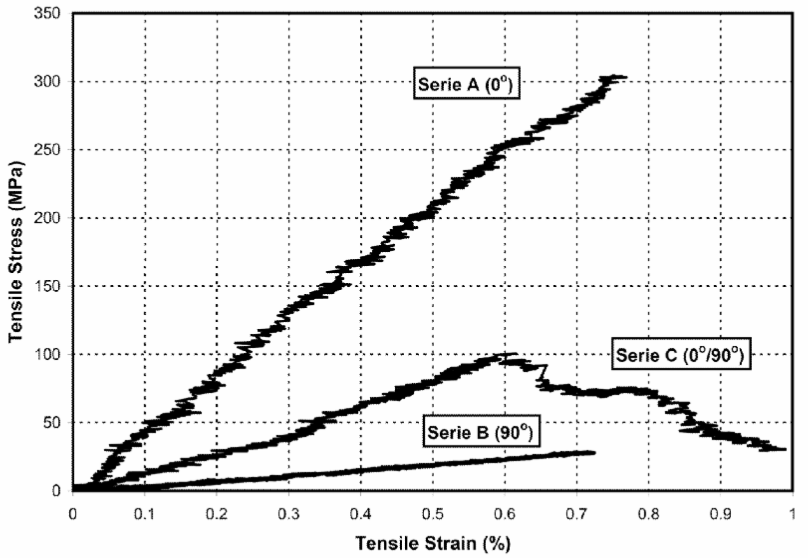


Figure 5– Experimental stress-strain curves of series A, B, and C

Figure 6 shows stress-strain curve of series A (0), F (±45), and H (0/±45/0). The stress-strain of series F (±45) and H (0/±45/0) show a nonlinear behavior that is basically different in comparison with longitudinal, matrix, and orthotropic orientations. Fiber orientation of these series is noted as angle orientation. Stiffness and ultimate strength of coupon with angle orientation are less than longitudinal direction, but strain ductility in angle orientation is further. The behavior in pure angle orientation, serie F (±45), is fully nonlinear and closed to elastic-perfect plastic, while rupture strain is about 3.5%, yield strain by offset method is about 1%, so strain ductility is calculated about 3.5 for pure angle orientation. The strain ductility (μ) as given by

$$\mu = \varepsilon_u / \varepsilon_y \tag{1}$$

where ε_u = ultimate strain; and ε_y = equal yield strain by offset method.

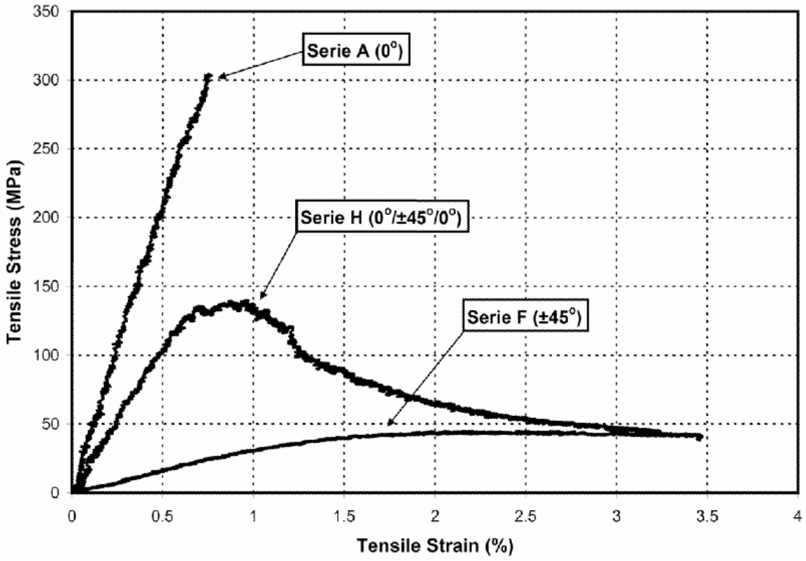


Figure 6– Experimental stress-strain curves of series A, F, and H

At combination of longitudinal and angle orientations, Serie H (0/±45/0), the stress-strain curve shows a nonlinear behavior up to a maximum strength, and then down to a ductile failure with a nonlinear softening. Table 4 shows the average results of the CFRP coupon tests. This nonlinear behavior is very important for wrapped concrete by pure angle orientation. Some available confinement models for wrapped concrete by FRP such as Samaan et al. [27] have based on linear-elastic and non-yielding behavior of FRP wrap.

