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Ductile strengthening using externally bonded and near surface mounted composite systems

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ABSTRACT

Externally bonded fiber reinforced polymers (FRP) has been established as an effective technique for strengthening concrete members. Other techniques, like near surface mounted (NSM) FRP bars, and steel reinforced polymers (SRP) have emerged as viable alternatives. In this study, four composite-based strengthening systems were used to provide equivalent flexural performance, namely: externally bonded CFRP sheets, NSM prefabricated CFRP strips, externally bonded SRP sheets and NSM stainless steel bars. The strengthening design was based on achieving approximately 38% increase in flexural capacity over the unstrengthened control beams. The mode of failure by design was brittle failure controlled by concrete crushing at 0.003 strain. However, the experimental program was designed to demonstrate the effectiveness of transverse anchoring reinforcement to control premature debonding failure modes and fully utilize the high strength of the composite systems. A more ductile behavior was also observed as a result of transverse strengthening and concrete confinement effects. Accordingly, an increase of approximately 50% in flexural strength is accomplished.

1. Introduction

One of the most prominent techniques available for repair and strengthening of concrete structures is the use of externally bonded fiber reinforced polymers (FRP) composite systems. These systems have demonstrated tremendous potential for use in infrastructure applications over the past 20 years, verified by considerable research and extensive field applications [1–6]. However, a predominant failure mode associated with this application has been characterized by premature FRP debonding or combined FRP and concrete cover delamination [7–9]. Some investigators proposed the use of FRP end anchorage to suppress these failure modes [8,10]. However, this technique was shown to delay premature failure at best since separation may initiate from shear or flexural cracks within the shear span [11]. Spadea et al. [12] suggested the use of external steel plate stirrups to improve the composite action. However, they did not provide a methodology to compute the needed stirrups. Reed et al. [13] formulated the design of the needed FRP U-wraps by adapting the ACI 318-05 shear friction model [14,15]. This approach was followed in the present testing program. Once the transverse FRP U-wraps are successful in suppressing the separation failure mode, RC beams strengthened with composites are anticipated to develop their full flexural capacity. This leaves FRP rupture and concrete crushing as the two predominant flexural failure modes. This would also increase the strength and ductility of the strengthened flexural members.

FRP rupture is a predictable design failure mode since the FRP ultimate strain can be accurately determined from coupon testing [6]. Concrete crushing could also be predicted if the beam fails near a compression strain limit of 0.003 without major confinement effects. However, if confinement of the compression concrete is secured, concrete in compression could achieve higher strength and ductility that would allow for a better utilization of higher strength properties of the composites. In this case, failure may be initiated by crushing and spalling of the concrete cover in compression then terminated by rupture or local debonding of external composite reinforcement.

Near surface mounted bars has emerged as another strengthening technique in which FRP bars or narrow strips are embedded and epoxy bonded into grooves made onto the surface of the member [16,17]. This technique offers some advantages over externally bonded systems in terms of protecting the added reinforcement against environmental exposure, mechanical abrasion and vandalism.

In order to evaluate the comparable effectiveness of composite systems, four different strengthening schemes were comparatively examined to produce maximum composite contribution to bending, improve ductility, and achieve similar response. Six beams were tested in three-points bending using four composite-based

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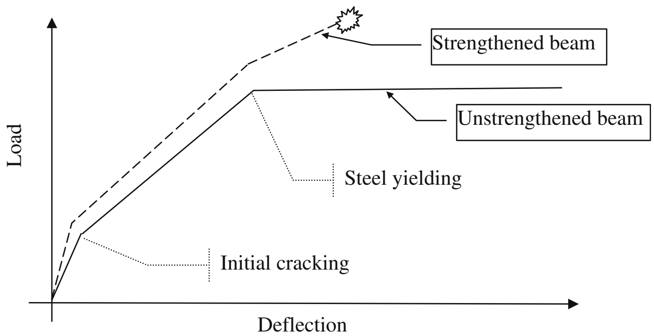

Fig. 1. Typical brittle response of FRP strengthened beams.

strengthening systems, namely: externally bonded CFRP sheets, NSM prefabricated CFRP strips, externally bonded steel reinforced polymer (SRP) sheets and NSM stainless steel bars.

It is well established that the ductility of reinforced concrete beams reduces with increased strengthening (Fig. 1). This is due to the non-ductile behavior of FRP with linear stress–strain relationship and the relatively brittle failure modes due to composites separation from concrete. In this study, higher strength increase and relatively more ductile flexural behavior was aimed for by using transverse FRP U-wraps to anchor the longitudinal composite systems and control the debonding failure modes up to ultimate flexural capacity. To prevent premature compression failure of concrete and allow for full utilization of the composite reinforcement, internal steel stirrups were used to confine the concrete and achieve post peak compression response.

