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# Research on the Application of Hybrid Fiber Reinforced High Performance Concrete in Civil Engineering

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This paper presents the hybridization of different types of fibers to overcome their shortcomings, to integrate their advantages, and to subsequently achieve the best performance-to-price ratio. In addition, through hybridization, the mechanical properties of the FRP composites can be tailored for specific applications. The behavior of hybrid FRP tendons was studied experimentally and analytically. Then, the behavior of partially pre-stressed FRP-RC deck slabs with the developed hybrid FRP tendons was experimentally investigated. Finally, numerical study on the pre-stressed FRP-RC bridge deck slab was conducted; the numerical study examines the macro and micro behavior of concrete bridge deck slabs reinforced with partially pre-stressed fiber reinforced polymers (FRP) bars under the effect of a concentrated load. Finally, a comprehensive parametric study was conducted.

## 1. Introduction

Fiber-reinforced polymer (FRP) composites have become competitive structural materials for civil engineering applications because of their superior advantages such as a high strength-to-weight ratio, corrosion resistance, a wide range of working temperatures, and the ease of handling and construction. FRP has been used for reinforcing / strengthening of new/existing reinforced concrete structures. However, the application of FRPs in structures cannot satisfy all of the structural integrity requirements. For instance, in the case of FRP with high strength and high elastic modulus, such as carbon FRP, the desired ductility of the structure is difficult to achieve (Liu et al., 2014) This is attributable to the inherently small failure strain of carbon FRP. Additionally, carbon FRP is also much more expensive than other types of FRP. In contrast, the relatively inexpensive FRPs, such as glass FRP with larger failure strain, can make structures more ductile; however, their relatively low modulus and poor creep behavior usually restricts their application because of structural deformation requirements.

Bridge deck slabs are one of the most corrosion-vulnerable bridge components due to the direct exposure to de-icing chemicals and severe weathering conditions. The use of fiber-reinforced polymer (FRP) as reinforcement for bridge deck slabs is a promising solution to corrosion-related problems. Recently, glass FRP (GFRP) bars have been widely used as internal reinforcement for concrete bridge deck slabs since they are less expensive compared to the other kinds of FRPs (Carbon and Aramid) (Ping et al., 2015; Huang et al., 2015; Tang et al., 2016). However, because of the relatively low stiffness of GFRP composites, RC-members reinforced with GFRP will have larger deflections and crack widths than steel reinforced members. Consequently, serviceability requirements govern the design of FRP-RC members. In such circumstance, previous studies on FRP-RC deck slabs concluded that to achieve the satisfactory of serviceability, FRP reinforced concrete bridge decks should sustain the same reinforcement stiffness as those bridge decks reinforced with the conventional steel reinforcement. However, the experiments of deck slabs tested in literature, revealed that the failure of deck in punching shear exhibited the carrying capacities of more than three times the factored design. Those results reflect the high material waste in the design of the FRP-RC bridge decks (Wang et al., 2014; Wu et al., 2014; Zhang et al., 2014).

To overcome the aforementioned limitations and to enhance the utilization of various FRP composites, this paper, introduces two levels of study incorporating advanced FRP composites in the design: performance of hybrid FRP tendons and an iterative analytical model to predict its properties were studied first; and then the hybrid FRP tendons were used to press FRP-RC bridge deck slabs in order to eliminate the material waste. State-of-the-art of the hybrid FRP composites, FRP-RC bridge deck slabs and FPR grids were included in the literature review. The paper presents a new methodology for predicting the tensile behavior of hybrid FRP tendons by considering the interfacial stress transfer between the resin and the fibers in hybrid FRP. Subsequently, the authors utilize the fundamental concepts of fracture mechanics to derive a model capable of predicting the mechanical properties of hybrid FRPs. The author conducted an experimental study on the tensile properties of hybrid basalt/carbon FRP tendons and hybrid glass/carbon FRP tendons.

