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Modeling FRP confinement effectiveness limited by failure of free edge of jackets

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ABSTRACT: Despite a large research effort, a proper analytical tool to predict the behavior of Fiber Reinforced Polymer (FRP) confined Reinforced Concrete (RC) has not yet been established due to the many factors jeopardizing the reliability of such tools. 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. The proposed model relates the maximum effective FRP strain in the confining jacket with both the interfacial shear and peel capacity at the free edge of the composite reinforcement thus limiting the confining capacity of the FRP wrapping. Numerical examples and a parametric study are presented to illustrate the governing parameters that control the debonding failure at the free edge of the FRP jacket. The results provided by the model have been finally compared to experimental data available in literature and a satisfactory agreement was achieved.

1 INTRODUCTION

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 in most cases this FRP ultimate tensile strain is not reached at the rupture of the FRP jacket. The ratio of the measured hoop strain in situ, in the FRP jacket at tensile failure, to the FRP ultimate strain in uniaxial tensile coupon tests is termed "efficiency factor". The possible reasons for this phenomenon have been suggested by De Lorenzis and Tepfers (2001) and Lignola et al. (2008). In order to predict "premature" tensile failures, the parameters exerting an influence on them may be identified: multiaxial stress state existing in the FRP even when loaded only due to some degree of bond to the concrete; non-homogeneous deformations in the cracked concrete at high load levels which may cause local stress concentrations in the FRP reinforcement; the curved shape of the wraps, especially at the corners with small radius; the quality of the execution (degree of fiber alignment, presence of voids or local protrusions); residual strains or uneven tension during lay-up; misalignment or damages in the jacket fibers; and cumulative probability of weaknesses in the FRP jacket since they are much larger than tensile coupon.
A model proposed by Zinno et al. (2010) analyzes the effect of the stress concentration at the free edge of the FRP jacket. The model is based on the evaluation of the interlaminar shear and normal stresses at that location. Normal tensile interlaminar stresses, or peel stresses, tend to separate each lamina from the others, while interlaminar shear stresses tend to slide a lamina

over the adjacent ones. In both cases interlaminar stresses can cause premature failure of the FRP wrapping due to separation or delamination, thus limiting the theoretical confining capacity of the FRP wrapping.
In the present paper, the analytical formulations and the governing parameters, controlling the stress concentration at the edge of FRP jacket, are discussed in the following relating the maximum effective FRP strain in the confining jacket to both the maximum interfacial shear and peel capacity at the free edge of the composite reinforcement (stress based failure criteria). However energy based criteria are also introduced to predict debonding failure due to the brittleness of the considered failure process.

2 ANALYTICAL MODEL

The analytical model proposed by Zinno et al. (2010), under the assumption that the FRP jacketing is made of the same material, allows computing the maximum achievable FRP strain ε_{FRP}, causing premature failure due to localized interfacial stresses, depending on the maximum shearing stress $\tau_{\max}$ and the maximum peeling stress $\sigma_{n\max}$, at the free edge as:

$$\varepsilon_{FRP} = \min\left\{\frac{e^{2\gamma L}-1}{1+e^{2\gamma L}}\tau_{\max};\frac{1}{t_a\gamma}\sigma_{n\max}\right\}\cdot\frac{1+n}{E_f tn\gamma} \tag{1}$$

where n is the number of layers composing the jacket, L is the anchoring length, t and E_f the thickness and the Young modulus of each FRP layer respectively, and γ is a parameter that can be computed as:

$$\gamma = \sqrt{\frac{K_s\left(\dfrac{n+1}{Ent}\right)}{1+tK_s\left(\dfrac{5+3n}{12G_f}\right)}} \tag{2}$$

where G_f is the shear modulus of the FRP material, $k_s=G_a/t_a$ is the shear stiffness of the adhesive, and G_a and t_a are shear modulus and thickness of the adhesive respectively.

