Construction and Building Materials 18 (2004) 9–19

Construction and Building MATERIALS

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Progress on understanding debonding problems in reinforced concrete and steel members strengthened using FRP composites

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Received 5 July 2003; received in revised form 23 August 2003; accepted 24 August 2003

Abstract

Use of fiber reinforced plastic (FRP) composite materials for strengthening and repair of structural members has become an increasingly popular area of research and application 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 a 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 or repair application. In recent years, there has been a concentration of research efforts on characterization and modeling of debonding failures. This paper provides a review of the progress achieved in this area regarding applications to both reinforced concrete and steel members.

Keywords: Fiber reinforced plastics; Repair; Strengthening; Debonding

1. Introduction

FRP composite materials have experienced a continuous increase of use in structural strengthening and repair applications around the world in the last decade. High stiffness-to-weight and strength-to-weight ratios of these materials combined with their superior environmental durability have made them a competing alternative to the conventional strengthening and repair materials. Local and federal agencies faced with the challenge of economically upgrading the ever-increasing number of aging and substandard structures have invested in this area leading to numerous research studies and applications. It has been shown through experimental and theoretical studies that externally bonded FRP composites can be used to improve the desired performance of a structural member such as its load carrying capacity and stiffness, ductility, performance under cyclic and fatigue loading and environmental durability. However, the method is yet to become a mainstream application due to a number of economical and design related issues. From a 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. In recent years, many researchers have focused on this important issue through both experimental and theoretical investigations. This paper provides a review of the progress on understanding and modeling of debonding failures in FRP strengthened reinforced concrete (RC) and steel members.

2. FRP strengthening of RC and steel members

Applicability and effectiveness of strengthening with FRP composites depend largely on the material and the type of the member to be strengthened. Research up to date in this area has mainly focused on applications to RC members. In a strengthening application, the strengthening material is generally expected to have a similar or higher stiffness compared to the base material of the member being strengthened. While this is generally the case for concrete and soft metals such as aluminum, the stiffness of most FRP composite systems

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doi:10.1016/S0950-0618(03)00094-1

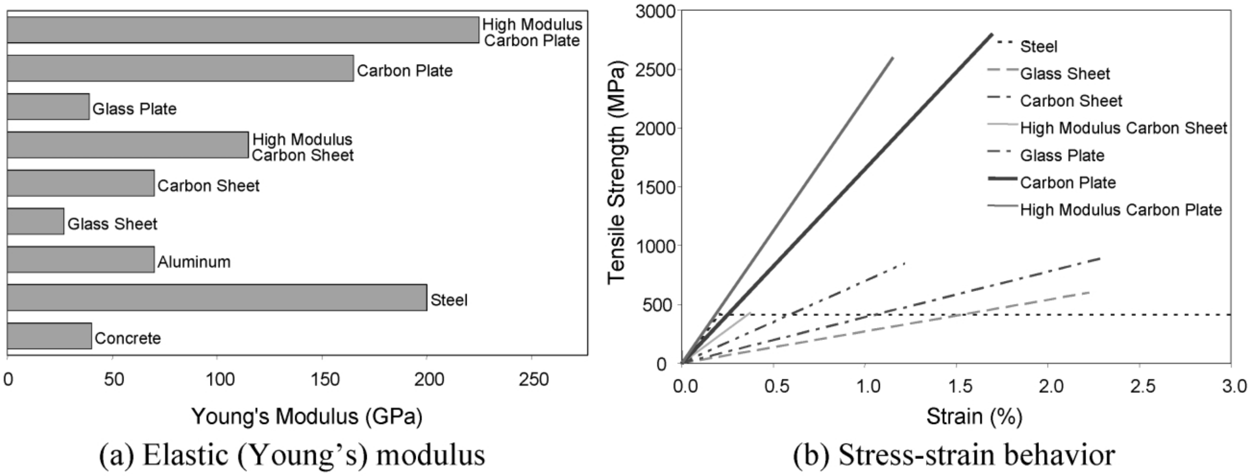

Fig. 1. Elastic and strength properties of FRP composites compared with conventional construction materials, (a) Elastic (Young's) modulus (b) Stress–strain behavior.

are considerably less than that of structural steel. Fig. 1a compares the elastic modulus of concrete, aluminum and steel with those of several commercially available FRP composite systems and Fig. 1b shows a comparison of strength–strain behavior in tension. It can be interpreted from this comparison that strengthening of steel members with FRP composites may be mechanically less advantageous and economically less feasible compared to concrete and aluminum members. Nevertheless, a specific type of application involving steel structures, which is both mechanically and economically well justified, is repair of fatigue damaged steel members with FRP composites. Recently, research and applications in other types of applications involving steel members have also increased due to continually decreasing costs of FRP materials, ease of installation and the potential of eliminating welded and bolted repairs.

