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Correlation between the Barcelona test and the three-point bending test for the characterization of SCFRC

Eduardo Galeote\textsuperscript{1} Sergio H. P. Cavalaro\textsuperscript{2} Albert de la Fuente\textsuperscript{3} Ana Blanco\textsuperscript{4}

ABSTRACT

Self-compacting concrete has proved itself to be a suitable solution in many scopes of construction industry. Its higher performance and better flowability has allowed considering its use in new applications. Nevertheless, the brittleness commonly associated to concrete is still present even though it may be compensated with the use of fibres. Several methods included in different guidelines propose tests in order to characterize fibre reinforced concrete, although some of them present some drawbacks concerning the execution or material consumption. The goal of this document is to briefly show the main characterization tests and provide an initial vision of the potential possibilities the use of alternative tests may offer. In this study the three-point bending test, the Barcelona test and the inductive method are described and correlated. In this concern, the results of an experimental campaign which consisted of nine mixtures that included both steel and plastic fibres were analysed in terms of correlating the results obtained between tests. Correlation factors above 0.85 were obtained, proving that an approach to standardised methods by means of non-standardised tests is possible.

Keywords: SCFRC, bending test, Barcelona test, quality control, correlation.

1. INTRODUCTION

The increasing use of self-compacting fibre reinforced concrete (SCFRC) for construction purposes requires reliable testing methods in order to guarantee the quality of the material. For this reason, different codes and guidelines specify the requirements the concrete needs to satisfy by means of specific tests. In fibre reinforced concrete (FRC) one of the most widely spread methods is the three-point bending test, which is performed according to EN 14651. However, the results of this test commonly show a high scatter, reaching values even above 20\%. Furthermore, the size and the weight of the specimens make them hard to handle and hinder the test procedure.

In this regard, it is worth noting the Barcelona test \cite{1, 2} as an alternative method for FRC. This test strongly reduces the scatter and simplifies the execution due to smaller and lighter specimens. Recent research has allowed to substantially simplify this test by developing a new analytical model \cite{3} based on the mechanism of failure of the specimens. Additionally, the results of the Barcelona test can be

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used to predict the behaviour of FRC by means of a constitutive model [4] specifically designed for this test.

Despite the advantages the Barcelona test entails, the parameters of the current constitutive models for FRC are obtained from bending tests [5]. Nevertheless, even though the test EN 14651 is the recommended one for the characterization of FRC, alternative tests may be accepted if proven correlation factors are used. Because of this, the aim of this paper is to determine a correlation between both tests, contributing to the development of an improved quality control for SCFRC by means of simple and reliable testing methods.

For that purpose, an experimental campaign involving Barcelona tests on 150 mm cubic specimens and flexural tests on 150 x 150 x 600 mm beams was conducted. Nine dosages of SCFRC were designed, including into their mixtures either steel or plastic fibres.

2. EXPERIMENTAL PROGRAM

2.1. Mixtures and specimen preparation

Nine concrete mixtures were designed at w/c ratios varying from 0.40 to 0.46. Seven dosages included steel fibres in contents of 30, 45, 50 and 60 kg/m$^3$, whereas the content of plastic fibres was established at 3.5 kg/m$^3$ for the two remaining mixtures. Superplasticizer was added in contents between 1.20-1.69% and accelerator was used in the range of 2.00-3.33% (percentages by weight of cement). The composition of the mixtures is described in detail as follows in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
<th>D5</th>
<th>D6</th>
<th>D7</th>
<th>D8</th>
<th>D9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filler</td>
<td>-</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
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<td>-</td>
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<td>-</td>
</tr>
<tr>
<td>Sand</td>
<td>1050</td>
<td>1050</td>
<td>1050</td>
<td>1050</td>
<td>1050</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Fine Agg.</td>
<td>470</td>
<td>470</td>
<td>470</td>
<td>470</td>
<td>470</td>
<td>470</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Coarse Agg.</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Water</td>
<td>155</td>
<td>153</td>
<td>160</td>
<td>153</td>
<td>157</td>
<td>160</td>
<td>165</td>
<td>165</td>
<td>165</td>
</tr>
<tr>
<td>Cement</td>
<td>390</td>
<td>360</td>
<td>380</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td>380</td>
<td>380</td>
<td>380</td>
</tr>
<tr>
<td>Fibres</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>30</td>
<td>45</td>
<td>60</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>1.23%</td>
<td>1.19%</td>
<td>1.00%</td>
<td>1.49%</td>
<td>1.20%</td>
<td>1.69%</td>
<td>1.40%</td>
<td>1.20%</td>
<td>1.20%</td>
</tr>
<tr>
<td>Accelerator</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.33%</td>
<td>-</td>
<td>3.33%</td>
<td>2.00%</td>
<td>2.00%</td>
<td>2.00%</td>
</tr>
</tbody>
</table>

