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Design and Analysis of Composite Wraps for Concrete Columns

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Composite jackets for concrete columns can potentially renew deteriorated structures and improve seismic resistance. Several experimental investigations have demonstrated that composite wraps increase load-carrying capacity and ductility of concrete columns subjected to axial compression. This paper describes a theoretical model to predict the nonlinear stress-strain response of the wrapped columns as a function of geometry and the constitutive behavior of the concrete and column wrap. Model predictions are compared to experimental results. The analytical equations can be used to develop relevant guidelines for optimum reinforcement efficiency as a function of column size and wrap architecture.

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DESIGN AND ANALYSIS OF COMPOSITE WRAPS FOR CONCRETE COLUMNS

1. INTRODUCTION

Recent studies [Fyfe 1994; Seible and Priestley 1993] have shown that composites can be effective and cost-efficient materials for repairing and strengthening bridge supports. While steel jackets have been used extensively to strengthen bridge columns [Taylor and Stone 1993], composite jackets may prove to be superior for concrete columns due to their lower density, increased corrosion resistance, and ease of installation. Studies by Karbhari et al. [1993] have shown that concrete cylinders wrapped with composites exhibit much higher strength and ductility than do baseline cylinders (with no wrap). In this report, the stress state in a concrete cylinder with a composite wrap is evaluated, and the resulting nonlinear response is compared to experimental results from a separate study [Howie and Karbhari 1994]. The theoretically based solution in this report is developed to offer a predictive capability for the mechanical behavior of columns of different scale or with different constituent materials.

1.1 Background

Howie and Karbhari [1994] have conducted an extensive experimental study of the compressive strength of composite wrapped concrete cylinders. In their study, relatively small diameter (15.24 cm) concrete cylinders 30.48 cm long were wrapped with graphite fiber-reinforced epoxy (0.254 mm thick). The composite wrap extended from 1.27 cm (0.5 in) below the top of the cylinder to 1.27 cm above the bottom. The cylinders were loaded in compression in the axial direction until failure, and stress versus strain curves were generated, as shown in Figure 1. The unreinforced concrete exhibited linear elastic behavior until failure; once the brittle material began to crack, failure was catastrophic. The average failure strength of the unreinforced concrete was 38.6 MPa (5.6 kips/in^2 [ksi]). The cylinders with composite wraps generally displayed a two-stage failure process: they responded elastically until they reached a stress slightly higher than the failure strength of the unreinforced concrete, then displayed nonlinear response until final failure, exhibiting substantial ductility. For a specimen with four layers of hoop wrap (see Figure 1), for example, nonlinear response begins at a stress level σ_A (30% greater than the baseline strength of unreinforced concrete). The composite wrap retains structural integrity until catastrophic failure occurs at a stress level σ_B which is 120% greater than the baseline strength.

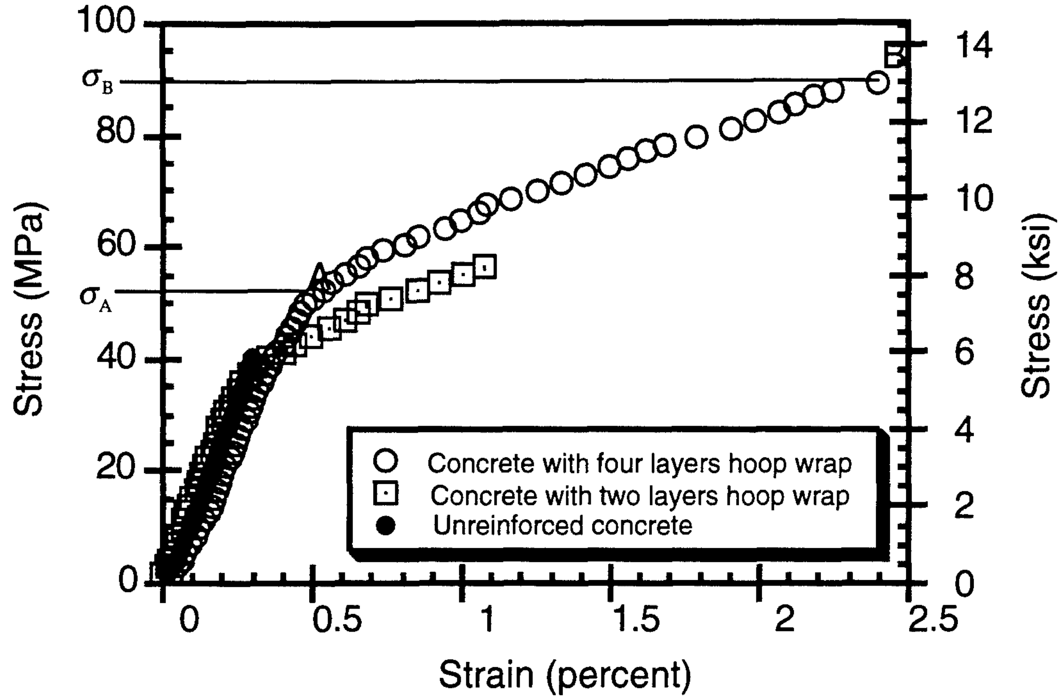

Figure 1. Stress versus strain curves for unreinforced concrete and concrete with composite hoop wrap. (Note that the concrete typically displayed some scatter in the elastic modulus.)