## 2. Overview

Fiber Reinforced Polymer (FRP) products are composite materials consisting of reinforcing fibers embedded in a polymer resin matrix. The fibers are ideally elastic, brittle and stronger than the matrix. The mechanical performance of the composite depends on the fiber quality, fiber orientation, length, shape, volumetric ratio, adhesion to matrix, and on the manufacturing process. Typical FRP reinforcement products are sheets, grids, bars, fabrics, tendons and ropes, as shown in Fig. 1. The bars have various types of cross-sectional shapes (strip, round, solid, and hollow). The fibers are the main load resisting component of the composite. They must have high strength, high modulus of elasticity, sufficient elongation at failure, and sufficient resistance to the environment to which the structure will be implemented. The performance of the fibers is affected by their length, cross-sectional shape, and chemical composition. Fibers are available in different cross-sectional shapes and sizes. Depending on the type of the fiber, the diameter of the fibers is in the range of 5 to 25 microns. The most commonly used fibers for FRPs are Carbon, Glass, Aramid, and Basalt where the corresponding composite products would be known CFRP, GFRP, AFRP, and BFRP respectively. Carbon Fibers: Carbon fibers have a high modulus of elasticity (200-800 GPa), high strength and stiffness to weight ratios, low sensitivity to fatigue loads, and excellent moisture and chemical resistance. However, carbon fibers have low impact resistance due to their low ultimate strain. Carbon fibers can also be highly conductive to heat and electricity, which may be an advantage or disadvantage, depending on the designer's viewpoint (Zhang et al., 2014; Jin et al., 2014).


*Figure 1: Typical FRP reinforcement products*

Carbon fibers can be classified into four types based on modulus of elasticity. The four types include low modulus (230-250 GPa), intermediate modulus (290-300 GPa), high modulus (350-380 GPa), and ultrahigh modulus (480-760 GPa). In general, the low-modulus carbon fibers have lower density, lower cost, higher tensile and compressive strength, and higher tensile strain to failure than the high modulus fibers. Glass Fibers: Glass fibers are the most common type of all reinforcing fibers for FRPs. The glass fibers are low cost and possess high tensile strength and excellent insulating properties. However, glass fibers have a low tensile modulus, high density, sensitivity to abrasion and alkaline environments, and relatively low resistance to moisture, sustained loads, and cyclic loads. The fibers are categorized in three different types: C-glass, S-glass, and E-glass. C-glass provides excellent chemical stability and is used in a variety of environments. E-glass is a low- cost general purpose fiber, which provides strength, electrical resistance, and acid resistance. S-glass fibers have higher strength, stiffness, and ultimate strain than E-glass, but they are more expensive and more susceptible to environmental degradation. Aramid Fibers: Aramid, an abbreviated term for aromatic polyamide, is made from Para type fibers with straight-chain benzene nuclei. Aramid fibers are almost fully crystalline, strong in the longitudinal direction but have weaker bonds in the transverse direction (Manic (1988).

Three types of Kevlar aramid fibers are available for fabricating FRP There are Kevlar 149, Kevlar 49, and Kevlar 29 with a modulus of elasticity of 179, 131, and 82 GPa.

Aramid fibers have excellent impact resistance, high stiffness, high thermal stability, and low density compared with other fibers. However, ultraviolet light causes degradation of the aramids and exposure to moisture facilitates creep. The cost of aramids is higher than glass, but less than carbon.

Basalt Fibers: Basalt is a natural, hard, dense, dark brown to black volcanic igneous rock originating at a depth of hundreds of kilometers beneath the earth and reaching the surface as molten magma. It differs from granite in being a fine-grained extrusive rock with a higher content of iron and magnesium. Basalt density ranges between 2.7 and 2.8 m3. This gives basalt a superior abrasion resistance, and cast basalt is often used as a paving and building material. Further characteristics are good resistance to low and high temperatures, insulation properties, and acid and solvent resistance. Basalt-based products are also ideally suited to fire- protective applications since they are able to maintain their volumetric integrity and about 90% of strength if exposed to temperatures over 600 “C. Absorption of humidity comes to less than 0.1% at 65% relative air humidity and room temperature. While the commercial applications of cast basalt have long been known, it is less known that basalt can be formed into continuous fiber with unique mechanical and chemical properties. Basalt fibers are produced with the same technology used for E-glass, but their production process requires less energy and the raw materials are distributed worldwide. This explains the lower cost of basalt fibers compared to glass fibers.

