



Slip effects in reinforced concrete beams with mechanically fastened FRP strip

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ABSTRACT

This investigation concerns the flexural behavior of reinforced concrete (RC) beams strengthened with a mechanically fastened pultruded FRP strip (MF-FRP beams). Twelve small size MF-FRP beams and two control RC beams were tested under flexural loading. The main failure mode observed in this experimental program was nail rotation and bearing damage under increasing flexural load, which resulted in FRP slip with respect to the soffit of the RC-beam and loss of stress transfer. Strain gage data and visual observations obtained during the experiments provided useful insight for developing a new procedure for estimating the nominal moment capacity of the MF-FRP beams. The proposed method is guided by experimental evidence pointing to the significance of nail rotation associated with flexural cracking in RC beams. The developed procedure, based on a “strain reduction factor” of 24%, is able to estimate the nominal moment capacity of the MF-FRP beams with good accuracy.

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1. Introduction

Fiber-reinforced polymer (FRP) composites are rapidly gaining acceptance as a cost effective, durable means of strengthening reinforced concrete (RC) structures. In most cases reported to-date, wet-laid and pultruded FRPs have been adhesively bonded to RC structures using epoxy resins. While the epoxy bonding method can be highly effective, it can be limited by lengthy surface preparation and curing times as well as the possibility of bond failure at the interface between concrete and FRP [1]. To overcome these limitations, Lamanna et al. [2] developed a method of using powder-actuated nails to mechanically fasten specially-made, pultruded, hybrid-fiber FRP strips to flexural RC members for strengthening purposes (MF-FRP method). Several combinations of unidirectional glass fibers (rovings), carbon fibers (tows), continuous strand glass mat, and matrix materials were evaluated [3]. As a result of these investigations, a new type of multidirectionally reinforced pultruded FRP laminate now known as Safstrip™ was developed specifically for mechanical fastening to concrete. The distinguishing feature of this pultruded FRP strip versus typical pultruded laminates for strengthening RC structures is that bearing failures induced by mechanical fasteners are designed to be ductile in Safstrip™. Therefore, this type of laminate is an appropriate choice for the MF-FRP strengthening method. A detailed description of the Safstrip™ laminate is given by Lamanna [3]. Recent research has demonstrated the significant enhancements of

strength in flexurally loaded MF-FRP beams in comparison to unstrengthened beams, without a substantial decrease in ductility as is generally observed with epoxy-bonded FRP (EB-FRP) strengthening [2–5].

Lamanna [3] and Bank et al. [6,7] developed an analytical model for predicting the flexural behavior of MF-FRP RC beams. The force-carrying capacity per fastener was used to predict the bearing failure and consequent reduction of stress transfer in the FRP strip. In this model, if the shear force on a fastener exceeds the defined force-carrying capacity, the associated section of FRP is assumed to slip with a constant fastener force equal to the defined capacity. The capacity of a fastener was obtained from pull-off tests, where the FRP was attached by one fastener to a concrete block. The analytical model agreed well with experimental results from small-scale rectangular beams and full-scale T-beams in terms of load capacity. However, predicted mid-span deflections were not in agreement with experimental results for the small-scale beams, indicating a deficiency in the moment–curvature relationship in those cases.

El Maaddawy and Soudki [8] developed an analytical model for predicting yield and ultimate flexural loads of one-way RC slabs strengthened with FRP strips (Safstrip™) anchored by bearing plates. The bearing plates clamped the FRP strip to the concrete using bolts running through the thickness of the slab at a few select positions (mainly at the ends), which is a fundamentally different anchoring approach than that used by Lamanna [3] and Bank et al. [6,7] in earlier investigations. The analytical model developed by El Maaddawy and Soudki uses an empirically-based “bond factor” to account for the slip between the concrete and FRP. The bond

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factor is multiplied by the strain at the soffit of the concrete to determine the strain in the FRP. Values of the bond reduction factor ranged from 0.9 to 0.7. Using this bond factor approach, predictions of yield load of the slabs were consistently conservative (by up to 8%) while predictions of ultimate were mostly nonconservative (by up to 24%).

The present investigation aims to improve the prediction of the flexural behavior of MF-FRP beams by accounting for slip between the FRP and concrete caused by factors such as bearing failure and nail rotation. The proposed method is guided by experimental evidence pointing to the significance of nail rotation associated with flexural cracking in RC beams. Predictions of the nominal moment capacity of the beams used in the present investigation are made using Lamanna's method [3,6,7] along with the proposed method.

2. Experimental investigation

FRP strips attached to concrete blocks with one or two nails were pulled off to estimate the shear capacity of the concrete-FRP joint. RC beams with mechanically fastened strips were subjected to flexure tests to evaluate the effectiveness of the MF-FRP strengthening method. Observations made during these tests guided the development of a new model accounting for slip between the FRP and concrete caused by factors such as bearing failure and nail rotation.

