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CHARACTERIZATION AND MODELING OF DEBONDING IN RC BEAMS STRENGTHENED WITH FRP COMPOSITES

Oral Buyukozturk[1], Member ASCE
Oguz Gunes[2]
Erdem Karaca[3], Member ASCE

ABSTRACT

Use of fiber reinforced plastic (FRP) composites for strengthening reinforced concrete (RC) beams have become a frequently used method in the last decade. However, the method is yet to become a mainstream application due to a number of economical and design related issues. From structural mechanics point of view, an important concern regarding the effectiveness and safety of this method is the potential of brittle debonding failures. Such failures, unless adequately considered in the design process, may significantly decrease the effectiveness of the strengthening and may even make the member less safe due to decreased ductility. Despite considerable research progress, continued research in this area is needed to develop the necessary analysis and design procedures and related codes and standards. This paper summarizes the findings of a comprehensive experimental and preliminary analytical research work aimed at modeling debonding failures in FRP strengthened RC beams.

Keywords: Beams, FRP, Strengthening, Debonding

INTRODUCTION

Use of FRP composite materials for seismic retrofitting of structural members have continuously increased around the world in the last decade. Numerous research studies and applications have shown that FRP materials can effectively be used to increase the stiffness, load carrying capacity, ductility, and durability of various types of structural members including columns, beams, slabs, walls, and joints. Although the potential of the method is widely recognized, its wide range use is hindered by the common encounter of premature and brittle debonding failures. Inadequately designed strengthening applications may not only become ineffective, but may also reduce the level of safety of the member by decreasing its ductility. Design procedures that properly consider debonding problems are urgently needed to ensure the safety and effectiveness of beams strengthened with FRP composites. In this paper, debonding mechanisms in FRP strengthened beams are discussed in view of experimental investigations and theoretical modeling studies.

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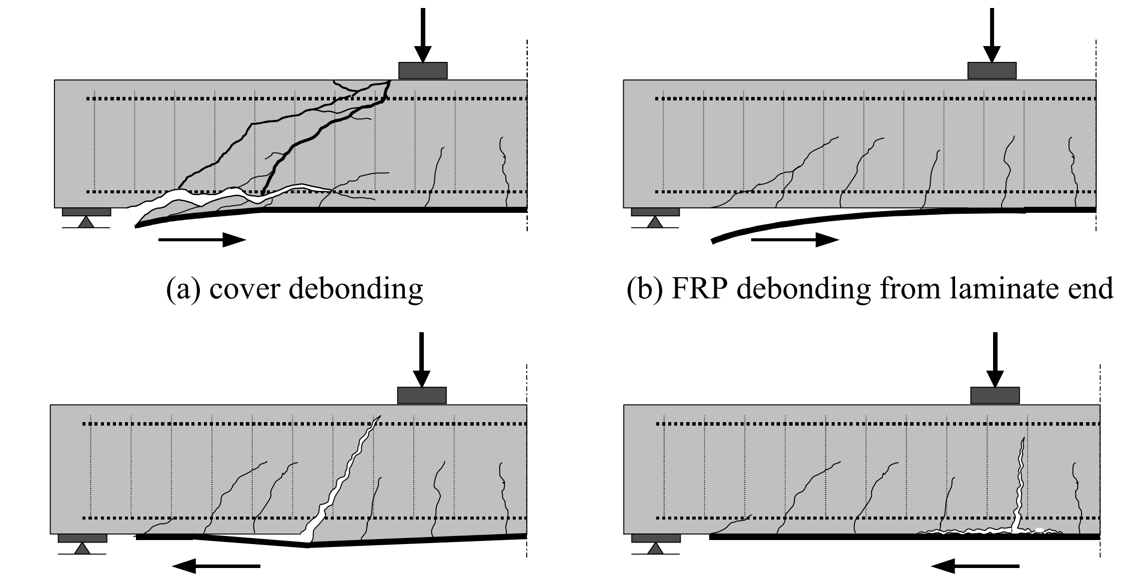
[1] Dept. of Civil & Env. Eng. Massachusetts Institute of Tech., Cambridge, MA, 02139, E-mail: obuyuk@mit.edu
[2] Dept. of Civil & Env. Eng. Massachusetts Institute of Tech., Cambridge, MA, 02139, E-mail: ogunes@mit.edu
[3] Dept. of Civil & Env. Eng. Massachusetts Institute of Tech., Cambridge, MA, 02139, E-mail: karaca@mit.edu

FAILURE MODES OF FRP STRENGTHENED BEAMS

Failure of FRP strengthened beams may take place through several mechanisms depending on the beam and strengthening parameters. Recently, ACI Subcommittee 440F (2000) developed a report specifically on analysis and design and construction of externally bonded FRP systems. In this report, the failure modes of beams strengthened in flexure with external FRP reinforcement are classified as follows: (1) concrete crushing before reinforcing steel yielding, (2) steel yielding followed by FRP rupture, (3) steel yielding followed by concrete crushing, (4) cover delamination, (5) FRP debonding. In addition to these, shear failure occurs if the shear capacity of the beam cannot accommodate the increase in the flexural capacity. An investigation of each of these failure modes is required in the design process to ensure that the strengthened beam will perform satisfactorily.