3 NUMERICAL STUDY

As showed by Eq. (1) the maximum achievable FRP strain, limited by premature failure due to localized interfacial stress at the free edge, is related to the FRP mechanical properties, the number and the thickness of the layers; the anchoring length and the interfacial properties, such as thickness and shear modulus of the applied resin. These resin properties are both involved in the definition of shear stiffness and are relevant only in the analysis of bond slip at the free edge of the jacket. In the present section, the parametric analyses have been run, under the assumption that the failure takes place whenever the maximum shearing (peeling) stress reaches interfacial strength value $\tau_{\max}=\tau_u$ ($\sigma_{n\max}=\sigma_{nu}$) (i.e. stress assessment criterion), considering FRP jacketing obtained involving both carbon and glass fabrics with epoxy resin. Dry fabric properties are adopted throughout, from a mechanical point of view, instead of total properties of the impregnated FRP system. The average properties, available in Daniel and Ishai (2006), have been considered. All the influences have been analyzed considering different shear stiffness of the adhesive layer that is variable because the composite wrapping is applied by hand-layup.

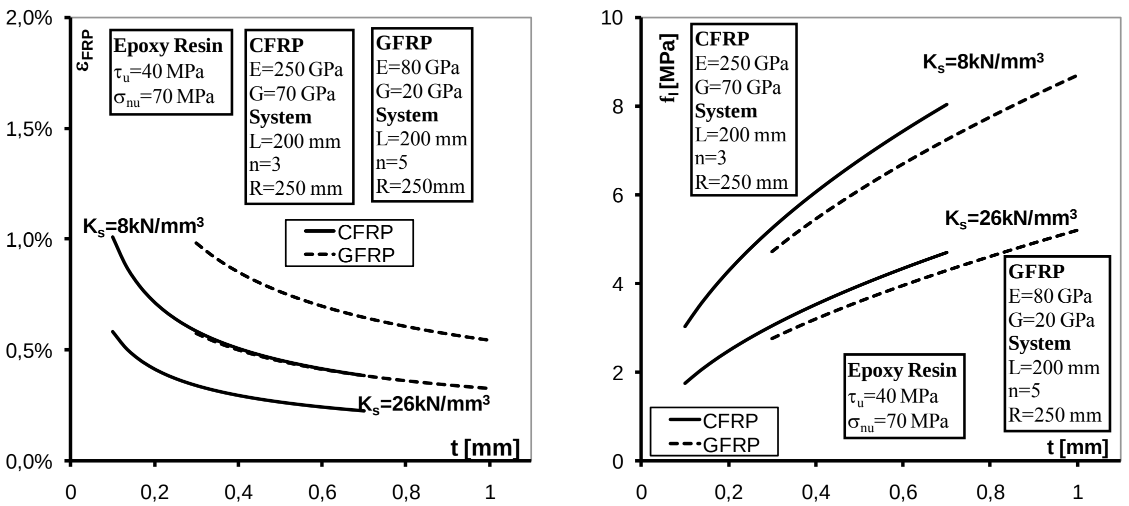
Moreover, the parametric study has been also run in order to evaluate the influence of the described parameters on the confinement lateral pressure evaluated according to the well known equation adopted also in International Codes:

$$f_l = \frac{1}{2} \rho_f E_f \varepsilon_{FRP} \tag{3}$$

where ρ_f is the geometrical strengthening ratio as a function of the shape of the section (circular or rectangular) and the FRP configuration (continuous or discontinuous wrapping). In the case of circular section and continuous wrapping, it is given by:

