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Abstract

This paper presents the results of experimental studies about axial stress-strain behavior of retrofitted slender concrete columns with CFRP composites. In this study, 30 unreinforced concrete cylinders 100 mm diameter with variable height of 200, 400, 600, 800, and 1000 mm were prepared and retrofitted. In each group, a plain specimen (unwrapped) and five wrapped specimens with different fiber orientations (0, 0/0, 90/0, 45, and 45/0) were tested under compressive axial force up to failure. At the end, analytical models were proposed for ultimate strength and ultimate strain of the slender specimens. The results have shown that the CFRP composites are most effective in increasing the strength and ductility of slender columns.

Keywords: Concrete column, slenderness, retrofitting, CFRP, fiber orientation, strength, ductility.

1. Introduction

In recent years, retrofitting of concrete structures is the major problem of existing civil structures. Using FRP (Fiber Reinforced Polymer) wraps for retrofitting of concrete elements, especially concrete columns, is common. It is commonly accepted that the FRP wraps increase the strength and ductility of columns [1-3], But this improvements are depend on several parameters such as columns geometry, material properties, and fiber orientation of the wrap [4].

Most researches have been focused on the stress-strain model, the compressive strength, and the shape of cross section of short columns [5], so other subjects such as slenderness of columns have been ignored. The slenderness can affect on column performance as the column may become predisposed to buckling and instability when the slenderness ratio is increased. In addition, because the FRP composites have a higher strength and lower stiffness than steel jackets or steel bars, the FRP wrapped columns tend to be more susceptible to the effects of slenderness. The effects of slenderness seems to be important, while the standard design codes such as ACI 440 [6] and ISIS M04 [7] have not proposed any design criteria about the subject.

2. Background

Since first 1990's, FRP composites have been used for retrofitting of bridges and buildings, and many researches have been done about retrofitting of concrete columns with FRP composites. These researches have been mainly focused on small scale specimens under axial loading or large scale specimens under cyclic loading. There are few researches about buckling of concrete columns wrapped with FRP composites.

Mirmiran et al. [8] tested concrete-filled FRP tubes (CFFT) with slenderness proportion of 2.1 to 18.6 under axial compressive and observed maximum 20% decreasing of strength. Complementary tests were performed on CFFT by Mirmiran et al. [9] and it was observed that effect of slenderness was more on ductility and some equations were proposed for slenderness limit of columns.

In another research, Silva and Rodriguez [10] performed compressive tests on cylindrical specimens with height of 300 to 750 mm and diameter of 150 to 250 mm. The specimens were wrapped with glass FRP (GFRP) composites. It was not seen any performance degradation in their studies, in spite of Mirmiran et al. [8-9] tests results. There was no focus on slenderness and the effect of specimens dimension on compressive strength was studied generally.

Recently, a number of compressive tests were performed by Pan et al. [11] on reinforced concrete rectangular section specimens (6 specimens) with slenderness of 4.5 to 17.5 while the specimens were wrapped with carbon FRP (CFRP) composites. They were proposed equations for strength degradation of slender columns.

It is obvious that the studies are so limited and there are different ideas between researches about the effect of slenderness. So, according to previous studies, there are two basic questions about behavior of slender columns: What is slenderness effects on compressive strength and ductility of columns wrapped with FRP composites? What is fiber orientation effects on strength and ductility of slender columns wrapped with FRP composites? These subjects are considered in current study.

In this study, thirty unreinforced cylindrical specimens were wrapped with different fiber orientation of CFRP composites, and tested under compressive uniaxial loading. Main purpose of these experimental studies was to assess the effects of slenderness on strength and ductility of columns wrapped with CFRP composites under uniaxial loading. Experimental studies is explained in the below section.

3. Experimental Studies

3.1. Specimens layout

Six series of unreinforced cylindrical specimens were prepared with diameter of 100 mm and height of 200, 400, 600, 800, 1000 mm. Variables were column height (20 to 1000 mm), wrap thickness (1 and 2 layers), and fiber orientation (orientations of 0, 0/0, 0/90, 45, and 45/0). The fiber orientations were hoop, longitudinal, and angle direction which mean 0, 90, and 45 degree with respect to transverse direction respectively. Concrete strength, specimen diameter, and wrap types were constant. Five plain specimens, five specimens wrapped with one hoop layer (0), five specimens wrapped with two hoop layers (0/0), five specimens wrapped with one angle layer (45), five specimens wrapped with two longitudinal-hoop layers (90/0), and five specimens wrapped with two angle-hoop layers (45/0) were tested. Properties of specimens are shown in Table 1, where "L" is the longitudinal direction of the fibers (90), "H" is the transverse or hoop direction (0), A is the angle or diagonal direction (45), and "P" is the plain or unwrapped specimen.