2.2. Test procedure

Three beams for each mixture were produced and tested using the three-point bending test. A notch was performed at the mid-span of each beam, weakening the central section of the specimen where the load is applied. A CMOD (Crack Mouth Opening Displacement) transducer was installed at the notch to measure the crack opening of the specimen while the load was being applied. The speed of loading during the test was 0.05 mm/min until the crack opening reached 0.1 mm. Afterwards, the speed was increased to 0.2 mm/min until a crack opening of 4 mm was achieved, point at which the test was considered to be finished.

Once the beams were tested, the crack produced during the test divided each beam into two pieces. By cutting each of these two parts, two 150 mm cubic specimens were obtained from each beam. The beams were cut 10 cm away from the centre of the sample in an attempt to eliminate the possible influence of the crack produced by the bending test. A new cut was performed 5 cm away from the edge of the specimen as a way to eliminate the wall-effect. This has led to obtaining 54 extracted specimens. Additionally, 6 cubic specimens per dosage were casted in 150 mm cubic moulds, increasing to 108 the total amount of cubic specimens.

2
The inductive method [6], [7] was conducted on both cut and casted specimens with steel fibres. A coil was used in order to measure the impedance variation produced by the fibres. By spinning the specimens around the three main axes, the orientation number may be calculated for each direction as well as the quantity of fibres inside of the specimen [7].

The Barcelona test for cubic specimens [2] was used to determine the post-cracking behaviour in SCFRC. Two cylindrical punches arranged concentrically above and below the specimen transmit the load at a speed rate of displacement of the piston jack of 0.5 mm/min. Unlike the standardised Barcelona test (UNE 83515), the chain gage cannot be used to control the test due to the cubic geometry of the specimen. Instead, the test must be controlled using the axial displacement [3]. The setups of the three tests described are shown in Fig. 1.

![Figure 1. a) Bending test, b) inductive method and c) Barcelona test.](image)

### 3. CORRELATION ANALYSIS

#### 3.1. Type of specimen

The cubic specimens used to perform the Barcelona and the inductive tests in this experimental campaign were cut or casted. Due to the origin of the specimens, fibres were found to be oriented differently in each kind of specimen. The orientation of the fibres inside the concrete has a great influence on the behaviour of the material [8] as its efficiency can decrease to a 30% when randomly distributed [9], [10]. Fig. 2 shows the orientation and the schematic position of steel fibres in the direction of the Cartesian axes. In both types of specimens axes X and Y correspond to the horizontal plane, whereas the axis Z corresponds to the vertical direction or the direction of pouring. In the case of cut specimens, axis X matches the longitudinal axis of the beams.

![Figure 2. Orientation in a) cut specimens and b) casted specimens.](image)

A clear trend of the fibres towards an orientation in the horizontal plane was found in cut and casted specimens. The total amount of fibres oriented in the horizontal plane raised to a percentage around 80% in both cases. This effect may be attributed to the external vibration during the production of concrete, which limits to only a 20% the fibres oriented in the vertical direction.

In cut specimens fibres are preferentially aligned to the axis X. Assuming the moulds of the beams as confined elements, the flow of concrete while pouring them shows a distribution of forces and speed that may be identified with a parabolic law [9], [11] (Fig. 3). This causes that the torque produced by the concrete make fibres rotate and align themselves in the direction of the flow.
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Figure 3. Mechanism of fibre orientation in a confined flow [12].

