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Flexural behaviour of RC beams strengthened with wire mesh-epoxy composite

Ismail M.I. Qeshta, Payam Shafigh, Mohd Zamin Jumaat *

Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

HIGHLIGHTS

- A new strengthening material for RC structures was introduced.
- Wire mesh-epoxy composites can be fabricated as a laminate.
- The structural performance of RC beams strengthened with a new laminate was studied.

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ABSTRACT

In this research work, the flexural behaviour of reinforced concrete (RC) beams strengthened with a new type of strengthening material, namely wire mesh-epoxy composite, was investigated. The flexural behaviour of RC beams strengthened using this new material was compared with RC beams strengthened with carbon fibre reinforced polymer (CFRP) sheet. In addition, the structural performance of a beam strengthened using a hybrid of wire mesh-epoxy and CFRP sheet was investigated. The results showed that the use of wire mesh-epoxy composite provides considerable enhancement in the performance of strengthened beams. Compared to CFRP, the wire mesh-epoxy strengthened beams showed more improvement in the first crack load, stiffness and yield strength. In addition, the use of hybrid wire mesh-epoxy-carbon fibre composite indicated better post-yield behaviour and prevented the debonding of the CFRP sheet.

1. Introduction

The strengthening and rehabilitation of reinforced concrete (RC) structures are among the most challenging tasks in the civil engineering field. The upgrading and retrofitting of structures is a necessity for many reasons, such as increase in vehicle load, to overcome original design or detailing errors and the deterioration that occurs during the service life of structures. Over the last three decades, significant research has been documented on the use of different materials for the flexural strengthening of RC structures.

Steel plates bonded to the soffits of beams are among the earliest materials adopted and investigated [1,2]. Despite the improvement in flexural capacity, stiffness and cracking behaviour of the strengthened beams, the use of steel plates has shown some drawbacks, such as the corrosion of steel and the difficulties of transportation and handling of long plates [3–5]. In order to resolve the problems associated with steel plates, fibre reinforced polymer (FRP) was introduced. The use of FRP materials for strengthening has gained considerable attention around the world due to the good durability properties and high strength to weight ratio [4,6]. However, FRP strengthened beams have shown a loss in ductility compared to normal unstrengthened beams [7–12]. This reduction in ductility is mainly attributed to the brittle behaviour of the FRP material. In recent years, hybrid FRP materials were introduced and investigated by a number of researchers to overcome the problems of ductility [13–16]. However, the use of hybrid FRP material for strengthening is still limited due to the small number of reported studies and lack of proper design guidelines [17,18]. In addition, the high cost of different FRP materials is another concern.

However, the use of ferrocement laminates has been shown to be an effective and economical method for structural strengthening and retrofitting. Ferrocement laminate consists of different layers of wire mesh embedded in cement mortar. Due to the relatively low flexural strength of cement mortar, the flexural strength of ferrocement laminate is gained entirely from the wire mesh, which

* Corresponding author. Tel.: +60 379675203; fax: +60 379675318.
E-mail addresses: ismailqeshta@siswa.um.edu.my, ismailqeshta@gmail.com (I.M.I. Qeshta), pshafigh@gmail.com (P. Shafigh), zamin@um.edu.my (M.Z. Jumaat).

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has a ductile behaviour. The test results by Basunbul et al. [19] showed that RC beams strengthened using ferrocement laminates exhibited an increase in flexural strength and stiffness and an improvement in cracking behaviour. The main problem associated with the use of ferrocement is the separation of ferrocement laminate from the beam soffit. This issue was investigated by Paramasivam et al. [20,21]. The researchers used epoxy adhesive and shear connectors at different spacing to bond the ferrocement laminate to the tension face of beams. In addition, the amount of wire mesh reinforcement in the laminate was varied. It was found that the increase in the flexural capacity of strengthened beams is mainly dependent on the amount of wire mesh reinforcement and maintaining the composite action between the laminate and beam until failure. Furthermore, a study by Al-Kubaisy and Jumaat [22] showed that the use of Hilti bolts and steel bars as shear connectors together with epoxy adhesive maintains a full composite action between the ferrocement laminate and the beam.

Xing et al. [23] used steel wire mesh with polymeric mortar for strengthening reinforced concrete T-beams. A wire mesh with a wire diameter of 3.2 mm was embedded in polymeric mortar and bonded to the soffit of the beams. The strengthened beams showed an improvement in the flexural capacity and stiffness. However, debonding of the steel-mortar composite was the failure mode in all the strengthened beams, which shows a similar problem to that associated with the ferrocement laminates. Qeshta et al. [24,25] recently developed a new composite for strengthening and retrofitting. The composite consists of the wire mesh commonly used for ferrocement laminates and the epoxy resin. The behaviour of beams bonded with wire mesh-epoxy composite was compared with beams bonded with FRP sheets. It was found that beams bonded with the new composite had superior performance with respect to flexural capacity and energy absorption compared to FRP. In addition, a better ductile and gradual behaviour was achieved with the use of hybrid wire mesh-epoxy-carbon fibre composite. However, the researchers investigated the wire mesh-epoxy composite on small-scale plain concrete beam specimens. Thus, the aim of this paper is to study the behaviour of large-scale RC beams strengthened using the wire mesh-epoxy composite. The development of the wire mesh-epoxy composite requires a clear understanding of the behaviour of strengthened RC beams at different loading stages. The type of strengthening material significantly affects the behaviour of the strengthened beam. Therefore, the work presented in this paper is the first step in investigating the effectiveness of using the wire mesh-epoxy composite for strengthening RC structural elements, which helps for further development and making it more practically acceptable. The effect of wire mesh-epoxy composite on load carrying capacity, serviceability and cracking behaviour is investigated and compared with the carbon fibre reinforced polymer (CFRP) and hybrid wire mesh-epoxy-carbon fibre composite. In addition, this paper studies the preparation and development of wire mesh-epoxy composite as a laminate to examine the practical aspect of the application of the composite on site.

