STATIC FLEXURAL PERFORMANCE OF GFRP-POLYMER CONCRETE HYBRID BEAMS

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ABSTRACT
In this paper it is reported a research undertaken in hybrid beams, where GFRP pultruded profiles are assembled, in an innovative way, with a layer of polymer concrete. The various beams were designed considering a pultrusion profile that will work in tension, and a polymer concrete filling that will work mainly in compression, in order to take benefit from the best mechanical properties of both materials. A model implemented in a finite element code was developed in order to predict the experimental results. Several beams, with four different hybrid designs, were tested in four-point bending and the flexural behaviour of such structures was studied. The results obtained show the synergetic effect of the joining of these two classes of materials.

KEYWORDS
GFRP profiles; Polymer concrete; Hybrid beams design; Flexural behaviour; Finite element model.

1 INTRODUCTION
Structural engineers always have valued the combination of materials into a composite structural system that takes advantage of the properties inherent to each of its constituents. Reinforced concrete is a classic example of this type of structural system, combining the superior carrying capability of steel with the compression capacity and low cost of concrete (Davol, 1998).
Fiber-reinforced composite materials are best known for its specific stiffness and high strength in tension. These materials consist of glass, aramid or carbon fibers embedded in a thermoset polymer matrix, such as polyester or epoxy resin and which can be easily moulded using specific heated dies in the pultrusion process. Reinforcement, strengthening and rehabilitation of structural elements, with FRP rods or FRP laminates externally bonded, are the most common applications of these materials. Recent research in advanced fibrous composites is mainly focused in those subjects (Meier et
In recent years, an innovative structural concept was developed involving the combination of fiber reinforced plastic profiles with conventional cement concrete to produce lightweight, corrosion-free and yet inexpensive beams (Deskovic, 1993; Deskovic et al., 1995; Sekijima et al., 1997).

The research undertaken in polymeric concrete, initiated in the latest fifties, knew a fast development in recent years (Mebarkia, 1993; Fowler, 1997; Chawalwala, 1999). Polymer concrete is made from thermoset resins and natural aggregates. Typically, polyester or epoxy resins are used as well as siliceous sand or gravel. This type of concrete has very high compressive strength, good chemical resistance, and relatively low tensile strength. The good characteristics of this material did promote its industrial production, which is already established in the market, mainly in the field of precast components for building construction due to its good workability and early high strength development (Dikeou, 1986; ACI Committee 548, 1986).

This paper presents the preliminary work of a research undertaken with hybrid structures composed by GFRP profiles and polymer concrete. Models of four different hybrid beams were manufactured and tested in four-point bending test. The flexural behaviour of such composite structures was analysed and compared with the flexural behaviour of its material constituents. The hybrid beams were designed considering a pultrusion profile that will work in tension and acts as permanent formwork or mould, allowing fast moulding. They also considered a polymer concrete filling that will work mainly in compression. Only available pultrusion profiles in the market were used in this study, and therefore, some of the hybrid beams are over-designed in the sense that some concrete will act in tension, which is a waste. A model implemented in a finite element code was developed in order to predict the experimental results.

2 EXPERIMENTAL PROCEDURE

2.1 Materials

A low viscosity epoxy resin and foundry sand with a very uniform and fine grain (d₅₀ of 342 microns) were used for the polymer concrete mixture. Resin content, without charge, was 20% in weight. This formulation of polymer concrete was studied in previous works (Ferreira et al., 2000) and its mechanical properties are already known. Compression behaviour was obtained from uniaxial testing according to RILEM TC-113 standards (1995). Compressive strength and compression elasticity modulus were 82 MPa and 11.5 GPa, respectively, with ultimate strain defined to be equal to 0.01.

Three kinds of U-shaped GFRP pultruded profiles and a GFRP laminate were used. The pultrusion profiles consisted of continuous strand mat and roving of glass fibers, impregnated with unsaturated polyester resin and having an external veil pull through a die. Volume content of glass fibers was 60% to 65%, and roving occupied the most part of it. The GFRP profiles dimensions and mechanical properties obtained from uniaxial tension tests (ISO 527-4:1996) are summarized in Table 1.