2. Material properties

Six reinforced concrete beams were manufactured and tested in this study. The beams were poured in two stages. Beams designated as Control 1 and Specimens 1, 2 and 3 were cast from one concrete batch (Series 1) and beams designated as Control 2 and Specimen 4 were cast from another batch (Series 2), both using ready mix concrete. The concrete compressive strength was determined from 4×8 in. (102×203 mm) test cylinders according to ASTM C 39. The correction factor to adjust to the strength of 6×12 cylinders is only 0.94 [18]. This small correction is neglected in this study. The average strength f'_c for both batches was found to be 5000 psi (34.5 MPa), as listed in Table 1. The concrete modulus of rupture was determined experimentally to be 660 psi (4.6 MPa) using ASTM C 348.

The reinforcing steel properties were obtained from the manufacturer and were determined through tensile coupon tests. Results from material testing indicated that the yield strengths of reinforcing steel of Series 1 and Series 2 were 83.5 ksi (576 MPa) and 69.2 ksi (477 MPa), respectively (Table 1).

Each of the four different strengthening systems used in this investigation has its unique material properties. Two different carbon fiber products, two different types of steel products, and three different types of epoxy polymers were used to achieve these four strengthening systems. The following describes these systems.

The first strengthening system used with Specimen 1 was MBrace CF 130 carbon fiber strengthening system provided by Master Builder's Technologies of Cleveland, Ohio. The dry fiber sheets consisted of unidirectional carbon fibers with an average thickness of 0.0065 in (0.165 mm). The stress–strain relationship of the dry fibers is linear-elastic up to rupture with an elastic modulus of 33,000 ksi (231 GPa), based on the fiber area, and an ultimate strain of 0.017 in./in., as reported by the manufacturer. Tensile coupon testing of the cured composite laminate yielded a strength of 91.9 ksi (634 MPa), modulus of 6720 ksi (46.361 GPa), and an ultimate strain of 0.014 in./in. [13]. The fiber volume fraction is 0.2 and Type 2 Epoxy resin is used in the wet lay-up process.

Specimen 2 was strengthened using NSM CFRP Strips, Aslan 500 pre-cured CFRP strips, as provided by Hughes Brothers Inc. of Seward, Nebraska. The manufacturer recommended a two-part non-sag general-purpose gel epoxy, Concresive® 1420, provided by Degussa Building Systems (currently BASF) of Shakopee, Minnesota. The Aslan 500 CFRP strips have cross-sectional dimensions of 0.63×0.079 in. (16×2 mm) and are made with 60% carbon fibers by volume, embedded in a bisphenol epoxy vinyl ester resin. The stress–strain relationship of the pre-cured strips is linear-elastic up to rupture with an effective elastic modulus of 19,000 ksi (131 GPa) and an ultimate strain of 0.017 in./in., as reported by the manufacturer. The NSM strips were installed in grooves that were cut into the tension face of the beam specimen using an angle grinder with a diamond blade. After cleaning the inside surface of the grooves, the NSM CFRP strips were bonded into the grooves using Concresive® 1420 epoxy adhesive.

The strengthening of Specimen 3 was achieved using SRP reinforcing system known as Hardwire, as provided by Hardwire LLC of Pocomoke City, Maryland. The system consists of unidirectional ultra high strength, 460 ksi (3170 MPa), steel cords made into 24″ wide sheets. The sheets consist of 3×2 type cords that are made by twisting two filaments around three straight filaments. The Hardwire sheets were made of 23 cords per in. with a total area of 0.0173 in.^{2} per in., or equivalent sheet thickness of 0.0173 in (0.44 mm). The cords had a linear stress–strain curve up to rupture with an elastic modulus of 30,000 ksi (207 GPa) based on the steel area and an effective ultimate strain of 0.0153 in/in, as reported by the manufacturer. Longitudinal and transverse Hardwire reinforcement were installed using a two-part epoxy adhesive that was recommended by the manufacturer and referred to as Type 2 Epoxy resin. The composite properties of a hardwire laminate are as follows: elastic modulus is 10,952 ksi (75.6 GPa), tensile strength is 164.211 ksi (1133 MPa) and the wire volume fraction is 35%.

The materials used for strengthening of Specimen 4 were NSM stainless steel #4 (13 mm) 2205 Duplex Hot Finish Unannealed Pickled deformed bars provided by Talley Metals Technology, Inc.

Table 1
Summary of material properties.

Material	Modulus of elasticity E, ksi (GPa)	Ultimate strain ε_u (in./in.)	Yield stress f_y, ksi (MPa)	Ultimate stress f_u, ksi (MPa)	Bilinear modulus E_2, ksi (GPa)
Concrete	4.031 (27.8)	0.003	–	5.0 (34.5)	–
Mild steel (control set 1)	29.000 (200)	0.16	83.5 (576)	105.5 (728)	685 (4.73)
Mild steel (control set 2)	29.000 (200)	0.09	69.2 (477)	110.1 (759)	467 (3.22)
Carbon FRP (sheets)	33.000 (231)	0.014	–	440 (3,080)	–
Carbon FRP (strips)	19.000 (131)	0.017	–	300 (2,068)	–
Hardwire	30.000 (207)	0.0153	–	460 (3,170)	–
NSM Stainless Steel Rebar	29.000 (200)	0.23	99.0 (683)	128 (883)	1100 (7.59)