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Behaviour of CFRC beams strengthened by FFRP laminates under static and impact loadings

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HIGHLIGHTS

- Behaviour of a novel flax fibre reinforced concrete (FFRP-CFRC) composite was studied.
- Effect of FFRP thickness on the flexural response under static and impact loading was investigated.
- Impact failure mechanism and dynamic increase factor of the FFRP-CFRC beams was analysed.
- The relationship between FFRP thickness and energy absorption during impact was examined.

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ABSTRACT

This paper investigates the impact resistance of a new construction material, being coconut fibre reinforced concrete (CFRC) beams strengthened with flax fibre reinforced polymer (FFRP) laminates. To study the impact resistance of the material, a series of CFRC specimens with various FFRP thicknesses (2-, 4- and 6-layer) were experimentally studied through static and drop weight impact tests. Parameters of the FFRP-CFRC beams, i.e. the impact force, deflection, energy absorption, dynamic increase factor (DIF) and damage pattern were studied. In addition, the influence of the FFRP laminate thickness was investigated in terms of (1) flexural strength and toughness under static loading, (2) flexural behaviour under impact loading, and (3) failure mode. The results showed that FFRP laminates were effective in enhancing the flexural strength under both static and impact loadings. It is also suggested that FFRP-CFRC composites could be used as environmentally-friendly materials for protective structures in resisting impact loadings.

1. Introduction

Reinforced concrete flexural members such as beams and slabs with procured fibre reinforced polymer (FRP) strips and laid-up FRP sheets, have been studied extensively in recent decades. Based on these world-wide researches, America Concrete Institute (ACI) Committee developed guiding specifications ACI 440.2R-02 for design and construction of external FRP reinforced concrete under static loadings. However, it is evident that the performance of FRP strengthened concrete composites subjected to impact loading differs from that of the static loading. Concrete structures can be subject to severe impact loadings in many situations, such as earthquakes and explosions. Many researchers have carried out studies on the impact behaviour of FRP strengthened concrete composites, with carbon and glass fibre reinforcement for example.

Research has shown that synthetic fibre (e.g. carbon and glass) reinforced polymers enhanced the impact resistance of concrete structural members. Erki and Meier [1] conducted drop weight impact tests on concrete beams strengthened with carbon fibre reinforced polymer (CFRP) laminates. It was found that the beams strengthened with CFRP laminates performed well under impact loading. White et al. [2] conducted impact experiments to investigate the effect of strain rate on reinforced concrete beams strengthened by CFRP laminates. The results showed that ductility and mode of failure were not directly affected by impact velocity. Tang and Saadatmanesh [3] conducted both experimental and analytical research on concrete beams strengthened with carbon and Kevlar fibre reinforced polymer laminates under impact loadings. It was concluded that the composite laminates increased both the initial stiffness and the residual stiffness. Kevlar laminate reinforced beams were found to exhibit higher residual stiffness than that of the CFRP reinforced beams. Soleimani [4] studied the impact behaviour of reinforced concrete strengthened with spray

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glass fibre reinforced polymer (GFRP) and concluded that this reinforcement improved the flexural strength. Boyd et al. [5] considered spraying FRP as a possible method of repairing impact-induced damage in concrete girders. The study showed that FRP repaired concrete girders achieved 95% strength of the original undamaged girder. Teng et al. [6] made a review of FRP concrete structures. This indicated that FRP can enhance the flexural and shear strength of reinforced concrete beams under static and seismic loads.

Different FRP reinforcement configurations, e.g. laminating, wrapping and U-stripping, can result in different behaviour for concrete members under static and impact loadings. For example, Min et al. [7] studied the flexural performance of FRP beams both under static and impact loadings. Three ways of retrofitting were considered, i.e. beams were retrofitted at the bottom surface, with a U-strip at the centre, and with both surface and U-strip reinforcement. The results indicated that beams reinforced with both bottom surface and U-strips absorbed the highest energy. Pham and Hao [8] studied the contribution of CFRP to shear strength and the response of RC beams under drop weight loadings. The beams were strengthened with different wrapping schemes, i.e. CFRP U-wraps and 45°-angle wraps. The results showed that with regard to the load carrying capacity and displacement, using the 45°-angle wraps provided better performance than the U-wraps. Fully wrapped RC beams with CFRP were found to be more efficient than wrapping with distributed FRP strips. Pham and Hao [9] further investigated both the static and impact properties of RC beams reinforced with CFRP. It was recommended that the de-bonding of CFRP and shear dominance in impact tests should be carefully taken into account.