Matrix polymers in FRPs have multi functions. The first is to bind fibers together and produce a more even distribution of stresses. Secondly, the matrix provides compressive and shear strength and protects the fibers from lateral pressure and abrasion. And thirdly, the matrix protects the fibers from environmental conditions such as moisture, acid and alkali attack, and ultraviolet radiation. To accomplish the above purposes, the resin must have relatively high elastic modulus, tensile strength, compressive strength, shear strength, and yield and ultimate elongation, as well as good chemical, thermal and moisture resistance. The most widely used matrix resins in the production of FRPs are thermosetting polymers. Before curing thermosetting polymers have low viscosity and are thus readily process able, but after curing they become rigid, intractable and insoluble and burn off when heated. Thermosetting polymers have advantages as well as disadvantages depending upon the type. In general, they exhibit good thermal stability, load-bearing performance, and chemical stability, but can be susceptible to hydrolysis, ultraviolet radiation, and acid and alkali attack.

## 3. Hybrid fiber reinforced high performance concrete model and algorithm

A decrease in the rigidity of a thermosetting polymer causes an increase in its ductility and toughness. However, decreasing the rigidity of a thermosetting polymer makes it more sensitive to solvents which may cause swelling due to hydrolysis and/or stress cracking. The most widely used thermosetting polymers for the production of FRPs are polyester, vinyl ester and epoxy resins. Polyester Resin: Polyester resins are used mainly in the construction, marine and automotive industries. They have poor impact and mechanical properties and high curing shrinkage. Typically, polyester resins give good adhesion between fiber and resin, are easy to process, can withstand temperatures greater than 150 0C, and are low cost, but, they are generally easily attacked by acids, alkalis, moisture, and ultraviolet radiation. Polyesters have tensile strengths in the range of 45 to 190 MPa, tensile elastic modulus between 23 to 12 GPa, ultimate tensile elongation between 1 to 3%, and coefficient of thermal expansion as great as 120 x 10"6/0C, ACI. Commercially available polyester resins include polyester and polyester. Polyesters have poor thermal stability and chemical resistance. For this reason, it is unlikely that they will be used for demanding structural applications such as advanced composites for reinforced concrete.

Polyesters have superior thermal stability, mechanical properties, and moisture and chemical resistance compared to polymers. Although isophthalic polymers are more expensive than orthophthalic polymers, they are highly process able for use in pull torsion of bars and tendons. The properties of vested include tensile strength in the range of 40 to 100 MPa, tensile elastic modulus of 3 to 5 GPa, ultimate tensile elongation of 1 to 7% coefficient of thermal expansion between 80 to 160 x 10, and heat distortion 1400C, ACI of 120 to Vinyl esters are more expensive than orthophalic and isophthalic polyesters but provide increased mechanical and chemical performance. Vinyl esters have good fatigue and impact resistance, are flexible, and are resistant to acids and alkalis. For these reasons, many researchers believe that vinyl ester should be used as matrix resin for FRP bars and tendons. However, vinyl esters can be attacked by moisture, ultraviolet radiation and high temperatures, although not to the same extent as polyesters (Li et al., 2015).

Epoxy Resin: The tensile strength of epoxy resin ranges from SO to 100 MPa, tensile elastic modulus from 3 to 6 GPa, ultimate tensile elongation from 2 to 8%, and heat distortion temperature from 120 to 200$^{0}$C. Epoxy resins are widely used in the aircraft, aerospace, and defense industries. They have low shrinkage compared to polyester resins, excellent fatigue resistance, good strength, excellent mechanical properties, and good adhesion to a variety of fibers. Epoxy resin is widely recognized as having better resistance to acids, alkalis, and ultraviolet radiation than either vinyl esters or polyesters. But some epoxies are sensitive to moisture, although still Less permeable than polyesters. Other disadvantages include high cost and low impact strength- Also, some epoxies can cause rashes on skin when exposed to it; therefore, must be handled with care, ACI.

