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Concrete wedge and coarse sand coating shear connection system in GFRP concrete composite deck

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HIGHLIGHTS

- Numerical investigation on deflection of GFRP concrete deck using concrete wedges.
- We proposed interface element properties as a shear bond between GFRP and concrete.
- FEM results show GFRP is more brittle than the steel.
- GFRP concrete fails after elastic level with no ductility.
- We proposed an equation to calculate deflection of GFRP concrete composite deck.

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ABSTRACT

In recent years, Glass Fiber-Reinforced Polymer (GFRP) has become a widely used material in Fiber-Reinforced Polymer (FRP) composite structures. Several studies have been performed on the bonding methods of FRP sheets and plates, but limited research has been undertaken on the critical shear connection systems for innovative GFRP concrete composite bridge decks structures. Coarse sand coating shear connection systems for GFRP structures show strong bondage in the shear direction but poor grip in the normal direction. An innovative concrete wedge system, supplementary to coarse sand coating overcomes the normal split between GFRP panel and concrete, in composite bridge deck structures. This study presents a finite element (FE) investigation on GFRP concrete composite deck using a concrete wedge shear connection system based on existing experimental evaluation. In this research, the thickness of the GFRP module was varied and the deflection behaviour of GFRP concrete composite deck was furthermore studied. FE results indicate that thickness increments of the GFRP module significantly reduce the mid-span deflection of the composite deck and subsequently increase the ultimate load. In order to investigate the interaction behaviour between GFRP and concrete in the numerical analysis, a structural interface element is proposed for finite element modelling (FEM) analysis. In order to undertake a rapid evaluation of deflection of the composite deck, an equation is proposed to estimate the deflection at the mid-span of the GFRP composite bridge deck based on the FEM results. In addition, the GFRP composite bridge deck was numerically analysed using light-weight concrete (LWC) and results were compared with GFRP composite deck with conventional concrete. The results indicate that using LWC increases the ultimate load proportionally till failure.

1. Introduction

Fiber-reinforced polymer (FRP) composites widely used these days include glass fiber-reinforced polymer (GFRP) composites and carbon fiber-reinforced polymer (CFRP) composites [1–3]. The main issue with FRP composites, similar to that encountered by conventional composite structures is concerns on the transfer mechanism of shear strength between various materials with differing material properties. On the other hand, the composite structural interaction behaviour between two different materials is a key factor in the strength of composite structures. Due to the lack of a standard design procedure for FRP composites, the studies for

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developing physical models and innovative solutions to improve structural composite behaviour systems are presently still ongoing [4].Typically the shape of the FRP panel would help in selection of the method to combine FRP and concrete [5]. For instance, when the FRP panels are protruded to perform as shear connections, the additional use of coarse sand coating is essential for the composite system to improve the shear components in both the shear and normal direction [6,7]. In composite structures, when the FRP panel is a hollowed section, the usage of an additional shear connecting plate or epoxy is an appropriate combination method [8,9]. Improvement of the structural interaction between different material properties in FRP composite structures is critical and as the degree of composition can directly affect the behaviour of the structure [10]. Over the past two decades, GFRP has been increasingly used in concrete composite bridge decks. Several researchers have concluded that GFRP composites are an economical, efficient and durable material for composite structures in the long term [11–13].The composite interactive action between the GFRP deck and concrete can be further enhanced by using various shear connection systems such as; applying perfobond, studs, using coarse sand coating, concrete wedges, etc. Coarse sand coating has been used in combinations of FRP and concrete to bond the aggregates with diameters of between 4 and 7 mm on the FRP surface and to prevent slip between FRP and concrete. Perfobond shear plates are furthermore fabricated on the top of the FRP module to prevent normal splitting between FRP and concrete.The Concrete wedge is a method specifically applied for GFRP concrete composite deck. This method is created by boring holes followed by disposing bolts in the GFRP panel and pouring concrete over it. In this method, both the concrete and bolts prevent normal and shear splitting between the GFRP and concrete [5,14,15]. This structural system furthermore offers several advantages such as; better quality control, lightweight material and longer spans, all of which lead to an efficient and economical system, as compared to typical conventional systems [1,5,15–17].

