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Sensitivity analysis of reinforced concrete beams strengthened with FRP laminates

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Abstract

Numerical procedures are proposed to predict the failure of reinforced concrete (RC) beams strengthened in flexure with fiber-reinforced polymeric (FRP) laminates. The framework of damage mechanics was used during the modeling. Numerical results were validated against experimental data obtained from 19 beams strengthened with different types of FRP. These beams failed by concrete crushing, cover failure and plate debonding. The numerical models were capable of predicting the experimentally observed load–deflection, failure load and failure modes. The sensitivity of the numerical results was studied. In particular, the effect of the concrete constitutive behavior and different modeling considerations was evaluated. It was found that the fracture energy of the concrete–repair interface plays a central part in predicting plate-debonding failures.

Keywords: Composite materials; Fracture energy; Finite element modeling; Damage mechanics; Debonding; Numerical modeling; FRP laminate; Reinforced concrete beam

1. Introduction

Strengthening reinforced concrete (RC) beams with fiber-reinforced polymer (FRP) composites is becoming an attractive alternative for the construction industry. These laminates offer all the advantages of composite materials, such as a low volume to weight ratio, and a high strength-to-weight ratio. Experimental tests of FRP-strengthened beams have identified a number of possible failure modes: tensile rupture of the composite laminate, debonding failure between the FRP laminate and the concrete substrate, concrete cover failure, and concrete crushing [1]. Although experimental data is valuable in understanding the behavior of this strengthening system, analytical and numerical solutions are needed to further comprehend and predict the behavior and failure mechanism of the strengthened beams.

Numerical modeling of FRP-strengthened beams represents a formidable challenge because other aspects—such as loading sequence, construction procedure, nonlinear material behavior, crack propagation and residual stresses—may have a significant impact on the results obtained in such an approach. Different modeling approaches, partially incorporating these aspects, have been proposed up to now; but sensitivity analyses are needed in order to identify the principal parameters controlling the numerical response of FRP-strengthened beams and to simplify the modeling procedures currently available.

Among different modeling approaches proposed to date, Ziraba and Baluch [2] presented a nonlinear finite-element code to simulate the global behavior, up to failure, of RC

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beams externally reinforced. They were able to predict the behavior of strengthened members subjected to arbitrary load histories previous to strengthening. In this approach, the interfacial behavior between concrete and the internal and the external reinforcement was modeled using six-node interface elements; nine-node Lagrangian elements were used for modeling the concrete and external laminate, whereas a three-node element represented the internal reinforcement. Arduini et al. [3] conducted a finite-element analysis of eight FRP-strengthened beams using the commercial code ABAQUS. During this study, the concrete was modeled using the smeared crack approach, and a perfect bond was assumed between the FRP and the concrete. This analysis was limited to beams with a monotonic loading history and without damage prior to FRP installation. Wong and Vecchio [4] used link and contact elements following linear and elastoplastic bond laws in order to model the bond-slip behavior at the bond interface of FRP-strengthened beams. A two-dimensional nonlinear finite-element code based on the Modified Compression Field Theory was used during the analyses. The procedure was able to predict the load–deflection behavior of FRP-strengthened beams failing by laminate debonding only when using an elastoplastic bond-slip behavior. However, the authors stated that a more clearly defined constitutive relationship for the bond elements must be developed to further improve and validate the model capability.

From these previous studies, it can be concluded that due to the challenges faced during the numerical analysis of FRP-strengthened beams, most of the research in this area has been devoted to improving the modeling techniques. From a practical point of view, it is also necessary to identify the principal material properties affecting the outcome of the numerical simulations; evaluate the sensitivity of the numerical results to variations in these material properties; and to recommend procedures for estimating such properties when experimental data are not available. This study aims at fulfilling these needs.

For this purpose, numerical results were validated against experimental data obtained from 19 beams strengthened with different types of FRP, and their sensitivity to concrete constitutive behavior and different modeling considerations was evaluated. In addition, practical recommendations are given for the modeling of FRP, epoxy, selecting model parameters and element size.

2. Experimental program

Experimental data was obtained from a previous research project [5] and from the literature review [6]. A total of 19 beams, strengthened with different FRP types, were selected for comparison with the numerical results. These beams failed by concrete crushing, cover failure, and/or plate debonding.

Series A corresponds to three large-scale beams tested by Benkert [5]. Geometric properties of these specimens are described in Table 1. The beams were tested under four-point bending. Beam A2 was used as a control specimen, whereas beams A1 and A3 were strengthened with two plies of Carbon FRP of different lengths. Material

Table 1
Experimental database

Series specimens	Width, height, length (mm)	FRP type	A_{FRP} (mm^2)	FRP length (mm)	Type of failure
Series A	305, 406, 4064				
A1		CFRP	83.8	3195	CC
A2		None	–	–	SY
A3		CFRP	83.8	3500	CC
Series B	200, 150, 2300				SY
B1		None	–	–	SY
B2		None	–	–	C/P
B3		CFRP	60	2100	C/P
B4		CFRP	60	2100	C/P
B5		CFRP	180	2100	C/P
B6		CFRP	180	2100	C/P
B7		GFRP	270	2100	C/P
B8		GFRP	270	2100	
Series C	200, 150, 2300				
C1		None	–	–	CC
C2		None	–	–	CC
C3		CFRP	60	2100	CC/P
C4		CFRP	60	2100	CC/P
C5		CFRP	180	2100	CC/P
C6		CFRP	180	2100	CC/P
C7		GFRP	270	2100	CC/P
C8		GFRP	270	2100	CC/P

Note: CC = concrete crushing; SY = steel yield; C/P = cover failure followed by plate debonding; CC/P = concrete crushing followed by plate debonding. Specimen details.