Development of a novel beam-to-column connection system for pultruded GFRP profiles
João Consiglieri Bastos Pinto

Department of Civil Engineering, Architecture and Georesources, Instituto Superior Técnico, Universidade de Lisboa, Portugal

Abstract: This paper presents the study of a novel beam-to-column connection system between pultruded GFRP profiles. The novel system is a cuff-type connection fully made of stainless steel, the behaviour of which was evaluated under monotonic loading. Mechanical characterisation tests on the stainless used in the connection were performed, followed by 32 double-lap tests, in order to study the plane response of the connection with different configurations. Later, eight different beam-to-column typologies were tested under monotonic loading (two specimens for each typology), varying the cross section of the profile, the length and the wall thickness of the connection system. Therefore, it was possible to analyse the influence of each parameter on the connection’s stiffness, strength and ductility. From all typologies tested between tubular (SC) and I-section (IC) profiles, typologies BC-SC-360-1,5 and BC-IC-360-1,0 were those which presented the best mechanical properties when subjected to monotonic loading. When compared with previously studied connections, this novel system presents a better compromise between stiffness, resistance, ductility and amount of steel. The numerical study, carried out using the Abaqus finite element software package, presented a good agreement to the experimental results in terms of stiffness and initial development of the force-displacement curve. Nonetheless, the model was not able to simulate the pre- and post-failure behaviour of the connection due to the simplifications in the modelling of response of the materials, namely the GFRP material.

Keywords: Beam-to-column connections; pultruded GFRP profiles; stainless steel cuff; experimental tests; numerical models.

1. Introduction
Fibre Reinforced Polymer (FRP) composites are structural materials comprising oriented fibre reinforcements embedded in a polymeric matrix. Of all the typologies of FRP materials, pultruded Glass Fibre Reinforced Polymers (GFRP) profiles stand out due to their low cost, lightness and mechanical properties. Pultrusion, the manufacturing process, consists of an automatic process that brings together continuous fibre reinforcements and then combines them with a resin to produce constant cross-section FRP profiles, which present better mechanical properties on the pultrusion direction. The use of pultruded GFRP profiles in civil engineering applications has been increasing in the past years due to: (i) high strength-to-weight ratio; (ii) high resistance to aggressive environments; and (iii) low maintenance and installation cost. However, due to their constitution and their manufacturing process, GFRP profiles present an orthotropic behaviour and brittle failure.

With the application of pultruded GFRP profiles in structures, the use of beam-to-column connection systems has become necessary. Initially, this connection system mimicked steel structures by using GFRP angles to connect the web of the beam to the flange of the column, being designed as pinned connections, leading to uneconomical profile sections. Therefore, in order to increase their rotational stiffness and allow semi-rigid design, new connections were developed. At the beginning, they were developed to connect I-section profiles, but soon new solutions for pultruded tubular profiles started to appear. The pultruded tubular profiles are more attractive since they are less susceptible to instability phenomena and shear deformability. The material of the connection was another topic of study throughout the years. Although these connections were initially made of GFRP, due to the anisotropy of the material they were later replaced by steel. This study was motivated by the need to develop a novel connection system between pultruded GFRP (tubular and I-section) profiles completely made of stainless steel in order to increase the corrodibility resistance, the stiffness, the strength and the ductility of the connection.

To analyse this new connection system, an experimental and numerical study was carried out. Starting with performing characterisation tests in stainless steel specimens, it was possible to evaluate their mechanical response and to ensure a proper definition of the models.
Double-lap tests were then performed in eight different types of stainless steel connections, with two different diameters of the threaded rod, edge distance of the bolt hole and thickness of the specimen. Afterwards, sixteen full-scale beam-to-column tests were conducted. The connections were subject to a monotonic loading, where different cross section of the GFRP elements and different lengths and wall thicknesses of the connection system were combined. At the same time, a numerical study was performed, where one of the connections tested was simulated. A parametric study of the normal behaviour of the contact (defined by its stiffness) was conducted in order to calibrate the numerical results. Lastly, the experimental and numerical results were compared in terms of the connections’ stiffness, strength and failure modes.

2. Literature review

The connections between pultruded GFRP profiles can be materialized by: (i) bolting, (ii) bonding or (iii) a combination thereof (hybrid) [1]. Bolted connections tend to mimic metallic construction, leading to higher stress concentrations around the bolts’ holes [2]. In spite of that, these connections are inevitable in complex structures due to their low cost, ease of maintenance, inspection, and repair. Bonded connections are the most suitable to the anisotropic and brittle behaviour of the GFRP material, enabling a more uniform load transfer [2]. However, there is a lot of uncertainty about the durability of these types of connection; therefore, their use in civil engineering applications is less common than bolted connections. The use of hybrid connection is only justified in one-off cases where there are requirements of deformability and resistance.

