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Effective Strain in FRP Jackets on Circular RC Columns

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ABSTRACT: Fiber Reinforced Polymer (FRP) composite materials have been widely used and have been extensively studied in the last decades in the form of jacketing to enhance axial strength as well as ductility, and their effectiveness has been extensively proven in many research programs investigating confined concrete column behavior. The existing models available for confined concrete assessment both in terms of ultimate capacity and of stress-strain relationships rely on an assumed value of the ultimate FRP strain. It is commonly assumed that FRP fails when hoop strain in the jacket reaches its ultimate tensile strain determined according to flat coupon tests. However, FRP confined concrete experimental results showed that in most cases, FRP experimental ultimate tensile strain is clearly not reached at the rupture of the FRP jacket. The discrepancies may include misalignment or damage to jacket fibers, residual strains or uneven tension during lay-up, cumulative probability of weaknesses in the FRP jackets since they are much larger than tensile coupons and, more likely, the radius of curvature in FRP jackets on cylinders as opposed to flat tensile coupons and the multiaxial stress state due to the transfer of loads through the bond with concrete. Since for confined sections the average absolute error of all models showed a remarkable decrease when the confining device effective strain is inserted in the equations, it is very important to assess the effective FRP jacket strain capacity. A criterion to directly evaluate the FRP strain efficiency factor as the strain ratio between effective FRP failure and straight coupon test outcomes has been formulated. Multiaxial failure criteria have been adopted (i.e. Tsai-Wu criterion for FRP) considering axial, circumferential and radial stresses. Results of theoretical analyses and experimental tests (experimental data available in literature) showed that a good agreement was achieved.

1 INTRODUCTION

Fiber Reinforced Polymer (FRP) composite materials approached the construction market as a cost viable and time effective solution to retrofit existing concrete structures in the last decades. The FRP composites are excellent materials with extremely high strength to weight ratio, corrosion resistance and electromagnetic neutrality. Their use instead of steel for confinement of concrete is one of the most attractive applications.

A reliable stress-strain behavior of concrete is in fact necessary particularly to model complex reinforced concrete structures. The existing models available for confined concrete assessment both in terms of ultimate capacity as of stress-strain relationships rely on an assumed value of the ultimate FRP strain, and it is commonly assumed that FRP fails when hoop strain in the jacket reaches its ultimate tensile strain determined according to flat coupon tests. Once the confining material fails, the now overloaded unconfined concrete experiences a very brittle failure.

Despite the great research effort in the experimental field, considerable work is still needed to fully outline a definitive analytical model to predict the behavior of FRP confined concrete. Most of these models are empirical in nature and have been calibrated against their own sets of experimental data (De Lorenzis & Tepfers 2003).

A confinement model was recently proposed by the authors (Lignola et al. 2008), based on solid mechanics and able to predict the fundamentals of the behavior of solid and hollow members confined with FRP. The model traces the evolution of stresses and strains in the concrete and in the confinement jacket and it allows to evaluate, at each load step, the multiaxial state of stress, and eventually the failure, of the concrete or the external reinforcement.

In the following, the ratio of the effective hoop strain in the confining FRP at failure to the FRP ultimate strain in straight coupon test is termed "efficiency factor", β. Experimental outcomes show that the efficiency factor ranges from more than 1 to less than 0.1.

2 REDUCED EFFECTIVE FRP ULTIMATE STRAIN

In most cases, FRP ultimate tensile strain determined experimentally according to flat coupon tests is not reached at the rupture of the FRP jacket in confined concrete columns compression tests. The possible reasons for this phenomenon have been suggested by many authors (few of them are cited: Matthys et al. 1999, Fam & Rizkalla 2001, Pessiki et al. 2001, De Lorenzis & Tepfers 2003, Harries & Carey 2003, Lam & Teng 2004). The main reasons have been briefly reported here.

Firstly this phenomenon may be attributed to the scatter in the FRP tensile strength and in the strain measurement. The characterization of tensile properties of FRP is actually influenced by the testing procedure, thus standard test protocols are needed.

When concrete is internally cracked and further loaded it experiences non-homogeneous deformations thus leading to local stress concentrations in the FRP jacket. This effect is likely more evident in large diameter columns. Moreover the presence of voids, protrusions and misalignments of fibers in the FRP can reduce the capacity of the composite material.