DEBONDING FAILURE MECHANISMS

The term debonding failure is often associated with a significant decrease in member capacity due to initiation and propagation of debonding. Debonding initiation in beams strengthened with FRP composites generally take place in regions of high stress concentration at the concrete-FRP interface. These regions include the ends of the FRP reinforcement, and those around the shear and flexural cracks. Fig. 1 shows the fundamental debonding mechanisms that may result in premature failure of FRP strengthened beams. The cover debonding mechanism shown in Fig 1(a) is usually associated with high interfacial stresses, low concrete strength, and/or with extensive cracking in the shear span. An experimental investigation of the interaction between the beam shear capacity and debonding failures is presented in this paper. If the concrete strength and the shear capacity of the beam are sufficiently high, potential debonding failure is most likely to take place through FRP debonding, which initiates at the laminate ends and propagates towards the center of the beam, as shown in Fig. 1(b). Depending on the material properties, debonding may occur within the FRP laminate, at the concrete-FRP interface, or a few millimeters within the concrete. If the shear span of the strengthened beam is sufficiently long to enable proper bond development, or the laminate ends are anchored by some means, debonding may initiate at flexure-shear cracks and propagate towards the ends of the beam, as shown in Fig. 1(b). If the shear capacity of the beam is sufficiently high, debonding may also initiate from flexural cracks. However, this failure mechanism is very rare, especially in four-point bending tests. Propagation of debonding within the constant moment region does not change the stress distribution within the strengthened system, thus, a conceptual interpretation suggests that debonding propagation within the constant moment region is energetically not justified. It is possible, even expected, that high stress concentrations around flexural cracks may promote debonding (Leung, 2001), however, such stress concentrations diminish rapidly with propagation of debonding, resulting in a limited debonded area. For this reason, research into debonding from flexural cracks generally involves three point bending tests, which mechanically makes more sense. In four-point bending tests, debonding from flexural cracks close to the load points, i.e. close to the ends of the constant moment region, may propagate into the shear span and result in failure of the beam, which is a scenario similar to three-point bending tests. Debonding failures in FRP



(a) cover debonding (b) FRP debonding from laminate end

(c) FRP debonding from flexure-shear crack (d) FRP debonding from flexural crack

FIG 1. Debonding failure mechanisms

strengthened beams are likely to involve a combination of the mechanisms described above, failure being determined by the dominant mechanism.

A noteworthy issue regarding the debonding mechanisms illustrated in Fig. 1(a) and 1(c) is the potential of shear failure in combination with debonding failure. It is often the case that the debonding and shear failures are not properly differentiated and reported. This is partly justified considering that the member is considered as failed in both cases. However, a fundamentally important difference between debonding and shear failures is the ductility behavior. Debonding failures significantly reduce the beam capacity, however, provided that the beam has adequate shear capacity, it can still display the ductile failure behavior of an unstrengthened beam. This is not the case for shear failures where total beam failure takes place in a brittle fashion. Thus, it appears that ensuring adequate shear resistance of the beam must be considered as the first priority in strengthening design. This vital issue, which still remains underinvestigated, must be given the attention it deserves through further experimental and analytical studies.

PREVIOUS RESEARCH INTO DEBONDING PROBLEMS

Characterization and modeling of debonding in structural members strengthened with externally bonded reinforcements has long been a popular area of interdisciplinary research due to critical importance of debonding failures in bonded joints. In the last decade, there has been a concentration of research efforts in this area with respect to FRP strengthened flexural members, and considerable progress has been achieved in understanding the causes and mechanisms of debonding failures through numerous experimental, analytical, and numerical investigations (Buyukozturk et al, 2002). Modeling research in this area can be classified in general terms by their approach to the problem as strength and fracture approaches. In addition to these, a number of researchers have proposed relatively simple semi-empirical and empirical models that avoids the complexities of stress and fracture analyses and can be relatively easily implemented in design calculations.

