**Debonding Failures in FRP-Strengthened RC Beams: Failure Modes, Existing Research and Future Challenges**

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## Abstract

Both the flexural and shear capacities of reinforced concrete (RC) beams can be increased by bonding fibre-reinforced polymer (FRP) composites. A variety of debonding failure modes are possible in these strengthened beams, and for reliable strengthening measures, these debonding failures must be designed against. This paper provides a review of existing research on debonding failures in FRP-strengthened RC beams. Various failure modes are identified, and for each failure mode, existing research is summarised, with particular attention to studies on strength models. Issues which require future research are also outlined.

## Introduction

Extensive research has been carried out in recent years on the flexural and shear strengthening of reinforced concrete (RC) beams using fibre-reinforced polymer (FRP) composites. This research has identified a variety of debonding failure modes as the limiting factor of the ultimate strength (Teng et al. 2001a). This paper provides a review of existing research on debonding failures in FRP-strengthened RC beams. Various failure modes are identified, and for each failure mode, existing research is summarised, with particular attention to studies on strength models. Issues which require future research are also outlined. Only beams strengthened with plates/sheets without prestressing or mechanical end anchorage are covered, as these are the more common and due to space limitation. Also due to space limitation, the review is relatively brief and the list of references is limited, but more details and a comprehensive list of references can be found in Teng et al. (2001a).

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Only debonding failures which occur in the concrete are treated here. Debonding at the adhesive-to-concrete interface and away from the concrete should be avoided by the use of strong adhesives and appropriate surface preparation. For such debonding failures in the concrete, studies on RC beams strengthened with a bonded steel plate are often as relevant as those on RC beams bonded with an FRP plate, and reference to the former are made in this paper when appropriate.

## FRP-to Concrete Bond Strength

***General.*** In the strengthening of RC beams, FRP plates or sheets are externally bonded to RC beams using adhesives. For the external FRP to be effective in enhancing the load-carrying capacity of the beam, effective stress transfers between the FRP and the concrete are required. The bond strength between FRP and concrete has thus been a major topic of research and is first discussed in this section.

***Test Methods, Failure Mode and Effective Bond Length.*** Substantial experimental and theoretical work exists on the bond strength of FRP or steel plate-to-concrete joints (Chen and Teng 2001a, Teng et al. 2001a). Most of the experiments have been carried out using simple shear tests (Figure 1), on which the discussion here is based, but several other test set-ups have been used. A numerical investigation showed that significant differences exist between different test set-ups (Chen et al. 2001a). Provided strong adhesives are used, FRP and steel plate-to-concrete bonded joints fail within the concrete adjacent to the adhesive-to-concrete interface, starting from the critically stressed position in most cases (Chen and Teng 2001a).

An important feature of plate-to-concrete bonded joints is that the bond strength, in terms of the force in the bonded plate, cannot always increase with an increase in the bond length $L$ (Figure 1), and that the ultimate tensile strength of an FRP plate may never be reached however long the bond length is. This leads to the concept of effective bond length, beyond which any increase in the bond length cannot increase the bond strength, as confirmed by many experimental studies (e.g. Täljsten 1994, Maeda et al. 1997) and fracture mechanics analyses (e.g. Holzenkämpfer 1994, Yuan et al. 2001). However, a longer bond length can improve the ductility of the failure process. This phenomenon is substantially different from the bond behaviour of internal reinforcement and must be accounted for in the development of bond strength models and design rules.

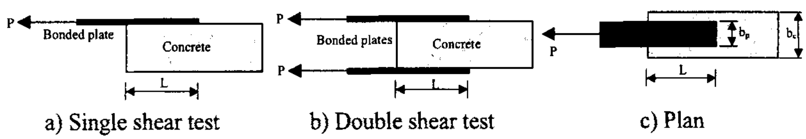
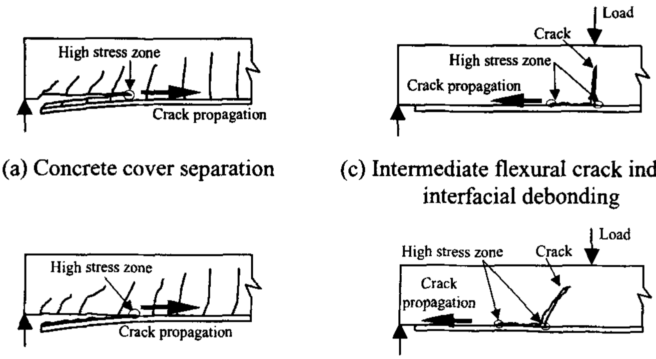



Figure 1. Single and double shear tests

***Bond Strength Models.*** Several bond strength models (Maeda et al. 1997, Hiroyuki and Wu 1997, Tanaka 1996, Täljsten 1994, Neubauer and Rostásy 1997, Holzenkämpfer 1994, Yuan et al. 2001) and design proposals (van Gemert 1980, Khalifa et al. 1998, Chaallal et al. 1998) have been advanced in the last few years. Chen and Teng (2001a) recently examined these models by comparing them with experimental data collected from the literature. They further developed a strength model based on a fracture mechanics solution (Chen and Teng 2001a). This new model not only captures all the characteristic behaviour of an FRP-to-concrete bonded joint, but is also in better agreement with existing test data.

