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FRACTURE MECHANICS APPROACHES TO CONCRETE STRENGTHENING USING FRP MATERIALS

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Abstract

The use of fibre reinforced polymer (FRP) materials in the form of thin laminates or fabrics bonded to the tension face of reinforced concrete (RC) members is becoming an increasingly attractive solution to the strengthening of such elements. Central to the performance of FRP-strengthened concrete structures is the transfer of stresses from concrete to the FRP reinforcement through a thin adhesive layer. Failure in this transfer region may result in brittle failures that must be taken into account in design properly. Recent research in this area has demonstrated that proper understanding and modelling of FRP-adhesive-concrete interface-related phenomena and failures may be improved via the application of fracture mechanics theories. Hence, the scope of this paper is to present fracture mechanics - both linear and nonlinear - modelling procedures for mechanisms associated with premature failures (bond failures) of FRP-concrete interfaces. The implementation of these procedures in practical design equations is also demonstrated.

Key words: Concrete, fibre reinforced polymers, fracture mechanics, strengthening

1 Introduction and background

Due to the infrastructure's increasing decay, which is frequently combined with the need for upgrading so that structures can meet more stringent design requirements, the strengthening of RC structures has received considerable emphasis over the past few years throughout the world. At the same time, seismic retrofit has become at least equally important, especially in earthquake prone areas.

Today's state-of-the-art techniques for the strengthening of RC structures bear the stamp of a relatively new class of structural materials, namely fibre reinforced polymers (FRP) or simply advanced composites, which offer the designer an outstanding combination of properties not available from other materials. FRP used as strengthening materials today are typically made of continuous carbon, aramid or glass fibres in one or two directions, bonded together with a matrix such as epoxy, vinylester or polyester. The resulting materials are characterized by excellent corrosion resistance, low density coupled with very high tensile strength and stiffness, excellent fatigue strength and creep/relaxation performance (superior than steel for carbon FRP - CFRP), and satisfactory chemical resistance. On the other hand, the designer should keep in mind that FRP materials are brittle but highly deformable (almost linear elastic up to failure strains of about 1-2% for carbon FRP and 2.5-3.5% for others) and that they cost many times more than mild steel. However, when cost comparisons are made on a strength basis and other than materials costs are taken into account (transportation, handling, labour, obstruction of occupancy etc), FRP are quite often cost-effective.

Fibre reinforced polymers have found their way as strengthening materials of RC structures in a variety of applications involving epoxy-bonding of sheets (laminates or fabrics) in the tension zones (plate bonding), and/or jacketing through wrapping of flexible sheets. More details may be found, for instance, in the review article published recently by Triantafillou (1998).

Central to the performance of FRP-strengthened RC elements is the transfer of stresses from concrete to the FRP reinforcement through a thin adhesive layer. Failure in this transfer region may result in brittle bond failures, which must be taken into account in design properly. Bond failures of either steel or FRP plates epoxy-bonded to the tension zones of RC elements have been analyzed extensively in the past according to a variety of strength-based theories (e.g. Yuceoglu and Updike 1980, Roberts 1989, Oehlers and Moran 1990, Brosens and Van Gemert 1997, to name a few).

Recent research has demonstrated that proper understanding and modelling of FRP-adhesive-concrete interface-related phenomena and failures may be improved via the application of fracture mechanics theories. Hence, the scope of this paper is to present fracture mechanics - both linear and nonlinear - modelling approaches for mechanisms associated with premature failure of FRP-concrete interfaces. The implementation of these procedures in practical design equations is also demonstrated.

2 LEFM approach

A concrete element strengthened with epoxy-bonded FRP reinforcement can fail in various different modes. Such modes include the classical ones, involving steel yielding, concrete crushing etc, and bond failure modes, which may occur at the FRP-concrete interface.

2.1 FRP debonding in RC beams

According to Triantafillou and Plevris (1992), who were the first to apply fracture mechanics to the failure analysis of FRP-strengthened RC elements (Fig. 1a), the bond between the FRP and the concrete may fracture in a sudden manner as the result of the catastrophic propagation of a crack along the FRP-concrete interface. Possible reasons for the existence of such a crack are: (a) imperfections in the spreading of the adhesive; (b) flexural cracking in the concrete (Fig. 1b); (c) unevenness of the concrete surface (Fig. 1c); and (d) fatigue loading.