Strengthening with FRP composites can be applied to various types of structural members including beams, columns, slabs and walls. Depending on the member type, the objective of strengthening may be one or a combination of several of the following: (1) to increase axial, flexural or shear load capacities; (2) to increase ductility for improved seismic performance; (3) to increase stiffness for reduced deflections under service and design loads; (4) to increase the remaining fatigue life; (5) and to increase durability against environmental effects. In general, applications where the accessibility conditions allow wrapping of the member with FRP composites, such as FRP wrapping of RC columns, may not usually suffer from debonding problems, and thus, are not included in this paper. Instead, emphasis is given to shear and/or flexural strengthening of RC and steel beams and repair of fatigue damaged steel members where debonding problems are frequently encountered and play an important role in the behavior and performance of the member.

Failure of FRP strengthened RC and steel flexural members may take place through several mechanisms depending on the beam and strengthening parameters. In the case of RC beams, failure may take place through (1) concrete crushing before yielding of the reinforcing steel, (2) steel yielding followed by FRP rupture, (3) steel yielding followed by concrete crushing, (4) cover

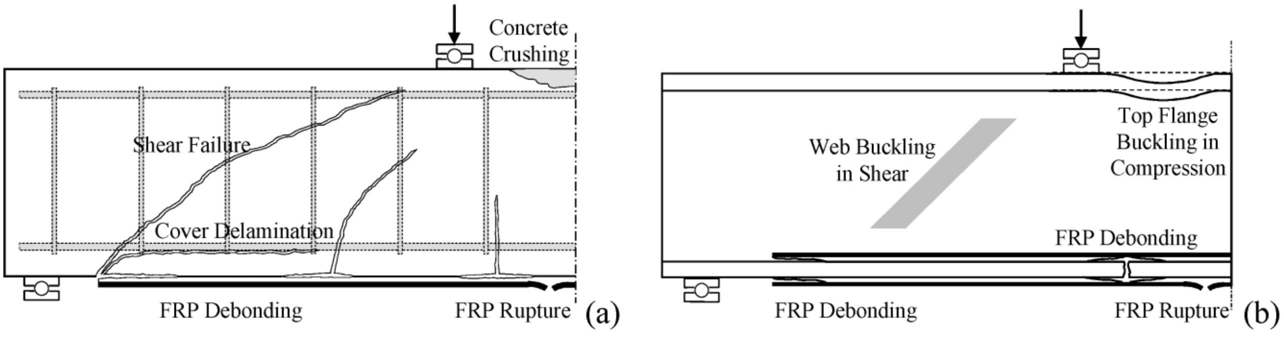

Fig. 2. Failure modes of FRP strengthened flexural (a) RC and (b) steel members.

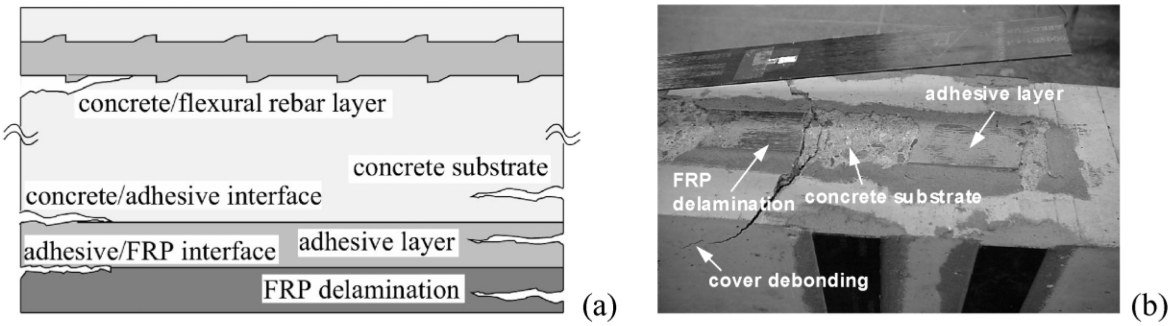

Fig. 3. Types of debonding in FRP strengthened RC members.

delamination, (5) FRP debonding [2,12]. In addition to these, shear failure occurs if the shear capacity of the beam cannot accommodate the increase in the flexural capacity. These failure modes are illustrated in Fig. 2a. Similarly, Fig. 2b shows the failure modes of an FRP strengthened steel member as (1) top flange buckling in compression, (2) web buckling in shear, (3) FRP rupture, (4) FRP debonding. An investigation of each of these failure modes is required in the design process to ensure that the strengthened member will perform satisfactorily. Knowledge provided in this paper is limited to debonding problems.