As for impact behaviour, research on concrete reinforced with natural fibres, is limited. Some studies focused on impact resistance of the concrete composites internally reinforced with the natural fibres. For example, Ramakrishna and Sundararajan [10] compared four natural fibre (coir, sisal, jute and hibiscus cannebinus) reinforced concretes under impact loading. The study carried out repeated impacts on the specimen from a height of 200 mm and using a sphere striker with the weight of 0.475 kg. The number of blows required to initiate the first crack and ultimate failure was recorded. The results suggested that coir performed best in resisting impact among these four types of natural fibres. The impact resistance of bamboo and palm oil sheet reinforced concrete has also been reported [11–14]. Wang et al. [11] studied the impact resistance of hybrid steel/bamboo fibre reinforced concrete slabs using repeated impact tests. Different fibre volume ratios of steel/bamboo (V_s/V_b) were considered, i.e. 0/0, 0/0.5, 0/1, 0/2, 0.5/0.5 and 1/0. By comparing the number of impact blows required for damage, it was concluded that the specimens with V_s/V_b of 0.5/0.5 provided the best impact strength as well as the best resistance against crack propagation through the whole specimen. Muda et al. [12] experimentally discussed the effect of bamboo diameter on the impact resistance of light weight oil palm shell reinforced bamboo concrete slabs. Hung Mo et al. [13] carried out repeated impact experiments from a height of 600 mm and a weight of 10 kg to discover the impact resistance of hybrid fibre reinforced oil palm shell concrete (FROPSC). An addition of different amounts of steel (0.75%, 0.9%, 1%) and polypropylene fibres (0.1%, 0.25%, 1%) were considered. The results concluded that the 0.9% steel and 0.1% polypropylene (PP) hybrid-FROPSC specimens had the best impact resistance compared with other configurations. Yahaghi et al. [14] investigated the impact resistance of oil palm shell (OPS) concrete taking into consideration the effects of polypropylene fibre content and slab thickness. The experiments showed the increase in slab thickness and polypropylene fibre content led to an increase in energy absorption and impact resistance, but decreased the impact residual strength ratio. Muda et al. [15] focused on impact properties of kenaf fibre reinforced concrete. The relationship between the impact resistances and the slab thicknesses was investigated and the results indicated a clear linear relationship between them.

As a novel and environmentally-friendly material, the impact behaviour of FFRP-CFRC composites has not been reported. In this study, the behaviour of FFRP-CFRC beams under static and impact loadings was investigated through a series of static and impact tests on CFRC specimens strengthened with various thicknesses of FFRP (2-, 4- and 6-layer). The ASTM C1609 standard and a drop weight impact test machine were applied in quasi-static bending tests and impact tests, respectively. During the experiments, parameters of the FFRP-CFRC specimens, i.e. the impact force, displacement, energy absorption, dynamic increase factor, and damage patterns were studied. The effects of FFRP thicknesses were also investigated in terms of (1) flexural strength and toughness under static loading, (2) flexural behaviour under impact loading, and (3) failure mode.

2. Experimental works

2.1. Materials and specimen preparation

The proportions of materials used in the coconut fibre reinforced concrete (CFRC) were 1: 0.52: 2: 2 for cement, water, sand and gravel, respectively. The cement used was Golden Bay Cement's premium Portland cement. The gravel had a unit mass of 1480 kg/m^3 and a maximum diameter of 13–15 mm. The washed sea sand was used as a fine aggregate with a fineness modulus of 2.75. The coconut fibre content in the mixture was 3% of the cement mass, corresponding to an approximate fibre volume content of 1.2%. The mechanical properties of coconut fibres are summarised in Table 1.

A detailed preparation of the coconut fibres as well as the CFRC casting process can be found in the authors' previous work [17]. Both CFRC cylinders and beams were prepared, with a detailed mix design was listed in Table 2. All specimens were cured in a concrete curing room at a stable temperature of 23.0 ± 2.0 °C and a relative humidity level of 95% for 28 days.

To investigate the effects of FFRP thicknesses on the static and impact load induced flexural behaviour, three thicknesses of 2-, 4- and 6-layer of FFRP were adopted. The flax fabric was bonded to the tensile surface the beam, where it is subjected to tensile stress, using SP High Modulus Prime 20LV epoxy, as shown in Fig. 1. A detailed specimen preparation chart is shown in Fig. 2. The properties of the flax fabric yarns, the epoxy system and the tensile properties of FFRP composites based on ASTM D638 standard [18] are summarised in Table 3 and Table 4, respectively. Table 5 lists test matrix of the specimens.

2.2. Testing procedure

2.2.1. Static test

The CFRC cylinders (200 mm × 100 mm) were used to determine 28 days compressive strength following the standard ASTM

Table 1
Mechanical properties of coconut fibre [16].

Properties	Coconut fibre
Diameter (mm)	0.25
Length (mm)	50
Density (g/cm^3)	1.20
Tensile modulus (GPa)	2.74
Tensile stress at break (MPa)	286
Tensile strain at break (%)	20.8