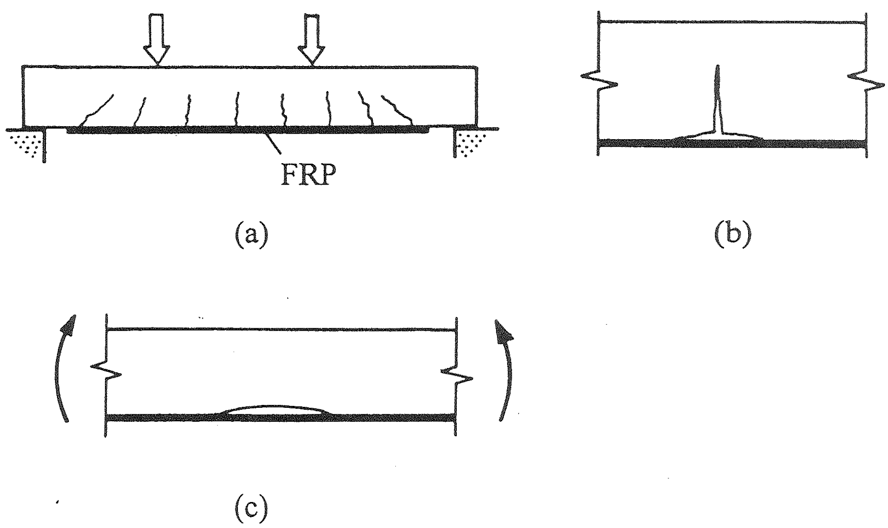


Fig. 1. (a) Flexural strengthening of RC beam; (b) FRP-concrete interface crack due to flexural cracking; and (c) interface crack due to unevenness of the concrete surface.

During loading of the RC element the adhesive is loaded primarily in shear, providing the necessary shear connection between the concrete and the FRP. Hence, the crack propagation mode will resemble fracture mode II.

Following classical principles of linear elastic fracture mechanics (LEFM) within the framework of the *compliance method*, that is relating the strain energy release rate G_{II} required for crack propagation to the compliance C of a member, one may write (e.g. Knott 1973, Triantafillou and Gibson 1989):

$$G_{II} = \frac{kP^2}{b}\left(\frac{\partial C}{\partial a}\right) \quad (1)$$

where P = applied load, b = width of FRP (assumed equal to the width of the beam), a = crack length, k = constant and C = u/P = reciprocal of the gradient of the load deflection curve (u = displacement under the load P). The constant k relates the load and displacement to the strain energy U as follows:

$$U = kPu \quad (2)$$

Fracture occurs when the strain energy release rate equals the critical strain energy release rate for the interface, G_{IIc}. Thus, the load corresponding to debonding is calculated from Eq. (1), with G_{IIc} substituting for G_{II}.

Note that $\partial C/\partial a$ in Eq. (1) depends on the applied load P. For a particular value of P the relationship between the compliance, C, and the crack length, a, may be established by analysing the beam using a finite element procedure. This approach was recently employed by Wu et al. (1997) in an attempt to analyse debonding in 900 mm long, 100 mm wide and 150 mm deep concrete beams strengthened in flexure with a 0.25 mm thick and 90 mm wide CFRP sheet. Using plane stress eight-node isoparametric elements and a very fine mesh close to the crack tip, Wu et al. (1997) performed parametric analyses (neglecting the nonlinearity of concrete) and compared the results with experimental. They concluded that the number of flexural cracks as well as the value of G_{IIc} have a considerable effect on the debonding load. The author's view is that such type of analyses need further refinements.

As far as the value of G_{IIc} is concerned, it can be measured using double-shear specimens pulled in tension (Triantafillou and Gibson 1989). Such specimens were used by Fukuzawa et al. (1997), who applied the above procedure to measure experimentally the critical strain energy release rate associated with mode II fracture at the interface between carbon fibre sheets and mortar.

2.2 FRP bond failure in the anchorage zone

In a recent study, Täljsten (1996) applied LEFM to the failure analysis of concrete prisms strengthened with epoxy-bonded plates (steel or FRP). The element analysed, shown in Fig. 2b, may be thought of as a simple model of the anchorage zone shown in Fig. 2a. Based on the assumptions that: (a) all materials are homogeneous, isotropic and linear elastic; (b) the adhesive is only exposed to shear forces; and (c) the thickness of the adherents and the adhesive, and the width of the plate are constant throughout the bond line, one may apply the compliance method to calculate the maximum tensile force in the FRP, T_{max}, corresponding to crack propagation in the bond line as follows:

$$T_{max} = \sqrt{2bG_{IIc} \Big/ \frac{\partial C}{\partial a}} \tag{3}$$

Considering small (axial) deformations, and ignoring the development of bending moments and the deformations in the bond layer, simple beam theory (e.g. Täljsten 1996) may result in the following expression for the derivative of the compliance:

$$\frac{\partial C}{\partial a} = \frac{1}{E_f t_f} + \frac{1}{E_c t_c} \tag{4}$$