If shear is not transferred across the interface between the jacket and the concrete, then the strain in the jacket would be uniform around the perimeter of the cross section. But, if a degree of bond between the jacket and underlying concrete allows jacket stresses to be transferred into the concrete, then the average strain in the jacket is reduced. Moreover if the jacket crosses a splitting crack, there would be a strain concentration. Unless the measurement is made exactly at the strain concentration, obviously the measured jacket strains at rupture are lower than the real capacity. Furthermore, at a given confining pressure, the FRP hoop strains are inversely proportional to the thickness of the jacket, rising in the overlapping zone.

Several other factors may lead to a "premature" failure of the FRP likely as an uneven tension during lay-up, the temperature, creep, and shrinkage incompatibility between concrete and FRP jacket, the cumulative probability of weaknesses in the FRP material, since jackets are much larger than tensile coupons.

The transfer of axial load through bond with concrete and the radius of curvature in FRP jackets on cylinders leads to a multiaxial stress state in the FRP and these phenomena are likely to produce an average FRP hoop rupture strain in the confined cylinders that is much lower than the one experimentally measured with flat coupon tests.

3 PROPOSED MODEL TO EVALUATE THE EFFICIENCY FACTOR

Among the possible reasons for the noticeable reduction of the hoop strain at failure compared to the ultimate strain in straight coupon test, in this model the radius of curvature in FRP jackets on cylinder columns as opposed to flat tensile coupons and the multiaxial stress state due to the transfer of loads through the bond with concrete, are explicitly considered.

3.1 *Micromechanics of the FRP jacket*

FRP composites are heterogeneous and anisotropic materials; the three dimensional FRP constitutive equations (stresses σ and strains ε) can be expressed as follows in cylindrical coordinates for the case under study of a transversely isotropic jacket (i.e. wraps made of uniaxial fibers):

$$\varepsilon_\theta = -\left(\frac{\upsilon_{TL}}{E_T}\right)\sigma_z - \left(\frac{\upsilon_{TL}}{E_T}\right)\sigma_r + \frac{\sigma_\theta}{E_L} \tag{1a}$$

$$\varepsilon_r = -\left(\frac{\upsilon_{TT}}{E_T}\right)\sigma_z + \frac{\sigma_r}{E_T} - \left(\frac{\upsilon_{LT}}{E_L}\right)\sigma_\theta \tag{1b}$$

$$\varepsilon_z = \frac{\sigma_z}{E_T} - \left(\frac{\upsilon_{TT}}{E_T}\right)\sigma_r - \left(\frac{\upsilon_{LT}}{E_L}\right)\sigma_\theta \tag{1c}$$

where *r* and θ are the radial and circumferential components, respectively; *r* and θ directions, along with the longitudinal, or z, direction, are principal directions. Constitutive equations include effective longitudinal, E_L, and transverse, E_T, moduli and Poisson's ratios ν_{LT}, ν_{TL}, ν_{TT} only one of which is independent. The others can be found from symmetry conditions:

$$\frac{\nu_{LT}}{E_L} = \frac{\nu_{TL}}{E_T} = \frac{\nu_{TT}}{E_T} \tag{2}$$

where the elastic properties of the FRP (in eqs. 2) are governed by fibers and matrix properties and composite microstructure. Assuming the simplified rule of mixtures, it is:

$$E_L = E_f V_f + E_m V_m\,; \qquad \frac{1}{E_T} = \frac{V_f}{E_f} + \frac{V_m}{E_m}\,; \qquad \nu_{LT} = \nu_f V_f + \nu_m V_m \tag{3}$$

where V_f and $V_m = 1\text{-}V_f$ are the fiber and matrix volume fraction, respectively, and, in eqs. 3, *f* and *m* subscripts identify the fiber and matrix properties, respectively.

