STRUCTURAL BEHAVIOR OF COMPOSITE CONCRETE/GFRP BEAMS

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Abstract
A new composite slab system consisting of a fiber-reinforced concrete top laid on GFRP pultruded profiles, filled in with foam blocks is being developed mainly for footbridge deck applications but it could also be applied to other structures. In this work, the structural behavior of this system is evaluated with the use of composite model beams representing half-width of the slab. Static loading tests were performed on six GFRP-concrete composite beams and three profiles in order to verify shear failure mechanisms.

1 Introduction
Although fiber reinforced polymers (FRP) materials have been widely used in the automotive, naval, railroad, and aerospace industry for many years, only more recently such materials are being employed in the civil engineering sector. FRP have shown to be a feasible alternative to construction conventional materials such as timber, steel and concrete especially in structures susceptible to deterioration due to their higher resistance to corrosion. Moreover, FRP shows some other favorable characteristics such as lightweight, high specific strength, high specific stiffness, high resistance to fatigue, and electromagnetic transparency [1]. There are several examples of the use of FRP in civil structural applications ranging from applications in the rehabilitation of existing construction to applications in new ones [2].

One of the most developed structural systems using FRP is the all-composite bridge decks. Bridge decks are usually the elements of a bridge superstructure that demand higher maintenance [3]. The higher specific strength and specific stiffness of FRP decks as compared to conventional reinforced concrete decks provides a rapid replacement and reduction of dead load in rehabilitation projects, thus raising the allowable live load of the structure [4]. Prefabricated slabs produced combining pultruded FRP plates and concrete is another application of FRP in bridge systems. The FRP elements provide the tensile resistance and serve as permanent formwork to concrete.

A variation of such system is the one being developed in the Federal University of Santa Catarina, Brazil [5], shown in Figure 1. This system consists of a composite slab made of a thin fiber-reinforced concrete slab top laid on GFRP pultruded profiles filled with foam (expanded polystyrene – EPS) in between. The foam blocks used for filling are nonstructural elements, but together with the profiles serve as formwork for the concrete. Although it has been originally designed for footbridge applications, it can also be used in industrial buildings or marine structures. The slab is designed to sustain constructive loads and live pedestrian loads for footbridge deck applications.

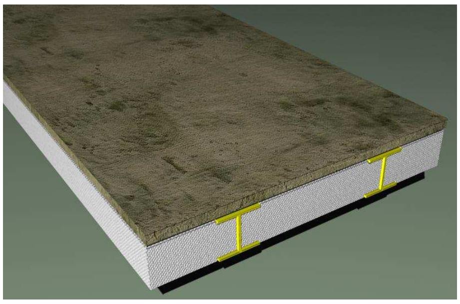

Figure 1. Composite slab concrete/GFRP profiles.

The slab flexural behavior has already been investigated up to failure [5]. Three modes of failure were observed: lack of bond at the concrete top/GFRP profile interface; shear failure in both profile webs, simultaneously; and a combination of both previous failure modes (bond and shear failure). It was also observed that the Serviceability Limit State governs the slab design for the span tested.

The present work investigates the composite slab behavior under shear. Composite model beams representing half-width of the slab were tested under static loading. Six GFRP-concrete composite beams subjected to two different shear span aspect ratio were tested. In addition, tests directly on GFRP profiles with mortar stiffeners were performed.

2 Composite Slab/GFRP Profiles

The structural system proposed for footbridge deck applications can be seen in Figure 2. It consists of a concrete cover placed over GFRP WF or I-section pultruded profiles, filled with foam (expandable polystyrene - EPS) in between.