The mechanical performance obtained in the Barcelona tests conducted on both types of specimens is shown in Fig. 4. Due to the setup of the test, the crack is always produced in a plane perpendicular to the horizontal. Even though fibres are responsible of the post-cracking behaviour of SCFRC in terms of the amount of fibres sewing the crack produced, no significant differences were found between both kinds of specimens. This may be attributed to the fact that almost the same percentage of fibres is found in the horizontal plane for both kinds of specimens. Consequently, both cut and casted specimens can be used indistinctly at the analysis.

Figure 4. Mechanical performance in Barcelona test in cut and casted specimens.

3.2. Preliminary analysis and results

The analysis of the correlation between both tests involved parameters related with the mechanical performance and the quantity of fibres. As the post-cracking behaviour in SCFRC is one of the most relevant aspects, the analysis focused on delving specifically into it. For the beam test, and in order to consider the same parameters established at the standard, the most suitable results taken into account to correlate were the loads at four different crack openings.

Among all the parameters which are directly obtained or may be calculated after the execution of the Barcelona test, only one has been found to fit best the correlation. This has been the load at a displacement of the jack of 1.5 mm after the peak value. Nevertheless, the more parameters involved in the correlation, the better the equation will fit the results. Hence, taking into account the major importance of the quantity of fibres, it was considered their influence should not be neglected. For this reason, either assessed with the inductive method for steel fibres or considering the theoretical content for plastic fibres, the quantity of fibres into the specimen was also introduced at the study.

Table 2 shows the experimental results used at the correlation analysis. The parameters show the values of quantity of fibres, load at the Barcelona test and the load at the bending test. Each data set is identified with the dosage it corresponds to.

An in depth analysis by means of some software has prompted the obtaining of an equation which allows calculating the load of the bending test out of the Barcelona and the inductive test. Eq. (1) shows the expression used to calculate the parameter sought. There is a concern on the selected equation for a balance between its ease of use and simplicity and a good adjustment of the data.

\[ L_{b,d} = A \cdot L_{BCN,1.5} \left( \frac{B}{\mu_f} \right) \]  

(1)
Correlation between the Barcelona test and the three-point bending test for the characterization of SCFRC

Table 2. Data used at the analysis of correlation [kN].

<table>
<thead>
<tr>
<th>Dosage</th>
<th>$V_f$</th>
<th>$L_{bcn, 1.5}$</th>
<th>$L_{b, 0.5}$</th>
<th>$L_{b, 1.5}$</th>
<th>$L_{b, 2.5}$</th>
<th>$L_{b, 3.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>49.82</td>
<td>71.36</td>
<td>16.04</td>
<td>17.52</td>
<td>17.15</td>
<td>16.24</td>
</tr>
<tr>
<td>D2</td>
<td>42.73</td>
<td>52.88</td>
<td>14.79</td>
<td>14.42</td>
<td>12.66</td>
<td>11.67</td>
</tr>
<tr>
<td>D3</td>
<td>39.60</td>
<td>54.06</td>
<td>14.48</td>
<td>13.42</td>
<td>11.18</td>
<td>9.30</td>
</tr>
<tr>
<td>D4</td>
<td>3.50</td>
<td>20.55</td>
<td>1.32</td>
<td>1.46</td>
<td>1.60</td>
<td>1.61</td>
</tr>
<tr>
<td>D5</td>
<td>3.50</td>
<td>18.74</td>
<td>1.55</td>
<td>1.71</td>
<td>1.88</td>
<td>1.93</td>
</tr>
<tr>
<td>D6</td>
<td>52.02</td>
<td>90.72</td>
<td>17.26</td>
<td>16.52</td>
<td>14.20</td>
<td>11.13</td>
</tr>
<tr>
<td>D7</td>
<td>42.94</td>
<td>68.49</td>
<td>8.98</td>
<td>8.78</td>
<td>8.19</td>
<td>7.79</td>
</tr>
<tr>
<td>D8</td>
<td>56.73</td>
<td>77.27</td>
<td>12.85</td>
<td>15.40</td>
<td>14.81</td>
<td>13.74</td>
</tr>
<tr>
<td>D9</td>
<td>68.63</td>
<td>118.93</td>
<td>22.45</td>
<td>23.57</td>
<td>22.33</td>
<td>20.00</td>
</tr>
</tbody>
</table>