The relation of the tangential stresses σ_θ in the jacket material to the radial stresses σ_r acting on the concrete specimen may be derived by stress equilibrium in the lateral direction as:

$$\sigma_r = -\frac{t}{R}\sigma_t \tag{4}$$

where t is the jacket thickness and R is the radius of curvature of the jacket, equal to the radius of the wrapped concrete column. Inserting eq. (4) in (1a) and (1c) and manipulating, it is:

$$\varepsilon_\theta = -\left(\frac{\upsilon_{TL}}{E_T}\right)\sigma_z + \left(\frac{\upsilon_{TL}}{E_T}\frac{t}{R}\right)\sigma_\theta + \frac{\sigma_\theta}{E_L} \tag{1'a}$$

$$\frac{\sigma_z}{E_T} = \varepsilon_z - \left(\frac{\upsilon_{TT}}{E_T}\frac{t}{R}\right)\sigma_\theta + \left(\frac{\upsilon_{LT}}{E_L}\right)\sigma_\theta = \varepsilon_z + \frac{\upsilon_{LT}}{E_L}\left(1 - \frac{t}{R}\right)\sigma_\theta \tag{1'c}$$

Inserting eq. (1'c) in (1'a) and looking at eq. (2), it is:

$$\varepsilon_\theta = -\upsilon_{TL}\varepsilon_z + \frac{\sigma_\theta}{E_L}\left(1 - \upsilon_{TL}\upsilon_{LT} + \upsilon_{TL}\upsilon_{LT}\frac{t}{R} + \upsilon_{LT}\frac{t}{R}\right) \tag{5}$$

It is pointed out that even though axial load is not applied directly on the FRP, part of the axial strain level induced in the concrete core is transmitted to the FRP by means of bond stresses at the contact surface and ε_z in the FRP can be assumed equal to it (negative because in compression). At this step the axial strain in the concrete core is not known as it is usually evaluated after determining ε_θ. To avoid an iterative procedure, it is possible to demonstrate that neglecting ε_z is on safe side as the evaluated σ_z stress (eq. 1'c) is smaller than effective value and also the evaluated ε_θ strain (eq. 5) is underestimated.

3.2 *Failure Criteria*

The efficient use of FRP composite confinement requires a proven failure criterion. Several failure criteria have been proposed, but the lack of critical experimental results usually makes it difficult to assess the accuracy of these models. There is no fiber composite model, and especially three-dimensional failure model, that has experienced wide acceptance, as, for example, criteria for metallic isotropic materials.

These criteria are sometimes formulated in a tensor-polynomial form as linear combinations of mixed invariants of stress tensor and strength tensors of different ranks, allowing for stress interaction. A generalized quadratic interaction failure criterion can be given as:

$$F_i\sigma_i + F_{ij}\sigma_{ij} = 1 \tag{6}$$

where F_i and F_{ij} are experimentally determined strength tensors and contracted tensor notation is used (i,j=1–6). The linear terms, F_i, are necessary to account for differences in tensile and compressive strengths. Numerous variants of these formulations have been proposed for traditional and composite structural materials. It should be emphasized that experimental data have usually rather high scatter, and the accuracy of more complicated and rigorous strength criteria can be more apparent than real.

Tsai & Wu (1971) presented a form of eq. (6) for transversely isotropic composites that has been adapted to the present case in principal directions, neglecting differences in tensile and compressive strengths (thus neglecting linear terms, F_i) as:

$$\left(\frac{\sigma_\theta}{f_\theta}\right)^2 + \left(\frac{\sigma_r}{f_r}\right)^2 + \left(\frac{\sigma_z}{f_z}\right)^2 - \frac{\sigma_\theta \cdot \sigma_r}{\sqrt{f_\theta^2 \cdot f_r^2}} - \frac{\sigma_\theta \cdot \sigma_z}{\sqrt{f_\theta^2 \cdot f_z^2}} - \frac{\sigma_r \cdot \sigma_z}{\sqrt{f_r^2 \cdot f_z^2}} = 1 \tag{7}$$

where f_θ and $f_r \cong f_z$ are the longitudinal and transverse strength of the FRP, respectively, with respect to the circumferential direction. Strength and stiffness under longitudinal tension are determined using unidirectional strips. Unidirectional composites under compression across the fibers exhibit traditional shear mode of fracture, but compression across the oblique failure plane increases the strength.

