

# CORRELATION OF RESIDUAL STRENGTH AND FIBRE ORIENTATION FOR HIGHLY ANISOTROPIC SFRC

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## ABSTRACT

The objective of this research was to evaluate the mechanical response of Steel Fibre Reinforced Concrete (SFRC) with high anisotropy (produced by spraying). The results of an experimental program conducted with the inductive method – to determine the fibre orientation – and the Barcelona Test – to evaluate the residual mechanical response – are presented and discussed. Results show that core failure planes in the Barcelona test, and therefore the residual strength, are highly determined by fibre orientation when SFRC has high anisotropy. The main crack in the Barcelona test takes place orthogonally to **the direction with minimum fibre orientation**. Therefore, the Barcelona test may underestimate the real strength capacity of structural elements in which the principal tensile stresses take place in directions away from **the direction with minimum fibre orientation**. Furthermore, it can potentially provide more realistic results in structures without a clearly defined cracking plane. Finally, based on the experimental results, a correction factor is proposed for design.

*Keywords:* SFRC, Inductive method, Barcelona test, fibre orientation, anisotropy

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## 1. INTRODUCTION

The tendency of fibres to adopt specific alignments in the concrete production process has been studied since the earliest studies into fibre reinforced concrete (FRC) [1]. The wall-effects related to the mould shape, the fresh-state properties of the FRC, the way the concrete is poured, the effects of vibration, and the flow of the fresh concrete (for self-consolidating/compacting concrete (SCC)), are all aspects governing fibre orientation [2]. In particular, the spraying process causes a clear fibre alignment, with a preferential orientation parallel to the sprayed surface [3, 4].

Fibre orientation has a direct influence on the residual strength of FRC. Usual methods to evaluate residual strength and toughness of FRC are based on prismatic beams (via 3 or 4 point loading) or panels (mainly for sprayed FRC). New test methods are being developed to overcome the drawbacks of these tests, namely, the large scatter in their results; their complexity; the effort and time required to conduct the tests; and the heavy test specimens required. Among the new tests, the DEWS (Double edge wedge splitting) test, developed in the Politecnico de Milano [5], and the Barcelona test, developed in the Universidad Polit cnica de Catalunya [6], are worthy of mention.

In particular, it has been shown that the post-cracking strength of FRC is proportional to the average fibre orientation [7–9]. In this sense, several methods, including manual counting and x-ray image analysis, are available to evaluate fibre orientation. A summary of these methods is presented by Pujadas *et al* [10]. More recently, non-destructive methods, such as the Inductive method [11], have been developed. These methods can only be applied to Steel Fibre Reinforced Concrete (SFRC), due to the magnetic properties required.

Considering these issues, for design purposes, as much as possible regarding the relationship between fibre orientation and the mechanical characteristics of FRC should be known. Furthermore, the test used to evaluate the FRC should simulate, as close as possible, the behaviour of the real structure which the test sample represents, in particular related to the alignment of fibres with respect to the applied tensile stresses.

The objective of this research was to assess the mechanical response of SFRC with high anisotropy (produced by spraying) in order to evaluate its correlation between fibre orientation and residual strength.

## 2. METHODOLOGY

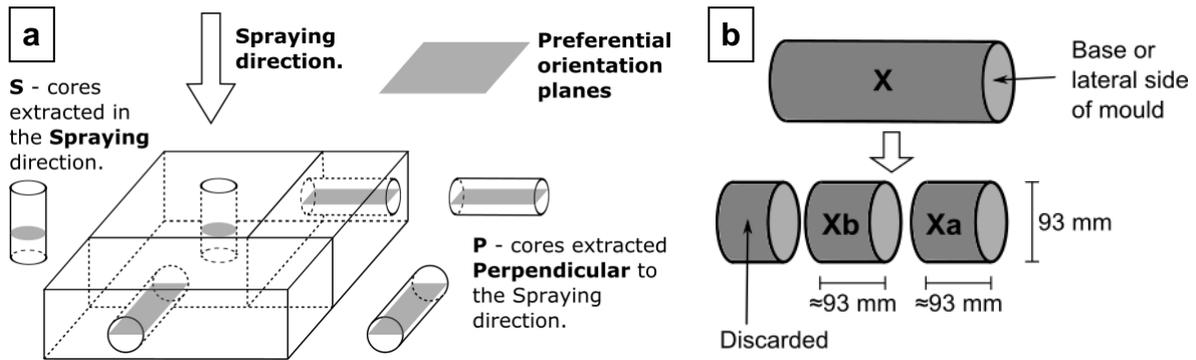
Two types of test (Inductive and Barcelona) were conducted on cores extracted from different directions from a concrete mould, as described below.