Where $L_{b, i}$ is the load of the bending test at a crack opening $i$, $L_{bcn, 1.5}$ is the load of the Barcelona test at a displacement of the jack of 1.5 mm, $V_f$ is the quantity of fibres for each dosage and $A$ and $B$ are adjustment constants. The load corresponding to the Barcelona test is calculated considering the peak load as the initial displacement, which implies eliminating the elastic stage of the test output. The quantity of fibres is calculated as described in [7]. The values of $A$ and $B$ can be calculated and generalised for any crack opening $i$ by the empirical parabolic laws shown in Eqs (2) and (3).

$$A = -9.5 \cdot CMOD^2 + 53.5 \cdot CMOD + 36.2$$

$$B = CMOD^2 - 6.9 \cdot CMOD - 12.8$$

3.3. Discussion of correlations

The estimated load corresponding to the bending test calculated by means of the equation proposed has been linearly correlated with the experimental results. This has led to four different correlations considering the four crack openings mentioned before. Even though the main amount of dosages include steel fibres, a joint analysis with plastic fibres has been considered adequate in order to obtain generalised results for both types of fibre.

Further analysis has been conducted in order to establish an interval of confidence with the purpose of providing more sensitivity and avoid outliers due to the scatter of the results. These intervals have been calculated on the basis of a normal statistical distribution. The values under study to establish the upper and the lower limit were the difference between the theoretical values obtained from Eq. (1) and the real value from the experimental campaign. Fig. 5 shows both the correlation coefficients and the intervals of confidence calculated, representing the theoretical loads in abscissae and the real values in ordinates.

Results show a high degree of linear association between both the experimental and the calculated parameters. Correlation coefficients have been found to be higher than 0.85, reaching values up to 0.91 in the case of a crack opening of 1.5 and 2.5 mm. However, no theoretical basis is presented to justify the accuracy of the method.

An interval of confidence was calculated in each case to represent the results with a 95% of probability of being adjusted to the theoretical value calculated through Eq. (1). Table 3 shows the upper and the lower limits of the intervals for each crack opening considered at the analysis.

Table 3. Confidence intervals at different crack openings [kN].

<table>
<thead>
<tr>
<th>Probability</th>
<th>$I_{c, 0.5}$</th>
<th>$I_{c, 1.5}$</th>
<th>$I_{c, 2.5}$</th>
<th>$I_{c, 3.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>95%</td>
<td>+1.5</td>
<td>+1.3</td>
<td>+1.2</td>
<td>+1.1</td>
</tr>
<tr>
<td>50%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5%</td>
<td>-1.5</td>
<td>-1.3</td>
<td>-1.2</td>
<td>-1.1</td>
</tr>
</tbody>
</table>
Correlation between the Barcelona test and the three-point bending test for the characterization of SCFRC

Figure 5. Correlation coefficients and intervals of confidence for bending loads at different crack openings.

These loads represent the upper and the lower range values that can be added or substracted from the results calculated with the equation proposed. Note that the highest range of variation is ±1.5 kN, which entails an acceptable ratio considering that this result is around a 10% of the average of the loads obtained at the post-cracking behaviour.

4. CONCLUSIONS

This study analysed the possibility of a new methodology to characterize self-compacting fibre reinforced concrete. Nine types of concrete blended with steel fibres in contents of 30, 45, 50 and 60 kg/m³ and plastic fibres in a content of 3.5 kg/m³ were prepared. Beams were tested under the three-point bending test, whereas the Barcelona test and the inductive method to assess the orientation and quantity of fibres were performed on 150 mm cubic specimens.

In cut specimens, fibres align preferentially in the direction of the flow when pouring the beams cut specimens are extracted from. Despite of the differences in the orientation of the fibres, both cut and casted specimens were found to be suitable for their joint analysis. The correlation proposed allows calculating the results of the bending test out of two tests using data that can be quickly obtained. The following conclusions can be drawn from the study performed:

- A simple equation was obtained to calculate the post-cracking behaviour determined by a three-point bending test with correlation coefficients between 0.85 and 0.91. Results at any crack opening can be calculated by adjusting two constants included in the equation proposed.
- An interval of confidence allows an adjustment of the data with maximum differences in the load of 1.5 kN (0.5 MPa). These confidence intervals determine the error rate which might be produced with respect to the average value. Moreover, they can be used as a method to adjust the results upwards or downwards depending on the degree of adjustment desired by the user.
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