3. Debonding problems in FRP strengthened RC and steel members

Debonding in FRP strengthened members takes place in regions of high stress concentrations, which are often associated with material discontinuities and with the presence of cracks. Propagation path of debonding initiated from stress concentrations is dependent on the elastic and strength properties of the repair and substrate materials as well as their interface fracture properties. The term debonding failure is often associated with a significant decrease in member capacity due to initiation or propagation of debonding.

Theoretically, debonding in FRP strengthened members can take place within or at the interfaces of materials that form the strengthening system, favoring a propagation path that requires the least amount of energy. Crack propagation in one of the constituent materials is generally preferred over interface debonding in design of structural joints; however, the latter is often encountered, especially in cases of poor surface preparation or application. Fig. 3a shows possible types of debonding in FRP strengthened RC members. A majority of the debonding failures reported in the literature took place in the concrete substrate. However, depending on the geometric and material properties, other debonding mechanisms can also be observed. Fig. 3b shows that a combination of different debonding types and mechanisms can take place in a single experiment. Types of debonding in FRP bonded steel members shown in Fig. 4a are similar to those in RC, in this case involving the steel substrate. Fig. 4b shows the failure and debonding surfaces on an FRP strengthened notched steel specimen failed under tensile fatigue loading.

4. Experimental research on debonding problems

Early experimental observations of debonding in FRP strengthened RC and steel flexural members were reported after studies at the Swiss Federal Materials Testing and Research Laboratories (EMPA) in Switzerland. Kaiser [35] showed that CFRP plates can be used to

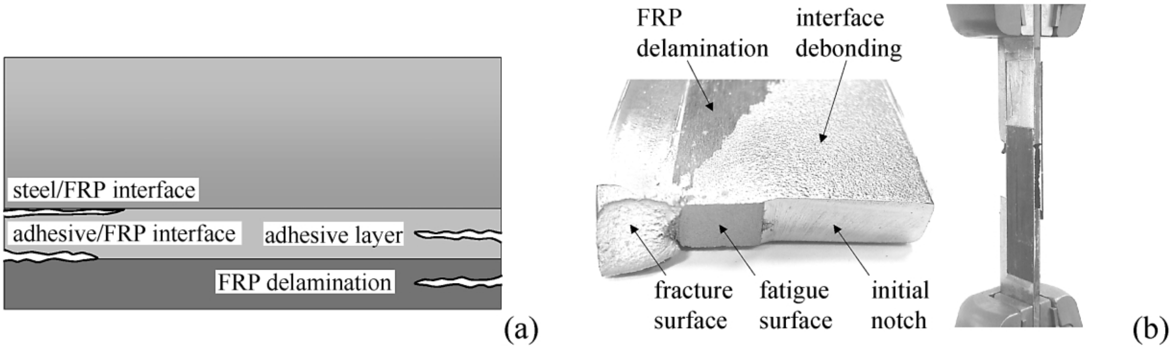

Fig. 4. Types of debonding in FRP strengthened steel members.

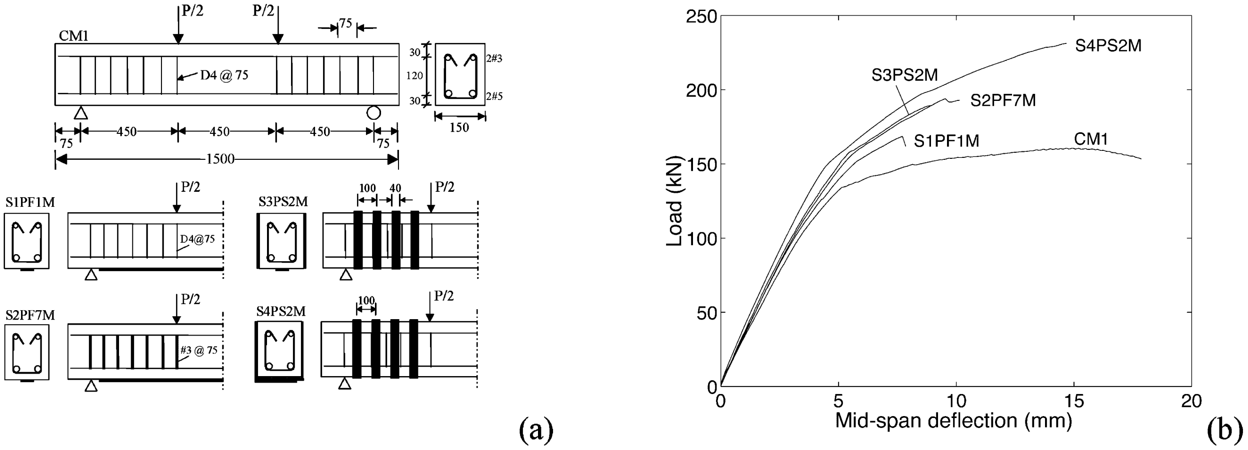

Fig. 5. Influence of shear strengthening and anchorage on strengthened beam behavior under monotonic loading.