### 2.1. Spraying process and extraction of cores

A pre-mixed wet mixture was sprayed using an Aliva 503 spraying robot towards 100 X 80 X 15 cm moulds on a construction site, as described in [12].

The characteristics of the concrete were: 450 kg/m<sup>3</sup> cement, water/cement ratio 0,4, 30 kg/m<sup>3</sup> DRAMIX RC-65/35-BN fibres, maximum aggregate size of 20 mm, 6,75 kg/m<sup>3</sup> nano-silica (1,5% in kg) and 6,75 kg/m<sup>3</sup> super-plasticizing (1,5% in kg). The complete dosage can be seen in [13]. After 24 hours the moulds were transported to the lab to prepare for the extraction of cores for testing.

The mould boundaries (15 cm) were cut off as they were considered not representative of the concrete due to edge effects. 93 mm diameter cores were extracted in the three main directions of the mould, as is schematically represented in Fig. 1a. The cores labelled ‘S’ were extracted oriented in the **spraying** direction, and the cores labelled ‘P’ were extracted **perpendicular** to the spraying direction. With this extraction procedure, cores with different preferential planes were obtained.



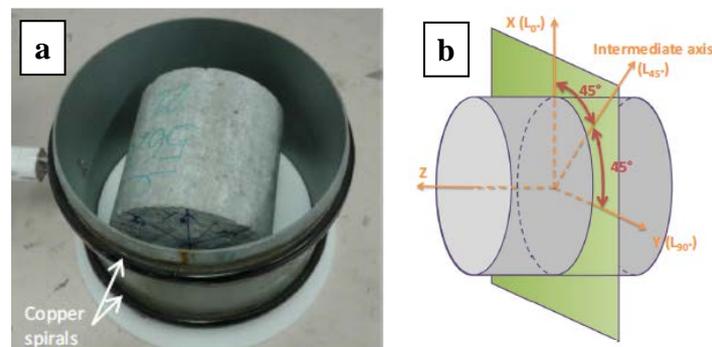
**Figure 1.** Core preparation: a) scheme of core extraction positions and directions; and b) cutting of cores.

The extracted cores were further prepared for the tests by cutting them into sections of approximate slenderness of 1 (Fig. 1b). Two sections were obtained per core extracted, and the remaining part of the core was discarded.

## 2.2. Fibre orientation (Inductive method)

The assessment of the fibre distribution in the concrete mould was conducted by means of a non-destructive magnetic method [11, 14, 15] applied on the extracted cores. This method is based on the measurement of the alterations produced in four directions (Fig. 2b) in a magnetic field when the SFRC specimen is placed within a coil (Fig. 2a). The summed measurements from the three orthogonal axes are related with the fibre content, whereas the differences amongst measurements in each direction are correlated with the alignment of the fibres in the correspondent direction.

Furthermore, due to the third measure taken in the local  $xy$  plane, the determination of the orientation number distribution in any in-plane direction within the local  $xy$  plane is possible through the equations proposed in [11], as well as the directions with the maximum and the minimum fibre contribution and the anisotropy level in that plane.

