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# Debonding failure along a softening FRP-to-concrete interface between two adjacent cracks in concrete members

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**Abstract**

A concrete beam can be strengthened by bonding a fibre reinforced polymer (FRP) plate to the tension face, and a common failure mode for such beams involves the debonding of the FRP plate that initiates at a major flexural crack, which is widely referred to as intermediate crack (IC) debonding. To understand IC and other debonding failures, the bond behaviour between FRP and concrete has been studied extensively using simple pull-off tests, in which a plate is bonded to a concrete prism and is subject to tension. However, the behaviour of the FRP-to-concrete interface in a beam can be significantly different from that captured in a pull-off test as, in a beam, whether debonding along the FRP-to-concrete interface occurs at a major flexural crack or not depends on the conditions at this crack as well as at the adjacent crack on the path of the debonding propagation. This paper is therefore concerned with the debonding process of an FRP-to-concrete bonded joint where the FRP plate is subject to tension at both ends, which closely approximates the IC debonding process in a flexurally strengthened RC member. The same problem has been the topic of a previous study by the authors, where a bilinear local bond–slip model was employed for the FRP-to-concrete interface. However, that solution is rather complex and difficult to apply in practice. The aim of this study is to produce a simplified solution by employing the simple linearly softening local bond–slip law for the interface. Results from this simplified analytical solution are compared with those from the previous solution, showing little loss of accuracy in predicting the load–displacement response and the ultimate load. The most significant outcome of the new solution is a simple expression for the ultimate load of the bonded joint which offers the potential for direct practical application. While the emphasis of the paper is on FRP-to-concrete joints, the solution and methodology are applicable to similar joints between other materials such as FRP-to-steel or steel-to-concrete bonded joints.


*Keywords:* FRP; Concrete; Interface; Debonding; Bond–slip model; Ultimate load; Interfacial stresses; Fracture energy; Effective bond length

## 1. Introduction

External bonding of fibre reinforced polymer (FRP) plates (or sheets) has become a popular method for the strengthening or retrofitting of reinforced concrete (RC) structures [1–3]. In this strengthening method, the performance of the FRP-to-concrete interface in providing an effective stress transfer is of crucial importance. Indeed, a number of failure modes in FRP-strengthened RC members are directly caused by interfacial debonding between the FRP and the concrete [4–7]. One of the failure modes, referred to as intermediate crack-induced debonding (IC debonding) by Teng et al. [7], involves debonding of the FRP plate which initiates at a major crack where the plate is under tension and propagates along the FRP-to-concrete interface towards the stress-free end of the plate (Fig. 1). A number of studies [7–10] have been concerned with IC debonding failure, which is also recognized in a number of design guidelines [11–13]. A recent review and comparison of these models can be found in Ref. [14].

IC debonding failures may be further divided into two types. In the first type, no crack exists between the free end of the plate and the crack where debonding initiates. The stress state of the interface in this case is similar to that in a simple pull-off test specimen in which a plate is bonded to a concrete prism and

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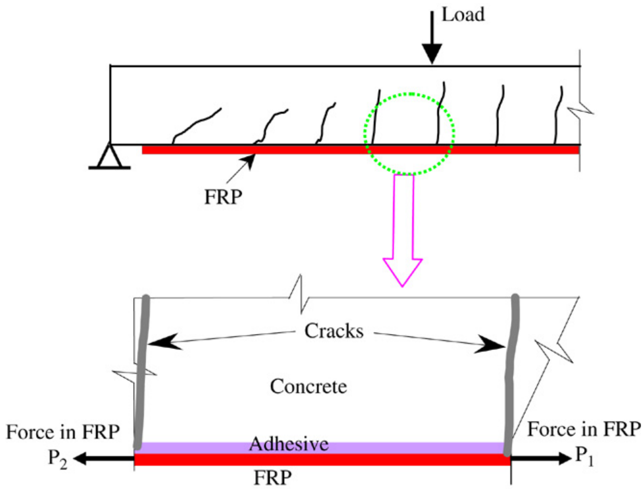
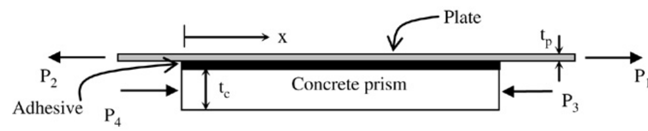
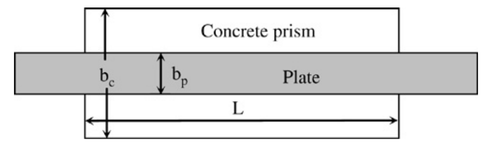



Fig. 1. Intermediate crack-induced debonding in FRP-plated RC beams.