strengthen RC beams and identified different failure modes. Among these, debonding of the FRP reinforcement from the concrete substrate was identified as an important mode of failure since it could take place at premature load levels and the failure was generally very brittle [47,48]. This is followed by numerous studies reporting various aspects of FRP debonding problems in FRP strengthened RC beams. It was suggested that improper selection of adhesives might promote debonding failures [68]. Debonding failure behavior of strengthened beams was shown to be highly dependent on the existing steel reinforcement ratio and the type and amount of external FRP reinforcement [25,43,60, 63,67,72,74,86]. For a fixed FRP ratio, debonding potential was shown to increase significantly with increasing FRP thickness [25]. Experiments on simply supported beams strengthened with different lengths of FRP reinforcement have revealed that debonding failure load and ductility decreases with decreasing lengths of the FRP reinforcement. The general conclusion of these studies is that by extending the FRP reinforcement to the supports as much as possible, potential of debonding failures may be decreased, although not eliminated [80,32,4,23,54]. Laboratory test studies on FRP strengthened beams with notches in the shear span or mid-span revealed that unstable debonding may also originate from flexural and flexural/shear cracks [88,31,70]. A number of researchers have investigated debonding problems in beams precracked before strengthening. Mixed conclusions were drawn from these studies, calling for further research on this issue [6,7,32,60]. Role of bond anchorage in increasing debonding resistance of strengthened beams was demonstrated by several studies [25,26,50,56,74,78,79]. A recent experimental investigation by the authors has revealed that both failure load and ductility of precracked beams strengthened with FRPs can be significantly increased through shear strengthening and bond anchorage, as shown in Fig. 5 [14,15]. Performance of FRP strengthened beams under fatigue loading was investigated through several experimental studies, which generally concluded that unless adequate bond anchorage is provided, debonding problems may become significant under fatigue loading [9,20,33,45,73]. Experimental investigations regarding durability of FRP strengthened concrete systems under various environmental exposure conditions including freeze-thaw, wet-dry and temperature cycles and various aqueous solutions have shown that deterioration of the concrete–FRP interface may lead to debonding problems [16,18,27,28,38,85]. Reliable quantification of such effects is not possible at the current state of experimental and theoretical research.

Although the experimental research on FRP strengthened steel members has been limited compared to RC members, there has been a significant increase of research interest in this area in recent years. Initial experimental study in this area explored use of high modulus CFRP plates to repair a real scale fatigue damaged steel box girder [21,22]. This study revealed that FRP composites can increase the remaining life of fatigue-damaged members and that debonding was the governing failure mechanism. Basetti et al. performed laboratory tests on FRP repaired center-notched coupons and later implemented the method on a riveted bridge [10,11]. Both laboratory and field studies showed that FRP bonded repair of fatigue-damaged steel members is a powerful technique that provides high structural efficiency and extends the life of flawed structural components at an economical cost. An experimental study by the authors involving fatigue testing of side-notched steel specimens repaired with FRP patches in various configurations have confirmed the effectiveness of the technique by increasing their fatigue lives, while drawing attention to research issues in design and durability of the repair [13]. Results from this study, part of which are shown in Fig. 6, indicates that fatigue

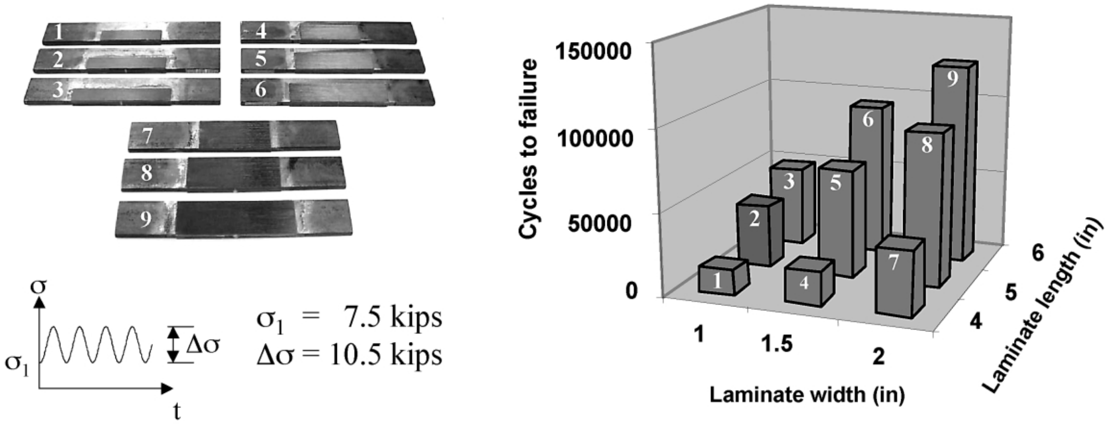

Fig. 6. Fatigue performance of FRP strengthened 3/8 inch-thick A36 notched steel specimens.