3.2. Material properties

The specimens were prepared by constant concrete mixture design. The 28th day compressive strength of the concrete was 20 MPa. The unidirectional carbon fiber sheets and the epoxy resin were used to prepare of CFRP wraps. The mechanical properties of CFRP wraps have been recorded through tension tests on CFRP coupons by Sadeghian [5]. The average test results in fiber and matrix direction are shown in Table 2.

3.3. Specimens preparation

For preparing each specimen, a PVC pipe with length of the specimen's height was used. For concreting, pipes were positioned vertically and were fixed on the laboratory floor. To prevent leaking of cement paste from bottom of pipe, it was insulated by nylon. Electric vibrator was used to compact concrete and the top surface was flattened carefully. 24 hours after concreting, the PVC pipes were cut in longitudinal direction and specimens were put in curing container for 28 days.

After the curing, the specimens were dried and cleaned for wrapping with CFRP composites. The wrapping was performed based on wrap configuration of the Table 1 by hand lay up technique. At first, carbon sheets were cut to necessary dimension with 50 mm overlapping in fiber direction. Then surface of specimens was covered with the epoxy resin and after carbon sheets were saturated by the resin, the composites were wrapped around the specimens and carefully vacuumed.

3.4. Test setup and loading

The specimens were tested by 2500 KN test machine under axial compressive loading up to failure. The test was performed in displacement control condition with rate of 0.1 mm/min. During the test, axial force and axial displacement were measured and saved by digital data collecting system of the test machine. In addition, hoop strain at middle height of the specimen was digitally recorded by a chain strain gauge. Also, lateral displacements at the middle height were digitally measured by four orthogonal potentiometers.

4. Experimental Results and Discussion

After data processing, the axial stress-strain curves of specimens have been drawn to consider the effects of slenderness ratio on retrofitted concrete columns and the fiber orientation effects on strength and ductility of the slender columns. The slenderness ratio is defined as L/D, where L is height of specimen and D is diameter of specimen. In the current paper, the stress-strain behavior of the specimens has been discussed and other results will be considered in another paper.

4.1. Fiber orientation effects

The axial stress-strain curves of specimens with height of 200 mm (L/D=2) have been shown in Figure 1, to consider the effect of fiber orientation on short specimens. In this Figure, the plain (unwrapped) specimen has a brittle failure with maximum stress of 20 MPa. The strain of the softening branch is about 0.48% at the stress point of 17 MPa. This strain happens at stress of 85 percent of maximum stress that is called ultimate strain of plain concrete.

The behaviors of wrapped and plain specimens have been basically the same up to stress point of about 20 MPa, but after that, the wrapped specimens' curve continued with a second slope until the rupture of the wrap happened. Generally, the performance of wrapped concrete depends to volume dilation of concrete core, because the wrap is activated when the concrete core begins to expand. This volume dilation has a constant ratio in linear behavior zone of the concrete core, because Poisson ratio is constant in this zone. So, there is no expectation of high activation of the wrap in linear behavior zone of the concrete core. As a result, the behaviors of wrapped and plain concretes are similar during increasing of stress up to the ultimate strength of the plain concrete. After that, the wrap is effectively activated and based on the wrap stiffness; the performance is improved with a second slope up to the failure at ultimate strength.

Figure 1 shows that, the second slope is constant in the wrapped specimens with hoop layers. The ultimate strength is increased from 20 (plain) to 40 MPa using one hoop layer (specimen S2-H), so there is 100% increasing. The ultimate strength is increased 125 percent, from 20 to 50 MPa, in two hoop layer condition (specimen S2-HH). In these two specimens when the wrap is broken, brittle failures happen suddenly. The ultimate strains are 1.43% and 2.12% for S2-H and S2-HH respectively. It shows that strain ductility of the specimens increase to 3.0 and 6.5 respectively. The strain ductility is defined as

$$\mu = \frac{\varepsilon_{cc}}{\varepsilon_{co}} \qquad (1)$$

Where μ is the strain ductility of wrapped concrete, ε_{cc} is the ultimate strain of wrapped concrete, and ε_{co} is the ultimate strain of plain concrete.

