Structural solutions for floors of buildings with GFRP-concrete hybrid beams

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ABSTRACT: In recent years, the need of systems for floors of buildings with improved durability and higher speed of construction led to the study and development of new structural solutions. This paper presents results of a study of an innovative solution for floors of buildings constituted by GFRP pultruded profiles connected to concrete elements. Shear connection tests were first conducted on GFRP I-profiles connected to concrete, with either stainless steel bolts or an epoxy adhesive layer. The results of those tests were then used to design simply supported and continuous beams with GFRP-concrete hybrid cross-section, which were tested in bending. The results of the investigations show the viability of using GFRP-concrete hybrid cross-sections in floors of buildings, either for rehabilitation or for new constructions. The technical advantages of using GFRP-concrete hybrid cross-sections when compared to the use of simple GFRP profiles are also demonstrated.

1 INTRODUCTION
Glass fibre reinforced polymer (GFRP) pultruded profiles have a great potential as construction materials, due to their strength, lightness, ease of installation, improved durability and low maintenance requirements (Keller 2002).

However, the low elasticity modulus leads to designs that are usually governed by instability phenomena and deformability (for which the shear contribution can be significant), rather than by strength limitations (Barbero et al. 1999, Nagaraj & GangaRao 1997). These conditions, and the associated limited use of the material's ultimate strength, as well as the high initial costs, may explain the fact that the use of fibre reinforced polymer (FRP) materials as load bearing elements is still limited to a few demonstration projects.

The alternative use of GFRP pultruded profiles in GFRP-concrete hybrid structural elements presents however a very interesting potential, either for rehabilitation or for new constructions. In fact, there are several structural advantages in connecting GFRP pultruded profiles to concrete compression elements, namely the increase of the flexural stiffness, reducing the structure's deformability, and the increase of the structure's strength capacity, making a better use of the GFRP profiles properties and preventing the occurrence of buckling phenomena.

This paper presents the results of a research project in which the static behaviour of GFRP-concrete hybrid beams was analysed regarding their use in floors of buildings. Shear connection tests were conducted on GFRP I-profiles connected to concrete, with stainless steel bolts and, in alternative, an epoxy adhesive layer. The results of those tests were then used to design beams with GFRP-concrete hybrid cross-sections, manufactured using those two shear connection systems, which were tested in bending, showing the viability for their use in building floors.

2 EXPERIMENTAL INVESTIGATIONS
The objective of the experimental program (Correia 2008) was to study and compare the flexural behaviour of GFRP-concrete hybrid beams using the two different shear connection systems shown in Figure 1: (i) stainless steel bolts and (ii) a continuous epoxy adhesive layer.
2.1 Materials

The GFRP I-profile used in the experimental programme, produced by pultrusion, is made of a polyester matrix reinforced with E-glass fibres (62% in weight) and has the following nominal dimensions: height of 200 mm, width of 100 mm and thickness of the web and flanges of 10 mm. Tensile, compressive, flexural and shear properties were determined through extensive mechanical characterization based on experiments on coupons cut from the original profile. The profile’s longitudinal flexural modulus ($E_p = 38.4$ GPa) and shear modulus ($G_p = 3.58$ GPa) were determined in a full-scale test performed on a profile similar to that used in the tested beams (Correia 2004).

Four different ready-mixed concrete compositions (C1 to C4) were used. Concrete’s average compressive strength ($f_c$) and Young’s modulus ($E_c$) were experimentally determined (Table 1).

In the bolted-hybrid beams, steel bolts with a class resistance of 8.8 (ultimate shear strength of $480$ MPa) were used as shear connectors. In the bonded-hybrid beams, the shear connection was provided by a two component-epoxy adhesive (MBrace Resin 220).

2.2 Shear connection tests

For the shear connection tests, the flanges of a segment of the GFRP profile used in the hybrid beams were connected to 20 cm concrete cubes with either steel bolts or a 2 mm thick epoxy adhesive layer (Fig. 2). The profile was then loaded in compression until failure. Results are listed in Table 1 and the measured load-relative displacement curves are plotted in Figure 3.

Table 1. Shear connection tests: material properties and results.

<table>
<thead>
<tr>
<th>Connection system</th>
<th>Mix</th>
<th>$f_{cm}$ [MPa]</th>
<th>$E_c$ [GPa]</th>
<th>$\phi_{bolts}$ [mm]</th>
<th>$K$ [kN/mm]</th>
<th>$F_{s,max}$ [kN]</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCS1</td>
<td>C1</td>
<td>43.3</td>
<td>33.9</td>
<td>8</td>
<td>56.0</td>
<td>67.5</td>
<td>Bolts (shear)</td>
</tr>
<tr>
<td>SCS2</td>
<td>C2</td>
<td>39.9</td>
<td>32.5</td>
<td>10</td>
<td>76.3</td>
<td>157.1</td>
<td>Bolts (shear)</td>
</tr>
<tr>
<td>SCS3</td>
<td>C3</td>
<td>36.9</td>
<td>30.9</td>
<td>10</td>
<td>55.1</td>
<td>108.3</td>
<td>Conc. (compression)</td>
</tr>
<tr>
<td>SCS4</td>
<td>C3</td>
<td>36.9</td>
<td>epoxy</td>
<td></td>
<td>427.4</td>
<td>55.5</td>
<td>Conc. (tensile)</td>
</tr>
<tr>
<td>SCS5 (2 specs.)</td>
<td>C4</td>
<td>27.1</td>
<td>29.0</td>
<td>epoxy</td>
<td>244.1 ± 65.6</td>
<td>44.9 ± 9.4</td>
<td>Concrete-adhesive interface</td>
</tr>
</tbody>
</table>

Figure 2. Shear connection tests: test setup.