Table 4- Average results of CFRP coupon tests

Fiber orientation (1)	Ultimate strength (Mpa) (2)	Tangent modulus (GPa) (3)	Ultimate strain (%) (4)	Strain ductility (5)
Longitudinal direction (0°)	303	41	0.74	1.0
Matrix direction (90°)	29	4	0.72	1.0
Orthotropic orientation (0°/90°)	100	17	0.97	1.6
Pure angle orientation (±45°)	47	4	3.50	3.5
Angle orientation (0°/±45°/0°)	140	22	3.20	3.7
Angle orientation (+45°/0°/-45°)	117	17	3.10	4.1

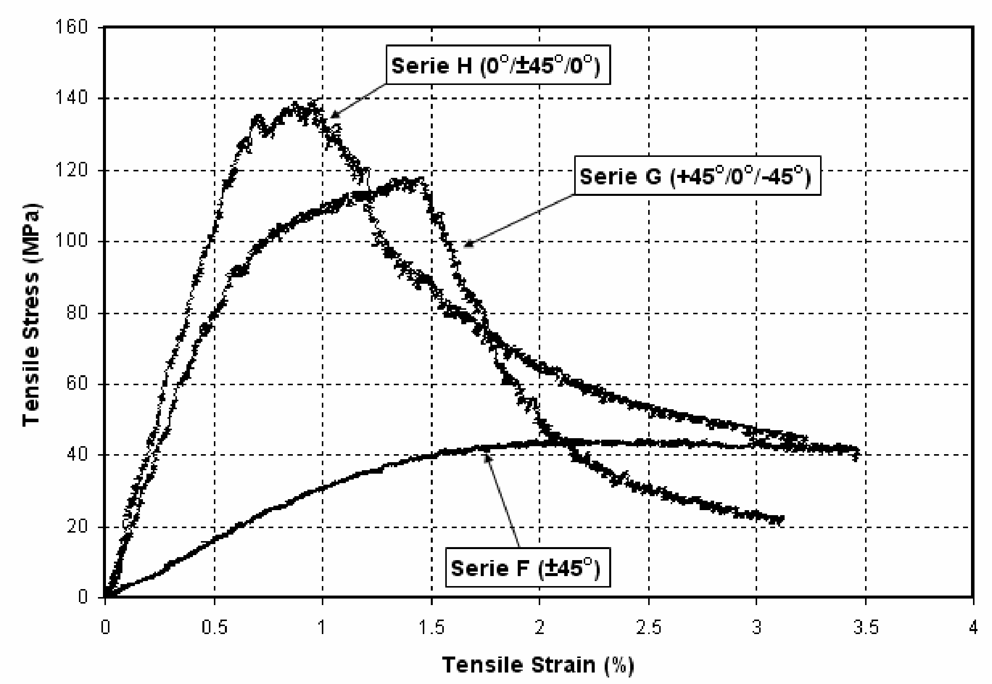


Figure 7– Experimental stress-strain curves of series F, G, and H

Figure 7 shows stress-strain curve of series B (90), F (±45), G (+45/0/-45), and H (0/±45/0). Comparison between behavior of series G and H shows that behavior of sticking together angle orientations (serie H) is better than separated angle orientations (serie G).

As this study indicates, by orienting the fibers in off-axis directions, we can get a behavior that is not linearly elastic to failure. This is a potential benefit that could be offered in making a ductile FRP. This could be great value not only for retrofit of columns but also for strengthening of flexural members, by allowing the fibers to break sequentially and thus introducing a more ductile failure. The ductile behavior of FRP composites could put forward some benefits in retrofit of walls and floors for blast loading as well as columns and beams for seismic loading.

Conclusion

In an attempt to explain effects of fiber orientation on mechanical properties of CFRP composites under axial loading, this paper has presented and compared results of axial tension testing on 24 CFRP coupons. Eight ply configurations were prepared with fiber oriented at 0, ±45 and 90 from the axial direction and with 1, 2, 3 or 4 plies. Stress-strain behavior in longitudinal direction (0) and matrix direction (90) is perfectly linear with brittle rupture, but in angle orientation (±45), shows a fully nonlinear behavior with a large plastic deformation same as elastic-perfect plastic behavior. At combinations of 0 and ±45, the stress-strain curve shows a nonlinear behavior up to a maximum strength, and then down to a ductile failure with a nonlinear softening. This is a potential benefit that could be offered in making a ductile FRP.

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