The first studies regarding bolted connections showed that there are four different types of failure modes, as illustrated in Figure 1. Of all initial investigations, the review of studies about the characterization of in-plane connections by Mottram and Turvey [3] stands out. Of all of these failure modes, bearing was highlighted as the one that offers more deformation capacity (ductility), unlike the other modes that present a brittle failure [4, 5].

Figure 1 – FRP bolted connections failure modes in bolted connection, adapted from [6]: a) net-tension; b) shear-out; c) cleavage; d) bearing.

In the past decades, many studies concerning beam-to-column connections have been conducted. In 1990, Bank et al. [7, 8] started studying pultruded GFRP I-section profiles connected by different configurations of pultruded seat angles, as shown in Figure 2-a and Figure 2-b. These first connections showed low values of stiffness and strength and led the authors to conclude that they required careful consideration of the unique local failure modes occurring on the GFRP profiles. This first study motivated Mosallam et al. [9] and Bank et al. [10] to develop a new GFRP connection system, as illustrated in Figure 2-c and Figure 2-d. With this new system, the authors were able to increase the joint strength and stiffness without losing ductility, when compared to the standard cleat angle joint.

Smith et al. [11] pointed out that most problems were associated with the use of I-section profiles. Thus, the author developed the first prototype of a GFRP cuff (Figure 2-e)) to connect pultruded tubular profiles. This new typology showed an increase of strength and stiffness. Later on, Singamsethi et al. [12] developed a new GFRP cuff connection produced by VARTM. Carrion et al. [13] subsequently studied this new system and achieved higher values of stiffness and strength.

Figure 2 – a) Banks et al. [7, 8]; b) Banks et al. [8]; c) Mosallam et al. [9]; d) Banks et al. [10]; e) Smith et al. [10]; and f) Singamsethi et al. [12] and Carrion et al. [13]. Adapted from [13].

Later on, Proença [14] and Wu et al. [15] studied a steel sleeve system, with the connection parts inside the tubular profiles. This system revealed a more ductile failure and was able to endure large deformations. Azevedo [16] tested a cuff connection system made of steel (external to the tubular GFRP profiles) concluding that the novel system provided good performance compared to previous systems. Finally, Mendes [17] presented a study about connection systems made of stainless steel angles, exploring the resistance and ductility provided by the steel.

Concerning numerical studies, many works have been carried out, being the work of Casalegno et al. [18] the one that stands out the most. Here, the authors studied the connection developed by Bank et al. [7] using finite element models, damage initiation criteria and damage progression models. The main difficulty associated to these damage progression models lies in the experimental definition of the fracture energies of the GFRP materials, which is still uncertain.
3. Experimental Study
3.1. Experimental program

The present study was divided into three different parts. First, characterisation tests were performed in six different stainless steel specimens, allowing to define properly the numerical models. Secondly, double-lap tests were carried out for eight different series, which varied in the diameter of the threaded rod, the edge distance of the bolt hole and the thickness of the specimens. For each series, four identical specimens were tested. With these tests, it was possible to study the in-plane behaviour of the connections. Finally, the novel beam-to-column connection system was tested monotonically up to failure, considering eight different typologies (four configurations connecting tubular profiles and four configurations connecting I-section profiles). The length (short or long) and the wall thickness (1.0 mm or 1.5 mm) of the connection element were varied, with two specimens being tested for each typology, in order to evaluate their stiffness, strength and ductility.

3.2. Material characterisation tests

Six stainless steel specimens (3 with 1.0 mm and 3 with 1.5 mm thickness) were tested in tension. Table 1 presents, for each thickness, the average results of the yield stress (\(\sigma_y\)), the maximum tensile strength (\(\sigma_u\)), the modulus of elasticity (\(E\)) and the Poisson ratio (\(\nu\)). As expected, the steel is characterised by a pronounced loss of the proportionality limit (end of the linear regime), presenting an extensive plastic (non-linear) stage, providing it with high plastic deformations and, consequently, high ductility.