During the wrapped cylinder tests, it was observed that at the point of onset of nonlinear behavior (σ_A on Figure 1), the concrete began to fail and that beyond this stress, the composite wraps held the cylinders together. Catastrophic failure occurred when the wrap fractured. These observations are important for the design of concrete structures wrapped with composite materials. The stress at which the concrete begins to fail (σ_A) represents a design limitation for axial stress. The failure stress (σ_B) represents the maximum stress that the structure can support. The difference in the strains at points A and B is a measure of the ductility of the column. The first part of the analysis described in the next section concerns the effects of the composite wrap on the stress state within the column until the stress is reached at which the concrete begins to fail (σ_A); the second part analyzes the final failure of the wrapped system.

2. ANALYSIS

2.1 Stress at Which the Concrete Fails

When a wrapped concrete column is loaded in axial compression, the concrete expands against the wrap due to Poisson's expansion, and a hydrostatic pressure state is developed in the concrete. Hydrostatic pressure has been shown to increase the compressive strength of geological materials [Heard 1963], polymers [Pae and Bhateja 1975], and composites [Sigley et al. 1991; Hoppel et al. 1995]. Physically, hydrostatic pressure increases compression strength during these conditions by reducing the shear stress state and suppressing crack initiation in the material. In concrete, Richart et al. [1928] originally proposed that the compressive strength increased linearly with increasing hydrostatic pressure according to Equation 1. Later studies [Newman and Newman 1969; Avram et al. 1981] showed that a linear rule such as Equation 1 overestimated the strength of concrete under high hydrostatic pressure, and thus the nonlinear form shown in Equation 2 was proposed as it provided a better fit to the experimental data.

$$\sigma_c(P) = \sigma_c(0) + 4.1 * \mathrm{P} \qquad (1)$$

$$\sigma_c(P) = \sigma_c(0) + 3.7(\sigma_c(0))\left(\frac{\mathrm{P}}{\sigma_c(0)}\right)^{0.86} \qquad (2)$$

In Equations 1 and 2, $\sigma_c(P)$ is the compressive failure strength of the concrete subject to hydrostatic pressure, P is the hydrostatic pressure, and $\sigma_c(0)$ is the baseline compressive failure strength of the concrete at atmospheric pressure (P=0). Note that when the hydrostatic pressure is low (less than half the compressive strength of the concrete), Equations 1 and 2 predict similar strength values.

The objective of the first part of this analysis is to relate the hydrostatic pressure state of the concrete within the composite wrap to the axial stress applied to the column. Then, through Equation 2, the axial stress at which damage initiation occurs (σ_A on Figure 1) can be explicitly determined. The hydrostatic pressure in a wrapped cylinder can be ascertained by determining the radial stress in the concrete cylinder, subject to hoop confinement. Assuming that axisymmetrical behavior holds, Figure 2 shows the pertinent free body diagrams for sections of the concrete and the composite wrap. At the interface between the concrete cylinder and the wrap ($r = r_O$), compatibility of the radial displacements for the concrete (U_r^c) and the wrap (U_r^w) requires that

$$U_r^c = U_r^w . \qquad (3)$$

Based on Equation 3 and the following strain-displacement relationship for axisymmetric bodies, the strain in the hoop direction can be calculated.

$$\varepsilon_\theta = \frac{U_r}{r} \qquad (4)$$

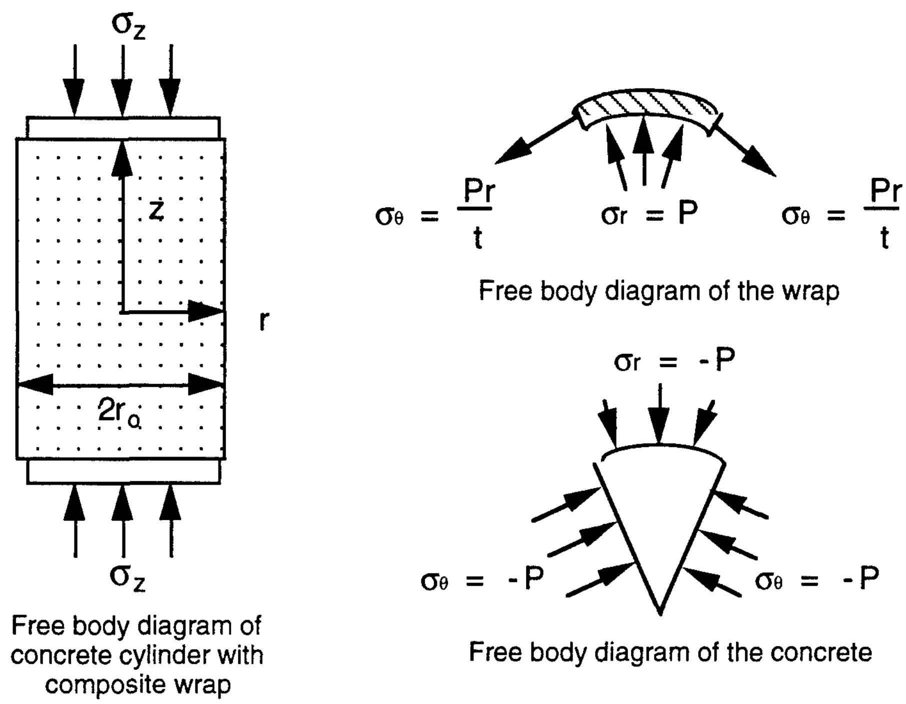

Figure 2. Free body diagrams. (Note that the coordinate system is shown on the diagram on the left and that the two coordinate systems on the right do not show the axial stresses (σ_Z).)