Strength approach involves prediction of debonding failures through calculation of the interfacial or bond stress distribution in FRP strengthened members based on elastic material properties. Calculated stresses are compared with the ultimate strength of the materials to predict the mechanism and load level of debonding failures. The fact that debonding is essentially a crack propagation promoted by local stress intensities has raised interest among some researchers to take a fracture mechanics approach to the problem and develop predictive models that utilize elastic and fracture material properties. The few fracture models proposed so far have limited success in predicting the failure load for FRP strengthened beams and need further improvement. The general objective of empirical models is to provide a simple methodology to predict debonding failures without going into complex stress or fracture analyses. Several such models were proposed for FRP strengthened beams based on certain parameters that influence their debonding behavior. The reader is referred to Buyukozturk et al (2002) and Teng et al (2002) for a comprehensive review of debonding models.

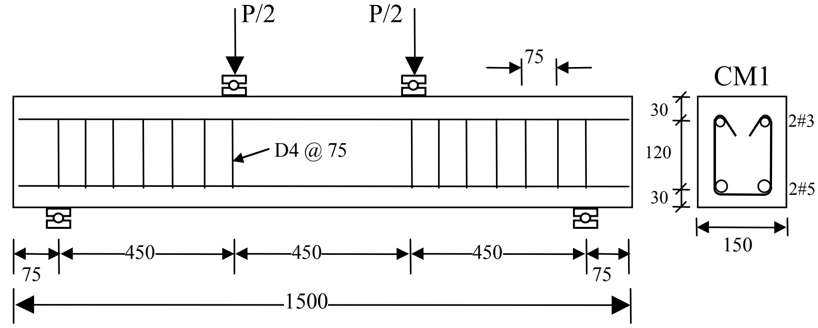
EXPERIMENTAL STUDY

The experimental study presented herein is part of a comprehensive experimental program designed and implemented to investigate the monotonic and cyclic load performance of precracked reinforced concrete beams strengthened in flexure and/or shear using FRP composites. The focus of the study is characterization and prevention of debonding failures as affected by the shear strengthening and anchorage conditions. In this paper, a limited number of experimental results that are used in the modeling studies presented in the next section are provided. Laboratory size reinforced concrete beams were FRP strengthened in shear and/or flexure with and without anchoring of the flexural reinforcement, and were loaded in four-point bending until failure. All beams were precracked prior to strengthening. The geometry and reinforcement details of the control specimen (CM1) is shown in Fig. 2(a) and the strengthening configurations of the tested beams are shown in Fig. 2(b). All specimens shown in this figure were strengthened with 1270-mm (50 in) long, 38.1-mm (1.5 in) wide, and 1.2 mm (0.047 in) thick FRP plates. For FRP shear strengthening, 40-mm wide straight and L-shaped plates were used. For comparison with external shear strengthening, the shear capacity of a beam was increased through increased internal shear reinforcement areas. Properties of the materials used in the experimental program are given in Table 1.

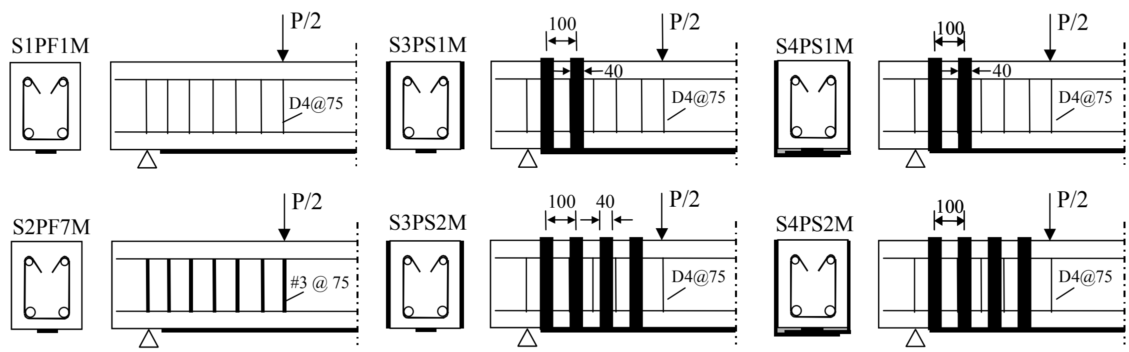
The load-deflection curves obtained from tests are shown in Fig. 3. Except for the beam S1PF1M, all beams shown in Fig. 2(b) failed through FRP debonding. Beam S1PF1M failed