life of notched specimens, which would fail under applied stress in unrepaired configuration, can be significantly increased with the application of FRP composites. Fundamental experimental research on durability of FRP bonded steel have shown that surface preparation and environmental exposure conditions can significantly affect bond durability and drew attention to potential galvanic corrosion problems in carbon FRP-steel systems [13,36,46,83]. Proven effectiveness of the repair technique and better understanding of the durability issues lead to consideration of the method for strengthening of steel members. Laboratory tests on FRP strengthened large-scale steel members with and without notches have shown that the method can be used to increase the stiffness, load capacity and ductility of steel members [42,71]. A field application of the method was performed to strengthen a bridge girder in Newark, Delaware [49].

5. Modeling research on debonding problems

Characterization and modeling of debonding in structural members strengthened with externally bonded reinforcement 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. Research studies 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 avoid the complexities of stress and fracture analyses and can be relatively easily implemented in design calculations.

5.1. Strength approach

Prediction of debonding failures through strength approach involves 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. Fig. 7a shows a conceptual illustration of the bond stresses at the concrete–FRP interface and in the FRP reinforcement in a RC beam strengthened in flexure. Similarly, Fig. 7b shows the stresses developed in a steel beam strengthened in flexure. For illustrative purposes, fatigue cracks are introduced in the bottom flange. As seen from these figures, high shear and normal stresses develop at the laminate ends and at crack locations, which lead to interfacial debonding and potential debonding failures.

Strength based research on debonding problems in FRP strengthened RC beams have produced several solution methods that predict bond stress distributions in plated beams, based on the common assumption that all materials are linearly elastic, although concrete cracking is considered. A majority of these methods give a relatively simple and approximate solution while others involve a higher-order analysis, yielding more accurate but also more involved solutions. The key difference between the approximate and higher-order solutions is that the former assume constant shear and normal stresses in the adhesive layer, whereas the latter takes the stress variations across the adhesive thickness into account. Due to constant shear assumption, the approximate solutions do not satisfy the zero shear boundary condition at the ends of the adhesive layer. Both solutions give close results except for a very small zone near the ends of the adhesive layer, in the order of the adhesive thickness.

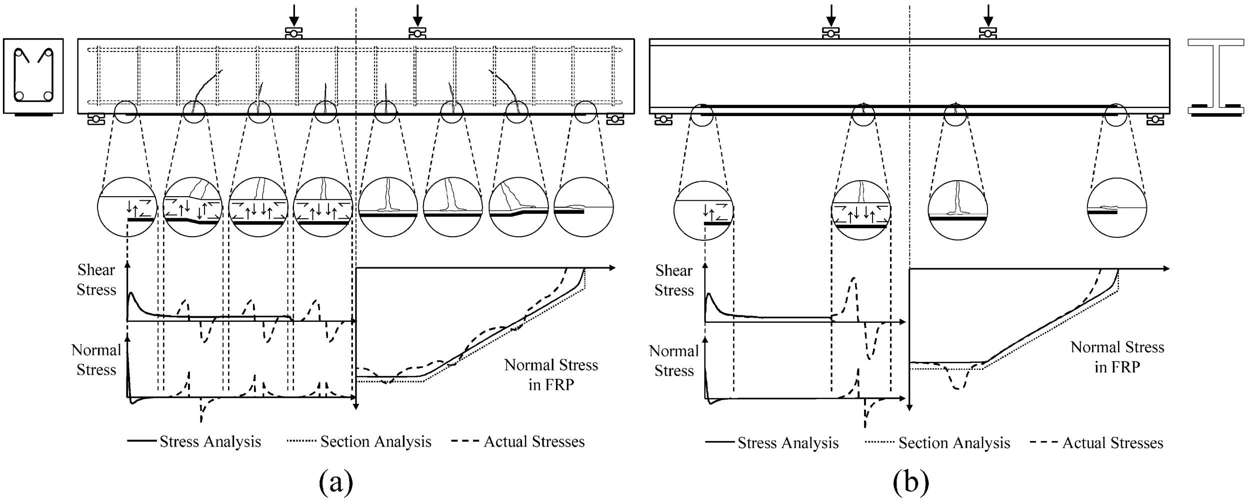

Fig. 7. Approximate and actual stress distributions in FRP strengthened (a) RC and (b) steel flexural members.