Based on Figure 1, there is no difference between the ultimate strength of specimens S2-LH and S2-AH comparing to S2-H, but the failure of these specimens (specially S2-AH) happens step by step and a suddenly failure doesn't be seen. So the energy absorption increase is more in the specimen with angle orientation (S2-AH). The stress-strain behavior of the specimen wrapped with pure angle orientation (S2-A) is totally different comparing with other specimens. As it shows in the Figure 1, the ultimate strength of S2-A is not different in comparison with the plain specimen, but its failure mode indicates that energy absorption capacity or the ductility of the specimen is much more. This capacity is important for seismic retrofitting of concrete columns.

4.2. Slenderness effects

In this section, the effect of slenderness on the stress-strain behavior of various specimens is studied. The effect of slenderness on plain specimens is shown in Figure 2(a). The ultimate strength for the specimen with height of 200 (S2-P) is about 20 MPa, but it is decreased when the slenderness is increased. The ultimate strength is decreased to about 12 MPa (40% reducing) in height of 1000 mm (S10-P). A plain specimen with height of 800 mm (S8-P) was crashed during transportation and it was not tested. As it is shown in Figure 2(a), with increase of slenderness ratio from 2 to 10, the strain at level of 5 MPa is decreased from 0.79% to 0.22%. On the other hand, the ductility decreases when the slenderness ratio increases, but the effect of slenderness on the ductility of specimens is more than the ultimate strength.

The effect of slenderness on the specimens wrapped with one and two layers in hoop direction (H and HH) are shown in Figure 2(b) and 2(c). The ultimate strengths have no important decrease with increasing of slenderness ratio. On the other hand, the ultimate strength is improved by the hoop orientation. The ultimate strains of H and HH decrease more slowly than the plain specimens, when the slenderness is increased. So the failure mode is improved and the energy absorption capacity is increased using the hoop orientation.

The effect of slenderness on the specimens wrapped with longitudinal-hoop (LH) is studied in Figure 2(d). It is observed that LH orientation like H orientation improves the ultimate strength of slender specimens, while the ductility shows a little decrease in specimens with LH orientation.

Figure 2(e) shows the effect of slenderness on specimens wrapped with pure angle orientation (A). It shows, when the slenderness ratio increases, the ultimate strength is constant. On the other hand, wrapping with angle orientation can improve the ultimate strength of slender specimens and remove the effects of slenderness. The angle orientation can't increase the ultimate strain similar to other orientations. This effect is explained by large deformation of slender specimens wrapped with angle orientation in low stress levels. The large deformation produces second moment that induces the early failure for the specimens. Even though in the hoop orientations, the large deformations happen on high stress levels, so the energy absorption capacity increase in compare with other fiber orientations.

The specimens wrapped with angle-hoop (AH) orientation are studied in Figure 2(f). Similar to the angle orientation, it is observed that AH orientation improves the ultimate strength of the slender specimens (except S4-AH and S6-AH), while the ductility shows some ambiguity. So there is a need for more research on this orientation.

The stress-strain behavior of the most slender specimens with the slenderness ratio of 10 is shown in Figure 3. It shows that the ultimate strength and strain reduce 38% and 60% respectively in the plain specimens, when the slenderness ratio increases from 2 to 10. Also it shows the CFRP wraps are so useful for improvement of strength and ductility of the slender specimens.

5. Analytical Modeling

In this section, analytical models are proposed for the ultimate strength and the ultimate strain of slender specimens. The experimental results are summarized in the Table 3, which shows considerable increase in the strength and ductility of slender specimens wrapped with CFRP wraps. Figure 4 shows the normalized ultimate strength ($f'_{cc} / \bar{f}'_{cc}$) versus the slenderness ratio (L/D), where f'_{cc} is the ultimate strength of the slender specimen and $\bar{f}'_{cc}$ is the ultimate strength of the corresponding short specimen with the same fiber orientation (H, HH, and LH). Based on the figure, the parabolic Equation 2 is proposed for the ultimate strength of the slender specimens by regression analysis. A good correlation is noted with $R^2 = 86\%$.