(a) Elevation.




(b) Plan.

Fig. 2. FRP-concrete bonded joint model between two adjacent cracks.

is subject to tension. This type of IC debonding may occur in an RC beam with no or very limited steel tension reinforcement. The debonding failure in concrete beams shear strengthened with FRP U jackets or side strips is also similar [6]. A large number of studies have been carried out on bonded joints in simple pull-off tests (e.g. [15–28]).

In the second type of IC debonding, one or more significant cracks exist between the debonding initiation crack and the plate end. The mechanics in this case are different from that of a simple pull-off test. The key feature in such an IC debonding failure is that the propagation of debonding from the initiation crack to the adjacent crack depends not only on the tensile force in the FRP at the initiation crack but also on that at the adjacent crack. The present paper aims to provide a theoretical basis for interpreting and predicting this type of IC debonding failure.

The behaviour of the FRP-to-concrete interface between two adjacent cracks may be approximated by a simple model, as shown in Fig. 2. The model is similar in geometry to a simple pull-off test. Their chief difference lies in that both ends (i.e. at both cracks) of the FRP plate are subject to tension in this model. Little attention has been paid to the failure of such a bonded joint model. Schilde and Seim [29] conducted an experimental and numerical study for such a bonded joint, but the applied loading is different. Their study was limited to the following idealized loading path for the convenience of testing, which significantly limits its applicability: the tensile forces at both ends of the FRP plate first increase to a prescribed value, and thereafter the force at one end remains constant while the force at the other end increases until failure of the bonded joint occurs. Teng et al. [30] presented an analytical solution for this simple FRP-to-concrete bonded joint (Fig. 2) employing a bilinear local bond–slip model between the FRP and the concrete. They assumed that all the forces, as shown in Fig. 2, remain proportional to each other throughout the loading process, consistent with the variations of forces in an RC beam flexurally strengthened with FRP at an IC debonding failure where the tensile steel reinforcement has yielded at both cracks.

Although a bilinear bond–slip model which features a linearly ascending branch followed by a linearly descending branch provides a close representation of the bond–slip behaviour of FRP-to-concrete interfaces [10,24,27,31], the solution of the problem, as shown in Fig. 2, using the bilinear model is involved and does not lead to an explicit expression for the ultimate load [30]. The present paper presents a simpler analytical solution for the same FRP-to-concrete bonded joint model (Fig. 2) based on a linearly softening bond–slip curve (i.e. neglecting the ascending branch in the bilinear bond–slip curve). The aim is to produce a simple yet sufficiently accurate solution that can provide better insights into the process of IC debonding failure in flexurally strengthened RC beams.

It should be noted that the term “ultimate load”, which is the maximum load capacity of the joint, is used in this paper instead of “bond strength” to avoid confusion with the local bond strength of the interface, which is the maximum shear stress on a bond–slip curve.

It should also be noted that, although the emphasis of the paper is on FRP-to-concrete joints, the analytical solution is general and applicable to bonded joints between thin plates of various materials (e.g. FRP, steel and aluminum) and a substrate of various materials (e.g. concrete, steel and aluminum). Examples include debonding failures of RC beams bonded with steel plates which have been studied extensively in the literature [e.g. [32]] and those of steel beams bonded with FRP [e.g. [33]].

## 2. FRP-to-concrete bonded joint model

Fig. 2 shows the FRP plate-to-concrete bonded joint model investigated in this study, which is the same as that in Ref. [30]. The plate is subject to two tensile forces: $P_1$ at the right end and $P_2$ at the left end. Without loss of generality, it is assumed that $P_1 \geq P_2 \geq 0$. The concrete prism is assumed to be subject to two forces, $P_3$ and $P_4$, which can be either tensile or compressive. It is assumed that all these forces remain proportional throughout the loading process. The width, thickness and the modulus of elasticity are denoted by $b_p$, $t_p$ and $E_p$, respectively, for the plate, and by $b_c$, $t_c$ and $E_c$, respectively, for the concrete prism. The length of the bonded part of the plate (i.e. bond length) is denoted by $L$.