## Debonding Failures in Flexurally-Strengthened Beams

***Failure Modes.*** A number of debonding failure modes have been observed in numerous tests on RC beams flexurally-strengthened with an FRP soffit plate (Teng et al. 2001a), which are often referred to as FRP-plated RC beams. These may be broadly classified into two types: (a) plate end debonding failures, including concrete cover separation (Figure 2a) and plate end interfacial debonding (Figure 2b); and (b) intermediate crack induced interfacial debonding failures including those due to a major flexural crack (Figure 2c) or a flexural-shear crack (Figure 2d).




(a) Concrete cover separation

(c) Intermediate flexural crack induced interfacial debonding

(b) Plate end interfacial debonding

(d) Intermediate flexural-shear crack induced interfacial debonding

Figure 2. Debonding failure modes of FRP-plated RC beams

***Interfacial Stresses.*** Plate end debonding failures are due to high interfacial stresses near the plate end, and a number of approximate closed-form solutions for these stresses suitable for direct exploitation in design have been formulated (Vilnay 1988, Roberts 1989, Roberts and Haji-Kazemi 1989, Liu and Zhu 1994, Täljsten 1997, Malek et al. 1998, Smith and Teng 2001a). All these solutions are based on the assumption that the shear and normal stresses are uniform across the adhesive layer thickness, and have been found to give closely similar results for RC beams bonded with a thin plate (Smith and Teng 2001a). Higher order solutions for interfacial stresses (Rabinovich and Frostig 2000, Shen et al. 2001) have also been obtained as well as finite element results (Teng et al. 2000). These studies showed that the distributions of interfacial stresses near the plate end are much more complicated than are predicted by simple approximate solutions such as that of Smith and Teng (2001a), although the latter does provide a useful approximation.

***Strength Models for Plate End Debonding Failures.*** Several strength models for plate end debonding have been developed for FRP-plated RC beams in the last decade (Varastehpour and Hamelin 1997, Saadatmanesh and Malek 1998, Wang and Ling 1998, Ahmed and van Gemert 1999, Tumialan et al. 1999, Raoof and Hassanen 2000). In addition, a number of strength models have also been developed for plate end debonding in steel plated beams (Oehlers 1992, Ziraba et al. 1994, Jansze 1997, Raoof and Zhang 1997).

These debonding strength models can be divided into three categories in terms of approaches, namely (a) shear capacity based models (Oehlers 1992, Jansze 1997, Ahmed and van Gemert 1999) in which the debonding failure strength is related to the shear capacity of the beam; (b) concrete tooth models (Raoof and Zhang 1997, Wang and Ling 1998, Raoof and Hassanen 2000) in which the behaviour of a concrete "tooth" formed between two adjacent cracks deforming like a cantilever under the action of lateral shears applied at the beam-plate interface is considered; and (c) interfacial stress based models (models I and II of Ziraba et al. 1994, Varastehpour and Hamelin 1997, Saadatmanesh and Malek 1998, Tumialan et al. 1999) in which predictions of interfacial stresses are made use of, generally in conjunction with a concrete failure criterion. Model II of Ziraba et al. (1994) in fact combines approaches (a) and (c). In addition, it should be mentioned that Oehlers' (1992) model is not purely based on the shear capacity, as it also takes into account the interaction between shear and bending.

An assessment of the performance of these models against existing test data of FRP-plated beams have been recently undertaken (Smith and Teng 2001b, c, Teng et al. 2001a) which shows that Oehlers' (1992) model is the best in terms of providing safe and close predictions for design use for the plate end debonding mode, despite the fact that it was developed based on test data of steel-plated beams. Smith and Teng (2001c) also proposed a new simple model by modifying Oehlers' (1992) model. This new model is superior to other existing models in terms of providing safe and close predictions for direct application in design (Smith and Teng 2001c, Teng et al. 2001a).

***Strength Model for Intermediate Crack Induced Debonding Failures.*** The intermediate crack induced debonding mode involves interfacial debonding in the concrete adjacent to the adhesive-to-concrete interface which initiates at a flexural or flexural-shear crack and propagates towards one of the plate ends. Limited experimental data show that the debonding failure strength of this mode can be closely predicted by Chen and Teng's (2001a) bond strength model with a simple modification (Teng et al. 2001a, 2001b).

**Debonding Failures in Shear-Strengthened Beams**

***Debonding Failure Mode.*** The common methods for shear strengthening using FRP composites include bonding FRPs on the sides of a beam only, bonding U jackets to cover both sides and the soffit, and wrapping FRPs around the cross-section. A detailed description of these strengthening schemes is given in Teng et al. (2001a). When an FRP-strengthened RC beam fails in shear, the two common failure modes are shear failure due to FRP rupture and that due to FRP debonding. It may be noted that, in the shear failure mode due to FRP rupture, FRPs are likely to have debonded before they rupture but this has little effect on the shear capacity of the beam.