An approximate staged solution of bond stresses developed by Roberts [64], which is a simplified version of a more rigorous solution by Roberts and Haji-Kazemi [65], is frequently used for its simplicity and applicability to general loading conditions. Modified versions of this solution were used by other researchers for FRP and steel plated beams [19,87,92]. Alternative solutions developed for FRP strengthened beams consider deformation compatibility condition and give similar results although they show differences in their solution approaches and applicability to different loading configurations [39,44,76,82]. A conceptual and numerical comparison of some of these solutions is provided in [76]. Rigorous higher-order solutions of the bond stresses in plated beams were also developed [58,75]. A comparison of the results obtained from higher-order and approximate solutions shows close agreement except for the previously mentioned small end zones [75].

Following the calculation of bond stresses, a failure criterion dependent on the material strength properties is needed for prediction of debonding failures. Some researchers suggested that debonding failure takes place when the maximum shear and normal stresses reach certain values [57,65]. Alternative failure criteria include concrete failure under biaxial stresses [19,44] or a Mohr–Coulomb type criterion [87,92].

Determination of bond stress distributions in FRP strengthened steel members is considerably easier compared to RC members. Development of solution methods for stresses in bonded joints with elastic adherends has been a popular area of research since the 1930s due to their use in diverse industries. A review of the developed solution methods for various cases of geometry and loading conditions are reviewed in various texts [3,84]. A general numerical solution procedure was developed by Yuceoglu and Updike [90] for stress analysis of bonded plates and joints. Besides these methods, the solution procedures mentioned above can be used for strengthened steel members upon certain simplifications. Failure loads of these systems can be predicted based on point-based, zone-based or strain energy density-based criteria [3,84].

5.2. Fracture approach

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. Hamoush and Ahmad [29] used Linear Elastic Fracture Mechanics (LEFM) and finite element method to model debonding in steel plated concrete beams with no internal reinforcement. Taljsten [81] derived linear and non-linear mode II fracture equations for symmetric and asymmetric overlap joints, which can be used in bond shear tests. Fukuzawa et al. [24] measured mode II fracture toughness of interfacial debonding between FRP and mortar by use of double shear specimens pulled in tension. In a similar study, Neubauer and Rostasy [53] performed bond strength tests to determine the FRP–concrete interface fracture energy. Karbhari and Engineer [37] used a modified shear test to measure the mixed mode interface fracture energy between concrete and FRP. Wu et al. [88] performed an experimental and numerical study to investigate debonding in plain concrete beams strengthened in flexure with FRP composites. Beams with a mid-span notch, simulating a flexural crack, were loaded in three-point bending and initiation and propagation of debonding around the notch was measured. Results were validated by the compliance method through a finite element analysis. Yuan and Wu [89] later developed an analytical methodology to model debonding initiated at the FRP concrete interface at either middle or end of the laminate by use of fracture mode partitioning. Hearing and Buyukozturk [32] employed a fracture energy based criterion to predict debonding failures in reinforced concrete beams. Leung [41] derived the shear stress distribution at the FRP–concrete interface around a flexural crack in plain concrete beam based on linear elastic fracture mechanics (LEFM) and superposition method. Using a similar approach, Lau et al. [40] estimated the mode I stress intensity factor, K_I, at the tip of a flexural crack in a concrete beam strengthened in flexure with FRP composites. Neubauer and Rostasy [52] developed a fracture mechanics based bond strength model to investigate the effects of the differential displacements at the shear crack mouths on the overall bond strength and suggested a bond strength reduction factor of 0.9 to include such effects. Rabinovitch and Frostig [59] extended their high-order bond strength model [58] to a fracture mechanics approach and included the effect of debonding around flexural and shear cracks. The few fracture models proposed so far have limited success in predicting the failure load for FRP strengthened beams and need further improvement.

Service life prediction of fatigue damaged steel members repaired with FRP patches calls for a fracture approach since the system behavior is based on fatigue crack propagation. There is an extensive research background in this area due to common use of the crack patching technique in the aircraft industry since 1970s [8]. Various researchers have developed analytical and finite element methods for the determination of stress intensities in the repaired system and for prediction of the fatigue life [51,66,69]. However, characteristics of the problem in structural strengthening applications are significantly different than those in the aircraft applications due to complexity of load conditions and thickness of the substrate material. Adoption of the existing modeling techniques to structural strengthening/repair applications is needed.