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>MECHANICAL CHARACTERISTICS AND DIMENSIONS OF GFRP PROFILES</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFRP</td>
<td>Tensile Strength</td>
</tr>
<tr>
<td>Profile A</td>
<td>395 MPa</td>
</tr>
<tr>
<td>Profile B</td>
<td>310 MPa</td>
</tr>
<tr>
<td>Profile C</td>
<td>350 MPa</td>
</tr>
<tr>
<td>Laminate D</td>
<td>455 MPa</td>
</tr>
</tbody>
</table>
2.2 Hybrid Beams Design

Four different hybrid beams were designed. Two of them (HB I and HB III) had all the section full of concrete with the profiles behaving, simultaneously, as reinforcement and as permanent formwork. The other two types of beams (HB II and HB IV) were lighter, with only a thin layer of concrete positioned in the upper part of the profile. The cross section of concrete layer was designed in order to support only compressive stresses in the elastic range. The chosen hybrid beam designs, all of them with 600 mm length, are illustrated in figure 1.

![Cross sections of the hybrid beams used in this study.](image)

2.3 Testing Procedure

Four-point bending tests on three specimens of each type of hybrid beams were carried out. All beam specimens were allowed to cure seven days at room temperature before being tested. The specimens were loaded with 510 mm of span and 100 mm of constant moment zone. Load was gradually increased up to failure at the rate of 1mm/min. Strains were recorded, by strain gauges, in the compressive and tensile faces at midspan, and central displacement was recorded in the compressive face. On two specimens of each constituent material of each type of hybrid beam, four-point bending tests were also performed, in order to evaluate the synergetic effect of the assembly.

2.4 Finite Element Modelling

The present work addresses the numerical study of GFRP reinforced concrete arbitrary shell structures. The proposed model is capable of predicting deflections and stresses in concrete and in composite reinforcement for geometrical and material non-linear behaviour. Different constitutive laws have been applied to concrete and reinforcement. The non-linear behaviour of concrete is inelastic. A perfect plastic and a strain-hardening plasticity approach are used to model the compressive behaviour of the concrete. A dual criterion for yielding and crushing in terms of stresses and strains is considered, which is complemented by a tension cut-off representation. Crushing or compressive type of fracture is assumed to occur when the effective total strain reaches the limit value, which is usually taken as the maximum compressive strain in a uniaxial compression test. Once crushing has occurred the concrete is assumed to lose all its characteristics of stiffness at the point under consideration. Therefore the corresponding elasticity matrix $D$ is taken as a null matrix and the vector of total stresses is reduced to zero. In this model, the reinforcement is modelled as layers of equivalent thickness. Each reinforcing layer exhibits a uniaxial response, having strength and stiffness
characteristics in the longitudinal direction only. This behaviour is treated incrementally as a one-dimensional problem.

3 TEST RESULTS

The load deflection curves, as well as relationships between load and strains of composite beams, are illustrated in Figure 2. Theoretical strain values obtained by elastic beam theory are also plotted. Figure 3 presents the experimental and numerical values obtained by the finite element modelling for one Type III tested beam.
Figure 3. Experimental and numerical results obtained by FEM for one Type III tested beam

Table 2 summarizes for each type of beam the failure modes, the flexural rigidities, the average of maximum loads and the related synergetic effects. Synergetic effect was calculated by dividing the capacity load of the assembly by the sum of capacity loads of its two elements. In Figure 4 it is shown, in a more perceptible way, the synergetic effect resulting of the assembly in the hybrid systems. Flexural specific rigidity is the ratio between the flexural rigidity and the specific weight.

