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Evaluation of hybrid joints strengthened by carbon plates connecting new steel frames with existing concrete slabs

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A B S T R A C T

This paper introduces hybrid joints strengthened by carbon plates for connecting new steel frames onto concrete slabs, enabling rapid and effortless assembly of frames relative to traditional wall frame construction; this study proved that the use of carbon strips was efficient in strengthening the joint. The nonlinear structural response of the proposed joints with carbon strips, which can transfer moments through the interconnected components, was evaluated experimentally and numerically based on identified parameters that influence the structural behavior of retrofitted frames. The parameters are also capable of evaluating failure modes of the extended structure with vertical additions by identifying the structural behavior of the joints with carbon strips. This study performed numerical analysis based on delamination growth predictions using cohesive finite elements, in an attempt to engender better practice for cost effective analytical investigations, and demonstrated a good correlation with test data obtained from extensive experimental investigations.

1. Introduction

The understanding of the utilitarian aspects of bond stress, especially slip relationships between Fiber-Reinforced Polymer (FRP) and the concrete interface, is of great interest in estimating the load bearing capacity of hybrid joints reinforced with carbon plates. The traction-separation law in the cohesive zone was studied by many researchers to explore the influence of the interfacial stiffness, resistance to allowable tractions, critical separations, and ultimate slips on the debonding forces. How damages evolve is also of urgent concern to the engineers who design concrete slabs reinforced using Fiber-Reinforced Polymer (FRP) based on the bond stress – slip relationships of the interface. Park et al. [1] presented a critical review of traction-separation relationships across fracture surfaces. The traction-separation relationship across fracture surfaces may be classified as either nonpotential-based or potential-based models. Nakaba et al. [2] performed research that examined the bond behavior between fiber-reinforced polymer (FRP) laminates and concrete. In their study, local bond stress-slip relationships were proposed, which were not influenced by the type of fiber. Their results describing local bond stress-slip relationships were employed in our traction-separation constitutive law, which was then implemented in finite element analysis. Yang et al. [3] presented a cohesive zone modeling approach for analyzing the damage tolerance of laminated composites, with or without the existence of stress concentrators. They showed that experimentally measured crack shapes can be successfully reproduced by cohesive zone model (CZM) simulations, which replaces significant, time-consuming, and expensive testing to establish damage tolerance certification. Alfano et al. [4] investigated the application of CZM concepts to study mode I fractures in adhesive bonded joints. They showed that these fractures have a sensitivity to different cohesive strengths. In this case, the value of the cohesive fracture energy was held fixed and equal to 550 N/m. As the critical strength increases, the peak load is increased while the global fracture energy is almost constant. Turon et al. [5] introduced a methodology to determine the constitutive parameters for the simulation of progressive delamination. In their procedure, the size of a cohesive finite element and the length of the cohesive zone were accounted for to ensure the correct dissipation of energy. In addition, a closed-form expression for estimating the minimum penalty stiffness necessary for the constitutive equation of a cohesive finite element is presented. Beyond the analytical and experimental investigations to understand cohesive behavior of the interfaces with the application of CZM concepts of mode I fractures in adhesive-bonded joints, extensive additional study is still required to understand the structural behavior of concrete and steel frames composited with composite FRP. There have been many studies similar to the one conducted by Joseph et al. [6] who performed

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analytical and experimental studies to investigate the behavior of concrete beams strengthened with FRP, with unidirectional laminates under loading. They used the finite element program ABAQUS to study the linear behavior of a beam. They also proposed the use of coupled stiffness coefficients for the cohesive model of the interface. More studies were reviewed in the literature [7,8]