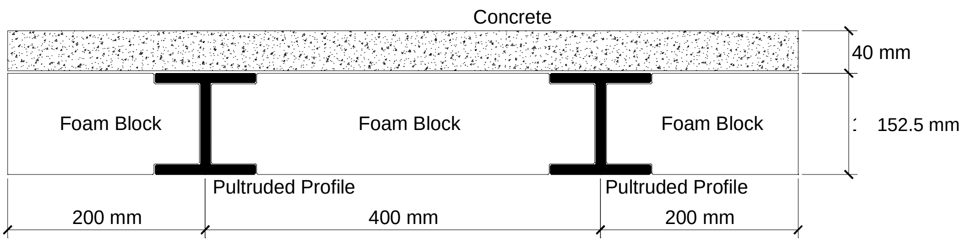

Figure 2. Composite slab representative section

Short polypropylene fibers were added to the concrete mixture in order to control plastic shrinkage cracking. An I-section GFRP profile fabricated in Brazil of 152.5 mm x 76 mm x 6.35 mm dimensions was selected for this work. The foam blocks used for filling are nonstructural; they have the usual dimensions employed in precast slabs. The profiles and foam blocks serve as formwork for the concrete, being designed to sustain constructive loads, thus avoiding the use of shoring. A resin is utilized for bonding the concrete to the profiles at the interface and also to avoid water penetration and thus aiding to prevent alkali attack in the glass fiber profiles. A concrete top thickness of 40 mm was selected to avoid buckling of the profile walls and shear failure of the concrete [6]. After the concrete hardens, the GFRP profiles and the concrete top behave structurally as a precast composite slab.

3 Experimental Program

In this work, the shear behavior of this new slab system was evaluated with the use of composite model beams representing half-width of the slab, as shown in Figure 3. The composite beams were of 1400 mm of length simple supported over a 1200 mm span. The beams were tested under 3-point bending varying the shear length. The ratios of shear length to beam depth (a/h) applied were of 1.0 and 1.5. The experimental design can be seen in Figure 4 and Table 1.

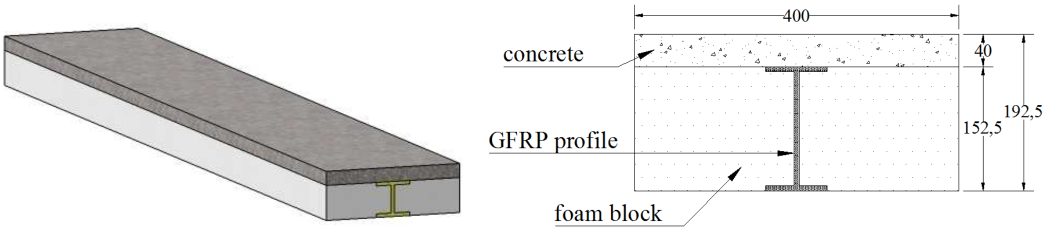

Figure 3. Composite model tested (dimension in mm)

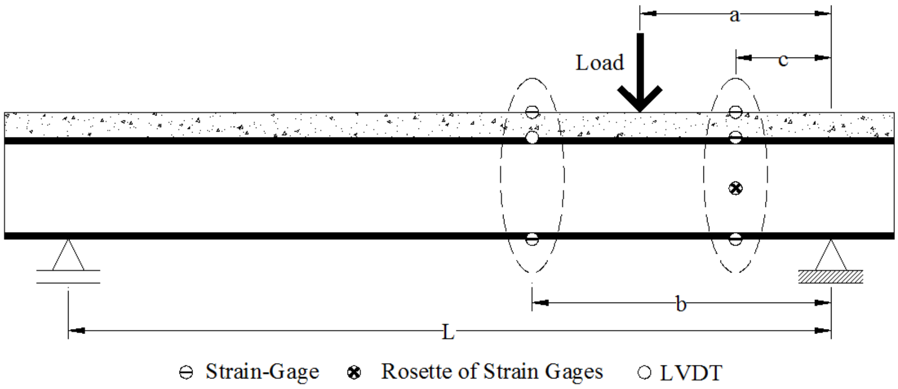

Figure 4. Experimental design and position of measuring devices

Beam	**L** (mm)	**h** (mm)	**a** (mm)	**b** (mm)	**c** (mm)	**a/h**
IC01	1200	192.5	192.5	520	100	1.0
IC02	1200	192.5	192.5	520	100	1.0
IC03	1200	192.5	192.5	520	100	1.0
IC04	1200	192.5	288.7	540	100	1.5
IC05	1200	192.5	288.7	540	100	1.5
IC06	1200	192.5	288.7	540	100	1.5

Table 1. Composite Beams Experimental set-up

In order to prevent plastic shrinkage cracking of the unreinforced concrete, polypropylene fibers were added to the concrete layer in a 0.10% volume ratio. Foam blocks were set on either side of the pultruded profiles. The external face of the profiles' top flange was sanded, cleaned to eliminate possible oxides and acids present on the surface of the profile. An epoxy-based mixture was then applied to the top layer of the profiles to increase bond with the concrete.