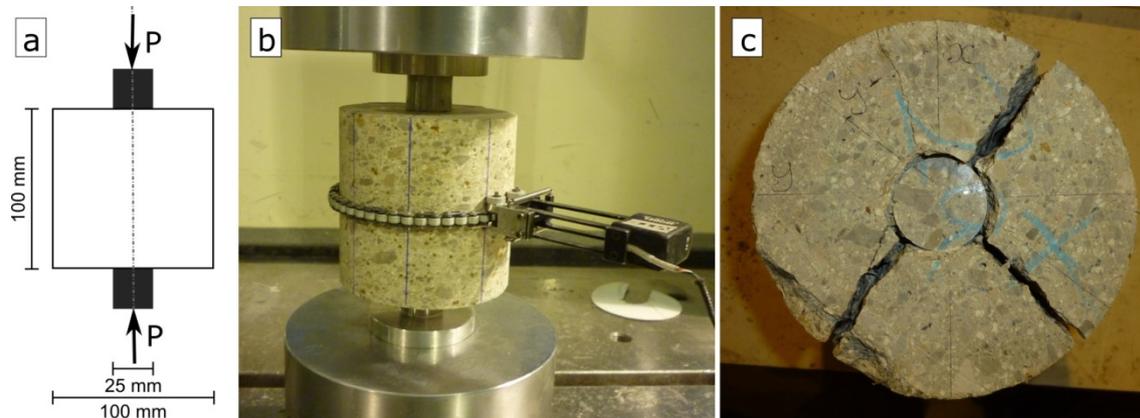


**Figure 2.** Inductive method: a) cylindrical coil; and b) Measurement axes. [taken from [11]]

## 2.3. Barcelona test (double punch test)

A modified Barcelona test method (presented by Molins et al. [6], and standardized by UNE 83515:2010 [16], which is based on the double punch test, was used to characterize the tensile behaviour of the cores. For this test, the cores were placed between two cylindrical steel punches centred at the top and bottom surfaces of the sample (see Fig. 3a). The applied compression produces transversal tensions which lead to the radial cracking of the core (Fig. 3b). Residual strengths are indirectly related to the axial load and the opening of the cracks, which are measured by a chain around the half-height of the sample, closed with an opening transducer (Fig. 3b). The opening of the transducer represents the Total Circumferential Opening Displacement (TCOD).

The modification introduced was a reduction of the dimensions of the specimen and of the cylindrical punches used. The specimen size was changed from a diameter and height of 150 mm, to a diameter and height of 93 mm. The punch diameter was reduced from 37,5 mm to 25 mm, approximately preserving the 1:4 ratio between the punch and the specimen diameter.

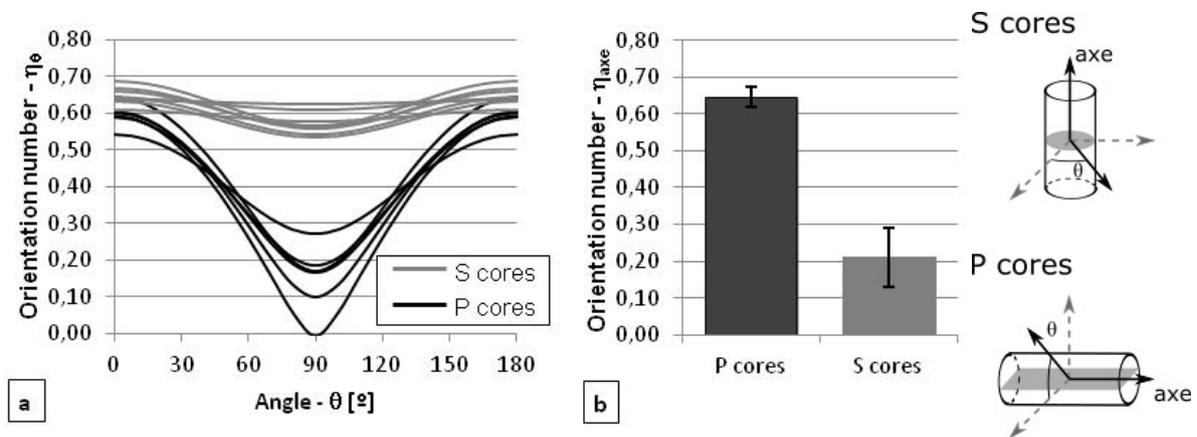


**Figure 3.** Barcelona test: a) device sketch; b) test set up; c) specimen after failure.

### 3. RESULTS

#### 3.1. Fibre orientation

Fig. 4a shows the calculated orientation number for the different angles around the cores for both types of core. The reference angles have been shifted to match the angle with the larger orientation number for each core, with  $\theta=0^\circ$ . The results clearly show the anisotropy of the sprayed SFRC and the existence of the preferential orientation plane, as explained below. Fig. 4b shows the average of the calculated orientation number in the direction of the axis of each core.



**Figure 4.** Inductive method results according to direction in cores.

For the S cores, the orientation number is smaller in the direction of the core axis ( $\eta_{axe}=0,20$ ), which coincides with the spraying direction, than in the remaining planes, where the variation is also small ( $\eta_\theta$  around 0,60).

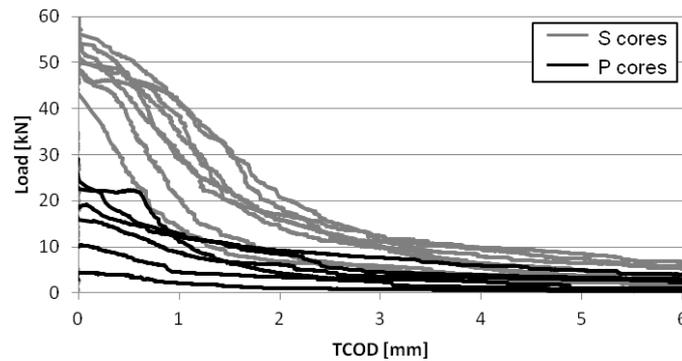
For the P cores, the orientation numbers have a large variation around the core ( $\eta_\theta$  from 0,15 to 0,60 on average), showing the difference in the orientation number as the evaluated direction changes from the spraying direction to the spraying plane. The value of the orientation number in the axis coincides with the values obtained in the spraying plane ( $\eta_{axe}=0,65$ ).