<table>
<thead>
<tr>
<th>Property</th>
<th>1.0 mm plate</th>
<th>1.5 mm plate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>CoV</td>
</tr>
<tr>
<td>(\sigma_y) [MPa]</td>
<td>182.73</td>
<td>7.38%</td>
</tr>
<tr>
<td>(\sigma_u) [MPa]</td>
<td>707.07</td>
<td>0.08%</td>
</tr>
<tr>
<td>(E) [GPa]</td>
<td>198.92</td>
<td>1.75%</td>
</tr>
<tr>
<td>(\nu) [-]</td>
<td>0.26</td>
<td></td>
</tr>
</tbody>
</table>

3.3. Double-lap tests

In order to evaluate the in-plane response of the connection system, eight different typologies of stainless steel configurations were tested, with different (i) diameters for the threaded rod (8 mm or 12 mm), (ii) edge distance of the bolt hole (20 mm and 60 mm) and (iii) thickness of the specimen (1.0 mm or 1.5 mm), as illustrated in Figure 3. For each typology, four specimens were tested using a threaded rod made of A2-70 stainless steel. The double-lap tests allowed evaluating the interaction between the threaded rod and the steel plate, determining the strength, stiffness and failure modes. It also allowed predicting the behaviour of the beam-to-column connection tests, namely to simulate beforehand which material (GFRP or steel) governs failure at the in-plane level.

3.3.1. Setup, instrumentation and procedure

Initially, two steel plates were connected to a universal test machine (INSTRON, model 1343 with a maximum load capacity of 250 kN). The specimen was bolted to them using A2-70 stainless steel threaded rods (with the respective diameter), after which, two displacement transducers (from TML with a stroke of 50 mm and precision of 0.01 mm) were installed in order to measure the relative displacement between the test setup and the specimens. The tests were carried out under displacement control at an average rate of 2 mm/min, measuring the relative displacement and the applied load (measured by the tests machines’ built-in load cell).

3.3.2. Results and discussion

After performing the double-lap tests, the load-displacement curves were generated and the values of the connections’ stiffness (\(K\)), ultimate force (\(F_u\)) and displacement at failure (\(\delta_u\)) were determined. These properties are presented in Table 2, allowing to investigate the influence of the diameter of the threaded rod, the edge distance of the bolt hole and the thickness of connection in those mechanical properties.

Regarding the connections’ stiffness, it is easy to conclude that it is not influenced by the position of the hole, as it shows similar results (maximum relative difference of 8%) between series. In opposition, the strength is strongly influenced by: (i) the thickness, showing a mean increase of 31% with the increase of the thickness (from 1.0 mm to 1.5 mm); and (ii) the diameter of the rod, showing a mean increase of 43% with the increase of the diameter (from \(\phi 8\) mm to \(\phi 12\) mm).

Concerning the connections’ ultimate force, the results show that it also does not rely on the position of the bolt hole (average difference of 3%). On the other hand, it is strongly influenced by the thickness of the plate, exhibiting an average increase of ~50% when the plate thickness increases from 1.0 to 1.5 mm.
s of the double-lap tests.

<table>
<thead>
<tr>
<th>Series</th>
<th>K Average ± Std. Dev</th>
<th>F_u Average ± Std. Dev</th>
<th>δ_u Average ± Std. Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>DL-34-20-1,0</td>
<td>5.6 ± 1.4</td>
<td>7.6 ± 1.0</td>
<td>8.4 ± 0.8</td>
</tr>
<tr>
<td>DL-34-20-1,5</td>
<td>9.0 ± 2.5</td>
<td>15.4 ± 2.2</td>
<td>11.7 ± 2.6</td>
</tr>
<tr>
<td>DL-34-60-1,0</td>
<td>6.8 ± 0.9</td>
<td>8.5 ± 0.7</td>
<td>7.8 ± 0.5</td>
</tr>
<tr>
<td>DL-34-60-1,5</td>
<td>8.3 ± 1.2</td>
<td>15.8 ± 2.1</td>
<td>10.5 ± 1.8</td>
</tr>
<tr>
<td>DL-72-20-1,0</td>
<td>9.6 ± 2.0</td>
<td>9.5 ± 1.3</td>
<td>7.3 ± 0.7</td>
</tr>
<tr>
<td>DL-72-20-1,5</td>
<td>15.0 ± 1.7</td>
<td>19.5 ± 0.7</td>
<td>8.5 ± 0.3</td>
</tr>
<tr>
<td>DL-72-60-1,0</td>
<td>11.6 ± 1.5</td>
<td>10.4 ± 1.8</td>
<td>6.6 ± 0.6</td>
</tr>
<tr>
<td>DL-72-60-1,5</td>
<td>16.3 ± 1.6</td>
<td>18.0 ± 1.4</td>
<td>7.8 ± 0.5</td>
</tr>
</tbody>
</table>

Finally, regarding the displacement at failure, it slightly depends on the position of the bolt hole, presenting an average decrease of ~10% with the decrease of the edge distance of the bolt hole. A reduction of 25% (in average) with the increase of the diameter of the rod and a decrease of 20% (in average) with the increase of the thickness were also registered for this parameter.