Figure 3. FRP debonding failure of a U jacketed RC beam

For test beams controlled by shear failure, available test data show that all beams with FRPs bonded on sides only, and many bonded with U jackets, failed by debonding of the FRP from the concrete. In this mode, once the FRP starts to peel off, the beam fails very quickly in a brittle manner. Bond strength between FRP and concrete thus plays the key role here. Figure 3 shows the shear failure due to FRP debonding of a U jacketed beam.

***Strength Models.*** A number of design proposals have been presented for the shear capacity of shear-strengthened RC beams (Chaallal et al. 1998, Triantafillou 1998, Khalifa et al. 1998, Triantafillou and Antonopoulos 2000). In all these proposals, the shear capacity of a shear-strengthened RC beam is expressed as the sum of the contributions from the concrete, the steel shear reinforcement and the bonded FRP.

Chaallal et al. (1998) treated the FRP as conventional shear reinforcement. Debonding is dealt with by limiting the design average shear stress between the FRP and the concrete to half the value expected at debonding. However, the debonding strength model used by them does not match well with experimental data and the effective bond length is not considered (Chen and Teng 2001a).

Triantafillou (1998) proposed to limit the strain in the FRP to an effective strain which was obtained from regression of experimental data. The model does not distinguish between different strengthening schemes and failure modes. Triantafillou and Antonopoulos (2000) extended Triantafillou's (1998) model so that different effective strain expressions are given for CFRP wrapping and other strengthening schemes, but no distinction is made between side bonding and U jacketing.

Khalifa et al. (1998) proposed a modification to Triantafillou's (1998) effective strain model in which the ratio of effective stress (or strain) in the FRP to its ultimate strength (or strain) is used instead of the effective stress (or strain) itself. In particular, they proposed a bond mechanism design approach based on the bond strength model of Maeda et al. (1997). However, the bond strength model of Maeda et al. (1997) adopted in deriving the design proposal cannot correctly predict the effective bond length (Chen and Teng 2001a).

Recognising the deficiencies of the above models, Chen and Teng (2001b) derived a rational debonding strength model for shear-strengthened RC beams based on their FRP-to-concrete bond strength model (Chen and Teng 2001a). The new model is in better agreement with test data than all other models.

**Future Challenges**

***General.*** The above review shows that significant advances have been made in the last few years in achieving a better understanding of debonding failures in FRP-strengthened RC beams. Rational strength models are now available for most of these debonding failure modes. However, a great deal of further work is required on a number of aspects. Some of the more obvious are discussed below.

***FRP-to-Concrete Bond Strength.*** Although many test results are now available, there is still the need for more tests, particularly those carefully conducted, instrumented and documented. For example, more experimental data on effective bond length are required.

***Flexurally-Strengthened RC Beams.*** For plate end debonding failures, the recently proposed Smith and Teng (2001c) model considers only the effect of plate end shear force and ignores any interaction between shear force and bending moment. Test results can be several times higher than the predictions of their model, which indicates that there is room for significant improvement to the accuracy of the model. The lack of interaction between shear force and bending moment is another aspect which needs attention. While this lack of interaction reflects the trend of the existing test database, it has been attributed to the limitation of this database in a subsequent study (Smith and Teng 2001d). Smith and Teng (2001d) showed that interaction between shear force and bending moment at the plate end is important through a series of experiments and proposed a bi-linear approximation to describe this interaction based on these experimental results. A great deal of further work is thus required on plate end debonding failures so that more accurate models can be developed.

For intermediate crack-induced debonding failures, existing test results are rather limited, so additional tests covering a wide range of dimensions are required. In particular, Teng et al. (2001b) assumed that the same strength model is appropriate for both failures due to a major flexural crack or a major flexural-shear crack. Further studies are required to confirm the validity of this assumption over a wide range of parameters.

***Shear-Strengthened RC Beams.*** Most experiments have been conducted on beams with a small range of shear-span/depth ratios and beam sizes. Further research is needed to establish a better understanding of the failure process, verify existing strength models in practical ranges of parameters and develop improved strength models if necessary.

***Numerical Simulations and Large Scale Experiments.*** Most existing studies on debonding failures have been experimentally based, or on the exploitation of experimental results to develop relatively simple strength models. Numerical simulations of debonding failures, to predict both failure processes and failure loads, have lagged behind. Efforts in this direction should be encouraged. Similarly, tests have been commonly conducted on small to medium sized beams, while those on larger beams, due to the considerable cost, have been relatively few.

## Conclusions

For both flexurally-strengthened and shear-strengthened RC beams, the main debonding failure modes have been identified and are reasonably well understood. Rational strength models are now available for these failure modes, although a great deal of further work is required both to gain better insight into failure mechanisms and to develop more accurate strength models.

## Acknowledgements

The authors wish to thank The Hong Kong Polytechnic University for the financial support provided to the project "Retrofitting of RC Structures using FRP Composites" through the Area of Strategic Development in Advanced Buildings Technology in a Dense Urban Environment and for a postdoctoral fellowship for the third author.

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