To predict the mechanical behavior of hybrid FRP tendons, the authors first investigated the mechanics of fracture and its progression. It reported that the load- strain curve of an alternating glass/carbon hybrid composite was virtually linear up to the first failure of carbon fibers. With increasing strain, the first macroscopic fracture occurred at the central carbon ply; the principal transverse crack ran across the entire cross section of the carbon ply. A delamination crack generated at the intersection between the inner carbon ply and the outer glass plies. Fig. 2 shows a schematic drawing of a glass/carbon hybrid FIZP specimen subjected to a strain that caused carbon fiber rupture. The figure indicates the random failure of LE fiber and the longitudinal delamination cracks between the glass and carbon fibers. Based on the aforementioned observations in prior studies, the authors proposed load-strain curves of hybrid FRP tendons/sheets as shown in Fig. 3 for this chapter. For each case, the curves divided into two stages. In the first stage, up to the failure strain of the LE fibers, the hybrid composite worked as a single unit, the curve was virtually linear, and the modulus could be accurately determined by the simple rule-of-mixtures. In the second stage, with increasing strain, LE filaments broke randomly, causing transverse cracking in the matrix and deboning between the LE filaments and the surrounding, resin. Meanwhile, delamination cracks at the interface between LE fibers and HE fibers also occurred, as shown in Fig. 2. The propagation of culmination between the LE and HE fibers increased with an increasing volume ratio of LE fibers.

Total delamination occurred when the load at LE fiber rupture was very high. Two types of load-strain behavior for hybrid composites were possible, as shown in Fig. 3; depending on whether there was partial delamination or total delamination. For the partial delamination case, the authors assumed that the stress in the HE fibers at the location of the delamination was higher than the stress in the HE fibers far away from the crack location. This phenomenon occurred, because the bond between the LE and HE fibers was still present, and bath materials worked together to carry the load away from the crack location. In contrast, the bond at the crack~ broken, and thus, only the HE fibers carried the load. The magnitude and the extent of delamination increased when the load increase and the contribution of the LE fibers to the stiffness of the hybrid FRP decreased nonlinearly.

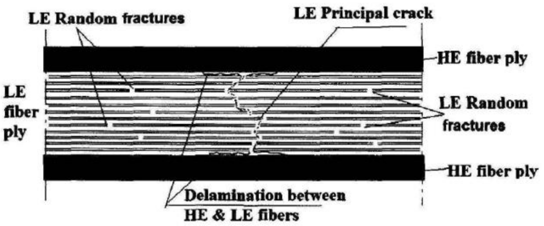


*Figure 2: Random failure of LE fibers and delaminaton cracks between LE fibers and HE fibers*

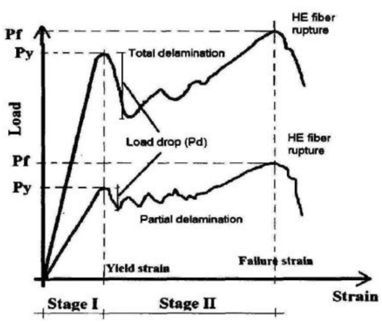


*Figure 3: Proposed tensile behavior of hybrid FRP cornposite*

The presence of several load drops in the load- stain curve was attributable to the random failure of the LE fibers and the sudden increase in the delamination length. The sudden drop in load could cause partial damage of the HE fibers, reducing the total failure load capacity. Finally, when total deboning between the LE and HE fibers occurred, only the HE fibers resisted the load so that the load-strain curve remained linear up to total rupture of the composite. For the total delamination case, the LE fibers did not contribute to the hybrid stiffness and the drop-in load was larger than that of the partial delamination case. As the load was carried only by the HE fibers, the load-strain curve was linear up to failure. The rule-of-mixtures method for predicting the hybrid behavior could only be used in the case of total delamination. Therefore, the authors proposed a model that predicts the tensile behavior of hybrid FRP composites on the basis of considering the contribution of the LE fibers to the hybrid composite after its failure and that can be achieved by computing the stress distribution over the entire length of the HE fibers after rupture of the HE fibers on the basis of the principles of fracture mechanics.

The discussions and investigations have been presented for the methods/technologies involved in the proposed methodology. It is believed that this methodology would considerably reduce the lead time of the innovative product design and development from nature at low cost and can also improve interactive and efficiency in the course of digital art design teaching.

## 4. Data analysis and experiment result

A total of seven full scale RC deck slabs were casted and tested to failure. The slabs were square in plan with 2400-mm side length and 200-mm thickness. Five slabs were partially pre-stressed with BFRP/CFRP hybrid tendons however the rest two slabs were served as control slabs without pre-stressing.

One of the control slabs, (SS) slab, was reinforced with steel bars, in which the bottom reinforcement assembly was designed according to the empirical design method of CSA-S6-06 (CSA) (2006) clause 8.18.4.1. Therefore, SS slab had a bottom orthogonal reinforcement matt of steel bars (QJ12Φ220-mm, p=0.35% in both directions). The second control slab, (SF) slab, was reinforced with non-pre-stressed FRP bars according to the empirical design method of the CSA-S6-06 code (CSA) (2006) clause 16.8.8.1 which account for bottom transverse assembly of minimum area of cross-section in 500 d/EF}; and the longitudinal bottom assembly shall be of GFRP with a minimum ratio of 0.0035.

