Construction and Building Materials 172 (2018) 562–573

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Flexural behavior of reinforced concrete beams externally strengthened with Hardwire Steel-Fiber sheets

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HIGHLIGHTS

- Beams were strengthened externally-bonded HSF sheets.
- Sheets were attached using epoxy adhesive.
- Two different densities of HSF sheets are used.
- Test results showed an increase up to 60% over control specimen.

ARTICLE INFO

Article history:
Received 27 February 2017
Received in revised form 19 March 2018
Accepted 22 March 2018

Keywords:
Reinforced concrete
Beams
Hardwire Steel-Fiber sheets
Strengthening
Ductility

ABSTRACT

Fiber Reinforced Polymers (FRP) has been used predominantly as externally-bonded strengthening materials using epoxy adhesives. Recently emerged Hardwire Steel-Fiber (HSF) sheets have desirable characteristics that made them attractive candidates as strengthening materials. The literature lacks information on the flexural performance of RC beams when externally strengthened with HSF composite sheets. This paper presents an experimental investigation consists of seven reinforced concrete (RC) beams strengthened in flexure with externally-bonded HSF sheets using epoxy adhesives. Two types of HSF sheets with medium and high-cord densities of 4.72 and 7.87 cords/cm were investigated. Four-point bending tests were conducted and the load-deflection and strain response data at the beams' mid-span section were recoded until failure of the beam specimens. The test results were compared with a control unstrengtherned beam specimen. Experimental results showed an increase in the load-carrying capacity of the strengthened specimens ranging from 29% to 62% over the control unstrengthened specimen. However, the ductility of the strengthened specimens was less than that of the control specimen and all strengthened specimens failed in flexure by delamination of the concrete cover. The ultimate load-carrying capacity of the tested specimens was predicted using the guidelines of ACI 318-11 and ACI 440.2R-08, while mid-span deflection response curves were predicted using ACI 318-11 guidelines. The predicted results were in close agreement with the experimentally measured ones. It has been concluded that HSF sheets, externally-bonded with epoxy adhesives to the soffit of concrete beams, can serve as effective flexural strengthening composite material.

1. Introduction

Ageing and deterioration of existing reinforced concrete (RC) structure have emerged as some of the major issues that need to be addressed during by the construction industry in the last few decades. RC structures are deteriorating over the years due to many reasons such as construction faults, design or detailing errors, corrosion of steel reinforcement, increase in live loads [1–7]. The rehabilitation and strengthening of structural members is currently a major concern for researchers and engineers. Over the last few decades, several investigations have been conducted on external shear and flexural strengthening of RC beams by using different types of strengthening materials and techniques [1–7]. Bond strength and bond durability of externally bonded strengthening material had also been studied [8–11]. In the early 1940 s, steel plates have been utilized for strengthening RC beams in flexure [12]. However, despite the increase in the load-carrying capacity of RC beams, major drawbacks were shown by the exposed steel plates such as corrosion, high interfacial shear stresses at the plate ends, premature debonding, and heavy weight of plates [13,14]. The limitation of steel plates as external strengthening materials,

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https://doi.org/10.1016/j.conbuildmat.2018.03.225
0950-0618/

led to the development of fiber-reinforced polymer (FRP) composite materials, which showed better performance due to their superior mechanical properties such as their high-strength-to-weight ratio, their non-corrosive and non-magnetic characteristics, thermal resistance, and their ease of handling and installation [1–7].

FRP materials gained wide acceptance in the structural strengthening of existing structures. FRP has also emerged and proven to be a promising and effective material for the external strengthening of RC elements in flexure and shear. Different type of composite materials such as Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), and combination of both of them (Hybrid) were used over the years in the form of sheets or laminates with an epoxy adhesive, to externally strengthen RC beams in flexure.

Numerous research studies have been conducted during the past three decades to examine the feasibility of CFRP [15–33] and GFRP [23–26] composite material or their hybrid combination [27–30] to externally strengthen RC beams in flexure. However very limited studies have been conducted to investigate the possibility of utilizing thin steel wire meshes to externally strengthen RC members in flexure [34–40]. Among those limited studies, Qeshta et al. [34] conducted an experimental program on small-scale plain concrete specimens that were externally strengthened in flexure with ferrocement steel wire mesh, CFRP sheets, and their hybrid combination. Strengthened specimens with ferrocement steel wire mesh showed better performance than that with FRP sheets. The flexural strength of the specimens has increased by 123% due to wire mesh laminate. Increase in ductility and energy absorption was also observed by the specimens strengthened with hybrid laminates. A similar research study was conducted by Qeshta et al. [35] on larger scale reinforced concrete (RC) beams externally strengthened with the same composite materials. All strengthened specimens failed due to rupture of wire mesh or debonding of laminates. Test results have shown that beams strengthened with wire mesh increased the first crack and yield strength by 90% and 47%, respectively over the unstrengthened control specimen. It was also observed that the use of hybrid laminates improved the pre-yield loading stage and also prevented premature debonding of the CFRP laminates.