2. Experimental programme

2.1. Material properties

2.1.1. Concrete and steel

One concrete batch was used to cast all beams. The 28-day average cube compressive strength of concrete, according to BS EN 12390-3:2009 [26], was about 53 MPa. The flexural strength, according to BS EN 12390-5:2009 [27], was about 5.30 MPa. The splitting tensile strength was about 4.25 MPa. The splitting tensile strength was obtained in accordance with ASTM C496/C496M-11 [28]. In addition, the elastic modulus of concrete was about 39 GPa.

Three types of steel bar were used for the beam reinforcement. Deformed bars with a diameter of 12 mm were used for flexural reinforcement while mild steel bars of 8 mm diameter were used for the stirrup reinforcement. In addition, deformed bars with a diameter of 10 mm were used as hanger bars for the stirrups. The yield strengths for the 12, 10 and 8 mm bars were 529, 521 and 317 MPa, respectively. The elastic modulus of 12 and 10 mm bars was 200 GPa while the 8 mm bars had an elastic modulus of 210 GPa.

Table 1
Mechanical properties of materials used for strengthening.

Material	Ultimate strength (MPa)	Yield strength (MPa)	Ultimate strain (Micro-strain)	Elastic modulus (GPa)
Welded wire mesh	665.0	270.4	12000	114.2
CFRP	4900.0	N/A[a]	21000	230.0
Epoxy	30.0	N/A[a]	9000	4.5

[a] Not applicable.

2.1.2. Welded wire mesh

The common galvanised welded wire mesh with square openings was used. The mesh had a wire diameter and spacing of 0.64 and 6.4 mm, respectively. The mechanical properties of the wire mesh obtained in accordance with ACI 549.1 R-88 [29] are shown in Table 1.

2.1.3. CFRP

A unidirectional CFRP sheet was used in this study [30]. The CFRP sheet has a thickness of 0.17 mm. The mechanical properties of CFRP are shown in Table 1.

2.1.4. Epoxy resin

A two-part epoxy impregnation resin was used for fabricating the wire mesh-epoxy composites [31]. In addition, it was used for bonding the CFRP and wire mesh-epoxy laminate to the beam surface. Table 1 presents the mechanical properties of the epoxy resin.

2.2. Specimens preparation and strengthening

The experimental work consisted of one control beam (CB) and four beams strengthened with wire mesh-epoxy composites (specimens A1 and A2) and CFRP (specimen B) as well as a hybrid of wire mesh-epoxy and CFRP (specimen HY). The description of the test specimens is provided in Table 2. The width of the wire mesh-epoxy composite in specimens A1, A2 and HY was 150 mm. Specimens B and HY were strengthened with a 75 mm width CFRP sheet. The length of strengthening materials in all specimens was 2420 mm.

The study by Qeshta et al. [24] showed that the use of four layers of wire mesh is optimum for increasing the flexural capacity of strengthened specimens. Thus, all the wire mesh-epoxy composites used in this study consisted of four wire mesh layers.

A proper concrete surface preparation was done before applying the strengthening materials. The surface preparation was done in accordance with the manufacturer's instructions for the application of epoxy resin [31]. The surface was first abraded to remove the cement laitance and loose materials that might interfere in the bonding. The dust was then removed using a brush and vacuum air cleaner. Acetone was used to ensure the cleanness of the surface from any material that can affect the bonding.

Two different methods for the application of the wire mesh-epoxy composite were adopted in this study. The wire mesh-epoxy composite in specimen A1 was applied directly on the beam surface. After the surface preparation was completed, a thin layer of epoxy was spread over the surface. This layer helped to fill the small voids on the prepared surface for perfect bonding. The multiple layers of wire mesh were then placed on the concrete surface and the epoxy resin was applied (Fig. 1). It should be mentioned that the amount of epoxy sufficient for bonding the wire mesh was 1.5 kg/m^2 per layer. An acetate release film was placed on the composite to obtain a smooth surface after hardening. A piece of plywood was then placed on the acetate film and clamped to provide good bonding with the surface of the concrete. The composite was left for one week for curing according to the manufacturer's recommendations. After one week, the clamp was finally opened and the acetate film was removed.

In specimens A2 and HY, the wire mesh-epoxy composite was applied as a laminate. The laminate was prepared away from the beams and applied to their surface after hardening using the same epoxy resin. The main aim of fabricating the laminate was to study the practical perspective of the application of the wire mesh-epoxy composite on site. It is important to develop the composite, which can be practically acceptable and less laborious for site application. The laminate was prepared by first applying the epoxy on the layers of the wire mesh placed in a special mould and left one week for curing. After hardening of the composite, the laminate was taken from the mould and prepared for bonding on the soffits of the beams.