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Effective methods of using CFRP bars in shear strengthening of concrete girders

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ABSTRACT

This paper presents the results of an experimental study that investigated the shear strength contribution of carbon fiber reinforced polymer (CFRP) bars attached with concrete beams using a near surface mounted (NSM) technique. In this research, four concrete beams were cast with regular steel reinforcement in flexure. The control beam had typical shear steel and the other three beams were strengthened in shear with CFRP bars. Strain gauges were attached with the shear reinforcement of all four beams at various shear critical locations. Strains during loading to failure of the beams were recorded using a data acquisition system. The performance of the NSM technique was found to be very effective with no occurrence of delamination, debonding or fracture of FRP. Effective strains in the NSM CFRP bars were determined through analyzing the collected strain data. A new formula to calculate the nominal shear strength provided by NSM CFRP bars has also been proposed.

1. Introduction and background

Shear failure is a common problem in concrete structures. Natural disasters, such as hurricanes and earthquakes, may also cause shear failure of structures before full flexural capacity is achieved [1]. Reinforced concrete (RC) and prestressed concrete (PC) structures, such as buildings and bridges that were designed several decades ago, also exhibit shear cracks because of regular and unintended or unforeseen loads, unaccounted loads in the earlier designs, inferior material behavior, and loss of concrete strength due to aging [2]. Efficient and cost-effective method of strengthening concrete members in shear is of utmost importance to encounter shear-deficiency problem in RC and PC structures.

Fiber reinforced polymer (FRP) systems have been used in the United States for almost 20 years and are becoming a widely accepted method for strengthening concrete structures in flexure and shear. American Concrete Institute (ACI) Committee 440 [3] has developed guidelines for the design and construction of externally bonded FRP systems for strengthening concrete members. In this paper, the term 'externally bonded FRP' refers to FRP composites attached on the external surface of concrete members by means of epoxy or cement-based adhesive. On the other hand, in the near surface mounted (NSM) FRP technique, grooves are cut into the surface of the concrete members, and FRP bars, sheets or strips are inserted into the grooves and attached using epoxy or cement-based adhesive. The grooves are normally cut 1.5–2 times the diameter of the FRP bars to ensure adequate bonding between FRP composites and surrounding concrete, although a groove size of twice the bar diameter has also been recommended as the optimum size [4]. Unlike externally bonded FRP strengthening, the NSM technique does not require additional precautions during surface preparation. In fact, the technique has been proved to be very practical, efficient, and economical in strengthening negative moment regions of beams and slabs. ElHacha and Rizkalla [5] reported that the strength of the reinforced concrete beam strengthened using the NSM technique provided a significant increase in the overall ductility of the member when compared with the externally bonded FRP strips.

Numerous experimental data exists on the shear strengthening of concrete members with externally bonded FRP sheets, laminates and strips, whereas an insufficient amount of data are available on shear strengthening with NSM FRP bars. External bonding of FRP materials has disadvantages due to delamination or debonding of FRP materials under critical stress. On the other hand, even though the NSM technique is used less frequently, it may eliminate such delamination or debonding problems, which were observed during the testing phase of this research. Moreover, the contribution of NSM FRP bars to shear strengthening is quite unclear, which was investigated in this research. No final design guidelines on the shear strengthening of concrete members using NSM FRP bars have been developed yet possibly due to lack of analytical and experimental data. In this research, an experimental investigation has been conducted on beams strengthened with NSM carbon FRP (CFRP) bars to determine the effect and performance of NSM technique, and to calculate the contribution of NSM CFRP bars to the nominal shear strength of concrete members. As a result, the outcomes of this research are expected to provide useful guidance in developing design criteria for shear strengthening of concrete members with FRP bars attached using the NSM technique.

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Notations

V_n	nominal shear strength
V_c	nominal shear strength provided by concrete
V_s	nominal shear strength provided by shear steel
V_f	nominal shear strength provided by FRP bars
f_c'	specified compressive strength of concrete
b_w	beam web width
d	distance from extreme compression fiber to centroid of longitudinal tension reinforcement
A_v	area of shear steel
f_y	tensile yield strength of shear steel
f_{yf}	tensile yield strength of FRP bars
s	spacing of shear reinforcement
A_f	area of FRP bars in shear
E_f	tension modulus of elasticity of FRP bars
ε_{ef}	effective strain in FRP bars
ε_{uf}	ultimate strain in FRP bars
ε_e	effective strain
ε_u	ultimate strain

Bousselham and Chaallal [2] reported that the lack of experimental data on deformations experienced by FRP and internal shear steel needs to be addressed. They also pointed out that there is a lack of data on the experimental measurement of strains in the FRP bars and shear steel. Shear steel reinforcement is internal; however, FRP composites are bonded externally, which makes the assessment of the FRP performance and bond mechanism more complex. Moreover, the detailed descriptions of the failure sequences are not fully provided, and are often unclear. Therefore, failure modes, strains in FRP bars, geometry of the member, type of applied loading, ratios of internal longitudinal and shear reinforcement, and shear span ratio (a/d) (defined as the ratio of the shear distance (a) to the effective depth (d) of the member) are some parameters, which have been investigated in this research.