$$f'_{cc} = \bar{f}'_{cc}\left[0.0079\left(\frac{L}{D}\right)^2 - 0.1030\left(\frac{L}{D}\right) + 1.1699\right] \quad (2)$$

Similarly, Figure 5 shows the normalized ultimate strain ($\varepsilon_{cc} / \bar{\varepsilon}_{cc}$) versus the slenderness ratio (L/D), where ε_{cc} is the ultimate strain of the slender specimen and $\bar{\varepsilon}_{cc}$ is the ultimate strain of the corresponding short specimen with the same fiber orientation. The following relationship (Equation 3) is proposed for the ultimate strain of the slender specimens with $R^2 = 96\%$. It shows an approximately linear reduction in the ultimate strain in slender specimens.

$$\varepsilon_{cc} = \bar{\varepsilon}_{cc}\left[0.0005\left(\frac{L}{D}\right)^2 - 0.0452\left(\frac{L}{D}\right) + 1.0792\right] \quad (3)$$

The Equation 2 and Equation 3 show respectively 9% and 42% reduction in the ultimate strength and strain of the specimens wrapped with H, HH, and LH fiber orientation, when slenderness ratio increases from 2 to 10.

6. Conclusion

In this research with the purpose of investigation of slenderness effects on concrete column wrapped with CFRP composites, 30 unreinforced concrete specimens with diameter of 100 mm and height of 200, 400, 600, 800, 1000 mm (slenderness ratio of 2, 4, 6, 8, and 10) were prepared and wrapped with unidirectional CFRP composites, in each slenderness ratio. A plain specimen (unwrapped) and five specimens wrapped with various fiber orientations (0, 0/0, 90/0, 45, and 45/0) were tested under the uniaxial compressive force up to failure. Results showed that strength and ductility of the plain specimens reduced 38% and 60% respectively when the slenderness ratio increased from 2 to 10. But they were averagely 9% and 42% for the wrapped specimens (0, 0/0, and 90/0). The angle orientation can improve the ultimate strength of slender specimens and remove the effects of slenderness. The behavior of specimens wrapped with (45/0) orientation had some ambiguity, so there is a need for more research on this orientation. At the end, analytical models were proposed for the ultimate strength and strain of slender specimens. Using the CFRP composites is so effective approach to improve strength and ductility of slender concrete columns.

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Table 1. Properties of experimental specimens

Height (mm)	L/D [a]	Fiber orientation					
		P (Plain)	H (0)	HH (0/0)	LH (90/0)	A (45)	AH (45/0)
200	2	S2-P	S2-H	S2-HH	S2-LH	S2-A	S2-AH
400	4	S4-P	S4-H	S4-HH	S4-LH	S4-A	S4- AH
600	6	S6-P	S6-H	S6-HH	S6-LH	S6-A	S6-AH
800	8	S8-P	S8-H	S8-HH	S8-LH	S8-A	S8-AH
1000	10	S10-P	S10-H	S10-HH	S10-LH	S10-A	S10-AH

[a] Slenderness ratio (height/diameter)

Table 2. Average results of CFRP coupon tension tests (per layer) [5]

Test direction	Ultimate strength (MPa)	Elastic modulus (MPa)	Ultimate strain (%)	Thickness (mm)
Fiber direction	303	41000	0.74	0.90
Matrix direction	29	4000	0.72	0.91

Table 3. Ultimate strength and ultimate strain of specimens

Slenderness ratio (L/D)	Fiber orientation											
	P		H		HH		HL		A		AH	
	f'_{co} (MPa)	ε_{co} (%)	f'_{cc} (MPa)	ε_{cc} (%)	f'_{cc} (MPa)	ε_{cc} (%)	f'_{cc} (MPa)	ε_{cc} (%)	f'_{cc} (MPa)	ε_{cc} (%)	f'_{cc} (MPa)	ε_{cc} (%)
2	19.5	0.48	39.2	1.43	49.3	2.12	38.3	1.70	20.1	1.00	38.9	1.39
4	18.5	0.33	37.4	1.18	43.3	1.88	31.6	1.42	20.3	0.30	23.9	1.60
6	14.9	0.32	35.5	0.93	44.2	2.15	23.6	1.45	20.9	0.58	29.2	0.89
8	13.5	0.26	36.1	0.82	49.6	1.75	28.5	1.02	17.9	0.87	40.5	1.43
10	12.0	0.19	33.5	0.79	47.5	1.32	35.5	0.98	19.3	0.35	39.0	1.51