Figure 3. Shear connection tests: load-relative displacement curves.
Bonded shear connection systems led to a considerably higher stiffness than bolted shear connection systems. In bonded shear connection systems failure was always brittle, while for bolted shear connection systems it was possible to achieve a certain ductility level. In bolted systems, strength and stiffness increased with the bolt diameter and, in both systems, strength increased with the concrete grade. The shear connection tests allowed for the evaluation of the connection's stiffness and ultimate flexural strength of the hybrid beams and also for the definition of the steel bolts diameter and longitudinal spacing in beams with bolted shear connection systems, according to a design procedure described in Correia et al. (2007).

2.3 Flexural tests on simply supported beams

Five simply supported hybrid beams were tested in bending, with different shear connection systems, total lengths and loading arrangements. All beams were manufactured with a concrete slab 100 mm thick and 400 mm wide. Hybrid beams HB1 and HB3 were built using bolted shear connection systems (SCS2 and SCS3, respectively), while hybrid beams HB2, HB4a and HB4b were built with adhesively bonded shear connection systems (SCS5, SCS4 and SCS5, respectively). Hybrid beams HB1 and HB2, with a simply supported 4.00 m span, were tested in bending subjected to a point load at midspan. Hybrid beams HB3 and HB4b (with web reinforcement in the support sections) and HB4a (without web reinforcement in the support sections), with a simply supported 1.80 m span, were also tested in bending, but subjected to two point loads applied at about 1/3 span.

The load-midspan deflection curves of beams HB1/HB2 and HB3/HB4 are plotted in Figures 4 and 5, respectively. In Figure 4 another curve is also shown, corresponding to a bending test performed in an identical GFRP I-beam, but without concrete slab. In this test, lateral-torsional buckling was prevented by a lateral bracing system and the beam failed suddenly by local buckling of the top flange (Correia 2004). This beam is used as reference to assess the improvements of the GFRP-concrete hybrid solution.

A comparison of the load-deflection behaviour of beams HB3 and HB4a shows that, for the same concrete composition, beams with bonded shear connection systems present higher stiffness than those with bolted shear connection systems. This could be attributed to the slippage that develops at the interface of beams with bolted shear connection systems (Figs 6 and 7).

Bolted-hybrid beams collapsed due to shear failure of the webs (in hybrid beam HB1, this was preceded by concrete crushing at midspan section, as shown in Figure 8), while bonded-hybrid beams presented a premature failure at the concrete-adhesive interface, a few millimetres inside the concrete slab (Fig. 9). As a consequence, within the range of geometries analysed in the experiments, bolted-hybrid beams attained higher ultimate loads.

Comparing the behaviour of beam HB1 with that of the simple GFRP I-beam, the following structural improvements of the GFRP-concrete hybrid solution can be referred: (i) flexural stiffness increased about 350%; (ii) flexural strength increased about 300%; (iii) the GFRP I-beam failed (due to local buckling), for a maximum stress of 269 MPa, while the hybrid beam failed...
for a maximum stress in the GFRP profile of 386 MPa, corresponding to a 40% increase in using the GFRP profile's strength capacity; (iv) regarding the first load cycle, the hybrid beam presented a pseudo-ductile behaviour, considering the loss of stiffness observed prior to failure, in opposition to the brittle failure presented by the GFRP I-profile.

Figure 6. Hybrid beam HB3: axial strains vs. section depth for varying moments [kN.m], midspan.

Figure 7. Hybrid beam HB4b: axial strains vs. section depth for varying moments [kN.m], midspan.

Figure 8. Hybrid beam HB1: web shear failure, following concrete crushing at midspan.

Figure 9. Hybrid beam HB2: failure at the concrete-adhesive interface.

2.4 Flexural tests on a continuous beam

Hybrid beam HB7, with a length of 6.00 m and two 2.80 m spans, was tested in bending, subjected to two point loads applied at approximately 3/8 span (sections S1 and S2), measured from the end supports – Figure 10. This beam comprised a bonded shear connection system (SCS5) and its concrete slab was reinforced with steel bars in order to resist negative bending moments. The objective of this test was to investigate the behaviour of the proposed system under negative bending moments and to assess the advantages of using a structurally redundant system.

