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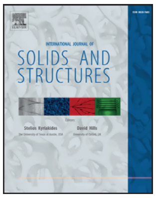

Experimental and analytical study of the dynamic debonding in FRP plated beams

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ABSTRACT

This paper presents an experimental study of the dynamic debonding failure mechanism in FRP plated beams. The experimental study is accompanied by an analytical/numerical study. The focus in the experimental investigation is on the dynamic aspects of the brittle, rapid, and abrupt failure mechanism and on its characterization and quantification. The experimental technique is based on four point bending tests of FRP plated steel beam specimens. The main dynamic monitoring technique uses high-speed digital photography with rate of 88,050 frames per second. The analytical and numerical aspects of the investigation use an extended high order layered beam theory with a physical modeling resolution that considers nucleation and evolution of the debonding mechanism in each physical interface. This is achieved by using cohesive interfaces and a specially tailored finite element formulation that is based on the theory. Digital image processing of the experimental results reveals and quantifies the dynamics of the interfacial failure with propagation velocities in the order of 100–1000 m/s and duration of less than 0.2 ms. The results reveal the dynamic nature of the failure process and provide an experimental benchmark for its consideration. They also provide direct experimental data for supporting and validating the theory and for determining the fracture energy and length scale parameters of the cohesive interfaces. With that, the combined experimental and theoretical study further explores the dynamic features of the failure mechanism.

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1. Introduction

The use of externally bonded fiber reinforced polymer (FRP) for strengthening or upgrading structural components made of concrete, steel, masonry, or timber has become widely accepted in the past three decades. Extending the service life of existing buildings, handling cases where there are access limitations or geometrical constraints, or reducing installation and downtime costs are only few examples where this method becomes relevant. Yet, along with the vast advantages of using the lightweight high performance material, the evolution of new modes of failure and their tendency to dictate the structural behavior, strength, and stability play a critical role.

One of the common and, in most cases, problematic mode of failure of FRP plated beams involves debonding of the external layers. This process is triggered by the formation of cracks in the substrate element yielding a phenomenon commonly referred to as Intermediate Crack (IC) Debonding. The stress concentration near the edge of the bonded layer yield a phenomenon called as Edge Debonding. In the latter, which is particularly relevant to FRP strengthened members that are not so sensitive to cracking (e.g. steel beams), the adhesive-beam interface fails and the FRP strip and the adhesive layer are rapidly ripped off from the substrate (see, for example, Deng and Lee (2007a) for steel beams, Rabinovitch and Frostig (2003) for concrete beams). The edge debonding process starts at the edge of the bonded layer and it rapidly propagates towards the other edge leading to a drastic drop in stiffness and a significant and sudden release of stored elastic energy. This debonding process is dynamic by nature and it is governed by dynamic phenomena with time scales in the sub-ms range (Rabinovitch, 2012, 2014a). The dynamic, abrupt, and catastrophic nature of the debonding failure mechanism, which is reflected as instabilities detected in static analyses (Cornetti et al., 2015; Cornetti and Carpinteri, 2011; Carpinteri and Paggi, 2010; Rabinovitch, 2008a, b), was documented in many experimental works. It was particularly documented in experimental works involved with quasi-static loading rates that commonly keep the response of "normal" structural systems well within the

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static regime. In spite of that, the majority of the analytical, numerical, and mainly, experimental efforts dedicated to the investigation of this process addressed the debonding failure mechanism in the framework of static structural analysis.

The dynamic nature of the debonding failure gives rise to a spectrum of theoretical, experimental, and practical challenges. Those range from the analytical modeling of the debonding structure, its numerical consideration, the nature of the physical aspects that have to be taken into account (e.g. material properties, inertial effects, strain rates, interfacial effects), and up to the type of design approaches suitable for the unique structure. An additional class of challenges refers to the behavior of the structure throughout the debonding process and the mechanisms that may lead to a stable arrest of the debonding crack. For example, a stable arrest of a dynamic IC debonding mechanism was observed in long concrete beams strengthened with FRP (e.g. Czaderski and Motavalli, 2007) but not in the edge debonding mechanism detected in laboratory scale FRP strengthened beams (e.g. Rabinovitch and Frostig, 2003).

The characterization, quantification, and handling of the dynamic nature of the debonding mechanism have to be based on two fundamental pillars. The first one includes analytical models or numerical tools. The second one is an experimental study. The latter, which is in the focus of this paper, is essential for gaining insight into the physical problem and for establishing experimental benchmarks for the validation, verification, and calibration of the former. This paper aims to achieve these goals.