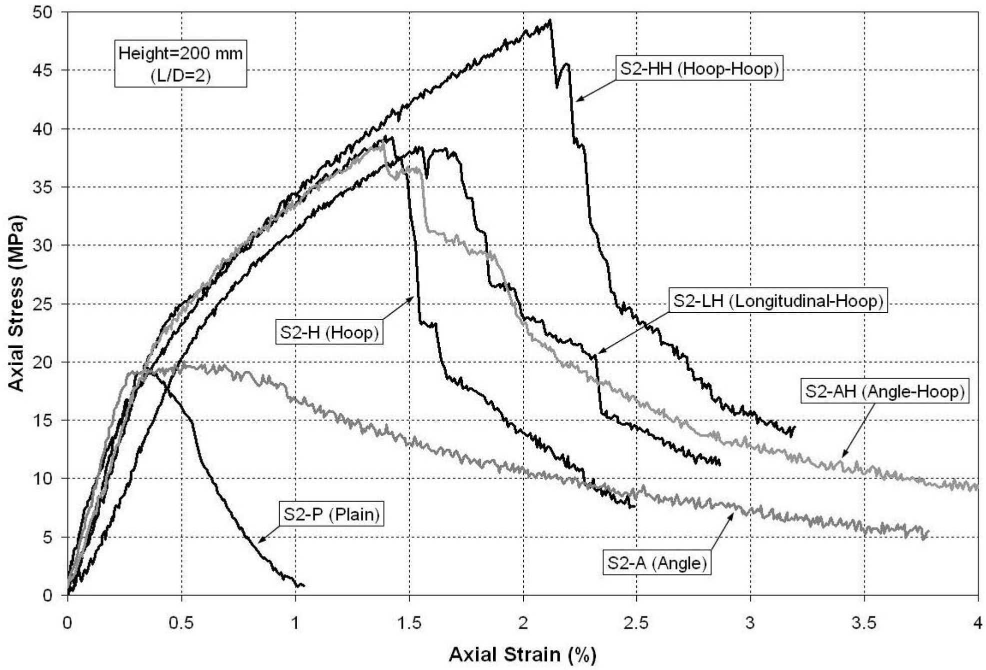

Figure 1. Effect of fiber orientation on stress-strain behavior of short specimens
309x211mm (96 x 96 DPI)