The fibres are less oriented with the direction of spraying, with an average  $\eta$  of around 0,20. Conversely, the remaining plane (i.e. the plane of spraying), has an approximate isotropic orientation

where the fibres are favourably aligned, with the average orientation number ranging from 0,57 to 0,65 in the different plane directions.

### 3.2. Barcelona results

The global results of load vs. TCOD for the Barcelona test are presented in Fig. 5. The TCOD values were shifted to start 0.0 mm after the first crack opening. It can be observed that, despite the scatter of the results, the cores extracted in the spraying direction (S cores) present larger loads for the same values of displacements than the cores in the spraying plane (P cores), confirming the anisotropy of the material regarding its mechanical behaviour.

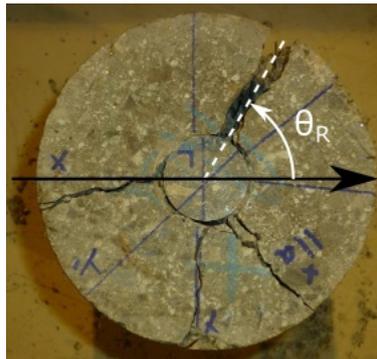


**Figure 5.** Load vs. TCOD.

Larger differences are observed for smaller values of TCOD. In the non preferential direction, the average load is around 30% that of the preferential direction. For further comparisons the characteristic TCOD opening of 0,5 mm will be used.

### 3.3. Angle of rupture

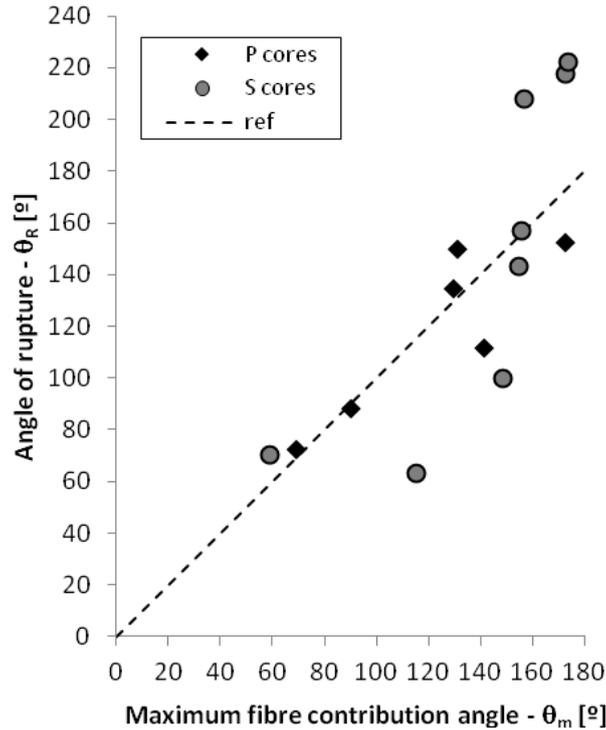
Between 2 and 4 cracks appeared during the loading process of the Barcelona test, in line with previous results [17]. Among these, there is usually one that develops a wider opening. The angle between the direction of this crack and the reference line marked in the core, as it can be seen in Fig. 6, was registered as the angle of rupture ( $\theta_R$ ). Conversely, the angle between the direction where the maximum orientation number takes place and the reference line is recorded as  $\theta_m$ .



**Figure 6.** Angle of rupture ( $\theta_R$ ) measurement after the Barcelona test.

The correlation between the angle of rupture ( $\theta_R$ ) and the maximum contribution angle ( $\theta_m$ ) for each core is presented in Fig. 7. **The dotted line indicates the identity.**

It can be seen that the P cores show a very good correlation between both values, showing a maximum difference of  $30^\circ$  for all the cores. It could therefore be suggested that the fibre orientation influences somehow the cracking pattern, particularly the main crack. Therefore, it should be possible to make a prediction of the direction of the main crack of rupture from the Barcelona test using the inductive method, if the fibres present a clear anisotropy.