### 3.4. Beam-to-column tests

#### 3.4.1. Description of the test series

The beam-to-column test specimens comprised one beam and one column, with lengths of 800 mm and 900 mm, respectively, with the cuffs being placed at half height of the column. Two different types of GFRP profiles were used (separately): (i) “SC”, square cross section profiles (120×120×12 mm³); and (ii) “IC”, I-section profiles (150×75×8 mm³). The company ALTO Perfis Pultrudidos, Lda, produced both profiles using E-glass type fibre and polyester resin.

The global geometry of the cuff elements is similar to those studied by Smith et al. [13] and Sigamsethi et al. [14]. However, instead of GFRP, they were made from a thin stainless steel sheeting (1.0 mm or 1.5 mm) that was latter cut, bended and welded to be on the size of the pultruded section in order to minimize the clearance between the elements (<1 mm). Regarding the connection between the SC-profiles, four M8 and two M12 threaded rods (made of A2-70 stainless steel) were used to connect the cuff to the column and beam, respectively. On the connection between IC-profiles six M8 threaded rods (made of A2-70 stainless steel) were used to connect the cuff to the column (using four of the six) and beam (using the other two). Given the greater wall thickness of the GFRP SC-profile compared to that of the GFRP IC-profile, higher diameter rods needed to be chosen in order to avoid their rupture, according to the results of Azevedo [16].

For each type of profile, four different typologies of the cuff were tested: (i) short configuration (BC-IC-240 or BC-IC-270), as illustrated in Figure 4; and (ii) long configuration (BC-SC-360 and BC-IC-360), as illustrated in Figure 5.

#### 3.4.2. Setup, instrumentation and procedure

The setup of the full-scale monotonic beam-to-column tests is illustrated in Figure 6. The tests were performed in a closed steel loading frame anchored to the laboratory strong floor. The load was applied to the beam at 0.6 m from the face of the column using a DAREC hydraulic jack (with stroke of 400 mm and a load capacity of 250 kN in both compression and tension) (Figure 6-B). A TML load cell (with capacity of 300 kN) and two hinges were installed in order to measure and guarantee the verticality of the applied load, respectively (Figure 6-C). In order to avoid local crushing of the beam in the load area, a steel plate (200×50×20 mm³) was placed between the specimen and the two hinges. Both column ends of the specimen were fixed to the steel frame (Figure 6-D), preventing their displacements and rotations.
Additionally, for the I-section specimen, two aluminium bars were placed at the end of the beam in order to restrict out-of-plane displacements (Figure 6-E). For the tubular specimen, a steel plate was fixed to the steel frame, restraining the horizontal displacements of the upper end of the column (Figure 6-F).

The vertical displacement of the beam was measured with a Celesco defleto meter (with stroke of 400 mm) attached to the hydraulic jack. The rotations of the beam and the column were measured with two TML inclinometers (with a range of $\pm 10^3$), as shown in Figure 6. The monotonic beam-to-column tests were carried out under displacement control at a rate of 0.25 mm/s.

![Figure 6 – Beam-to-column test setup and instrumentation: A – closed steel loading frame; B – hydraulic jack; C – load cell; D column fixations; E – beam lateral guides; F – column horizontal guide.](image)

### 3.4.3. Results and discussion

In order to evaluate the response of the connections, the load-displacement curves were obtained and the connections’ stiffness and strength measured. Additionally, the ductility index was also defined for the different test specimens, using the method defined by Jorissen and Fragiacomo [21] for timber bolted connections, which also include ductile materials, such as steel. Therefore, the ductility index is given by the following ratio, where $\delta_u$ is the displacement at failure and $\delta_y$ is the displacement at yield:

$$\mu = \frac{\delta_u - \delta_y}{\delta_u}$$  \hspace{1cm} (1)

Given the non-ductile nature of the failure modes observed, the yield displacement was considered the displacement corresponding to the end of the first linear branch and the displacement at failure as the displacement corresponding to 80% of the maximum force ($F_u$) in the descending branch of the load-displacement curve [22].

#### 3.4.3.1. Tubular profiles (SC)

Table 3 presents the experimental results obtained for the different typologies of connection between tubular profiles, as well as the results obtained by Proença [14] and Azevedo [16]. Regarding the global mechanical behaviour, all the typologies presented an initial linear behaviour followed by a gradual stiffness reduction and a second linear branch until failure. The main failure modes observed were: (i) bearing of the steel on the cuff bolt holes (Figure 7-a); (ii) shear-out on the GFRP beams (Figure 7-b); and (iii) buckling of the lateral plate (Figure 7-c). Of all typologies, the BC-SC-360-1.5 presented the best performance, presenting higher stiffness, yielding and ultimate force. In terms of ductility, the connection presented the lowest value, however this was balanced with the better performance in terms of strength and stiffness.