The strains in the hoop direction in the concrete and composite wrap must be equal at the interface.

$$\varepsilon_\theta^c = \varepsilon_\theta^w \text{ (at } r = r_O) \tag{5}$$

For linear elastic response, it can be shown from Hooke's law [Timoshenko and Goodier 1970] that in the wrap the hoop strain is given by Equation 6.

$$\varepsilon_\theta = \frac{\sigma_\theta}{E_\theta} - \frac{\sigma_z}{E_z}\nu_{z\theta} - \frac{\sigma_r}{E_r}\nu_{r\theta} \tag{6}$$

in which the z subscript indicates the axial direction.

In the concrete, the radial stress is equal to the radial pressure applied by the wrap (-P). The hoop stress is equal to the radial stress at all points and will also equal -P. If the concrete cylinder was not solid, this assumption would not be valid [Hearn 1977].

The axial stress (σ_z) in the cylinder will depend on the amount of load transferred to the wrap. Assuming that the wrap is perfectly bonded to the concrete and the cylinder is long, the axial strain will be the same in each of the constituents and the amount of load carried by the wrap can be described by the rule of mixtures [Agarwal and Broutman 1980]. The effective axial elastic modulus ($E_z^{eff.}$) for the wrapped concrete column can be expressed by Equation 7.

$$E_z^{eff.} = E_c A_c + E_z^w A_w \tag{7}$$

in which E_c and E_z^w are the elastic moduli of the concrete and wrap in the axial direction, respectively, and A_c and A_w are the cross-sectional area fractions of the concrete and wrap, respectively. The axial stress in each of the constituents can then be obtained from Equations 8a and 8b:

$$\sigma_z^c = -\frac{E_z^c}{E_z^{eff}} \sigma_z^o \tag{8a}$$

$$\sigma_z^w = -\frac{E_z^w}{E_z^{eff}} \sigma_z^o \tag{8b}$$

in which σ_z^o is the applied axial stress, σ_z^c is the axial stress in the concrete, and σ_z^w is the axial stress in the wrap.

The hoop strain in the concrete can be ascertained by substituting the three stresses (σ_z^c, σ_θ^c, σ_r^c) into Equation 6 and simplifying the equation:

$$\varepsilon_\theta^c = -\frac{P}{E_c} + \frac{\sigma_z^o}{E_z^{eff.}} \nu_c + \frac{P}{E_c} \nu_c \tag{9}$$

in which ν_c is Poisson's ratio for the concrete.

The wrap on the cylinder is assumed to have a thickness much smaller than its mean radius (r), and thus, it can be described as a thin shell. The hoop stress in the wrap then becomes Equation 10.

$$\sigma_\theta^w = -\frac{Pr}{t} \tag{10}$$

in which P is the radial pressure, r is the mean radius of the cylinder, and t is the thickness of the wrap. Substituting the axial and hoop stresses defined in Equations 8b and 10 into Equation 6, the hoop strain in the wrap can be defined by Equation 11.

$$\varepsilon_\theta^w = \frac{Pr}{tE_\theta^w} + \frac{\sigma_z^o}{E_z^{eff}} \nu_{z\theta} \tag{11}$$

Combining Equations 5, 9, 11, and 2, an expression relating the hydrostatic pressure (P) in the concrete cylinder to the other material and geometric quantities is obtained.

$$\frac{Pr}{tE_\theta^w} + \frac{P}{E_c}(1-\nu_c) = \frac{\sigma_c(0) + 3.7(\sigma_c(0))\left(\frac{P}{\sigma_c(0)}\right)^{0.86}}{E_z^{eff}}(\nu_c - \nu_{z\theta}) \tag{12}$$

A computer program has been written to solve Equation 12 for the pressure (P) as a function of the material properties of the concrete and the composite wrap. Once the pressure at onset of failure is known, it can be substituted into Equation 2 to compute the axial stress at which the concrete begins to fail in the presence of the wrap.

2.2 Simplified Solution

Equation 12 gives the pressure state in the concrete cylinder under the assumption that the wrap is perfectly bonded to the concrete along the entire length of the column. If the wrap is not bonded to the concrete or if the product of the axial stiffness and the area fraction of the wrap is much less than the product of the axial stiffness and the area fraction of the concrete ($\frac{E_z^w A_w}{E_z^c A_c}$ << 1), then it can be assumed that the axial load carried by the wrap is negligible and the axial stress in the concrete is equal to the applied stress σ_z^o. Furthermore, it will be assumed that the pressure is much less than the compressive failure strength of the concrete (P << $\sigma_c(0)$) so that Equation 1 is valid. Equations 9 and 11 then simplify to

$$\varepsilon_\theta^c = -\frac{P}{E_c} + \frac{\sigma_z^o}{E_c}\nu_c + \frac{P}{E_c}\nu_c \tag{13}$$

$$\varepsilon_\theta^w = \frac{Pr}{tE_\theta^w}. \tag{14}$$

Substituting Equations 13 and 14 into Equation 5, and substituting σ_z^o from Equation 1 into this result, Equation 15 is obtained.

$$\frac{PrE_c}{E_\theta^w t} + P - 5.1P\nu_c = \sigma_c(0)\nu_c \tag{15}$$

Poisson's ratio for concrete is approximately 0.22, making the terms ($P - 5.1P\nu_c$) small compared to the other terms. Neglecting these terms, the following expression for the hydrostatic pressure at the onset of failure in the concrete is obtained.

$$P = \sigma_c(0)\, \nu_c \frac{t}{r} \frac{E_\theta^w}{E_c} \tag{16}$$

The expression for the corresponding axial stress (σ_A) can then be determined by substituting Equation 16 into Equation 1:

$$\frac{\sigma_A}{\sigma_c(0)} = 1 + 4.1\nu_c \frac{t}{r} \frac{E_\theta^w}{E_c} \tag{17}$$

Equation 17 clearly shows the important role of geometry, size, and material properties on the strength of the wrapped column, providing insight into scaling and wrap design.