Manipulating eq. (7), recalling eq. (1'c) and neglecting ε_z, it is:

$$\left(\frac{\sigma_\theta}{f_\theta}\right)^2 \cdot \left[1 + \left(\frac{f_\theta}{f_r}\cdot\frac{t}{R}\right)^2 + \left(\frac{f_\theta}{f_z}\right)^2 \cdot \left(\upsilon_{TL} - \upsilon_{TL}\cdot\frac{t}{R}\right)^2 + \frac{f_\theta}{f_r}\cdot\frac{t}{R} + \left(\upsilon_{TL} - \upsilon_{TT}\cdot\frac{t}{R}\right)\cdot\left(\frac{t}{R}\cdot\frac{f_\theta^{\,2}}{f_r \cdot f_z} - \frac{f_\theta}{f_z}\right)\right] = 1 \tag{8}$$

The efficiency factor, $\beta = \varepsilon_\theta / \varepsilon_{fu}$, where $f_\theta = E_L \cdot \varepsilon_{fu}$ (clearly an underestimation of ε_θ yields to smaller efficiency factor predictions) can be expressed as follows:

$$\beta = \frac{\sigma_\theta}{f_\theta}\left(1 - \upsilon_{TL}\upsilon_{LT} + \upsilon_{TL}\upsilon_{LT}\frac{t}{R} + \upsilon_{LT}\frac{t}{R}\right) \tag{9}$$

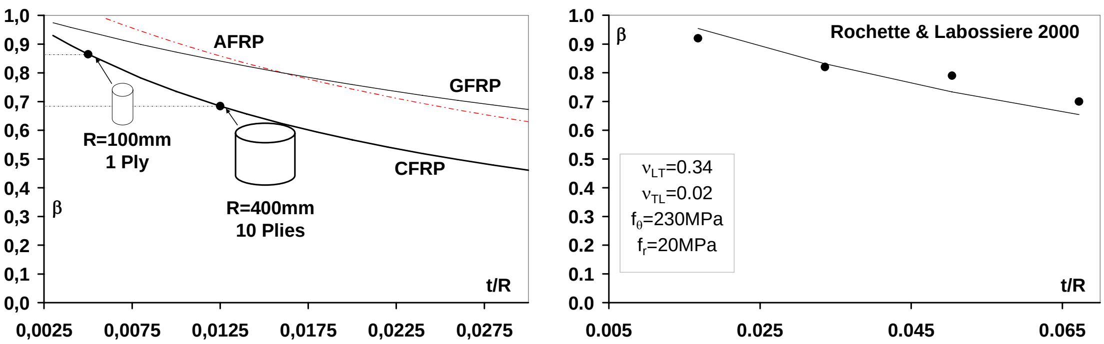
and recalling eq. (8), it is:

$$\beta = \frac{\left(1 - \upsilon_{TL}\upsilon_{LT} + \upsilon_{TL}\upsilon_{LT}\frac{t}{R} + \upsilon_{LT}\frac{t}{R}\right)}{\sqrt{1 + \left(\frac{f_\theta}{f_r}\frac{t}{R}\right)^2 + \left(\frac{f_\theta}{f_z}\right)^2\left(\upsilon_{TL} - \upsilon_{TL}\cdot\frac{t}{R}\right)^2 + \frac{f_\theta}{f_r}\frac{t}{R} - \left(\upsilon_{TL} - \upsilon_{TL}\frac{t}{R}\right)\frac{f_\theta}{f_z} + \left(\upsilon_{TL} - \upsilon_{TL}\frac{t}{R}\right)\frac{t}{R}\frac{f_\theta^{\,2}}{f_r \cdot f_z}}} \tag{10}$$

Hence the efficiency factor (eq. 10) depends on the thickness (t), elastic properties (ν_{LT}, ν_{TL}) and relative strength in orthogonal directions (f_θ, f_r ,f_z) of the FRP jacket as on the radius of the column (R).

4 MODEL VALIDATION

To validate the proposed model, results of theoretical model and experimental literature data have been compared. Usually an exhaustive description of FRP systems adopted in experimental tests, in terms of constituent elastic and mechanical materials properties, is not available in literature.



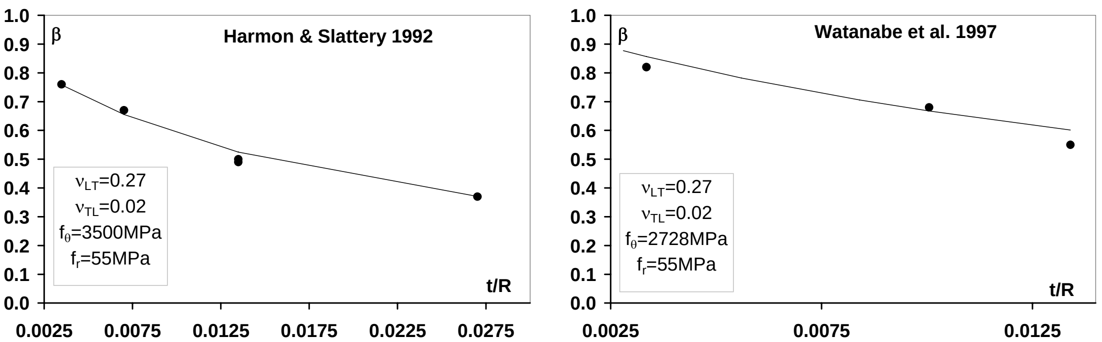
(a) (b)