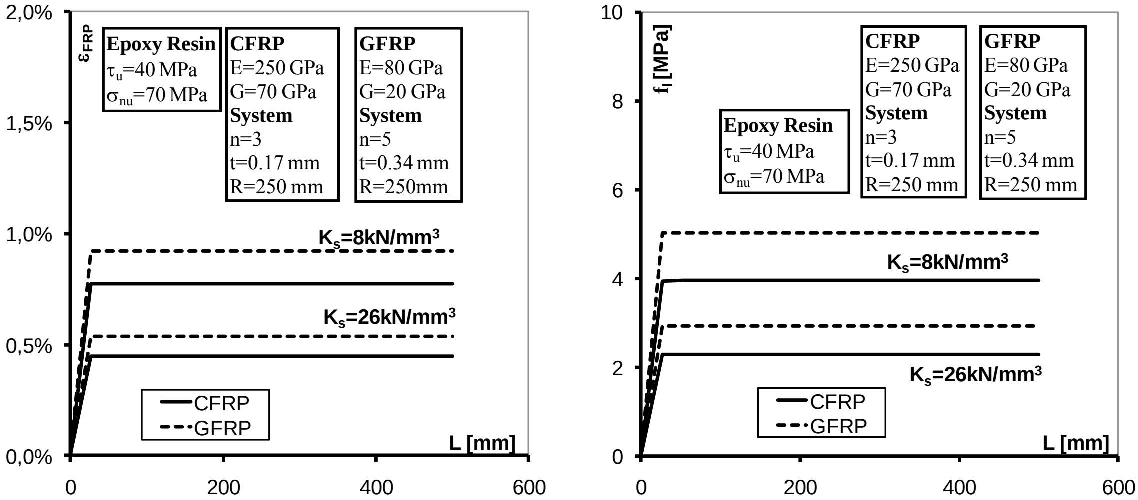
$$\rho_f = \frac{4t_f}{D} \tag{4}$$

where D is the diameter of the circular cross section and t_f is the FRP thickness, concerning the sum of each layer, t_f=*nt*. Figure 1, shows the influence of the thickness, *t*, of each FRP layer on both the FRP strain and confinement lateral pressure for both carbon and glass fabrics. As a result, the effective FRP strain decreases when the FRP thickness of the layers increases. It is also interesting to observe that the confinement lateral pressure is not linearly related to the FRP thickness (despite usual formulations adopted in International Codes, Eq. (4)). Similarly, both the effective FRP strain and the confinement lateral pressure have been related to the anchoring length of the FRP jackets. Figure 2 shows that the anchoring length influences the FRP behavior in a small range. Moreover the number of the layers, n, has been considered in the numerical analysis. In particular figure 3 shows that increasing the number of layers in an FRP jacketing, the FRP hoop strain decreases slowly (less than linearly), while according to Eqs. (3)-(4), the confinement lateral pressure should increase linearly. Figure 4 reports the FRP hoop strain and confinement lateral pressure in function of the shear modulus of the FRP jacketing. For both configurations, glass and carbon: the jacketing behavior is just influenced in the case of G modulus values below a threshold value, while according to Eq. (3), the confinement lateral pressure should be independent. Figure 5 reports the non-linear influence of elastic modulus of FRP jacketing, considering typical ranges for such materials, on the confinement behavior, while according to Eq. (3), the confinement lateral pressure should increase linearly. Figure 5 shows also that the variation in terms of FRP strain and lateral pressure is greater for GFRP materials.