Since the concrete and wrap are assumed to behave elastically for stresses as great as σ_A, the axial strain ε_z^A corresponding to σ_A is defined as the stress at point A divided by the effective elastic modulus of the column in the axial direction (from Equation 7).

$$\varepsilon_z^A = \frac{\sigma_A}{E_z^{eff}} \tag{18}$$

2.3 Nonlinear Response of Wrapped Column

In the experimental work conducted by Howie and Karbhari [1994], final fracture of the wrapped cylinders was observed to occur when the composite wrap failed in the hoop direction. The concrete inside the wrap was already reduced to rubble and did not have any residual axial strength. To develop an analytical model of this failure process, it is assumed that failure of the system is governed by failure of the wrap in the hoop direction.

The relation between the radial pressure induced in the concrete by the wrap and the hoop stress in the wrap is given by Equation 10. The next step in the analysis is to predict the axial stress-strain behavior of the confined concrete. Work in the literature [e.g., Chen and Yamaguchi 1985] indicates that concrete subjected to uniaxial compressive stress generally displays strain-softening behavior after the onset of failure. However, concrete subject to axial stress and confined in the transverse directions [Chen and Yamaguchi 1985; Buyukozturk and Chen 1985] displays strain-hardening behavior after the onset of failure. It has also been noted [Avram et al. 1981] that Poisson's ratio for concrete increases as cracks form. Initially, the Poisson's ratio will be low (approximately 0.2) due to the highly compressible nature of the cement paste [Chen and Yamaguchi 1985]; however, as cracks form, the ratio increases to 0.5, indicating that the concrete behaves as an incompressible material.

The nonlinear behavior of the concrete used in the present study was not evaluated. Therefore, to obtain a conservative estimate of the behavior of the concrete, it is assumed that at the onset of failure (σ_A on Figure 1), the concrete completely reduces to rubble and subsequently behaves as an incompressible material ($\nu_c = 0.5$). In this regime, all additional applied stress is transferred directly to the composite wrap. This approach is conservative because the possible strain-hardening behavior of the concrete (and the additional load-carrying capacity) is neglected.

The stress at which the wrapped cylinder fails can then be represented as follows:

$$\sigma_B = \sigma_A + \Delta\sigma \qquad (19)$$

in which σ_B is the stress in the wrapped cylinder at ultimate failure, σ_A is the stress at which the concrete failed (Equation 17), and $\Delta\sigma$ is the stress increment between initial failure (A) and final wrap failure (B). For an incompressible material, $\Delta\sigma$ can be expressed in terms of the hydrostatic pressures at points A and B. It is recognized that the pressure acting on the wrap at point B is sufficient to cause wrap failure in the hoop direction.

$$\Delta\sigma = P_B - P_A \qquad (20)$$

The failure stress for the wrapped column can then be calculated by substituting the pressure at point A (from either Equation 12 or 16) and the pressure at failure of the wrap into Equation 20, then substituting $\Delta\sigma$ and σ_A into Equation 19. If the axial load carried by the wrap is low (e.g., if the wrap has all the plies oriented in the hoop direction), then the Equations developed in Section 2.2 can be used, and the failure strength of the column can be expressed by Equation 21.

$$\sigma_B = \sigma_c(0) + 3.1\nu_c \frac{t}{r}\frac{E_\theta^w}{E_c}\sigma_c(0) + \frac{X_\theta^w t}{r} \qquad (21)$$

in which X_θ^w is the strength of the wrap in the hoop (θ) direction.

2.4 Strain at Which the Wrapped Column Fails

The strain to failure for the wrapped column can also be predicted using the assumption of incompressibility, i.e., the volume of the wrapped cylinder does not change between stress levels σ_A and σ_B.

The length of the cylinder at point A (L_A) is calculated from the original length of the cylinder (L_O) minus the displacement due to the axial strain (Equation 18):

$$L_A = L_O (1 - \varepsilon_z^A) \tag{22}$$

The radius of the cylinder at point A (r_A) is equal to the original radius plus the radial displacement U_r^A:

$$r_A = r_o + U_r^A \tag{23}$$

U_r^A is equal to the radius of the cylinder times the hoop strain in the cylinder at point A (given in Equation 9). The corresponding cylinder volume at point A can then be calculated with Equation 24:

$$V_A = L_A\left(\pi r_A^2\right) \tag{24}$$

At point B, the hoop strain in the wrap (ε_θ^B) is assumed to be equal to the failure strain of the composite in the hoop direction. The maximum radial displacement U_r^B in the cylinder at point B is then equal to the hoop strain in the wrap ε_θ^B times the radius of the cylinder r_B (by Equation 4). Thus, r_B can then be expressed by Equation 24.

