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Compressive and flexural behaviour and theoretical analysis of flax fibre reinforced polymer tube encased coir fibre reinforced concrete composite

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ABSTRACT

The use of cost-effective natural fibres, i.e. flax in fibre reinforced polymer composites and coir in concrete as building materials is a step to achieve a sustainable construction. Both flax fibre reinforced polymer tube encased-plain concrete and the tube encased-coir fibre reinforced concrete composites have potential to be axial and flexural structural members. However, in flexure, slippage between tube and the concrete core may compromise the performance of the composites. In this study, thin flax fibre reinforced polymer band rings were embedded into the tube inner surface in order to eliminate the slippage because a better tube and concrete interlocking was achieved. Therefore, one purpose of this study is to investigate the effect of band rings on the compressive and flexural properties of flax fibre reinforced polymer tube encased-plain concrete and the tube encased-coir fibre reinforced concrete. The ductility of these composites was evaluated using an energy ductility index based on measurement of fracture energy. Next, the cracking strength and neutral axis depth of the composite beams without band rings under flexure were analysed. Finally, based on linear elastic analysis, a simplified analytical method was developed to predict the resisting moment capacities of these composite beams. The test results indicate that in axial compression, the use of band rings reduced the ultimate compressive strength and ductility of both composites. In flexure, the band rings eliminated the slippage but increase the load carrying capacity and deflection. The predicted ultimate moment capacities of these composite beams match the experimental results well.

1. Introduction

The construction and building industries are two of the major and most active sectors in the world. In Europe, the construction and building industries are responsible for the depletion of large amounts of non-renewable resources and for 30% of carbon dioxide gas emissions [1]. To build a sustainable construction industry, recently the European Union (EU) announced that in a medium term raw materials consumption must be reduced by 30% and that waste production in this sector must be cut down by 40% [2]. Reducing the raw materials consumption by using by-products or renewable materials is considered as a significant step to achieve a sustainable construction industry [3]. Such strategies offer great advantages of creating new opportunities for these by-products while preserving natural resources and without changing the conventional construction methods [4,5]. Another great step is the development of natural building with alternative materials, technologies and methods for construction [6]. In this case, resources and energy consumption can be reduced remarkably and good energy efficiency without causing health and damaging eco-systems can be provided [7]. Therefore, the United States (US) Department of Agriculture and the US Department of Energy had also set goals of having at least 10% of all basic chemical building blocks be created from renewable and plant-based sources in 2020, increasing to 50% by 2050 [8].

Concrete is the most used construction material which is high in compressive strength and low in tensile strength with brittle characteristics. Thus, steel rebar is normally required within concrete to provide good compressive and tensile strength as well as ductility requirement of concrete structures. However, today steel reinforcement is still very expensive and comes from a non-renewable resource with high energy consumption. Normally each cubic meter of concrete structure requires an average of 200 kg of steel rebar [2]. Furthermore, the corrosion of steel reinforcement in concrete structures is one of the major challenges for civil engineers. In the US, the upgrading of civil engineering infrastructure was estimated as $20 trillion. In the EU, nearly 84,000 reinforced and pre-stressed concrete bridges require maintenance, repair and strengthening with an annual budget of £215 million, excluding

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traffic management cost [9]. Therefore, the development of new materials to replace steel rebar as reinforcement of concrete becomes a good method to achieve the sustainable construction. On the basis of this, most recently a new composite structure, natural flax fibre reinforced polymer (FFRP) tube encased-coir fibre reinforced concrete (FFRP-CFRC), was developed by Yan and Chouw [10]. This composite structure considers the use of two natural fibres, i.e. flax and coir fibres.

2. Overview of FRP tube encased concrete

In a FFRP-CFRC composite, the FFRP tube was manufactured using a hand lay-up progress. This pre-fabricated FFRP tubes made of flax fabric reinforced epoxy composites act as permanent formworks for fresh concrete and also provide confinement to concrete. The advantages of FFRP tubes are their high strength-to-weight and stiffness-to-weight ratios. FFRP composites have an approximate density of 1270 kg/m^3, which is about 1/6 of steel [29]. The tensile and flexural properties of the FFRP composites are introduced in the following Table 1. In tension, the typical tensile stress–strain curve of FFRP composite includes a purely elastic response and a non-linear response, followed by a sudden drop in load to zero after reached the peak stress, indicating a non-yielding characteristic as that of glass or carbon fibre reinforced polymer composite [16]. The non-corrosive FFRP shell replaces the functions of steel rebar in conventional reinforced concrete (RC) members, namely, tension carrying capacity and shear resistance, as well as confinement of concrete core. Coir fibre is the reinforcement of the concrete core. Coir fibre can reduce the crack width and number of the concrete core and in turn modifies the failure mode of FFRP tube encased concrete to be ductile as a result of fibre bridging effect [10]. Coir fibre inclusion also increases the damping ratio of the FFRP-CFRC composite structure significantly, thus reducing the effect of dynamic loading on the structural response [11]. Thus, the fibres may also be considered in plain concrete filled glass/carbon FRP tubes where brittle failure was commonly observed due to the non-yielding characteristics of FRP materials, e.g. in [12]. After tested, when removed the external tubes, the plain concrete cores developed excessive larger flexural cracks at the mid-span of the columns or even damaged to several blocks which distributed along the columns, as observed in [12]. Generally, coir fibre increases the ductility and flax FRP contributes to the significant increase in load carrying capacity of the composite structure.