Some research has been undertaken to study methods of bonding FRP and plate, but limited research has been carried out on the critical shear connection system in innovative GFRP concrete composite decks. Cho et al. (2006) performed some study to evaluate the coarse sand coating shear connection system in concrete composite deck. The study revealed that the bond strength of coarse sand coating is ideal in the shear direction but weaknesses exist in the normal split, and as such an additional shear connector is required for normal bond strength [5,18]. Many studies have been dedicated to steel perfobond but limited studies have been devoted to protruding FRP shear plate. In a research performed by the Ministry of Land, Transport and Marine Affairs (2007), perforated shear plates showed acceptable composition in normal direction but poor grip in the shear direction. The perforated shear plates are required to add to coarse sand coating to improve this system in the normal split between GFRP and concrete. However, shrinkage may occur if the height of FRP shear plate is larger than the depth of concrete [2,5,18,19]. Cho et al. (2010) examined a new concrete wedge to overcome this problem. A new concrete wedge was constructed by boring holes in GFRP panel, installing bolts in the holes and then pouring concrete over the panel. This method solved shrinkage cracking issues compared with perforated FRP shear plate. It was reported that shear connection system composing coarse sand coating and concrete wedge can improve the structural behaviour of GFRP concrete composition in both the normal and tangential directions for composite bridge decks [5].

In this study, with consideration for Cho et al. (2010) experimental testing and analysis, a finite element analysis was conducted to study the deflection behaviour of a GFRP concrete composite deck using concrete wedge as a shear connection system under flexural loading taking the thickness of GFRP panel as variable parameter. Due to initial high cost of experimental tests, especially for FRP and GFRP composites, this study was aimed specifically to develop further on the preliminary experimental investigations undertaken by Cho et al. (2010) by employing a finite element modeling (FEM) analysis approach.

2. Experimental test briefing

The experimental study initially performed by Cho et al. (2010) evaluated the connection system of the hollowed GFRP-concrete composite deck section. The proposed GFRP deck was then developed by the Korea Institute of Construction Technology for commercialization purpose [5].

In the bending tests, two specimens with 250 mm (PBW250) and 500 mm (PWB500) spacing between the holes were tested by applying loads through a loading plate with dimensions of 230 mm × 580 mm at the center of deck. Observations indicated that flexural cracks in concrete at the mid-span were initiated at 30 kN loading. By reaching the loading to 60 kN, slip and shear failure was observed to occur in the concrete wedges. Finally, the bending and shear cracks were observed to occur at about 160 kN and led to the split failure at interface between the concrete and GFRP panel. From the results it could be inferred that beyond a specific spacing between the holes, the concrete wedge will not enhance the performance of the composite. The deflection of PBW250 and PBW500 specimens are considerably larger compared to the perfect composition with deflections of 34.6% and 42.5% respectively. This shows that reduction of the wedge spacing does not significantly affect the behavior of the composite. For the numerical studies in this research, specimens at 500 mm spacing (PBW500) were selected.

3. Numerical model

In this study the LUSAS software was utilized to model the GFRP composite deck. This software was selected as it is capable enough to model composite structures using suitable isotropic, orthotropic and anisotropic materials for different component parts. Fig. 1 shows the cross section dimensions, loading and support condition of the specimen tested by Cho et al. (2010).Choosing the right mesh for elements is crucial in the finite element (FE) analysis. The results achieved from FE analysis are dependent on the element type, size, shape and distribution of the element as well as the mesh type, size and density. A finer (smaller) mesh may result in more accuracy though it may take several months to run an analysis, while a coarser (larger) mesh may possibly not achieve the desired results. Thus, the mesh density must be controlled in the FE analysis to obtain an appropriate result from the analysis [22]. Normally there is a slip at the interface between two connected materials with different material properties. It should be considered that even a full shear connection may result in a slip at the interface. In practice, the force-slip relationship for the interface element was obtained from elemental tests [20]. In 1992 a finite element of a composite slab was modeled by using FE software according to the shear and interaction between concrete and steel profile, which applied a nodal interface element with properties obtained from a push-out test. The interface property was then modified to determine a suitable shear interface for the numerical model. In another study, Abdullah (2004) used the modified shear interaction obtained from experimental tests in an analytical study. This model considers three components of separation in 3D problems i.e. one normal to the interface and two parallel to it [20,21]. The fracture energy for interface element in this model was a computed value for each fracture mode, depending on the type material used. The maximum relative displacement was used to express the stiffness of the interface prior to failure. The tensile stress of interface at which delamination was initiated was applied at a small value, as it has a small effect on results. In order to simulate the interaction between GFRP and concrete, a 16-node surface element for three dimensional analysis is applied to model composite delamination in the non-linear analysis. This element is inserted at planes with potential inter-layer failure and is assumed to have no thickness [11]. The interface material properties applied for the interface element (Table 1) were obtained