Table 1. Properties of materials used in the experimental program

Material	Compressive strength (MPa)	Yield strength (Mpa)	Tensile strength (MPa)	Tensile modulus (MPa)	Ult. tensile strain (%)
Concrete	41.4	-	-	-	-
#3 and #5 rebars	-	552	-	200,000	-
D4 deformed bars	-	552	-	200,000	-
CFRP plate	-	-	2800.0	165,000	1.69
Epoxy adhesive	-	-	24.8	4,482	1.00



(a) control specimen



(b) beams strengthened in shear and/or flexure in various configurations

FIG. 2. Tested beam specimens

through cover debonding followed by shear failure, although the theoretical shear capacity of the unstrengthened beam was approximately 20 percent higher than the failure load of beam S1PF1M. Comparing the load-deflection curves for beam S1PF1M and S2PF7M, the influence of the shear capacity of a beam on its failure behavior is immediately apparent. Both beams were strengthened in the same configuration and essentially both failed through debonding, however, the failure load of S2PF7M, which had sufficiently high shear capacity, was approximately 15 percent higher that that of beam S1PF1M. The beams strengthened in shear with side bonded plates along the half and full shear span, S3PS1M and S3PS2M, respectively, displayed essentially the same performance as S2PF7M. This suggests that the shear capacity of a strengthened beam is especially critical in the plate-end region, where the flexure-shear cracks initiated at plate ends propagate higher into the beam. The influence of shear strengthening combined with anchorage of the flexural reinforcement, which was achieved by L-shaped plates, was significant as shown in Fig. 3. Unlike side bonded plates, bonding L-shaped plates along the half and full shear span made a large difference due to increased bond area and fracture surface.

A FRACTURE MODELING APPROACH

The fracture modeling approach presented here is an improved version of that developed by Hearing and Buyukozturk (2002) to predict debonding failures. Considering the energy balance in the strengthened beam system, the energy dissipation can be written using the Clausius-Duhem inequality

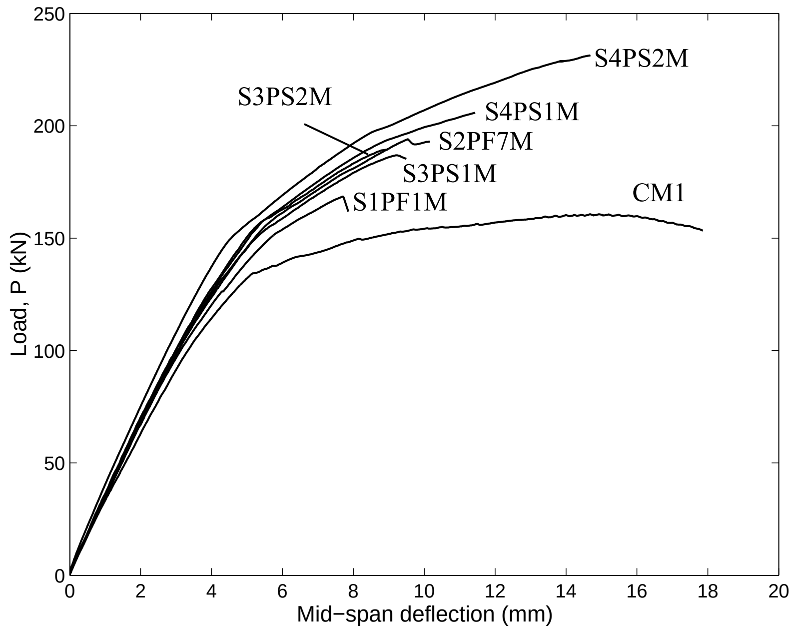


FIG. 3. Load-deflection curves of tested beams

$$dD = dW_{ext} - dW \geq 0 \tag{1}$$

which states that the amount of externally supplied work increment, dW_{ext}, that is not stored in the system as free energy, dW, is dissipated (D) into heat form and in our case in creating new fracture surfaces (Ulm and Coussy, 2001). The externally supplied work, W_{ext}, and the potential energy, ε_{pot}, of the system, with domain Ω and boundary $\partial\Omega$, can be defined as

$$W_{ext} = \int_{\Omega} \rho \mathbf{f}.\xi d\Omega + \int_{\partial_0 \Omega} \mathbf{T}.\xi da \tag{2}$$

Table 2. Experimental Results

Beam Designation	Yield Load	Failure Load	Failure mode
CM1 (control)	134.4	160.0	Cover debonding+shear
S1PF1M	152.0	168.5	FRP debonding
S2PF7M	157.0	194.0	FRP debonding
S3PS1M	154.0	187.0	FRP debonding
S3PS2M	157.0	189.5	FRP debonding
S4PS1M	150.0	205.8	FRP debonding
S4PS2M	150.0	231.3	FRP debonding