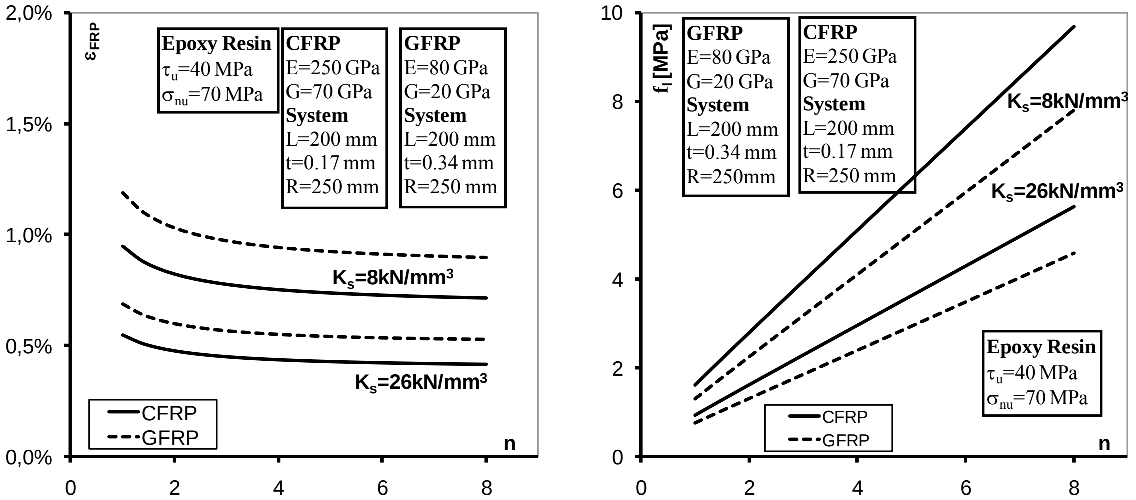
(a) (b)

Figure 1. Influence of FRP thickness on: (a) FRP hoop strain; (b) confinement lateral pressure.



(a) (b)

Figure 2. Influence of FRP anchoring length on: (a) FRP hoop strain; (b) confinement lateral pressure.



(a) (b)

Figure 3. Influence of number of FRP layers on: (a) FRP hoop strain; (b) confinement lateral pressure.

4 STRESS VS ENERGY FAILURE CRITERION

The stress failure criterion assumes that the strain causing delamination is attained when the maximum shearing (peeling) stress reaches the interfacial strength. The stress-based criterion, used in the numerical analysis, allows the first cracking of the interface to be detected, and it can be considered as a significant failure mode for the confinement design. Although able to catch the brittleness of the debonding failure, the stress failure criterion shows some shortcomings. In fact, in most cases, the existence of the first crack does not mean the debonding failure. Therefore, it can be expected that the use of stress-based criterion leads to underestimation of the effective FRP strain. In the present section, energy failure criterion is set by using the linear elastic fracture mechanics LEFM concept of the strain energy release rate SERR. For the sake of simplicity, no peeling stresses are considered within the adhesive layer, so the maximum achievable FRP strain can be computed as:

$$\varepsilon_{FRP} = \frac{e^{2\gamma L} - 1}{1 + e^{2\gamma L}} \cdot \frac{1+n}{E_f t n \gamma} \cdot \tau_{\max} \tag{5}$$

For fixed load conditions, the strain energy release rate is provided by the derivative of the strain energy of the whole structure with respect to the crack area, given by the crack length times its width. According to LEFM, debonding occurs whenever the SERR reaches its critical value Γ, the fracture energy that is a property of the material or, as in the present case, of the interface. The LEFM criterion corresponds to assume an elastic-purely brittle constitutive law for the interface. It allows to bypass the complex energetic analysis providing effective maximum interfacial shearing stress as function of the fracture energy, so that the conventional strength-based approach can be employed to give the same result of the energy-based fracture criterion:

$$\tau_{\max} = \sqrt{\frac{2\Gamma G_a}{t_a}} \tag{6}$$

Eq. (6) provides the maximum shearing stress as a function of the critical energy release rate for an interfacial crack propagating under mode II conditions (Γ_{II}). It has been recently proposed by Carpinteri et al. (2009) and is a result valid for all the shear lag models. Applying energy-based criterion, the effective maximum interfacial stress is dependent on the interfacial material parameter Γ as well as the properties and thickness of the adhesive (G_a and t_a). Generally the value of the fracture energy Γ is difficult to estimate. In the following applications, under the hypothesis of an epoxy adhesive with a thickness about 0.5 mm and a shear modulus of 1.3 GPa, the mode fracture energy is considered in a range of 0.5 - 0.9 N/mm.