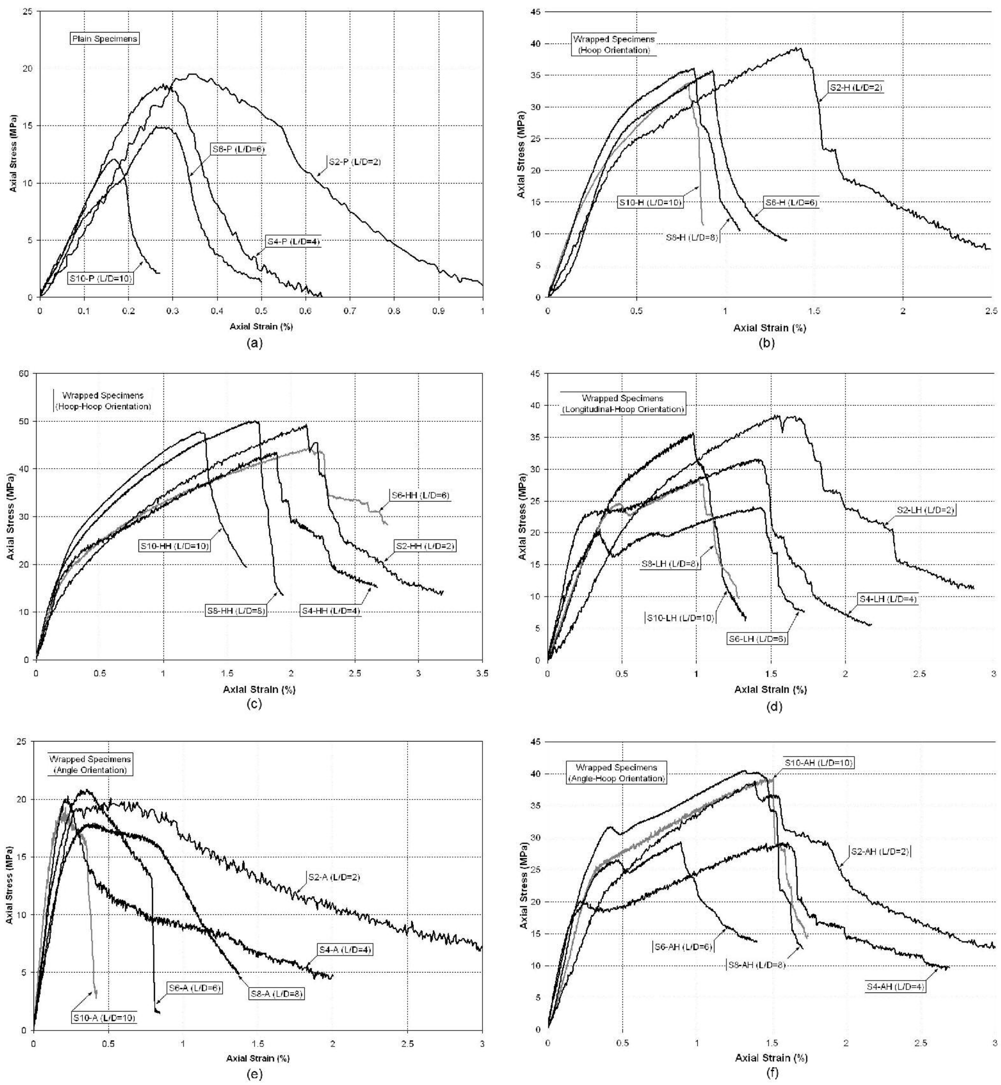

Figure 2. Effects of slenderness on stress-strain behavior of specimens
629x690mm (96 x 96 DPI)

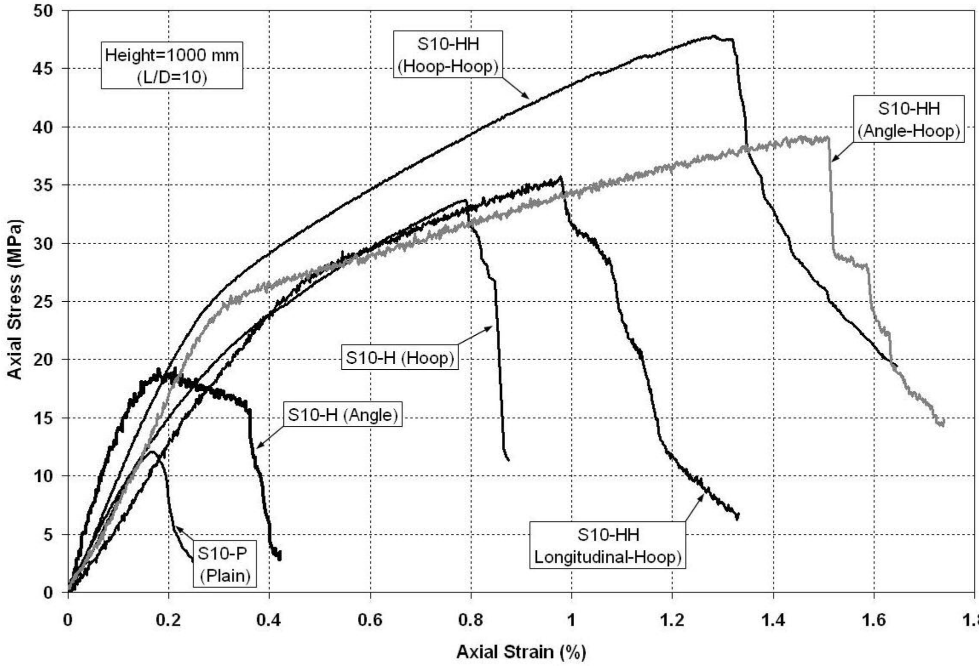

Figure 3. Stress-strain behavior of the most slender specimens
310x210mm (96 x 96 DPI)