Our study was devoted to the nonlinear structural investigation of complex hybrid joints reinforced with FRP for vertical additions to existing buildings, as described in Section 3. The structural influence of carbon plates on the capacities of the joint interconnecting the slab and metal base plate of the steel column, via headed bolts and chemical anchors, were explored using the traction-separation constitutive law in the cohesive zone. The nonlinear analytical model of the hybrid frame comprised of the steel column and the concrete slab reinforced by FRP strips was implemented in finite element code before it was compared with the test results. Section 3 describes the experimental investigation, including the description of details of the hybrid frames and the fabrication of test specimens which were subjected to testing. The selection of elements and related meshing techniques are introduced in Section 4. The traction-separation behavior of the interface between carbon plates and concrete slabs is explored in Section 5. Section 6 contributes to the evaluation of the seismic structural performance of hybrid joints, based on the cohesive behavior at the interface between fiber-reinforced polymer laminates and concrete. Progressive delamination growth, based on the cohesive zone model approach for modeling complex fracture mechanisms at the crack tip, was formulated and compared with test data. In this section, crack propagation in initially partially bonded surfaces via linear elastic fracture mechanics principles (LEFM), which was implemented using the Virtual Crack Closure Technique (VCCT), was modeled using surface-based cohesive behavior. Section 7 is dedicated to the estimation of failure modes of the hybrid joints based on the damage evolution law, defined as a nonlinear exponential function.

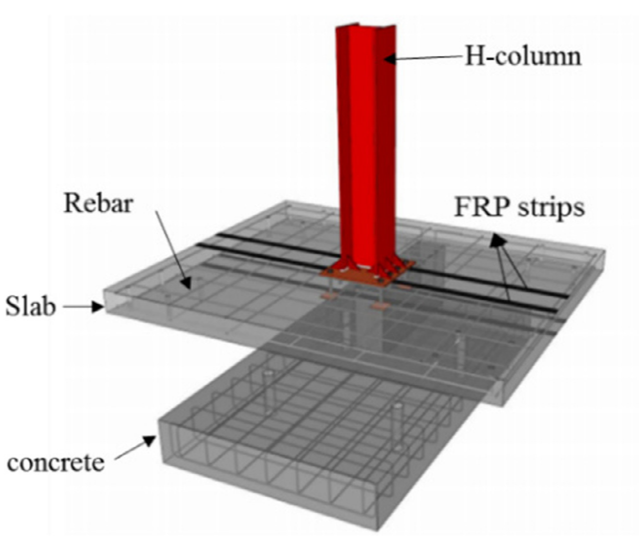

Fig. 1. Concrete slab reinforced by FRP plates (half straight wall, penetrating headed bolts) [9,10].

2. Research significance

The seismic structural performance of hybrid joints reinforced with FRP for vertical additions of existing buildings was evaluated experimentally and analytically, based on cohesive behavior at the interface between fiber-reinforced polymer laminates and concrete. The contribution of the carbon plates, which reinforce joints of the vertically extended frame, to the lateral flexural capacity is explored using cohesive zone-based-nonlinear finite element analysis, which was validated by extensive experimental investigation. Nonlinear finite element models, based on the traction-separation constitutive law in the cohesive zone model, are also suggested to investigate the influence of the reinforced joints on the failure mode. This study performed sensitivity analysis to diverse failure modes via experiments; extensive tests of the failure of the retrofitted frames has been performed by the authors to identify the strength of the column connections and damages to the concrete slab. This study also presents dependable analytical tools for finding the stress and strain fields of the complex structures of the joint protected by FRP, concrete in the vicinity of the base plates, and the cohesive interface between carbon plates and slab, resulting in recommended design procedures. Crack patterns, propagations, and failure modes of slab joints observed under displacement-controlled loading were compared with those estimated based on the traction-separation law with nonlinear damage evolution. Crack patterns with propagation trends which were measured and calculated are expected to serve as a basis for performing efficient joint design of vertically extended frames on existing structures. This study is also intended to devote attention to the use of the FRP plates as one of the practical and economical design options for the connection between new and old frames. It was also verified that the FRP plates provided the required strengths to the specimens, otherwise, the resistance of the frame would not have been sufficient.

3. Experimental investigation

3.1. Fabrication of test specimens and description of slabs retrofitted by carbon plates

Carbon fiber-reinforced polymer (CFRP) strips of 230 mm width were used to reinforce the slab, as shown in Fig. 1. Chemical resin was used to attach FRP plates to the concrete surface to provide bonding force to the interface. Table 1 and Fig. 2 provide the details

Table 1
Test specimen details [9,10].

Joint connection	CFRP reinforcement	Wall type	Specimen
Anchor bolts not penetrating slabs	No	Cross-type wall	1
	Yes	Straight wall	2
		Half straight wall	3
		No wall	4
Headed bolts penetrating slabs	No	Cross-type wall	5
	Yes	Straight wall	6
		Half straight wall	7
		No wall	8