The results obtained show that, as expected, with the increase of the wall thickness of the cuff, the connection presents an increase of 51% and 2% in terms of stiffness and strength, respectively, for the short configuration; and 28% and 26% for the long configuration. Regarding the ductility of the connection, the increase of the wall thickness of the cuff causes a decrease of the ductility index of 3% (short configuration) and 10% (long configuration), both within the margin of experimental uncertainty.

<table>
<thead>
<tr>
<th>Ensaio</th>
<th>$K$</th>
<th>$K_\phi$</th>
<th>$F_y$</th>
<th>$\delta_y$</th>
<th>$F_u$</th>
<th>$\delta_u$</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC-SC-241-1,0</td>
<td>103.5</td>
<td>48.9</td>
<td>2.60</td>
<td>25.1</td>
<td>7.89</td>
<td>200.3</td>
<td>0.87</td>
</tr>
<tr>
<td>BC-SC-241-1,5</td>
<td>211.8</td>
<td>83.9</td>
<td>3.68</td>
<td>26.0</td>
<td>10.13</td>
<td>177.6</td>
<td>0.84</td>
</tr>
<tr>
<td>BC-SC-360-1,0</td>
<td>186.0</td>
<td>78.6</td>
<td>3.89</td>
<td>21.9</td>
<td>8.82</td>
<td>247.3</td>
<td>0.91</td>
</tr>
<tr>
<td>BC-SC-360-1,5</td>
<td>259.6</td>
<td>102.5</td>
<td>5.43</td>
<td>22.1</td>
<td>11.96</td>
<td>127.9</td>
<td>0.82</td>
</tr>
<tr>
<td>F2S [REF]</td>
<td>182.6±20.0</td>
<td>66.4±7.7</td>
<td>4.70±0.60</td>
<td>24.0±5.0</td>
<td>8.73±0.75</td>
<td>127.5</td>
<td>0.79±0.03</td>
</tr>
<tr>
<td>F [REF]</td>
<td>330.8±25.76</td>
<td>138.9±17.7</td>
<td>8.67±0.82</td>
<td>26.6±4.7</td>
<td>15.37±1.82</td>
<td>117.6±1.8</td>
<td>0.77±0.03</td>
</tr>
</tbody>
</table>
Figure 7 – Main failure modes on tubular profiles specimen: a) Steel cuff failure (BC-SC-240-1,0-M1); b) GFRP beam damage (BC-SC-360-1,5-M1); c) Instability of the cuff (BC-SC-360-1,0-M1).

Regarding the length of the cuff, it was verified that its increase gives remarkable benefits in terms of stiffness, namely increases of 44% and 11% in the 1,0 mm thick and 1,5 mm thick typologies, respectively. The increase of length also leads to an increase of 11% and 15% in terms of ultimate force, for the 1,0 mm thick and 1,5 mm thick typologies, respectively. In terms of ductility, the increase of the length of the connection did not seem to have a significant influence, showing variations of 5% and -2%, for the 1,0 mm thick and 1,5 mm thick connections, respectively.

Figure 8 illustrates the moment-rotation curves obtained from the beam-to-column tests for the configuration BC-SC.

Figure 8 – Moment-rotation curves of configurations BC-SC.

Given the similarity between the present experimental study and those developed by Proença [14] and Azevedo [16], it is relevant to compare the best solution of each study. Comparing with the sleeve type “F2S” connection, studied by Proença, the BC-SC-360-1,5 connection presents better mechanical properties, showing an increase of 30% and 27% in terms of stiffness and ultimate force, respectively. The decrease of the mechanical performance is a consequence of the decrease in the thickness of the cuff by 25%. On the other hand, the BC-SC-260-1,5 has the benefit of being more ductile, showing an increase of 8% in the ductility index, taking better advantage of the plasticity of the steel.

3.4.3.2. I-section profiles (IC)

Figure 8 and Table 4 presents the experimental results and moment-rotation curves obtained from the beam-to-column tests, as well as the results obtained by Mendes [17]. Regarding the overall behaviour, the best performing typology is the BC-IC-360-1,0, since it shows the best balance between stiffness, strength, ductility and amount of steel used. Although the BC-IC-360-1,5 typology shows higher values of strength and stiffness, it is compromised by its lower ductility (32% lower).