$$r_B = r_o + U_r^B \tag{25}$$

Due to incompressibility at σ_B, the volume of the cylinder V_B is assumed equal to V_A. Therefore, the length of the cylinder at point B can be expressed as follows:

$$L_B = \frac{V_A}{\pi r_B^2}. \tag{26}$$

The axial strain ε_z^B at point B is then equal to the change in length of the cylinder divided by the original cylinder length.

$$\varepsilon_z^B = \frac{L_o - L_B}{L_o} \tag{27}$$

Substituting Equations 22 through 26 into Equation 27 and simplifying terms, an expression for the strain to failure of the wrapped column can be derived:

$$\varepsilon_z^B = 1 - \frac{\left(1 - \varepsilon_z^A\right)\left(1 + \varepsilon_\theta^A\right)^2}{\left(1 + \varepsilon_\theta^{wrap}\right)^2} \tag{28}$$

in which ε_θ^A is the hoop strain in the wrap at point A and $\varepsilon_\theta^{wrap}$ is the failure hoop strain of the wrap.

3. PREDICTED RESULTS

3.1 Stress at Which Concrete Fails

Equations 12 and 16 were both used to calculate the hydrostatic pressure (P_A) and the axial stress at which the concrete began to fail (σ_A) in the cylinders reinforced with composite wrap in the hoop direction. The results are presented in Figure 3 with data from the experimental work presented by Howie and Karbhari [1994]. Relevant material properties are listed in Table 1. There is very little difference in the strengths predicted by assuming that the wrap is perfectly bonded to the concrete (by Equation 12) and the strengths predicted by assuming that the wrap is not bonded to the cylinder, indicating that the degree of bonding between the wrap and the concrete has very little effect on the axial strength of the columns with the hoop wrap. The cylinders tested in the experimental study were examined after failure and the concrete appeared to be well bonded to the wrap.

Howie and Karbhari [1994] also investigated the axial compressive strength of concrete cylinders with several other wrap architectures, including [0/90/+45/-45], [+45/-45], $[+45/-45]_2$, [0/90], and [0/90/0] in which 0° denotes the hoop (θ) direction and 90° denotes the axial (z) direction. The experimental results are shown in Figure 4. Note. The cylinders wrapped with the [+45/-45] and the $[+45/-45]_2$ architectures displayed no inelastic behavior before failure (they failed at σ_A); thus, for those specimens ultimate failure stresses are shown in Figure 4.

Equations 12 and 16 were used to predict σ_A for the cylinders in Figure 4. However, if axial stresses are transferred to the composite wrap and the $z\,\theta$ Poisson's ratio in the wrap ($\nu_{z\theta}$) is greater than the Poisson's ratio for the concrete (ν_c), then tensile stresses will develop between the wrap and the concrete in the radial direction, and no hydrostatic pressure is generated in the concrete. Thus, for cylinders with the quasi-isotropic ([0/90/+45/-45]), the [+45/-45] and the $[+45/-45]_2$ wrap architectures, Equation 12 does not apply.

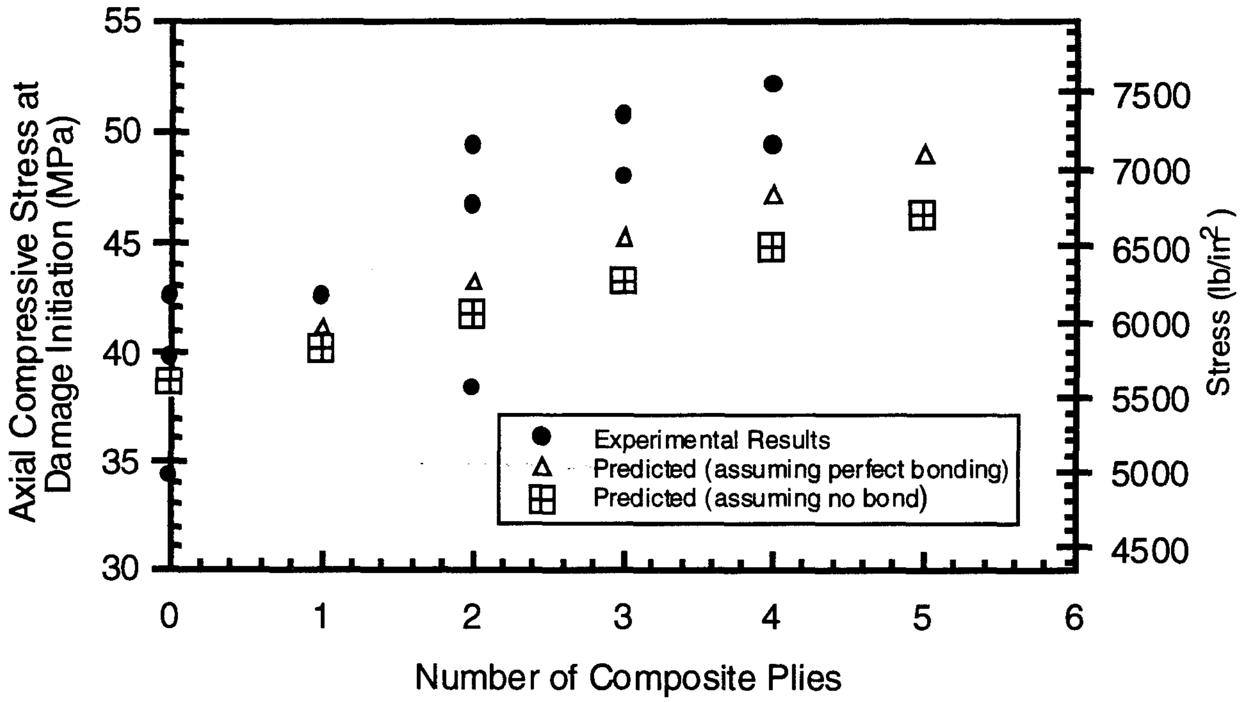

Figure 3. Experimental and theoretical stresses when the concrete begins to fail for concrete cylinders with graphite/epoxy wrap in the hoop direction.