TABLE 2
FLEXURAL TEST RESULTS

<table>
<thead>
<tr>
<th>Flexural specific rigidity (m$^3$)</th>
<th>Max. Load (kN)</th>
<th>Failure Mode</th>
<th>Synergetic Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>HB I 0.77</td>
<td>38.07</td>
<td>Bond failure with rupture of the concrete</td>
<td>233 %</td>
</tr>
<tr>
<td>HB II 1.04</td>
<td>26.96</td>
<td>Bond failure (PC and profile A)</td>
<td>203 %</td>
</tr>
<tr>
<td>HB III 0.41</td>
<td>32.06</td>
<td>Tensile failure of lower flange of profile C</td>
<td>258 %</td>
</tr>
<tr>
<td>HB IV 0.47</td>
<td>16.93</td>
<td>Bond failure (PC and profile C)</td>
<td>171 %</td>
</tr>
</tbody>
</table>

Figure 4. Capacity (ultimate) loads of the hybrid beam models and associated synergetic effects.
4 RESULTS DISCUSSION

4.1 Failure Modes

All Type I beams had a brittle failure rupture due to bond failure between concrete and lower surface of the GFRP profile, immediately followed by explosive rupture of concrete.

Collapse of Type II and IV beams was also due to bond failure although concrete did not break, and therefore rupture was more ductile. Instead horizontal cracks appeared in the profile surface at the shear span, which promoted the decrease of load capability. In these structures, there was no slip between the lower surface of concrete and GFRP profile B or laminate D. The loss of bonding in all specimens I, II and IV was progressive, and it started at the midspan, due to crushing and buckling of lateral faces of the GFRP profile (Fig. 5).

Type III beams failed due to tensile failure of lower surface of GFRP profile at the midspan (Fig. 5). The different failure mode of this kind of composite beam is not unexpected. None of the GFRP profiles received any further treatment to improve bond strength to polymer concrete after the usual surface degreasing. However, the cross section of profile C is slightly narrower at the top, which made slip of concrete more difficult.

4.2 Strains

In all test beams, for loads less than 20 kN, the measured strains agreed with the calculations by elastic beam theory. For loads up to 20 kN, experimental strains were larger than theoretical values. These calculations were based on the assumption that the GFRP profile and the concrete section were perfectly connected. The difference to experimental data may result of some slip between the concrete and the GFRP profile.

4.3 Synergetic Effect

Type III beams showed the highest synergetic effect. Capacity load of these beams is up to two and half more than the addition of both capacities of its elements. Type I beams presented the highest capacity load and also showed a significant synergetic effect. In absolute terms, Type II and Type IV showed less synergetic effect. This is due, certainly, to the fact that significant less material is used to build such beams. The lower contact surface area of concrete to GFRP profiles in those beams allows for a reduction of adherence. This fact makes the beams more susceptible to failure mechanisms related to shear in vertical walls. However, it is believed that this type of construction is of great interest, due to reduction of material and due to a more precise placement of material in stress zones.

Figure 5. Typical failure mode of Type II and Type III hybrid beams
Further studies are in progress to enhance bond strength in order to optimise the cross-section of the beams. In particular, T-shape beams are in the process of design.

4.4 Finite Element Modelling

The experimental and numerical results agree very well, according to the modelling hypothesis. This model has still to be improved to account for interface debonding. However, at this stage, this model can already predict with good accuracy the load-displacement curves. Due to homogenisation procedure in the layer modelling, this approach can only offer approximate results in stiffness and especially in stress. However, this approach is not only cost-effective, but also good in quality.

5 CONCLUSIONS

Hybrid rectangular beams were designed, manufactured and tested. The assembly allows for a critical combination of polymer concrete and composite pultruded materials. This innovative design produces highly optimised behaviour with a pronounced synergetic effect.

The numerical model used for this analysis was implemented in a finite element code. This model predicts with very reasonable accuracy the load-displacement curve for one tested type beam. This model is still in progress. The results so far allow for a very interesting expectation in terms of a finite element code for the analysis of this type of hybrid beams.

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REFERENCES

ACI Committee 548, 1986. Guide for the use of polymers in concrete.(ACI 548, IR-86), American Concrete Institute, Detroit