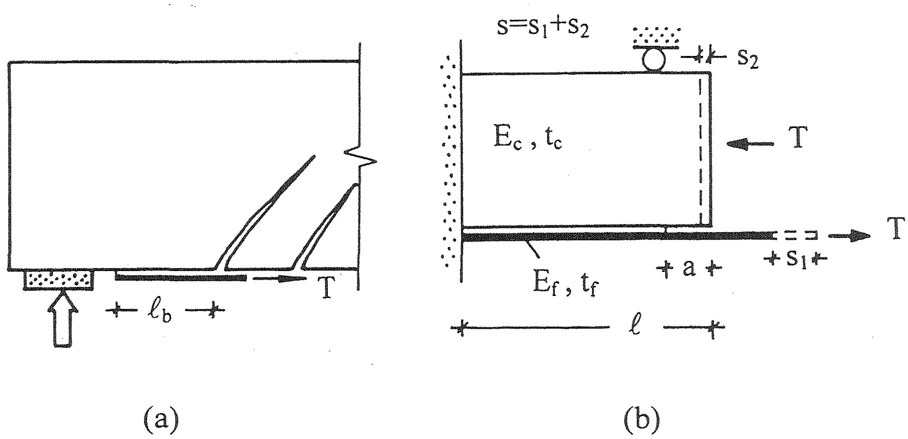


Fig. 2. (a) FRP plate anchorage zone; (b) simple model for describing bond failure in the anchorage zone.

Hence:

$$T_{max} = b\sqrt{\frac{2E_f t_f E_c t_c G_{IIc}}{E_f t_f + E_c t_c}} \tag{5}$$

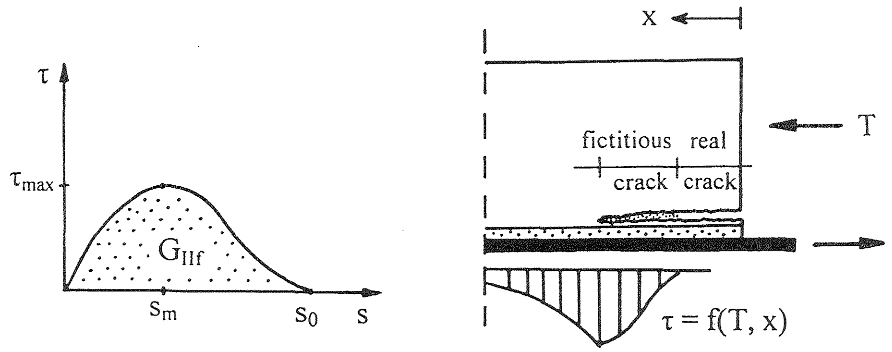
The apparent disadvantage of the LEFM-based methods described above is the assumption of linear elastic materials, an assumption which is typically not justified with concrete materials. Naturally, this has led to adoption of nonlinear fracture mechanics (NLFM) approaches, described in the next section.

3 NLFM approach: FRP bond failure in the anchorage zone

The problem of FRP bond failure in the anchorage zone (Fig. 2a) may be approached more realistically by assuming that the bond line is characterized by a nonlinear relationship between the local bond shear stress, τ, and the local slip, s, as shown in Fig. 3a. τ_{max} in Fig. 3a is the shear strength of the bond zone. Also note that the area below the τ - s curve represents the mode II fracture energy, G_{IIf}, which is defined as the energy required to bring a local bond element to shear fracture (debonding). It is important to note here that, as clearly suggested by experimental evidence, the constitutive material law of Fig. 3a and consequently G_{IIf} do not depend on the bond length ℓ_b, provided that this length does not fall below a certain value, $\ell_{b,max}$. In addition to the above constitutive law, a crack model for shear, the physical meaning of which is shown in Fig. 3b, may be used to derive the maximum tensile force in the FRP, T_{max}. Following this approach, Täljsten (1996) derived the expression for T_{max} corresponding to the geometry of Fig. 2b as given next:

$$T_{max} = \tau_{max} b(\ell - a) F\left(\frac{\tau_{max}^2 (\ell - a)^2}{E_f t_f G_{IIf}}, \frac{E_f t_f}{E_c t_c}, g\right) \tag{6}$$

where g represents the shape function of the τ - s curve. Simple shapes (e.g. linear ascending branch, linear ascending and descending branches) of τ - s curves result in analytical solutions for Eq. (6), while for more realistic shapes of the τ - s curve numerical stepwise calculations may be needed. For the simplest case of linear elastic bond behaviour (τ - s curve with linear ascending branch) Täljsten (1996) gives the following expression for F in Eq. (6):



(a) (b)

Fig. 3. (a) Local bond constitutive law according to NLFM; (b) fictitious crack model for bond failure in the anchorage zone.

$$F = \frac{\sqrt{2}}{\omega_1}\tanh\left(\frac{\omega_1}{\sqrt{2}}\right) \tag{7a}$$

$$\omega_1 = \left(\frac{\tau_{max}^2(\ell - a)^2\left(1 + \frac{E_f t_f}{E_c t_c}\right)}{E_f t_f G_{IIf}}\right)^{1/2} \tag{7b}$$

One of the main difficulties in applying the above method in practice is the choice of the proper value for the mode II fracture energy, G_{IIf}. Pure shear tests on concrete are difficult to perform, but approximate testing techniques inducing "almost" pure shear in concrete may be adopted. Using one of these, Täljsten (1996) established an upper (but close) bound to G_{IIf}, which is in the order of 1.21 Nmm/mm^2.