Table 1. Material Properties

Property	Unreinforced Concrete	Graphite Fiber-Reinforced Epoxy
Elastic Modulus (principal direction)	11.7 GPa (1.7 Msi*)	135.9 GPa (19.7 Msi)
Elastic Modulus (transverse direction)	11.7 GPa (1.7 Msi)	8.4 GPa (1.22 Msi)
Poisson's Ratio (trans./prin. direction)	0.22	0.02

*Msi = 10^6 lb/in^2

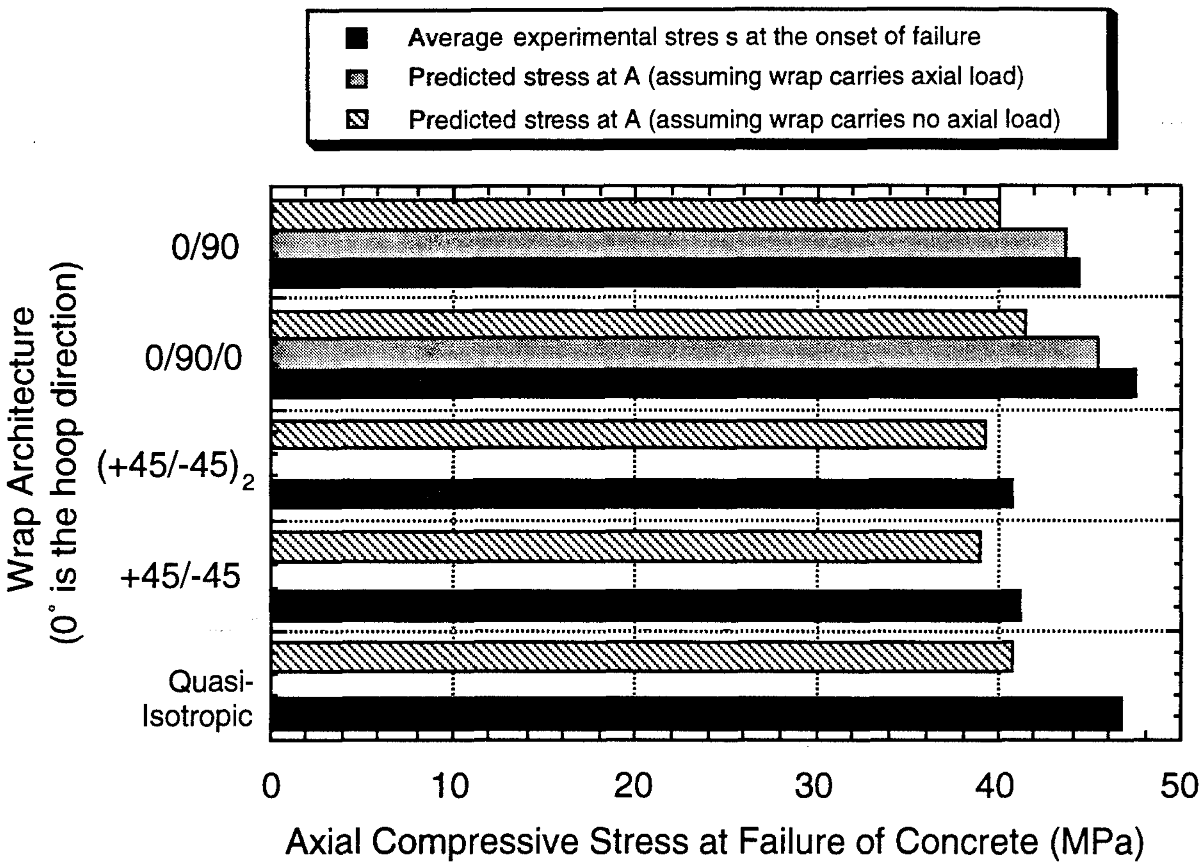

Figure 4. Axial compressive stress at the onset of failure of the concrete (architectures other than hoop wraps).

For the [0/90] and the [0/90/0] wrap architectures, notice that there are significant differences in the predicted results depending on whether the wrap carries or does not carry axial load. Since these wraps are much stiffer in the axial direction than the hoop wraps (see Figure 3), the axial load carried by the wrap is more significant. The theoretical predictions in which it is assumed that the wrap carries axial load agree much better with the experimental data.