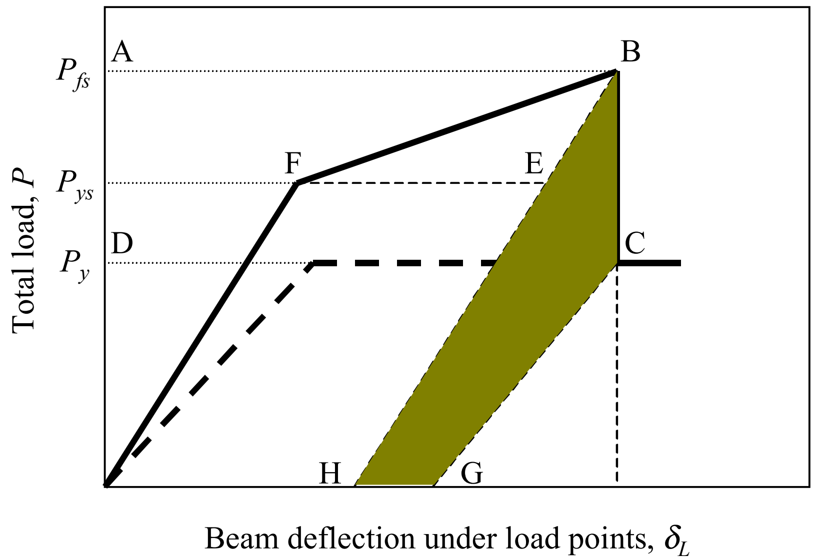


FIG. 4. Potential energy difference in the beam upon debonding failure

$$\varepsilon_{pot} = W - \Phi = \int_{\Omega} \psi d\Omega - \left[\int_{\Omega} \rho \mathbf{f}.\xi d\Omega + \int_{\partial_0 \Omega_{\mathbf{T}^d}} \mathbf{T}^d .\xi da \right] \tag{3}$$

where ψ = free energy volume density, ξ = displacement vector, $\rho \mathrm{f}$ = volume force density, and T = surface force density. Fig. 4 graphically shows the beam energy difference between the strengthened and debonded states. The strengthened beam, behavior of which is described by the solid line, is assumed to behave as an ordinary beam, shown with thick dashed line, once debonding failure occurs. The difference in the potential energy of the beam between before and after debonding is shown by the shaded area. Using equations (2) and (3), it can be shown that the change in the potential energy in of the system is related to the dissipation as follows

$$\Delta D = -\Delta \varepsilon_{pot} \geq 0 \tag{4}$$

Considering that the debonding failure criteria is defined as complete debonding of the FRP reinforcement bonded to the soffit through one or a combination of the mechanisms shown in Fig.1 in a brittle manner, then the energy dissipated during the fracture is equal to the total interface fracture energy and a plastic energy term that accompanies the fracture process.

$$\Delta D = G_f b_f l_f + W^p \tag{5}$$

Thus, in order to predict the debonding failure load, one needs to determine the dissipated interface fracture energy and the dissipated plastic energy. The interface fracture energy can be approximated by the relation proposed by Neubauer and Rostasy (1997), given by

$$G_f = k_b^2 C_F f_{ctm} \tag{6}$$

where k_b=1.3, C_F=0.202 mm, and f_{ctm} is the split cylinder tensile strength, measured as 3.1 MPa. The plastic energy dissipated during debonding is relatively more difficult to determine as it is dependent on various factors such as beam dimensions, reinforcement, and failure load and displacement. In the present study, it was observed that the dissipated plastic energy is a linear function of the failure displacement, and an approximate expression was obtained as

$$W^p \approx 3.0(P_{fs}^{\delta_f} - P_{fu}^{\delta_f}) \tag{6}$$

where $P_{fs}^{\delta_f}$ (kN) is the failure load of the strengthened beam at a failure displacement of δ_f, shown as point B in Fig 4., and $P_{fs}^{\delta_f}$ is the load in the control beam corresponding to the failure displacement of the strengthened beam, shown as point C in Fig.4. Recognizing that the resulting value obtained for W^p is in joules, the determined empirical expression is dimensionally nonhomogeneous. An improved estimation is needed that also takes into account the beam geometry and reinforcement based on a larger experimental database reported in the literature.

CONCLUSION

The presented experimental results indicate that increasing the total interface fracture energy in FRP strengthened beams in terms of anchorage reflects on the performance of the beam. Also, by preventing local interface debonding at flexure-shear cracks by increasing the shear capacity of the beam to a sufficient level improves the beam performance. The preliminary modeling approach is currently being employed by the authors to develop a model to predict debonding failure of FRP strengthened beams.

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