5.3. Semi-empirical and empirical models

Empirical models referred to in this paper are those that do not involve a systematic stress or fracture analysis, but involve the use of simplified relations on a phenomenological basis to predict failure. The general objective of these 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. A group of proposed models are based on the shear capacity of the strengthened beam [4,5,34,55,77]. Failure is assumed to take place when the external shear acting on the beam at the plate ends exceeds a predefined value. The so-called concrete tooth models consider the concrete cover between two adjacent cracks as cantilevers extending from the flexural steel reinforcement to the bottom of the beam [30,61,62,91]. Cover debonding is assumed to occur when the stresses at the root of the tooth reach the tensile strength of the concrete. An alternative model based on truss analogy predicts failure load by means of bond yield condition for the plate–concrete interface [17]. Investigation on the validity of the proposed semi-empirical and empirical models have shown that each model may hold for a group of beams with certain strengthening and load conditions, however, none has yet been proven to hold for the general case of FRP strengthened beams.

6. Cyclic loading effects on debonding

Seismic retrofitting of existing structures comprises a major portion of structural strengthening applications. Thus, performance of strengthened members under cyclic loading must be thoroughly investigated with emphasis on brittle debonding failures to ensure the seismic safety of strengthened systems. Although several researchers have studied the performance of strengthened beams under fatigue loading [9,20,33,45,73], high amplitude cyclic load performance of strengthened beams remains virtually uninvestigated. Fig. 8 shows selected results from a comprehensive experimental study performed by the authors on high-amplitude cyclic load behavior of beams strengthened in various configurations [15]. It is seen from the figure that performance of FRP strengthened beams under cyclic loading may fall below that under monotonic loading, the degree of which is dependent on the strengthening parameters and anchorage conditions.

Potential effects of cyclic loading on retrofitted beam performance can be conceptually deduced from known mechanical behavior of reinforced concrete beams under cyclic loading. Increase of plastic deformations in reinforced concrete beams under cyclic loading is a well-known phenomenon. Knowing that FRP materials display a linearly elastic behavior, the stresses both in the FRP composite reinforcement and at the concrete–FRP interface are likely to increase with the increasing beam plastic deformation under cyclic loading. Depending on the FRP reinforcement ratio and anchorage conditions, increase in interfacial and normal stresses may promote debonding and unexpected FRP rupture failures. Thus, these effects must be properly considered in the design process.

An important aspect of debonding failures in FRP strengthened beams under cyclic loading is the post-failure behavior. Although the load capacity of the beam may decrease due to a premature debonding failure, it is required that the beam displays a ductile post-failure