Figure 9 – Moment-rotation curves of configuration BC-IC.
From the analyses of the results presented, it is easy to conclude that the thickness of the cuff has high influence in the mechanical properties of the connection (stiffness, strength and ductility). The increase of the thickness caused an increase of 19% and 14% in terms of stiffness and ultimate force, respectively, for the short configuration; and 25% and 16% for the long configuration. Regarding the ductility of the connection, the thickness presented even more influence, with its increase leading to reductions of 37% and 32% for the short and long configurations, respectively. This pronounced loss of ductility is caused by the inability of taking advantage of the plasticity of steel, with higher concentrations of damage developing in the GFRP material. In case of the short configuration, with the increase of the thickness, the failure mode stops being caused by bearing on the steel plate (1.0 mm thick cuff) (Figure 10-a), and starts being caused by the shear-out of the GFRP (1.5 mm thick cuff) (Figure 10-b). Regarding the long configuration, with the increase of thickness, the damage on the bottom flange of the beam (Figure 10-c) was observed for lower values of displacement (~30-40 mm instead of -70-80 mm).

Regarding the variation of the length of the cuff, it is noted that it has high influence on the mechanical behaviour of the connection. The increase of the connection’s length caused an increase of the stiffness and strength by: 12% and 18%, respectively, for the 1.0 mm thick configuration; 19% and 20%, respectively, for the 1.5 mm thick configuration. Regarding ductility, the increase of the length of the cuff had a negative impact, showing a reduction of 7% and 3% on the ductility index of the 1.0 mm thick and 1.5 mm thick configuration, respectively. This occurred because increasing the connection’s length caused a premature damage on the GFRP material, namely delamination of the bottom flange and crushing of the web (Figure 10-d). Therefore, in spite of providing better mechanical properties, the performance of the connection is limited by the failure modes associated to the GFRP material.

Given the similarity between the present experimental study and the previous study developed by Mendes, it is relevant to compare both solutions. Analysing the results obtained by Mendes, it is easy to conclude that the BC-IC-360-1.0 typology presents better performance, namely in terms of stiffness, strength and ductility. It is also important to notice that the BC-IC-360-1.0 cuff uses a smaller amount of steel (less 8% in weight) when compared to the 8 mm thick flange-cleated connection studied by Mendes.

### Table 4 - Results of the beam-to-column monotonic tests for I-section profiles.

<table>
<thead>
<tr>
<th>Proveite</th>
<th>K [kN/m]</th>
<th>Kφ [kN.m/rad]</th>
<th>FY [kN]</th>
<th>δy [mm]</th>
<th>Fu [kN]</th>
<th>δu [mm]</th>
<th>Mu [kN.m]</th>
<th>φu [rad]</th>
<th>μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC-IC-270x1,0</td>
<td>202,1</td>
<td>114,2</td>
<td>2,50</td>
<td>9,7</td>
<td>6,05</td>
<td>83,2</td>
<td>3,97</td>
<td>0,12</td>
<td>0,88</td>
</tr>
<tr>
<td>BC-IC-270x1,5</td>
<td>252,8</td>
<td>137,8</td>
<td>5,02</td>
<td>20,5</td>
<td>7,20</td>
<td>49,0</td>
<td>4,71</td>
<td>0,06</td>
<td>0,58</td>
</tr>
<tr>
<td>BC-IC-360X1,0</td>
<td>228,9</td>
<td>125,8</td>
<td>3,87</td>
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<td>7,41</td>
<td>82,4</td>
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<td>0,12</td>
<td>0,79</td>
</tr>
<tr>
<td>BC-IC-360X1,5</td>
<td>306,0</td>
<td>167,1</td>
<td>5,48</td>
<td>19,2</td>
<td>8,86</td>
<td>45,9</td>
<td>5,80</td>
<td>0,06</td>
<td>0,58</td>
</tr>
<tr>
<td>BC-8-F2-M [REF]</td>
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<td>111,0</td>
<td>-</td>
<td>1,66</td>
<td>9,3</td>
<td>0,964</td>
<td>0,02</td>
<td>0,57</td>
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</tbody>
</table>

Figure 10 – Main failure modes on I-section profiles specimen: a) Steel cuff failure (BC-IC-270-1.0-M1); b) Shear-out of the GFRP (BC-IC270-1.5-M1); c) Delamination of the lower flange of the beam (BC-IC-360-1.5-M2); d) Crushing of the beam’s web (BC-IC-360-1.5-M1)

4. Numerical study

4.1. Model description

The following numerical study was performed using the finite element commercial software Abaqus 6.13 [23].

4.1.1. Geometry, mesh and discretisation

The pultruded GFRP profiles were modelled using solid elements (C3D8R); yet two different mesh sizes were used. In the areas close to the cuff (up to 120 mm from the ends of the cuff) a more refined mesh was chosen, whereas in the farther zones, a coarser mesh was adopted. The stainless steel elements (cuff and rods) and
the steel plate were also modelled using solid elements (C3D8R). At last, the bi-articulate load cell was modelled with a frame element (T3D2). In order to reduce the computational cost, only half of the connection system was modelled, applying the appropriate symmetry conditions. Regarding the mesh sensitivity study, three different refinements were studied, changing the number of elements of the column, beam and cuff. The most refined mesh of the three was chosen, whose main features are presented in Table 5.