The composite beams were cured inside the Laboratory, and tested at an age of 28 days. The maximum displacement was measured with two Linear Displacement Transducers (LVDTs), positioned on the lateral faces of the composite beam. In order to measure any displacements of the concrete cover relative to the GFRP profiles, two other LVDTs were placed at the beam's extremities, fixed to the concrete cover and supported by the profiles. Compressive and tensile strains were measured with strain-gages positioned in the shear span and at the point of maximum deflection, as shown in Figure 4. In addition, another strain-gage was installed at the concrete/FRP interface, on the external face of the profile's top flange at the shear span. A strain-gage rosette was also fixed at mid-depth at the shear span. These strain gages allowed to evaluate the neutral axis position.

An I-shaped pultruded element was used. Three GFRP profiles were also tested under 3-point bending with mortar stiffeners of 500 mm of length positioned under the load point and over the supports. Figure 5 shows the profile dimensions and experimental set-up.

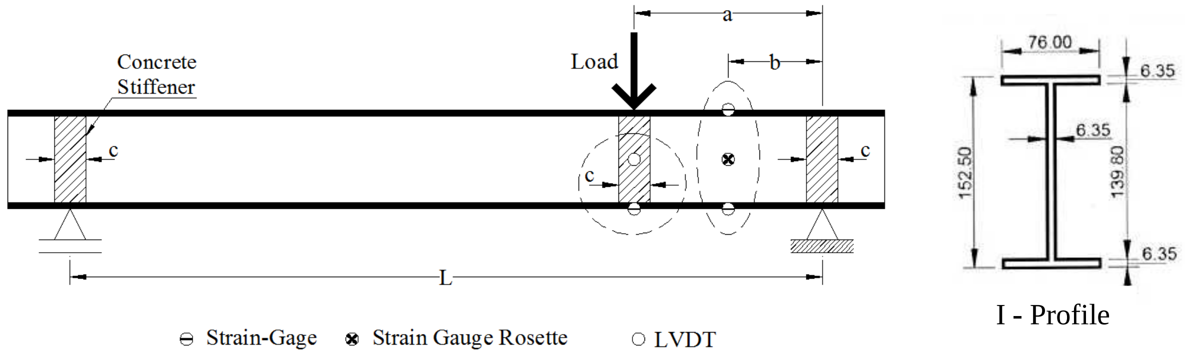

Figure 5. Experimental set up and Profile dimensions in mm

Profiles	L (mm)	h (mm)	a (mm)	b (mm)	c (mm)	a/h
P01, P02, P03	700	152.5	152.5	76.25	50	1.0

Table 2. GFRP Profiles Experimental set-up

The bond strength at the GFRP profile/concrete interface was obtained by a double shear test, [5]. An average bond strength of 2.53 MPa was obtained.

4 GFRP Profiles Properties

Pultruded profiles are not laminated structures in a rigorous sense. However, the profile flange/web walls usually display a material architecture that can be simulated as lamination configurations. The selected I-section profile is composed of fiber glass rovings (disposed parallel to the profile longitudinal axis) embedded in a polyester matrix, with a fiber volume fraction of 60%, and of laminates made of continuous strand mats.

The mechanical properties of each individual laminae was obtained approximately by micromechanics formulae, known as Rule of Mixtures [7], using the elastic properties of the fibers, resin, and mats as given by the profile producer. It was assumed that the profile web and flanges were laminated composites, with the same lay-up and equivalent orthotropic mechanical properties (E_1, E_2, G_{12} and ν_{12}) in their longitudinal (1) and transverse (2) direction. By using the Classical Lamination Theory (CLT), these equivalent properties can be found from the individual laminae properties and fiber orientation. The obtained profile mechanical properties are shown in Table 3. The matrix shear strength given by the fabricator was 34 MPa. The profile shear strength was estimated by means of the Rule of Mixtures yielding a value of 20.1 MPa.

	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12} (GPa)
I - Profile	26.73	7.19	2.44	0.34

Table 3. Estimated profile mechanical properties

5 Experimental Results and Analysis

Table 4 summarizes some of the experimental results obtained. The ultimate load for all composite beams varied from 28 to 36 kN. For the GFRP profiles, however, the ultimate loads were between 45 and 52 kN. The failure mode also differed from the composite beams to the GFRP profiles. For the composite beams, at a load of approximately 25 to 30 kN, the profile web just over the support area started to suffer a twisting action probably due to the absence of stiffeners. Failure occurred at the web profile near the bottom flange, as shown in Figure 6. For the GFRP profiles, however, only P03 showed this mode of failure, the other two profiles showed a shear failure on the web, as shown in Figure 7. Specifically for profile P03, the mortar stiffener over the supported debonded from the web profile at the ultimate load, and immediately failure occurred near the bottom flange.