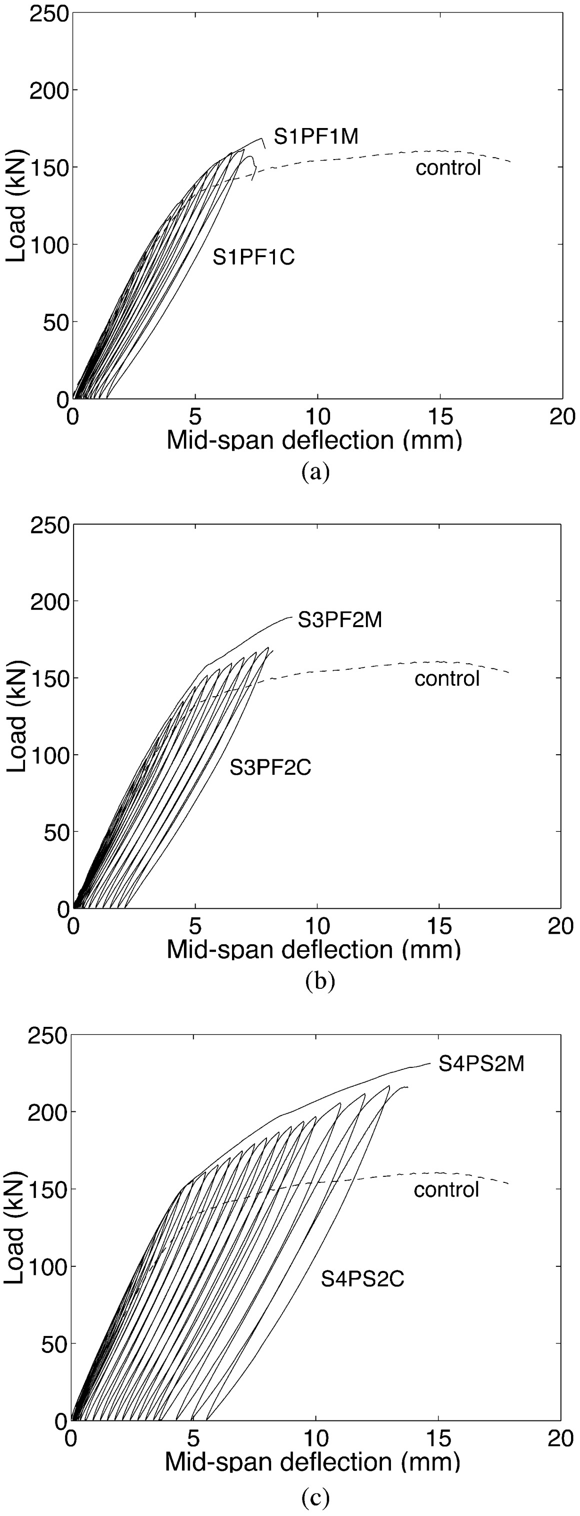

Fig. 8. Influence of shear strengthening and anchorage on FRP strengthened beam behavior under cyclic loading (a) flexural (b) flexural + shear (c) flexural + shear + anchorage.

behavior so that it can contribute to the structural performance at the pre-retrofit level. Experimental studies have shown that in some cases a brittle shear failure follows the debonding failure at load levels below the calculated shear capacity of the beam [15]. In such cases, not only the retrofitting is ineffective, but also harmful to the structure since the ductility of the member is decreased significantly. ACI 440F [2] requires that for beams strengthened only in flexure, it must be ensured that the shear capacity of the beam, calculated in accordance with ACI 318 [1], can accommodate the increased shear demand. However, experimental evidence indicates that a special consideration must be given to calculation of the shear capacity of beams to be strengthened in flexure with FRP composites.

Repair of fatigue-damaged steel members with FRP composites was shown to be an effective technique. Although the system is likely to perform satisfactorily under low amplitude fatigue loading, performance of such systems under high amplitude cyclic loading conditions is unknown. Considering that partial debonding in such systems is expected under extended fatigue loading, and that environmental exposure may adversely affect bond integrity, it is apparent that a thorough investigation of the high-amplitude cyclic load performance of these systems is of critical importance. Currently, no reports of experimental or analytical research studies on this issue exist.

7. Environmental effects on debonding

FRP composites are known for their resistance to environmental exposure conditions, however, durability of the FRP strengthening systems, as a whole, is a major concern in structural rehabilitation applications. Behavior of FRP strengthened beams subjected to freeze-thaw, wet-dry and temperature cycles or various aqueous solutions prior to loading have been studied by a limited number of researchers and varying degrees of strength deterioration have been observed [16,18,27,28,38,85]. Similarly, studies on bond durability of FRP bonded steel systems have reported deterioration caused by temperature and moisture cycles [13,36,46,83]. In addition, potential galvanic corrosion problems associated with strengthening of steel members with FRPs containing conductive fibers such as carbon raises durability concerns. Current state of knowledge on bond durability of FRP strengthened systems is limited to a few experimental studies. Theoretical modeling studies focused in this area are yet to be performed.

8. Research needs

A review of the experimental and modeling studies on debonding problems in FRP strengthened/repaired RC and steel members show that despite considerable progress, research in this area is still very young. Continued experimental and theoretical research at both material and structural level is needed in various aspects of debonding problems in FRP strengthened systems. Existing debonding models based on strength and fracture approaches and empirical relations must be further developed and improved for better prediction of debonding failure loads. Continued experimental studies focused on specific problem areas are needed for validation and calibration of developed models. Specific research need in strength-based models is the development of better failure criteria based on the calculated stresses, material properties and strengthening configuration. For better understanding of the brittle fracture phenomena in the debonding process, fracture tests on materials, systems and subsystems is needed for accurate characterization of the interface fracture energy and fracture criteria, including the effects of mixed fracture modes.

The modeling efforts described for monotonic load conditions are yet to be extended for cyclic loads conditions. Considering the ever-increasing field applications of the method, there is an urgent need to fill the research gap in this area. Experimental and theoretical research on cyclic load performance of FRP strengthened RC and steel members must be performed to ensure the seismic safety of existing and future applications.

Bond durability in strengthening systems must be thoroughly investigated both experimentally and theoretically in order to properly account for environmental degradation effects in the design and life cycle cost estimation procedures. Influence of environmental exposure on strength and fracture properties of the interfaces must be characterized through targeted experimental investigations.

Quality assurance of bond during installation and in service is another major area where immediate attention and increased emphasis is needed. Considering the limited knowledge on mechanics and durability of the strengthening applications, reliable NDT methods may play a vital role in assuring bond integrity and structural safety.

9. Conclusion

Debonding problems stand as a critical barrier against wide range use of FRP composites in structural strengthening and repair applications. Proper characterization of debonding problems and their inclusion in the design codes is essential for common use of the technique. A review of up to date research progress on debonding problems is made with presentation of recent research results supporting the discussions, and future research needs specific to debonding problems are stated.

Acknowledgments

This material is partially based upon work supported by the National Science Foundation under Grant No. 0010126.

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