However, in flexure, slippage between FFRP tube and concrete core is commonly observed for the tested specimens. Coir fibre inclusion has no effect on the prevention of slippage [10]. The slippage may compromise the performance of the composite [10]. This calls for an improved tube/concrete interfacial bond to increase the composite action.

With regard to the study of FRP tube encased-concrete with glass or carbon fibres, to prevent the slippage between tube and concrete core, a study by EI Chabib et al. [13] indicated that the use of expansive cement in concrete created a somewhat better tube and concrete interfacial contact, however, did not fully prevent the slippage. Mirmiran et al. [14] used shear connector ribs which placed at the inner surface of the GFRP tube to increase the tube and concrete interfacial bond. It was found that the ribs significantly improved the axial load-carrying capacity of GFRP tube confined concrete. Ji et al. [15] proposed a novel advanced grid stiffened (AGS) FRP tube which includes a lattice of interlaced FRP ribs. Test results indicated that the lateral load carrying capacity was improved due to the enhanced interfacial bond strength between the tube and the concrete through the mechanical interlocking. The use of shear connector ribs and AGS tubes are beneficial to the interfacial bond. However, these manufacturing techniques are good for fabrication of FRP tubes made from glass/carbon yarns, but not appropriate for the hand lay-up FFRP tubes made from flax fabric considered in this study. In addition, the manufacturing techniques to place either shear connector ribs or grids on the FRP tube described in the studies [14,15] are a bit complex and time-consuming. Therefore, new consideration should be taken for FFRP tube on this subject.

3. Objectives

To prevent the slippage between FFRP tube and concrete core, an attempt is introduced to increase tube and concrete mechanical interlocking, i.e. along the longitudinal axis of the flax FRP tube, the embedment of three flax FRP band rings onto the interior surface of the FFRP tube with the help of epoxy. Schematic view of FFRP tube with inner rings for axial and flexural specimens is given in Fig. 1. One objective is to investigate the effect of this new FFRP/concrete interfacial contact on the compressive and flexural properties of FFRP-PC and FFRP-CFRC composite. In addition, a simplified analytical method based on linear elastic analysis is developed to predict the resisting moments of the tested specimens.

4. Experimental procedures

4.1. Material and fabrication process

Commercial bidirectional woven flax fabric (550 g/m^2) was considered and the epoxy used was the SP High Modulus Ampreg 22 resin and slow hardener. The fabric has a plain woven structure with count of 7.4 threads/cm in warp and in the weft directions [16]. The details of fabrication process of FFRP tubes were described in elsewhere [17]. Fabric fibre orientation was at 90° from the axial direction of the tube. The fabric arrangement of the FFRP tubes was 4 layers. The tensile and flexural properties of FFRP composites obtained from a flat coupon test were given in Table 1.

With regard to FFRP tube with inner band rings, after the manufacturing of the FFRP tubes, three extra flax fabric reinforced epoxy band rings were placed into the interior surface of the tubes with the help of epoxy. The rings were distributed along the longitudinal direction of the tubes. The location of the rings is given in Fig. 1. Each band ring was made by two layers of FFRP laminate. Considering the different sizes of the specimens for axial compression and flexural tests, the width of one band ring is 15 mm and 50 mm, respectively, as displayed in Fig. 1. A hollow FFRP tube (length of 600 mm) with inner band rings is given in Fig. 2.

Two concrete batches, i.e. plain concrete (PC) and coir fibre reinforced concrete (CFRC), were constructed. Both concrete batches were designed as PC with a 28-day compressive strength of 30 MPa. The concrete mix design followed the ACI Standard

Table 1
Mechanical property of FFRP composites.

No. of flax layers	FRP thickness (mm)	Tensile strength (MPa)	Tensile modulus (GPa)	Tensile strain (%)	Flexural strength (MPa)	Flexural modulus (GPa)	Flexural strain (%)	Fibre volume fraction (%)
4	6.5	134	9.5	4.3	144	8.7	5.2	55.1