### 4.1.2. Material properties

The pultruded profiles were modelled with an orthotropic linear elastic behaviour based on the experimental results of Proença [14] and Mendes [17], presented in Table 6 and Table 7, where the longitudinal direction corresponds to 1 and both transverse directions to 2/3.

#### Table 5 - Mesh properties.

<table>
<thead>
<tr>
<th>Structural element</th>
<th>Type of element</th>
<th>Number of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load cell</td>
<td>Frame (T3D2)</td>
<td>1</td>
</tr>
<tr>
<td>Steel plate</td>
<td>Solid (C3D8R)</td>
<td>32</td>
</tr>
<tr>
<td>Rods M8</td>
<td>Solid (C3D8R)</td>
<td>504</td>
</tr>
<tr>
<td>Cuff</td>
<td>Solid (C3D8R)</td>
<td>37814</td>
</tr>
<tr>
<td>Column</td>
<td>Solid (C3D8R)</td>
<td>8462</td>
</tr>
<tr>
<td>Beam</td>
<td>Solid (C3D8R)</td>
<td>7564</td>
</tr>
</tbody>
</table>

#### Table 6 - Profile’s elastic properties.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>41,3</td>
<td>5,74</td>
<td>0,29</td>
<td>3,14</td>
<td>2,4</td>
</tr>
<tr>
<td>W</td>
<td>43,6</td>
<td>5,74</td>
<td>0,22</td>
<td>3,12</td>
<td>4,36</td>
</tr>
</tbody>
</table>

#### Table 7 - Profile’s resistant properties.

<table>
<thead>
<tr>
<th>f1,T [MPa]</th>
<th>f1,C [MPa]</th>
<th>f2,T [MPa]</th>
<th>f2,C [MPa]</th>
<th>f1,S [MPa]</th>
<th>f2,S [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>347</td>
<td>328</td>
<td>29,0</td>
<td>46,7</td>
<td>47,1</td>
</tr>
<tr>
<td>W</td>
<td>384</td>
<td>375</td>
<td>29,0</td>
<td>42,3</td>
<td>47,7</td>
</tr>
</tbody>
</table>

In this numerical study, the damage (and its progression) of the GFRP material was not accounted for due to the uncertainties and difficulties related to the Continuum Shell elements, required for their modelling. The stainless steel was modelled using the results obtained from the characterisation tests as input. The material was defined with an elasto-plastic behaviour and true stress-true strain [24] was taken into account (Table 8) according to the expressions (2) and (3), in which \( \varepsilon_{TS} \) and \( \sigma_{TS} \) are the true strain and stress, respectively; and \( \sigma_E \) and \( \varepsilon_E \) are the engineering strain and stress, respectively [17]. The threaded rods were modelled with the same stainless steel’s properties (as a simplification).

\[
\varepsilon_{TS} = \ln(\varepsilon_E + 1) \tag{2}
\]

\[
\sigma_{TS} = \sigma_E \times e^{\varepsilon_{TS}} \tag{3}
\]

#### Table 8 - Properties of stainless steel.

<table>
<thead>
<tr>
<th>E [GPa]</th>
<th>v [-]</th>
<th>( \sigma_y ) [MPa]</th>
<th>( \sigma_u ) [MPa]</th>
<th>( \varepsilon_{u,pl} ) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>198,92</td>
<td>0,26</td>
<td>182,73</td>
<td>707,07</td>
<td>0,6</td>
</tr>
</tbody>
</table>

### 4.1.3. Boundary conditions

The vertical load was simulated with the imposition of a vertical displacement of 120 mm (Figure 11-1), applied to the top of the load cell (600 mm from the column’s face), which was coupled to the steel plate (coupling condition) (Figure 11-4). All elements that were coincident with the symmetry plane were modelled with a longitudinal sliding boundary condition (Figure 11-3) and both column ends were fixed (displacements and rotations restrained) (Figure 11-2).

#### 4.1.4. Contact and friction formulation

The connection between the steel plate and the flange of the beam was modelled with a tie restraint (Figure 11-5). A frictionless contact was considered for the contact between: (i) GFRP-GFRP; (ii) GFRP-SS; and (iii) SS-SS. Concerning their normal stiffness, a parametric study was developed in order to find the most suitable solution. All the contact stiffnesses were resorted to surface-to-surface and small sliding theory.

Figure 11 - Boundary conditions for the typology BC-IC-270-1.0.