Then, the (SF) control slab had a bottom transverse matt of FRP bars (BFRP/CFRP hybrid bars of Qfl2Φ110-mm, p=0.63% in the transverse direction; and GFRP of Q} 12Φ110-mm, p=0.4% in the longitudinal direction). The pre-stressed FRP-RC deck slabs were designed for three study- parameters: the FRP-reduction factor (RF), the pre-stressing level (P%), and the partial pre-stressing index (PPI). 'The FRP-reduction factor (RF) defined as the reduction in the FRP transverse reinforcement area with respect to the FRP-RC control slab.

The partial pre-stressing index (PPI) defined as the ratio of the pre-stressed FRP reinforcement to the total FRP reinforcement in the transverse direction of the slab. In order to find the minimum FRP-reduction factor that could be achieved without affecting the design requirements of the FRP-bridge deck slabs, three different (RF) values, namely, 0.45, 0.37, and 0.29, were considered in this study. The FRP tendons were tensioned to 35% or 50% of their ultimate strength. Two partial pre-stressing indices (PPI), namely, 0.5, and 0.6, were studied. All the pre-stressed FRP-RC slabs were reinforced and pre-stressed in transverse direction with BFRP/CFRP hybrid bars/tendons, as shown in Fig. 4-1. They were reinforced in the bottom longitudinal direction with GFRP bars of Q) 12Φ110-mm, p=0.4% similar to the FRP-RC control slab. In this study, it found that the top reinforcement assembly has a negligible effect on the short term behavior of the bridge deck slabs. Then all slabs were designed without top reinforcement assembly. A minimum bottom clear cover of 25 mm was used as specified by Clause 16.4.4 (35±10 mm) in the CSA-S6-06 for FRP reinforced concrete deck slabs. The same bottom clear cover was used in the control slab for comparison.

## 5. Conclusions

The paper identified the effects of resin type, fiber fraction, and fiber arrangement over the cross section. It investigates the behavior of full-scale deck slabs transversely reinforced and pre-stressed with basalt/carbon FRP hybrid tendons. The study aims to eliminate the FRP reinforcement amount for FRP-RC bridge deck slabs. A total of seven square slabs, with 2400 mm side length and 200 mm thickness were constructed and tested. Two non-pre-stressed deck slabs, steel-RC deck slab and FRP-RC deck slab, were designed according to the Canadian highway bridge design code CSA-S6-06 and served as control slabs. Three main variables, namely, FRP-reduction factor, pre-stress level, and partial pre-stressing index were investigated. It includes numerical study on behavior of partially pre-stressed FRP-RC bridge deck slabs. The aim of this chapter is to examine numerically the macro and micro behavior of concrete bridge deck slabs reinforced with partially pre-stressed fiber reinforced polymers (FRP) bars under the effect of a concentrated load of a vehicle-wheel.

The numerical simulation is based on previously tested seven FRP reinforced concrete full scale bridge deck slabs. Finite element (FE) analyses and findings of reinforced concrete slabs subjected to punching load is evaluated and compared with the experiment results. Based on the created model, parametric study on RC bridge deck slabs reinforced and pre-stressed with FRP tendons were also performed. The following key conclusions were reached based on the aforementioned studies:

a) The proposed model accurately identified the load drop at the LE fiber rupture, the failure load, and the failure strain of hybrid FRP composites;

b) Based on the experimental study on a series of hybrid FRP tendons, this study presented a new ductile basalt/carbon FRP hybrid tendon, with a failure strain of 3.61%, which was approximately 105% higher than its pseudo-yielding strain, and a failure load that was 1.35 times its pseudo-yielding load;

c) Through proper design of the FRP-pre-stressed slabs, FRP-reduction facto of 0.45, cracking load of 73% higher than the FRP-RC control slab, and failure load of 2.6 the design factored load could be achieved;

d) It has been shown that the load versus deflection diagram, reinforcement strains and ultimate load capacity obtained from FE analyses, with a reasonable degree, match with the experimental results.

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