	a/h	failure load (kN)	maximum strain at profile bottom (μm/m)	maximum shear strain (μm/m)
composite beam				
IC01	1.0	35.0	1702	8408
IC02	1.0	35.0	1156	8483
IC03	1.0	35.0	1342	8281
IC04	1.5	36.1	1250	12813
IC05	1.5	28.3	892	8484
IC06	1.5	27.9	941	9999
GFRP profile				
P01	1.0	45.6	1171	12497
P02	1.0	49.0	1415	14015
P03	1.0	52.0	3442	16348

Table 4 Summary of experimental results

Figure 6. Failure in web profile for composite beams

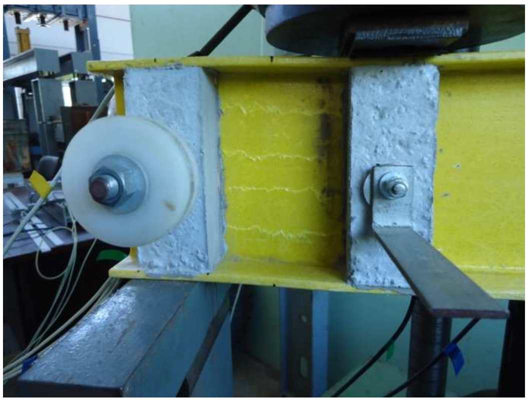

Figure 7 Shear failure in GFRP profiles

For the composite beam, at a load of approximately 15 kN, a longitudinal crack appeared over the top concrete layer. This crack initiated just underneath the loading area and travelled in the direction of the supported areas. The composite beam maximum deflection was measured up to the formation of this longitudinal crack.

Figures 8 shows the load deflection curves for the composite beams with shear length to beam depth ratio (a/h) of 1.0. It can be seen that up to the formation of the longitudinal crack, all composite beams presented a linear behavior. Similar behavior was observed for the composite beams with a/h ratio of 1.5.

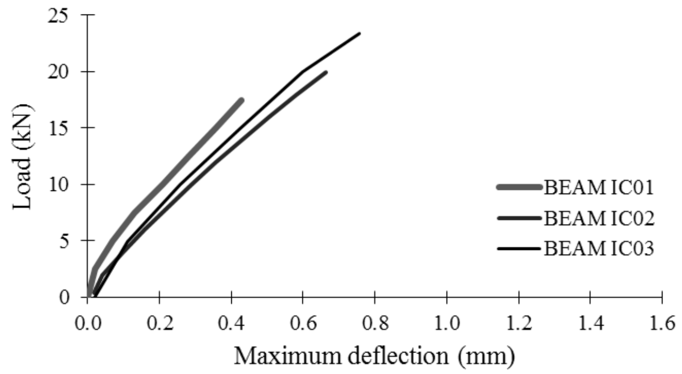

Figure 8. Load-deflection curve for composite beams with a/h of 1.0.

Figure 9 shows the load deflection curves for the GFRP profiles. It can be seen that all profiles presented a linear behavior. Profile P03 behaved somewhat differently than the others, achieving the highest maximum load with increased rigidity. This profile, as previously discussed, presented a different mode of failure.

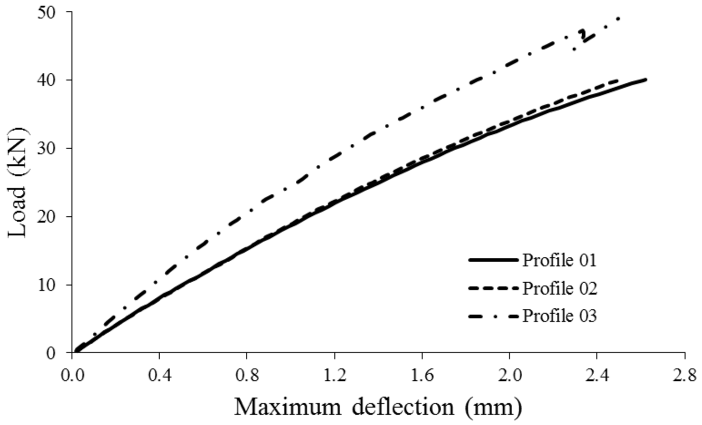

Figure 9. Load-deflection curve for GFRP profiles.