We should note here that the validity of Eq. (7) has been checked and verified successfully by Täljsten (1996) for concrete strengthened with steel plates and by Brosens and Van Gemert (1997) for concrete strengthened with CFRP.

A similar NLFM approach was also employed by Holzenkämpfer (1994), who characterized bond failure of steel plates bonded to concrete using the bond law of Fig. 3a with linear ascending and descending branches. Adopting the Mohr-Coulomb failure criterion, the value of τ_{max}

is expressed as a function of the concrete surface's tensile strength, f_{ctm}; the slips s_m and s_0 are derived from the deformation of a representative volume of the bond zone; and the mode II fracture energy can be approximated as:

$$G_{IIf} \approx C_f f_{ctm} \tag{8}$$

where C_f is a constant which may be determined by linear regression analysis of the results corresponding to fracture energy testing (e.g. double shear tests).

Finally, for bond lengths exceeding the limiting value, $\ell_{b,max}$, the maximum ultimate bond force is given as:

$$T_{max} = c_1 k_b b_f \sqrt{E_f t_f f_{ctm}} \tag{9}$$

where k_b is a geometry factor:

$$k_b = 1.06 \sqrt{\frac{2 - \frac{b_f}{b_c}}{1 + \frac{b_f}{400}}} \tag{10}$$

b_f is the width of the FRP and b_c is the width of concrete. $\ell_{b,max}$ is given as follows:

$$\ell_{b,max} = \sqrt{\frac{E_f t_f}{c_2 f_{ctm}}} \tag{11}$$

c_1 and c_2 in Eq. (9) and (11) may be obtained through calibration with test results. For bond lengths $\ell_b < \ell_{b,max}$, the ultimate bond force was calculated according to Holzenkämpfer (1994) as follows:

$$T = T_{max} \frac{\ell_b}{\ell_{b,max}} \left(2 - \frac{\ell_b}{\ell_{b,max}} \right) \tag{12}$$

Neubauer and Rostásy (1997) have recently performed 51 bond tests (similar configuration as in Fig. 2b) with variables the width and thickness of CFRP plates, the bond length and the concrete compressive strength. In these tests bond failure was characterized by sudden crack propagation either through the concrete only (for concrete with compressive strength f_c=25 MPa) or through the CFRP (interlaminar failure) after a few centimetres of concrete failure (for f_c=55 MPa), which started from the loaded end of the bond length. Despite the different failure modes, Rostásy and Neubauer (1997) concluded that the same fracture mechanism, dependent on the concrete fracture energy, was responsible for the initiation of bond failure, while the interlaminar failure was considered as a secondary effect, caused by the high local tensile stresses (peeling effect). Calibration of Holzenkämpfer's model using the data of Rostásy and Neubauer (1997), resulted in the following values for c_1 and c_2 in Eq. (9) and (11): c_1 = 0.75 and c_2 = 1.43, corresponding to a mean value of C_f = 0.204 and a standard deviation equal to 0.0527. Finally, it should be noted that the set of Eq. (9)-(12) may be considered as an appropriate tool for the design of the anchorages in CFRP-strengthened concrete elements.

4 Summary and conclusions

Fracture mechanics theories are valuable in explaining and analysing bond failures in FRP-strengthened reinforced concrete structures. Early LEFM approaches, such as the compliance method, are relatively simple to use but fail in accuracy by neglecting the nonlinearity of concrete. NLFM models have been used by various researchers to describe bond failure of FRP in the anchorage (end) zones. These models are based on the fundamental assumption that bond failure is attributed to mode II crack propagation, and hence the mode II fracture energy appears to be the most important modelling parametre. Design equations for the ultimate load in the FRP are expressed in terms of the fracture energy, which, in turn, may be related to the (tensile) strength of concrete.

The author believes that fracture mechanics modelling of FRP-strengthened concrete structures is only a little beyond its infancy. The research community today has to deal not only with a number of unsolved research problems (e.g. analysis of failure modes involving mixed mode cracking, expansion of experimental database to consider various FRP, adhesives, concrete qualities, geometries etc.), but also with the challenging task to introduce fracture mechanics in simple formulas which may be introduced in design codes.

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