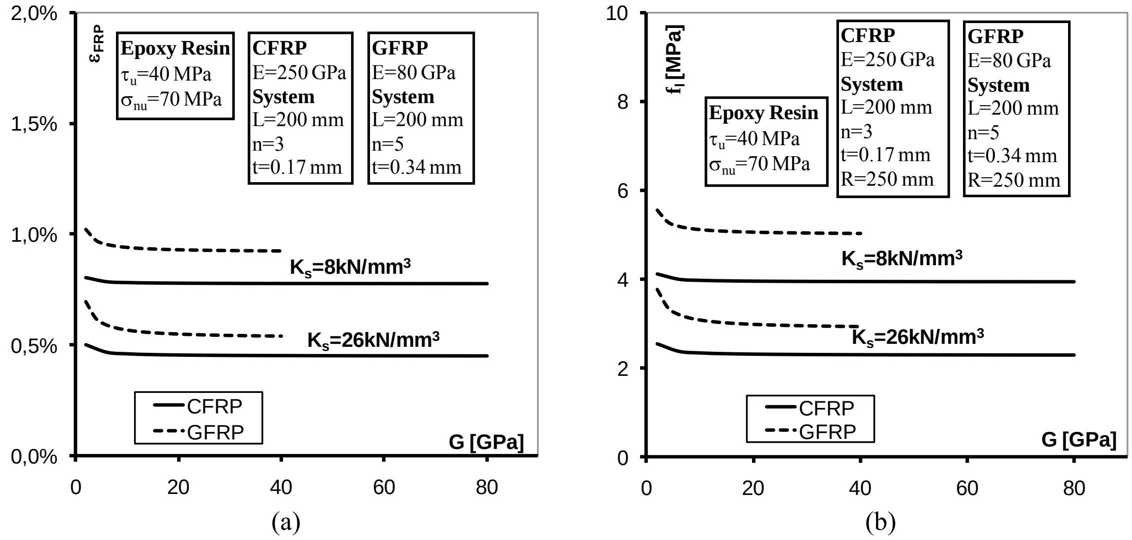
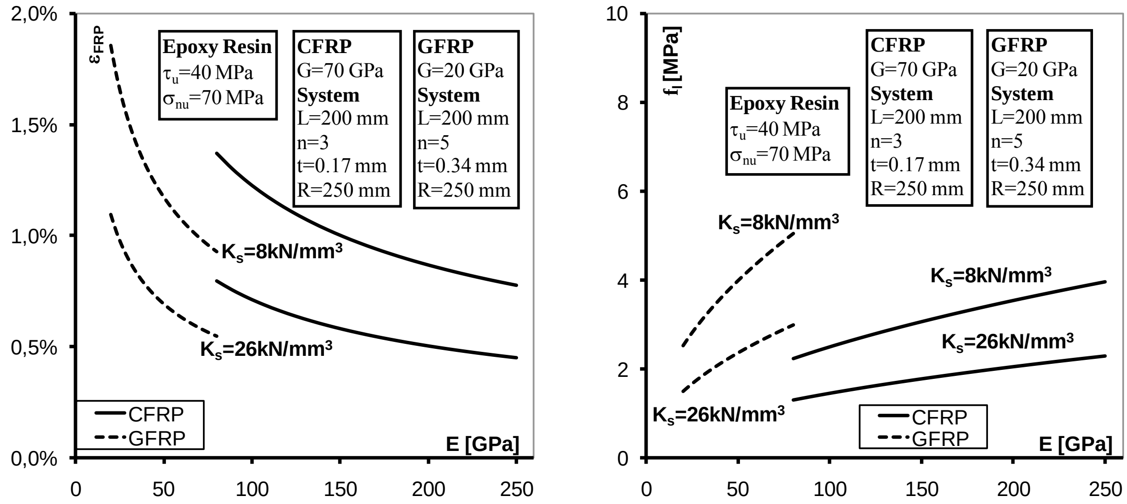


Figure 4. Influence of FRP shear modulus on: (a) FRP hoop strain; (b) confinement lateral pressure.