Design approaches for strengthening concrete members using NSM FRP composites have been based on system- or project-specific research. A bridge girder was strengthened in shear using rectangular CFRP bars following NSM technique combined with externally bonded pre-cured CFRP laminate for flexural upgrade, and showed significant increase in the shear strength [6]. The lighter weight and greater tensile strength of CFRP laminate greatly reduce the overall installation and maintenance costs as compared to steel plate bonding techniques. Moreover, FRP materials have gained popularity due to their non-corrosive nature and low maintenance cost. The results of several experimental investigations have shown that FRP systems can be effective in increasing the shear strength of concrete members. Shear strengthening with FRP materials, however, is still under investigation and the results obtained thus far are scarce and sometimes controversial [7]. However, the design methodologies and guidelines require information about strains in FRP bars during loading and failure, and the overall contribution to shear strength. In this research, the corresponding strains in the FRP bars and shear steel at various shear critical locations along the beam were measured, and a method to calculate the nominal shear strength provided by the NSM CFRP bars was developed and proposed.

2. Model beam shear strength

In recent years, many research programs have been conducted to develop appropriate calculation models and general design guidelines for strengthening RC members with externally bonded FRP composites. Current methods used for calculating the ultimate shear capacity of strengthened beams are essentially based on the truss analogy, assuming the contributions to shear resistance by the concrete, steel stirrups and externally bonded FRP composites to be additive [8]. The different models proposed in the literature basically differ in the evaluation of the shear contribution by the FRP reinforcement, while the determination of the concrete and steel stirrup contribution is based on expressions provided by ACI 318-05 [9]. Thus the nominal shear capacity (V_n) of a RC member strengthened in shear with NSM FRP composites can be given by Eq. (1).

$$V_n = V_c + V_s + V_f, \tag{1}$$

where V_c stands for the nominal shear strength provided by concrete, and V_s and V_f stand for the nominal shear strength provided by steel and FRP bars, respectively, within a length equal to the effective depth. The nominal shear strength contribution by concrete, steel and FRP bars can be calculated by using the following Eqs. (2)–(4), respectively.

$$V_c = \frac{\sqrt{f_c'}}{6} b_w d \quad [9] \tag{2}$$

$$V_s = \frac{A_v f_y d}{s} \quad [9] \tag{3}$$

$$V_f = \frac{A_f E_f \varepsilon_{ef} d}{s} \tag{4}$$

where f_c' = specified compressive strength of concrete (MPa), b_w = beam web width (mm), d = distance from extreme compression fiber to centroid of longitudinal tension reinforcement (mm), A_v = area of shear steel (mm^2), f_y = tensile yield strength of shear steel (MPa), s = spacing of shear reinforcement (mm), A_f = area of FRP bars in shear on both sides of beam (mm^2), E_f = tension modulus of elasticity of FRP bars (MPa), and ε_{ef} = effective strain in FRP bars.

3. Experimental program

3.1. Beam design and loading configuration

Typical beam dimensions and loading configurations used in this research are shown in Figs. 1 and 2. The beams were loaded under four-point bending, as shown in Fig. 1, until failure. Fig. 2 shows a plan and cross-section of a typical test beam. The beams were made with concrete with an average compressive strength of 49.75 MPa (7.215 ksi). The concrete compressive strength was later determined by taking the average strength of three concrete cylinder specimens taken during the pouring of concrete into the beam formwork. All four beams had 4 No. 19 (#6) steel bars at the bottom and 2 No. 19 (#6) steel bars at the top as flexural reinforcement, as shown in the cross section presented in Fig. 2. In order to achieve full shear capacity before full flexural capacity at failure, the beams were designed with stated reinforcement and concrete strength to make them fail in shear slightly before they fail in flexure. Grade 60 reinforcing steel with tensile yield strength of 413.7 MPa (60 ksi) was used to strengthen the beams in flexure and shear. The nominal flexural and shear capacity of the control beam were calculated as 112 kN m (using nominal moment capacity formula suggested by ACI 318-05) and 178.3 kN (using Eqs. (2) and (3), respectively, based on structural design. The theoretical 4-point bending force required to fail the control beam in flexure was calculated as 364 kN, whereas to fail in shear was calculated as 353 kN. Therefore, it was theoretically predicted that the beam would fail in shear before it would fail in flexure. This was done in order to assess any shear strength gain by the model beams as a result of shear strengthening by using NSM CFRP bars.