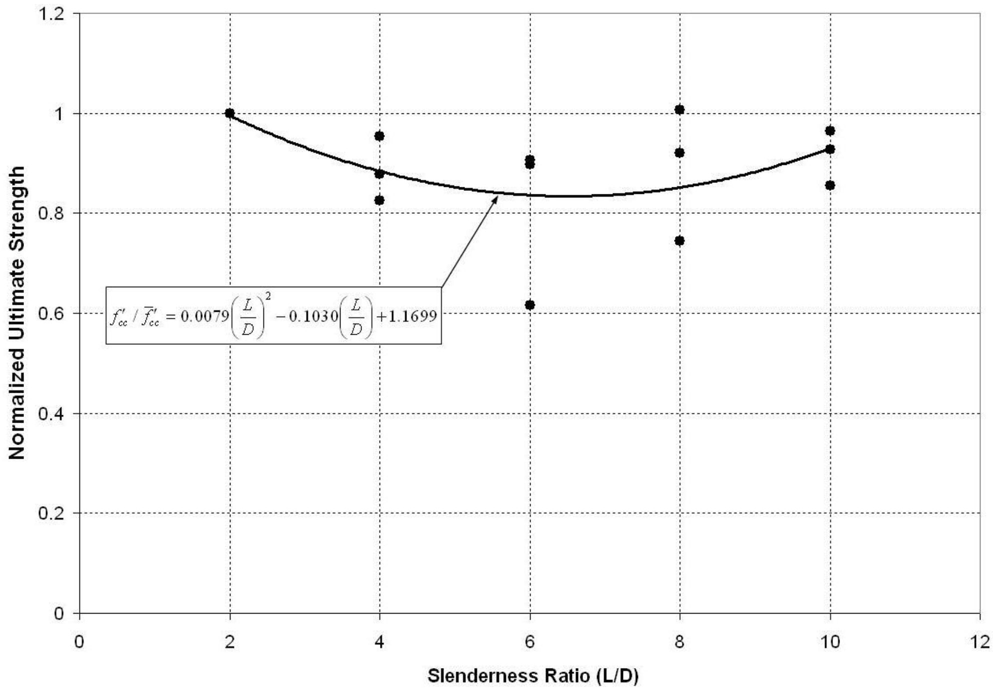

Figure 4. Normalized ultimate strength versus slenderness ratio
300x213mm (96 x 96 DPI)

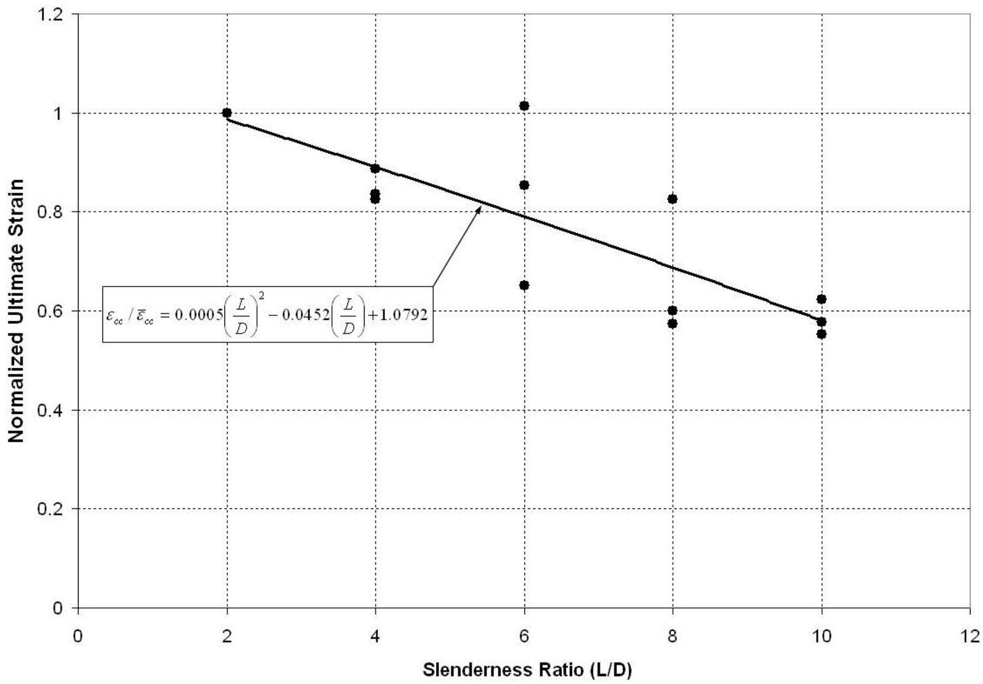

Figure 5. Normalized ultimate strain versus slenderness ratio
303x214mm (96 x 96 DPI)