(a) (b)

Figure 5. Influence of FRP elastic modulus on: (a) FRP hoop strain; (b) confinement lateral pressure.

5 FITTING OF EXPERIMENTAL DATA

In the present section, data derived from the experimental activities on small scale circular RC columns available in literature have been fitted with the analytical values of the maximum achievable FRP hoop strain using both stress and energy failure criterions. A database have been built based on test results obtained from CFRP wrapped concrete cylinders where all the FRP jackets were formed in a wet lay-up process by impregnating a continuous fiber/fabric sheet whit matching epoxy resin and all the FRP-confined specimens were found to fail due to the rupture of the FRP jacket. Since resin parameters are not reported in the referred papers, the validation of the model is performed adopting average properties of commercial epoxy resins as adopted in the parametric analysis. In particular, the database counts the results presented by Watanabe at al. (1997), Xiao and Wu (200), Lam and Teng (2004), Lam et al. (2006) and Jiang and Teng 2007 where different series of specimens were tested in order to provide the FRP hoop strains at failure, measured using strain gauges evenly distributed around the circumference of the cylinder, as function of the number of the FRP layers. The figures 6 shows that the model, continuous lines, provides values of FRP hoop strain that are lower than those evaluated through tensile tests on standard coupons, dashed line, and the slope of the curve fits the trend of experimental points. The numerical model has not taken into account the influence of column geometry and concrete strength reported in some experimental programs. However the scatter of FRP hoop strain values found during the experimental activities is also influenced by previous discussed phenomena, such as multiaxial stress, non homogeneous deformations due to cracked concrete, bond, etc. In fact the model does not aim at exactly reproducing the experimental behavior because it can be clearly affected by many premature failures, but it suggests an upper bound of the effective FRP ultimate strain in jacketing, in many cases much lower than the value given by flat coupon tests. In authors' opinion, in a single experimental program the variability in the FRP ultimate strain can be related much likely to variable thickness taking place in a wet lay-up application rather than to variability of the mechanical properties of the FRP materials.