3.2 Ultimate Failure of the Wrapped Column

In the development of equations to predict the failure stress and strain of the wrapped columns, the effects of defects in the wrap and the strain-hardening behavior of the concrete were ignored. In general, defects in the composite reduce the stress and strain at failure of the column, whereas strain hardening of the concrete allows the column to carry additional load in the nonlinear region. Howie and Karbhari [1994] measured the strain at ultimate failure of the wrap in the hoop direction of a few test specimens. The failure strain in the θ direction varied between 0.5% and 1.05%, with an average value of 0.76%. These values are considerably less than the average strain at failure for graphite fiber-reinforced epoxy observed in coupon tests (1.5%) and may be indicative of the effects of defects on the mechanical properties of the wrap. Since the graphite fiber-reinforced material displays linear elastic behavior in the fiber direction, it can be assumed that the strength of the wrap can be reduced accordingly. The reported fiber direction tensile strength and strain at failure were 2.1 GPa and 1.5% [Howie and Karbhari 1994]. If the composite failed at 0.76% strain in the fiber direction, then the strength of the wrap is reduced to 1.1 GPa. Note that this indicates a substantial difference in the predicted and experimental behavior of the wrap. This may be because the wrap is thin and therefore very sensitive to defects at the interface with the cylinder. Therefore, predictions of the failure stress and strain of the wrapped columns were made with the failure stress (2.1 MPa) and strain (1.5%) predicted by coupon tests and with reduced values due to the effects of defects in the wrap (failure stress of 1.1 MPa and failure strain of 0.76 %).

Figure 5 shows the predicted failure strengths for the wrapped columns and Howie and Karbharis' [1994] experimental data. Theoretical predictions were made for fiber direction tensile strengths of 2.1 and 1.1 GPa, respectively. The predicted strengths are lower than the experimental values for both cases. This is probably because the strain-hardening behavior of the concrete has been neglected. More analysis of the mechanical behavior of confined concrete needs to be conducted to improve these predictions.

The strains at failure for the wrapped columns were calculated using the method described in Section 2.4. The predicted results for cylinders with wrap in the hoop direction are shown, along with the experimental data in Figure 6. Notice that the predicted results show less sensitivity to the number of plies in the hoop wrap than the experimental results. This is probably because in the experiments, the thinnest wraps showed the most sensitivity to defects. As the number of plies is increased, the axial strain at failure of the columns approaches the axial failure strain predicted, based on baseline properties of the composite.

3.3 Predicted Stress-Strain Curves

Predicted stress-strain curves for a concrete cylinder with two layers of hoop wrap are shown in Figure 7 with the corresponding experimental data [Howie and Karbhari 1994]. The predicted results agree well with the data for stresses as great as σ_A. At higher stresses, the theoretical solution underpredicts the failure stresses. As discussed in Section 3.2, the lower predictions of failure stress are probably due to nonlinear behavior of the concrete which has not been modeled.

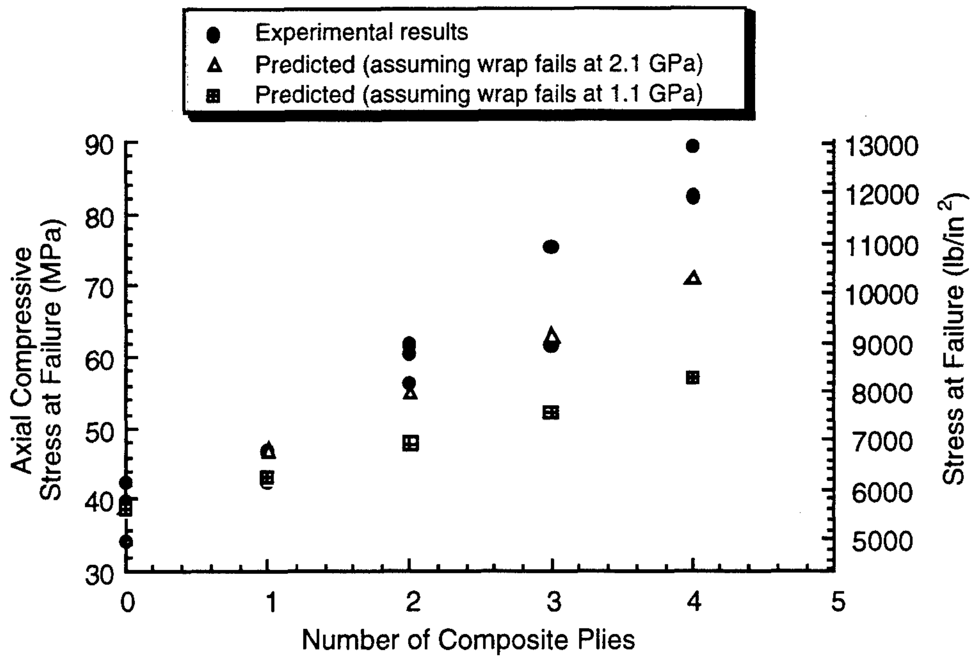

Figure 5. Experimental versus theoretical failure stress for concrete columns with graphite/ epoxy wrap oriented in the hoop (0°) direction.