Figure 10 presents the strain measurements at the shear span for composite beams IC03. It can be observed that there was not an observed lack of bonding in the interface since the strain measurements presented a continuous behavior. For all other composite beams, strain measurements revealed a similar behavior.

Figure 11 presents the variation of the neutral axis position during the duration of the experiment calculated by performing a linear regression of the four strain measurements obtained in the shear span. The 0-value stands for the GFRP/concrete interface. It can be observed that the neutral axis position did not change considerably during the experiments remaining close to the interface. The composite beam, thus, behaved as expected with the concrete top layer in compression and the I-profile in tension throughout the experiment.

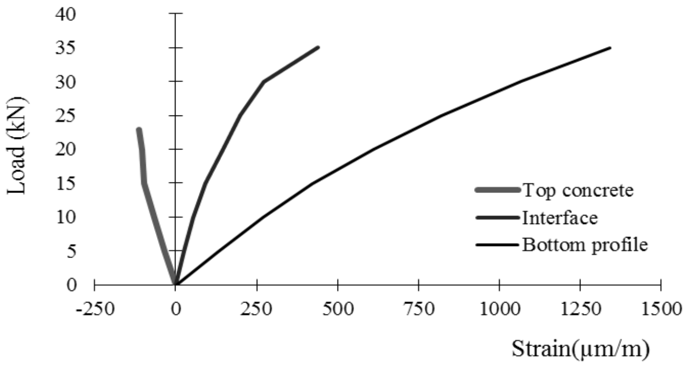

Figure 10 Strain measurements for beam IC03

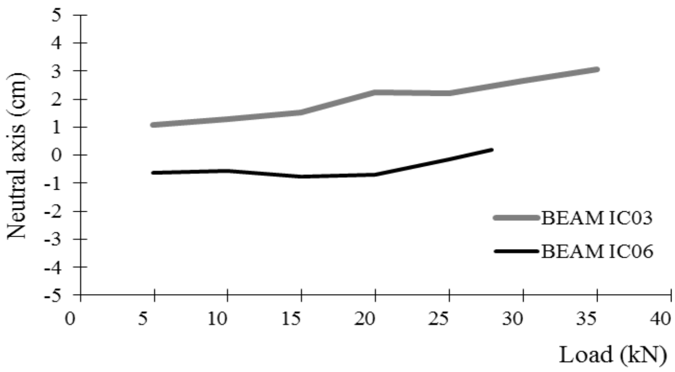

Figure 11. Neutral axis position for beam IC05

The shear strain results obtained from the rosette strain-gage measurements are presented in Table 4. It can be observed that with such values and the estimated shear modulus of 2.44 presented in Table 3, the shear strength at ultimate load would be on the order of 20 to 24 MPa for all beams but beam IC04. Although this value is in agreement with the estimated shear strength given by the Classical Lamination Theory, the observed failure mode was not due solely by shear. When only the GFRP profiles were tested, the shear strength obtained was between 31 to 39 MPa, value close to the matrix shear strength of 34 MPa given by the producer.

Therefore, it can be concluded that the composite beam would be able to withstand much higher loads should stiffeners were used, preventing the premature failure mode observed. Experimental tests with composite beams with stiffeners are being conducted as a continuation of this research project.

6 Conclusions

This work presents the results of an on-going research at the Federal University of Santa Catarina, Brazil. A composite slab system consisted of a thin fiber-reinforced concrete slab top laid on GFRP I-section pultruded profiles was tested under shear.

The experimental tests did not indicate a lack of bonding in the profile/concrete interface. Both the concrete and the profile were able to withstand compressive and tensile forces due to loading. Maximum tensile strain observed was in the order of 1700 μm/m at the bottom of the profile in the shear span.

For the composite beams, failure occurred at the bottom of the web/flange interface probably due to a combination of shear and twisting action. Although the observed shear strength at ultimate load was close to the one estimated by Classical Laminated Theory, the observed shear strength of the GFRP profiles with support stiffeners was much higher.

When the stiffened GFRP profiles were tested on shear, the observed shear strength was much higher than the one for the composite beams, with values similar to the matrix shear strength given by the producer. Failure occurred either by debonding of the stiffener from the web profile, or shear on the GFRP profile web.

These experiments revealed the need to stiffen the web profile near the support in order to prevent twisting action at higher loads and therefore leading to premature failure of the composite beams.

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