Figure 1. (a) Predicted efficiency factors for columns strengthened with AFRP, GFRP and CFRP- (b) Predicted efficiency factor vs. experimental outcome: Rochette & Labossiere (2000)

Due to this lack of knowledge and due to the noticeable scatter in these properties, an example of efficiency factor prediction curves versus t/R ratios for different FRP systems is shown in figure 1a. Possible values - in Table 1 according to CNR DT200 (2004) - of the anisotropic ratios (ratio between values of the composite properties in different directions) in unidirectional laminates are considered. On the curve related to CFRP (fig. 1a), for instances the theoretical cases of a small-size column with a radius of 100 mm and only one ply of CFRP (~0.5 mm), and the case of a large-size column with a radius of 400 mm and ten plies of CFRP (~5 mm), are pointed out. The predicted efficiency factor is smaller in the second case. Furthermore the proposed model is able to confirm the results reported by Lam & Teng (2004) on 61 CFRP and 15 GFRP wrapped columns with different sizes and t/R ratios for which the average efficiency factor related to CFRP confinement is lower than the average value related to GFRP.

In Figure 1b the case of columns wrapped with AFRP and tested by Rochette & Labossiere (2000) is considered. Since the value of transverse strength, f_r, for the AFRP adopted in the experimental campaign is not reported nor assessable, a value of 20 MPa is considered. This value and the value adopted for the Poisson's ratios are in the range of the typical values for AFRP wraps. Good agreement is found for different values of the t/R ratio and the assumed f_r.

In Figures 2a and 2b the case of two different sets of columns wrapped with CFRP tested by Harmon & Slattery (1992) and Watanabe et al. (1997), respectively, is considered. Again the value of the f_r strength, not reported in the original paper, has been taken equal to 55 MPa. This value and the value adopted for the Poisson's ratios are in the range of the typical values for CFRP wraps. Good agreement is found between the experimental outcomes and the predicted values of the efficiency factor, β, for the assumed f_r.



(a) (b)

Figure 2. Predicted efficiency factor vs. experimental outcome: (a) Harmon & Slattery (1992) – (b) Watanabe et al. (1997)

Table 1. Anisotropic ratios and properties of FRP unidirectional laminates (adopted for the first example).

	f_θ / f_r	E_L / E_T	ν_{LT}	ν_{TL}
E-Glass/Epoxy	17.7	4.42	0.23	0.05
Carbon/Epoxy	41.4	13.60	0.29	0.02
Aramid/Epoxy	26.0	15.30	0.31	0.02

5 CONCLUSIONS

Strain capacity of the jacket is the dominant design criterion for most external confinement applications. A model to directly evaluate the FRP strain efficiency factor as the strain ratio between effective FRP failure and straight coupon test outcomes has been proposed. The average absolute error of confinement models shows a remarkable decrease when effective strain is considered. Many possible reasons for this phenomenon have been suggested by different authors. In this study the radius of curvature in FRP jackets and the multiaxial stress state are explicitly considered as main reasons of the FRP effective strain reduction. A multiaxial failure criterion has been adopted considering axial, circumferential and radial stresses and strains. To avoid an iterative procedure and to obtain a closed form solution for efficiency factor, β, only vertical strains were neglected, but this assumption is on safe side as confirmed also by all numerical analyses performed. The results of theoretical analyses compared with experimental data available in literature showed that a good agreement was achieved and the model is able to account for different values of the t/R ratio and FRP confining jackets fiber types. The proposed model is based on the thickness, elastic properties and relative strength in orthogonal directions of the FRP jacket and on the radius of the concrete column. Usually an exhaustive description of the properties of the FRP systems adopted in experimental tests, in terms of constituent materials properties, is not available in literature. Analyzing the proposed model it seems important to avoid this lack of knowledge; as a research need, it will be important if this kind of data will be also collected and published in the future experimental works on FRP concrete confinement.

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