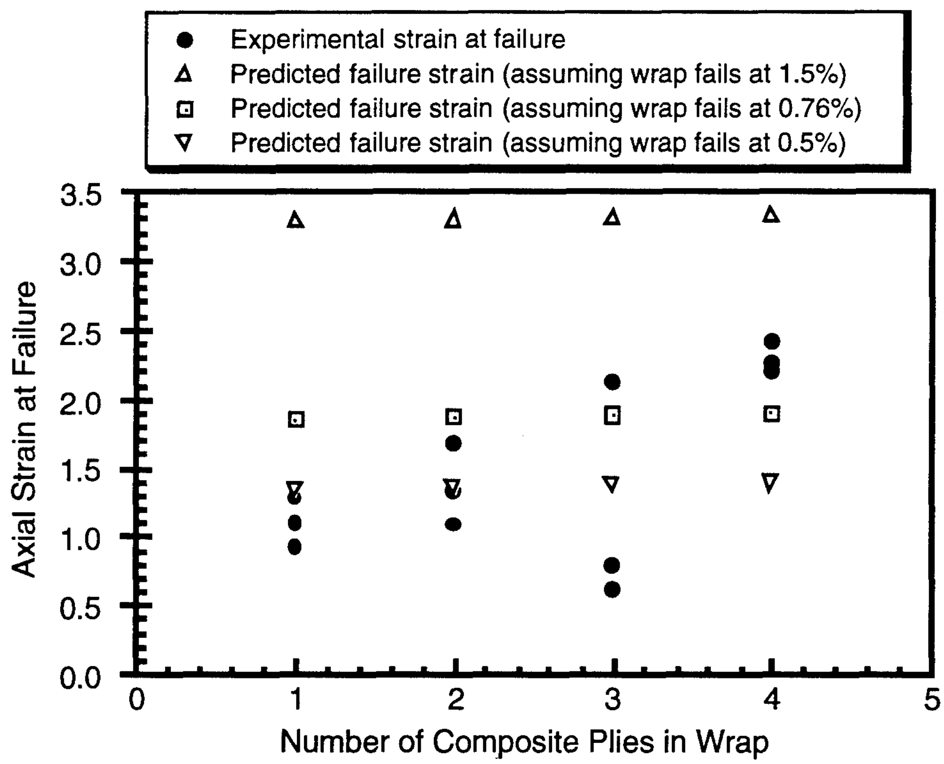

Figure 6. Axial strain at failure for columns wrapped with graphite fiber-reinforced epoxy in the hoop (0°) direction. (The average strain at failure for the wrap in static tensile tests was 1.5%. The average measured strain at failure in the hoop directions in the experimental tests was 0.76%.)

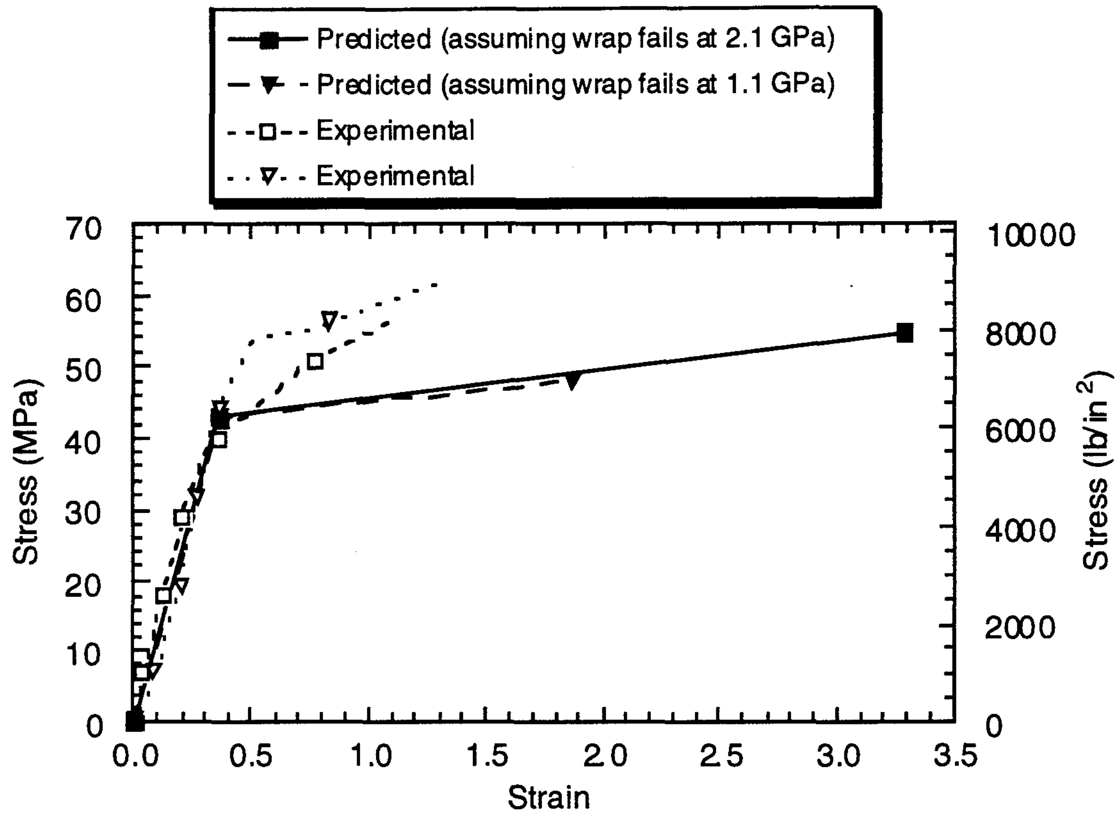

Figure 7. Predicted and experimental stress versus strain curves for concrete cylinders with two layers of graphite/epoxy wrap in the hoop (0°) direction.

4. CONCLUSIONS

The conceptual approach and simple analytical equations developed in this work can be used to gain fundamental insight into the dominant mechanisms governing the experimentally observed strengthening effects of composite wraps on concrete cylinders. This methodology may also be used to identify and control the particular material and geometrical parameters so as to optimize the axial strength-carrying capability of composite wrapped concrete cylinders. The predicted results show good agreement with experimental results for stresses until the point is reached when the concrete begins to fail. At higher stresses, the predictive models for strength and strain at failure of wrapped cylinders need to account for the effects of defects in the composite wrap, as well as the nonlinear behavior of confined concrete. Future research is needed in both of these areas to further improve the predictive capability.

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