### 4.2. Contact’s stiffness parametric study

The stiffness of the normal contact between the elements is associated with high uncertainty, given the difficulty in obtaining those values experimentally. In this context, a parametric study was developed to analyse the influence of different values of stiffness, namely using: (i) linear contact, with values of 1000, 5000, 7500 10000, 50000 and 100000 MPa/mm; and (ii) hard contact (rigid). In order to find the most suitable contact solution, the calibration took into account the following criteria: (i) the
initial response and global stiffness of the connection; (ii) the convergence of the model; and (iii) the computational cost. Figure 12 illustrates the load-displacement curves of the different configurations.

Figure 12 – Force-displacement curves for different contact configurations.

This study showed that the increase of the contact stiffness (for linear type) as no influence on the value of the global stiffness of the connection system, however, it presents convergence benefits. Thereby, the use of a contact with linear stiffness ($k=50000$ MPa/mm) was considered the most suitable taking into account the criteria previously defined.

4.3. Results and discussion

Figure 13 compares the load-displacement curves obtained in the experiments and with the FE model for typology BC-IC-270-1,0. The numerical curve shows a good agreement with its experimental counterpart until displacements of $\sim60$-$70$ mm were reached. Following the experimental curves, the FE model presents a non-linear behaviour characterised by a progressive loss of stiffness until it reaches the maximum force. However, for the post-failure behaviour, relatively high differences are observed between the curves. In fact, the numerical curve does not present a progressive reduction of the force but, on the contrary, it presents a relatively linear and ascending branch until the maximum force/displacement is reached. This occurs due to the simplifications assumed relatively to the mechanical behaviour of the materials: (i) the fracture of the stainless steel was not considered, neither (ii) the initiation and progression of the damage in the GFRP material.

Table 9 presents the results of the numerical and experimental studies. In terms of stiffness and load at the displacement corresponding to the maximum experimental force $F_{(83,2 \text{ mm})}$, the numerical results present relative differences of $-10\%$ and $6\%$, respectively. In terms of ultimate strength, the relative difference is more pronounced ($20\%$) due to reasons explained above.

Figure 14 illustrates the degree of plasticity of the connection model (PEEQ) for the reference points marked in Figure 13, allowing to observe the evolution of the plastic strains on the model. Initially (Figure 14-a), the connection shows higher deformation in the upper flange of the cuff, with bearing of the bolt and some plasticity on the corner of the cuff. At the deformation for which maximum experimental force was observed, in addition to the already deformed areas, the model shows instability phenomena on the side face of the cuff, as was observed experimentally.
Figure 15 illustrates the longitudinal stress (on the left) and the shear stress (on the right) on the GFRP elements, at the stage where the maximum experimental force was observed (83.2 mm of displacement). Therefore, as was observed experimentally, the propagation of the damage in the GFRP material due to these stress concentrations is verified.

Figure 15 –Longitudinal stress (left) and shear stress (right) in the model.

5. Conclusions

In the present study a novel beam-to-column connection system between pultruded GFRP profiles was developed. An experimental and a numerical study were carried out, in order to evaluate the performance of the connection system in terms of stiffness, strength and ductility, when subjected to monotonic loads.

The beam-to-column tests between tubular profiles allowed concluding that the cuff-type system presents an excellent balance between structural performance and compatibility with the other elements. It has been found that the increase of the cuffs’ thickness and length has benefits in terms of strength and stiffness, however it has a deleterious effect on the ductility to the connection. Regarding the tubular profiles, of all the typologies tested, BC-SC-360-1.5 showed the best performance when subjected to monotonic loading. When compared with the connections previously studied by Proença [14] and Azevedo [16], it stands out for having the best compromise between stiffness, strength, ductility and amount of steel.

Regarding the beam-to-column connection between I-section profiles, the novel system demonstrated great improvements when compared to the traditional cleat angle connections, studied by Mendes [17]. The results allowed concluding that the stiffness and the strength of the connection increase with the amount of steel, however, this also leads to lower ductility indices. Of all the typologies studied, BC-IC-360-1.0 presented the best balance between stiffness, strength, ductility and amount of steel.

Concerning the numerical study, the FE model developed was well able to predict the experimental behaviour up to ~80 mm of imposed displacement; however, it was not able to simulate properly the pre- and post-failure behaviour of the connection. It is important to note that ~80 mm of displacement (and ~0.13 rad of rotation) corresponds, from a real application point of view, to a relatively high deformation (and rotation) value. A mesh sensitivity analysis and parametric study on the contacts’ stiffness was performed to overcome convergence problems, which occurred due to the complexity of the model, in particular the high number of contacts. This parametric study was performed without affecting the value of the mechanical properties.

6. References


J. Azevedo, “Contributo para o desenvolvimento de um sistema inovador para ligações entre perfis de compósito de GFRP,” Dissertação de Mestrado Integrado em Engenharia Civil, Instituto Superior Técnico, 2016.