The analytical and numerical modeling of the debonding failure in FRP strengthened beams was the subject of a significant volume of research in the past three decades. Most of this research was dedicated to static conditions and only few works looked into the dynamic aspects of the failure mechanism. In one of the first works that did address dynamic aspects, Jerome and Ross (1997) examined the response of a strengthened beam to a weight drop loading and numerically addressed the response using finite element (FE) analysis. The FRP strip was modeled using truss elements and the concrete substrate was modeled using 2D plane-stress element. The deformations of the FRP truss elements were compatible with the ones of the concrete substrate reflecting a fully bonded interfacial condition. The consideration of debonding mechanisms and modeling of the adhesive layer were designated for future work. An analytical dynamic model that is based on the assumption that the displacements are linear through the thickness of the adhesive layer was introduced by Soleiman Fallah et al. (2008). This assumption, which was widely used in static analyses of FRP strengthened beams and extended in Soleiman Fallah et al. (2008) to the dynamic case, entails that the stresses are uniform through the thickness of adhesive layer. As a result, it tends to underestimate the stress concentration, which eventually triggers the edge debonding mechanism (see, for example, the discussion in Rabinovitch and Frostig, 2000). A higher order dynamic model for FRP strengthened beams was developed in Hamed and Rabinovitch (2005). This model incorporated the variation of the stresses through the thickness of the adhesive layer but assumed that the velocities and accelerations are uniform through the thickness. In addition, it did not take into account the effect of debonding.

The dynamic problem of the spectral response of the FRP strengthened beam was addressed in Perera and Bueso-Inchausti (2010). The analysis adopted a spectral element model with nonlinear constitutive laws but focused on the dynamic response of the intact (fully bonded) structure. The issue of debonding was addressed in Bruno et al. (2013) using a 2D FE model based on an Arbitrary Lagrangian–Eulerian formulation. The latter used a mesh that moves with the crack tip and changes with the evolution of the interfacial debonding process. A different approach was proposed in Sun et al. (2015) who developed a special cracked region element for the analysis of IC debonded concrete beams. The consideration of the inertial terms in the FE formulation allowed to detect the spectral response of the structure and to quantify the impact of cracking and IC debonding on the response in the frequency domain.

Chen et al. (2015) used a dynamic 2D FE model to study the response of an FRP strengthened reinforced concrete beam. The FRP layer was modeled using truss elements whereas the adhesive layer and its two physical interfaces were modeled using an aggregated bond–slip relation that was implemented in an interfacial element. The dynamic effects were introduced as means to overcome or avoid numerical convergence issues associated with similar static analyses whereas the abrupt phenomena involved with cracking or debonding were captured as discrete dynamic events. The IC debonding events were reflected by local amplifications of the kinetic energy but without a specific consideration of the dynamic properties of the failure mechanism itself (debonding front movement, velocity and duration of the failure process).

A model that combines a dynamic high order formulation for the adhesive layer and a cohesive interface that is implemented few millimeters within the concrete substrate was developed in Rabinovitch (2012). Later, Rabinovitch (2014a,b) presented extended dynamic and static models that take into account the complete stress fields in the adhesive layer. Unlike the model developed in Rabinovitch (2012), the extended dynamic models allow implementing two cohesive interfaces, one at the adhesive-beam interface and one at the adhesive-FRP interface. This is essential for capturing the independent evolution of the dynamic debonding failure mechanism in each of the physical interfaces of the adhesive layer. In Mulian and Rabinovitch (2015), the extended high order dynamic model was converted into a FE form that simplifies the analysis and allows using standard numerical procedures for the solution of the nonlinear PDEs. Mulian and Rabinovitch (2015) also presented a parametric sensitivity study that quantified the impact of various structural and interfacial parameters on the dynamic debonding response. The study quantified the impact of the properties of the cohesive interfaces on the movement and the velocity of the debonding front. This information, as well as the analytical/numerical models, provide insight into the dynamic failure mechanism; however, it is solely based on analytical and numerical considerations. An experimental benchmark that is based on spatial and temporal resolutions that allow validating the theory was not found in the literature.

The volume of experimental works that addressed the static response, either in terms of loading rates or in terms of response and monitoring rates, is impressive. On the other hand, the number of experimental works that addressed the dynamic nature of the debonding mechanism is very limited. The experimental works of Jerome and Ross (1997), Meier and Erki (1999), Tang and Saadatmanesh (2003), and Davidson et al. (2005) clearly indicated that the dynamic loading of the FRP strengthened member can eventually lead to a debonding failure. On the other hand, they did not get into the dynamic effects associated with the evolution of the debonding process itself. Deng and Lee (2007a, b) experimentally studied the response of small-scale FRP strengthened steel beams to fatigue and static loading. The initiation and growth of the interfacial debonding crack under fatigue conditions (Deng and Lee, 2007a) was monitored using a series of strain gauges mounted on the external face of the FRP strip. In the case of static loading (Deng and Lee, 2007b), the study pointed at the effect of the length and thickness of the FRP plate, different load cases, and the use of tapering and adhesive spew fillets at the ends of the plate on the debonding failure. The measured load versus time curves showed significant drops in load at the moment of the debonding initiation. The fatigue type of cyclic loading (Deng and Lee, 2007a) allowed to trace the interfacial debonding crack front and to follow its movement with the number of cycles. However, when the level

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