The use of ferrocement laminates in the form of welded wire mesh via cement mortar was investigated by Basunbul et al. [36] to strengthen RC beams in flexure. The test results showed that ferrocement laminates increased the beams' cracking strength, stiffness, and flexural capacity. Debonding of ferrocement laminates from the beams' surface was the major drawback of this strengthening technique. Paramasivam et al. [37] addressed this problem in their research and used epoxy with different types of shear connectors in order to ensure full composite action of the ferrocement laminates. Hawileh et al. [38] conducted a pilot study on flexural strengthening of RC beams using externally bonded Hardwire Steel Fiber (HSF) Sheets. The experimental results showed an increase in the load-carrying capacity of the strengthened specimens with medium and high density HSF sheets by 44% and 48%, respectively over the control specimen. Similarly, Xing et al. [39] conducted an experimental study on 3.2 mm diameter steel wire mesh, externally bonded to the soffit of RC beams via polymeric mortar. All strengthened specimens showed an increase in load-carrying capacity, and failed due to debonding of the steel wire mesh. Furthermore, finite element models were developed to simulate the behavior of RC members strengthened with externally bonded and near surface mounted CFRP and GFRP [41–43].

The literature lacks studies on the use of Hardwire Steel Fiber (HSF) sheets in external strengthening of RC beams in flexure. The main merit of using HSF as external reinforcement when compared to FRP is the enhancement of stiffness, bond, and strength performance of strengthened members, due to its high tensile strength and modulus of elasticity. In addition HSF composite sheets are lighter, less expensive than conventional FRP laminates, and could be easily pre-stressed [36–43].

The aim of this paper is to experimentally study the performance of RC beams externally strengthened with medium and high density HSF sheets via epoxy adhesives. A total of seven RC beams were cast and strengthened with different layers and widths of medium and high density HSF sheets, bonded to the beams' soffit via epoxy adhesives. In addition, a control unstrengthened beam was tested to serve as a benchmark specimen. Four-point bending tests were conducted on all beam specimens, and the load-midspan deflection response curves and strain readings taken at discrete location within the beam specimens were recoded until failure of the beam specimens. In addition, the load-carrying capacity and mid-span deflection response of the tested specimens was predicted using the ACI 318-11 [44], CEB-FIP [45] and ACI 440.2R-08 [46] guidelines.

2. Experimental program

2.1. Test specimens

In this study, a total of eight RC beam specimens of rectangular cross-section were designed, cast and then tested under four-point bending. The width of each specimen is 120 mm, the total depth is 240 mm and the total length is 1840 mm. The specimens were simply supported and tested at a span of 1690 mm. Fig. 1 shows the geometry and detailing of the tested beam specimens. All beam specimens had the same dimensions and internal steel reinforcement ratios and designed to fail in flexure. The beams were reinforced with 2Φ12 mm deformed bars in the tension zone, located at an effective depth (d) of 202 mm as shown in Fig. 1. Two steel bars, 8 mm in diameter were used as compression reinforcement to hold the stirrups and were located at a depth of 32 mm from the beam's top compression fiber. A clear concrete cover of 20 mm was provided all over the beam specimens. The shear span of the beam specimens was reinforced with 8 mm diameter steel stirrups, that were spaced 80 mm center to center as shown in Fig. 1. The stirrups spacing in the constant moment region was 140 mm as shown in Fig. 1.

All beam specimens comprise of one control unstrengthened specimen and seven specimens strengthened in flexure with one and two layers of 4.72 and 7.87 cords/cm HSF sheets via epoxy adhesives. The HSF composite sheets are bonded to the beams' soffit over a length of 1630 mm, as shown in Fig. 1. The equivalent design thickness of medium and high density HSF composite sheets are 0.72 mm and 0.87 mm, respectively as reported by the manufacturer [47]. The designation and description of every beam specimen is provided in Table 1. The variables of the experimental program are the width of the HSF sheets, sheet density (4.72 and 7.87 cords/cm), and number of HSF layers. The effective reinforcement ratio (ρ_{eff}) for every beam specimen is calculated using Eqs. (1) and (2) and the results are provided in Table 1.

$$\rho_{eff} = \rho_s + n\rho_f \tag{1}$$

$$\rho_{eff} = \frac{A_s}{bd} + \frac{E_f}{E_S}\frac{A_f}{bh} \tag{2}$$

where,

A_s = area of steel reinforcement (mm^2)
b = beam width in (mm)
d = beam depth in (mm)
h = beam height in (mm)
E_f = elastic modulus of sheets in (MPa)
E_s = elastic modulus of steel reinforcement in (MPa).