The load-displacement curves at sections S1 and S2 are plotted in Figure 11. Both curves are very similar in their first part, being linear up to a load of about 100 kN. For a load of about 220 kN, first local damage occurred, corresponding to the development of a crack at the adhesive-concrete interface (a few millimetres inside the concrete layer), along the first span, starting at the left extremity section and ending at load section S1. After this first local failure, load dropped to 175.5 kN and deflections in the first span (where shear connection failure occurred) increased significantly. The second part of the experimental load-deflection curves at sections S1 and S2 were both non-linear, but presented considerably different stiffnesses, with the first span presenting a much higher deformability due to the loss of composite action in part of its length. Second local damage occurred for a load of 280.9 kN, corresponding to the development of a second crack at the adhesive-concrete interface, along the second span, starting at section S2 and ending at central support section. After this second local damage, load dropped to 205.9 kN. Final failure occurred for a total load of 268.2 kN and was triggered by the local buckling of the top flange, in the vicinity of section S1, where the two materials became separated and the concrete layer no longer prevented the GFRP profile's top flange from buckling.
The redundancy provided at both the cross-section level (allowing for stress redistribution in the cross-section, following local failure of the shear connection system) and also at the structural element level (allowing for internal forces redistribution), led to a relatively ductile structural behaviour. The experimental load-deflection curves at sections S1 and S2, presented in Figure 11, illustrate this pseudo-ductility, due to the successive damages suffered by the hybrid beam and the consequent considerable deformation increase, which occurred in both spans prior to collapse.

3 NUMERICAL INVESTIGATIONS
In order to understand better the stress state at the interface between the GFRP profile and the concrete slab, in the vicinity of the support sections of the beams with bonded shear connection systems, and therefore the observed debonding failure mechanism, it was decided to develop a 3D FEA model of beam HB4b (Fig. 12).

Symmetry boundary conditions were exploited and all materials were modelled assuming a linear-elastic behaviour. The GFRP profile was modelled as an orthotropic material and the adhesive and the concrete were modelled as isotropic materials. A geometrically linear analysis was performed for a reference load of 100 kN (for this load value, the load-deflection behaviour of hybrid beam HB4b was still within its linear range). Shear and normal stresses in the concrete layer were determined at different depths along the beam's axis, namely at distances of 0.5 mm, 1.0 mm and 1.5 mm from the concrete-adhesive interface, where failure occurred. Figure 13 shows the results obtained for the distribution of normal stresses at those different depths.

The highest normal tensile (peeling) stresses in the concrete slab occur at the extremity of the beam (from 5.5 MPa to 6.1 MPa). These stresses are then reduced along the free length of the beam and present already a compressive sign above the support, which is maintained along the...
span. The maximum normal tensile (peeling) stress in the concrete slab is significantly higher than the value of concrete’s tensile strength, \( f_{ctm} = 2.1 \text{ MPa} \), estimated based on its relationship with concrete’s compressive strength \( (f_{ctm} = 0.3 \times (f_{cm} - 8)^{2/3}) \), given in EC2 (CEN 1992).

Although the performed FEA was linear elastic, not considering several non-linear effects such as concrete cracking or the non-linear bond-slip constitutive relationships at the interface, numerical results allow explaining the experimental observations. The cracks observed at the concrete-adhesive interface, inside the concrete slab, in most cases for load levels considerably lower than the failure load, can be related to the shear stresses and especially to the normal tensile stress peaks developed at the extremity of the beam. Taking into consideration these results, in order to increase the flexural strength of hybrid beams with bonded shear connection systems, effective anchorage systems have to be designed for the beam’s extremities. The placement of steel bolts in the vicinity of the supporting sections, in addition to the adhesive layer, seems an effective and easy-to-execute solution to increase the flexural strength of hybrid beams with bonded shear connection systems.

4 CONCLUSIONS

The following main conclusions can be drawn from the research presented in this paper:
1. GFRP-concrete hybrid beams, using the two alternative shear connection systems (bolted and bonded), are a viable structural solution for floors of buildings, that can be used in the rehabilitation of existing structures or in new construction, presenting reasonable stiffness, high strength and low self-weight.
2. Comparing with the behaviour of simple GFRP profiles, GFRP-concrete hybrid beams show a considerable stiffness and strength increase, with a better use of the profiles properties.
3. Comparison of the two alternative shear connection systems shows that a continuous epoxy layer provides higher stiffness than that obtained using steel bolts. Consequently, the use of the first shear connection system in hybrid beams provides lower deformations.
4. Experimental tests showed that in bonded-hybrid beams, with shear connection provided by epoxy adhesive layers, the strength of the concrete-adhesive interface can limit the strength of the structural element. Therefore, it is important to develop anchoring systems to be applied at the end sections, similarly to the procedures and methods developed for reinforced concrete elements strengthened with CFRP systems. One possibility, which seems effective and easy-to-execute, is the use of steel bolts in the vicinity of the supporting sections (in addition to the adhesive layer), where shear and peeling stresses maxima occur.
5. The use of GFRP-concrete hybrid sections in statically indeterminate structural systems, leads to a much lower deformability, when compared with isostatic systems. In what concerns the failure behaviour, the redundancy provided at both the cross-section level (allowing for stress redistribution in the cross-section, following local damage of the shear connection system) and at the structural element level (allowing for internal forces redistribution) led to a certain degree of ductility of the structural element.

5 REFERENCES