2.1. Specimen description

Concrete blocks of 130 mm × 130 mm cross section and 260 mm length were cast for use in the pull-off tests (see Fig. 1). The as-received FRP material was cut into 25 mm wide by 355 mm long strips and fastened to the concrete blocks using one or two nails of 32 mm length (see Fig. 1). Reinforced concrete (RC) beams were designed and fabricated based on ACI 318-05 [9] to fail by yielding of the tensile reinforcement followed by crushing of the concrete in both the unstrengthened and strengthened cases. The beams had a depth of 20 cm, a width of 15 cm, a length of 152 cm, and depth of concrete cover (to the center of the flexural steel reinforcement) of 38 mm. The reinforcing ratio and stirrup size and spacing were chosen based on these dimensions (see Fig. 2). Steel nails were employed to attach the FRP strips to the beams and blocks. Steel anchor bolts were used in place of one pair of nails at opposite ends of the FRP strip in the “production” beam specimens in order to obtain superior strengthening effects and ductility.

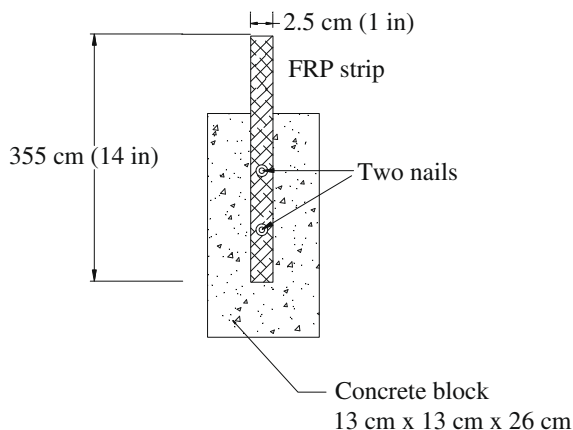


Fig. 1. Pull-off block specimen with FRP strip attached by two nails.

2.2. Material properties

A commercially mixed concrete with a 13 mm maximum aggregate size and 5% air entrainment was used for the blocks and beams. Grade 415 MPa deformed steel reinforcement bar was used. The Safstrip™ product discussed in the literature review was used for strengthening. The pultruded FRP strip, made by Strongwell (Bristol, VA, USA), is a hybrid carbon and glass fiber composite with vinylester matrix [3]. As manufactured, the strip is 102 mm wide and 3.2 mm thick. The properties of the concrete, steel bar and FRP strip were measured as a preliminary part of the investigation [10] and are listed in Table 1. Also, the bearing strength of the FRP strips was measured, according to ASTM D5961 [11], using nails and holes of 3.5 mm diameter. The load at the onset of bearing damage was found to be 3 kN, which translates to a 272 MPa bearing strength.

2.3. FRP pull-off test results

Fig. 3a illustrates the pull-off test set-up, which consists of a top plate and a bottom plate securing the concrete block using long threaded rods. Obtained load versus grip displacement graphs from the pull-off tests are shown in Fig. 4. On average, the maximum pull-off loads of concrete-FRP joints fastened with one and two nails of length 32 cm and diameter 3.5 mm were 6.10 kN and 11.7 kN, respectively. It was observed that the maximum pull-off load for one nail exceeded by a factor of two the 3 kN damage onset load of the bearing test. The cause of this apparent increase of bearing strength is hypothesized to be the rotation of the nail during the pull-off test and the consequent increase of clamping force acting through the thickness of the FRP strip near the nail. The appearance of extensive bearing failure of the FRP following a pull-off test is shown in Fig. 5a. The average pull-off load for two nails was approximately twice that for one nail. Additional experiments should be carried out to evaluate the maximum pull-off force for a larger number of nails.

2.4. Flexural behavior of MF-FRP beams

Three different types of MF-FRP beams and two control beams (i.e., no strengthening) were used for flexural testing. The fastener types and arrangements on three MF-FRP beams were varied at first in order to determine the most effective fastening scheme to be used in the remaining nine “production” beam specimens (beams 4–12). A description of the fasteners used for the MF-FRP beams, including nails and anchors, is given in Table 2. The 38 mm maximum nail length was limited by the depth of the concrete clear cover (22 mm) plus FRP thickness (3 mm) as suggested by previous research [3]. To prevent damage to the cover as the nails were inserted with a powder-actuated fastening tool, holes of 3 mm diameter were pre-drilled into the cover to a depth of 25 mm. The anchors, which screw into pre-drilled holes in the concrete, had a length of 54 mm and a diameter of 6.5 mm. Neoprene washers of 3 mm thickness were used to prevent damage to the FRP by the heads of the fasteners. Additional details of the fastening schemes are given by Lee [10]. Beams 1–3 and the two control beams were tested under 3-point loading (point load at midspan). The remaining MF-FRP beams (beams 4–12 in Table 2) were tested under a 4-point flexural load with a shear span length of 63.4 cm and an inner span of 15 cm, as shown in Fig. 3b).

All flexure tests were conducted under displacement-control using a hydraulic actuator at a rate of 0.75 mm/min. Applied load, mid-span displacement and strain at several locations on the FRP strip were continuously recorded using a data acquisition system. The two control beams failed, as expected, by yielding of the longitudinal steel reinforcement followed by concrete crushing on the

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