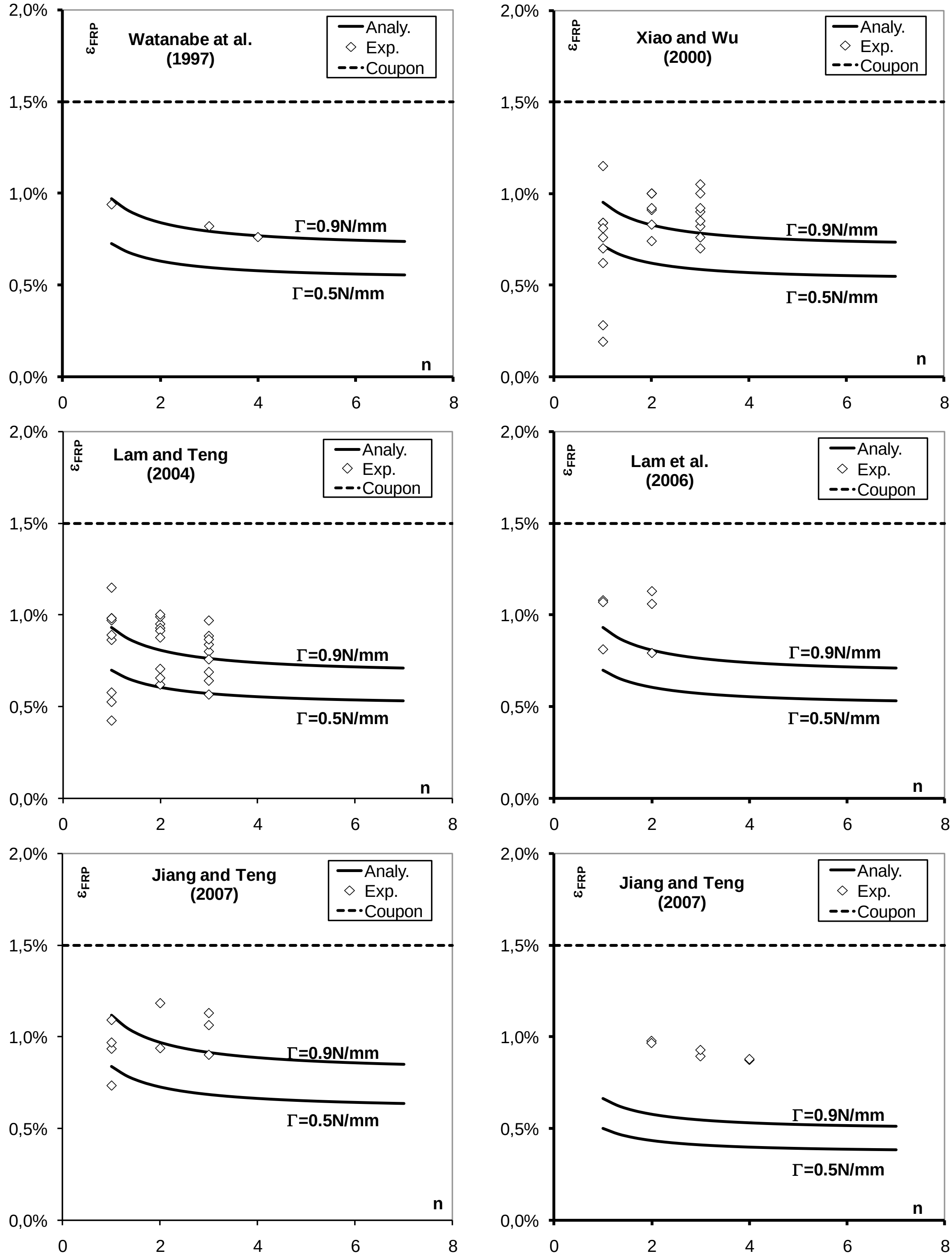


Figure 6. Experimental vs. analytical results on RC columns confined with CFRP jacketing.

6 CONCLUSION

The paper presents a numerical study on a proposed model able to evaluate the effectiveness of FRP in confinement applications due to stress concentrations at the edges of FRP jacket, as one of the possible premature failure modes of the system. The presented parametric study highlighted the driving parameters that control the stress concentrations at the edge of the FRP jacket. The main outcomes show that there is a theoretical background for the efficiency factor. However there are many influencing factors, which for time being are not fully under control. According to well known formulations available in International Codes and scientific literature, the confining pressure linearly depends on the total thickness and the Elastic Modulus of the FRP wrapping, while it is almost independent on the shear modulus G. According to the proposed model, based on the data collected in this study, a different relationship was observed: i) the thickness of each layer has lower influence than the number of layers; ii) the dependence on Elastic Modulus is non-linear; iii) values of Shear Modulus could determine FRP ultimate strain variations if they are below about 15 GPa; iv) if the overlapping length is longer than few centimeters, the ultimate FRP strain is usually not influenced by this parameter. Moreover a energy-based failure criterion was proposed to catch the brittleness of the debonding mechanisms instead of the stress failure criterion that in some cases can lead to underestimation of the effective FRP strain. The results of theoretical analyses compared with experimental data available in literature validated the model showing that interfacial properties of the resin layers are crucial parameters. Usually an exhaustive description of the resin adopted in experimental tests is not available in literature, while 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. The proposed model, eventually combined to models accounting for other premature failure modes could be used to capture the effective FRP strain for jacketing design. It is remarked that this value is, in many cases, much lower than the value given by the flat coupon test.

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