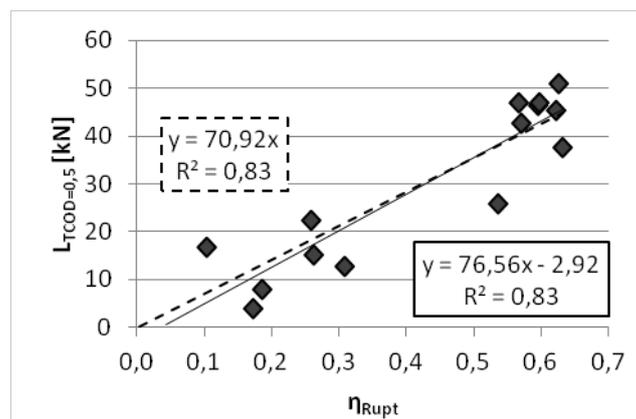


**Figure 7.** Angle of rupture vs maximum fibre contribution angle for each core.

For the S cores the difference in both angles is bigger than for the P cores, reaching differences of up to 52°. The bigger difference can be explained considering that in these cores the orientation number is quite similar in the different radial directions. Therefore, the main crack is less susceptible of being controlled in any particular direction. This leads to a crack opening in a more random fashion, increasing the differences measured between  $\theta_R$  and  $\theta_m$ .

### 3.4. Load vs fibre contribution

Fig. 8 presents the critical load for TCOD = 0.5 mm versus the orientation number in the direction orthogonal to the main crack ( $\eta_{Rupt}$ ) for each core. Two trend lines are included, the best fit linear (continuous line), and the directly proportional best fit (discontinuous line).



**Figure 8.** Critical load vs. orientation number in the rupture direction.

It can be observed that the critical load developed by the SFRC is fairly correlated with the orientation number  $\eta_{Rupt}$ , showing both lines correlation coefficient higher than 0,82. The result, in line with previous research [7–9], seems coherent if it is considered that the residual tensile strength through a crack is influenced by the amount of fibres crossing the crack, which is directly correlated with the orientation number.

Furthermore, in the previous section it was seen that in the Barcelona test the angle of rupture ( $\theta_R$ ) could be estimated using the direction of maximum fibre orientation. Therefore, it also seems plausible to use the minimum orientation number to predict an approximate residual strength given in the Barcelona test.

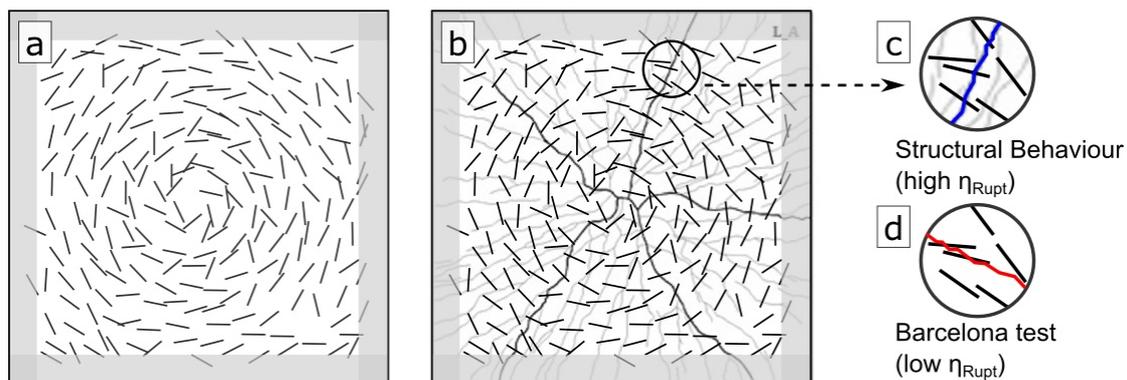
The analysis in this section were conducted for  $TCOD=0,5mm$ , but similar trends were also observed for  $TCOD=0,0mm$ . For  $TCOD=3,0mm$  and  $TCOD=6,0mm$  the relationship is less, partially because the residual strengths are much smaller.

#### 4. DISCUSSION

It is well known that the fibre orientation in the loading direction significantly influences the post cracking behaviour of the SFRC. In this sense, the test used to evaluate the SFRC should simulate, as close as is possible, the behaviour of the real structure which the sample represents. In almost all cases however, with test we can just have an approach to the real behaviour of the structure.

If a fairly isotropic fibre orientation is obtained from the structure, the Barcelona test will obtain a representative value of the residual strength. Conversely, according with the results presented here, if an anisotropic fibre orientation exists in the core tested from the structure, the Barcelona test results will be dominated by the weak planes (with less fibres bridging the cracks). In this case, if there is not a predominant loading direction (e.g. ground-bearing structural slabs), the Barcelona results would be representative of the behaviour of the structure.

If the loading direction is known however, and it does not correspond with the direction of minimum fibre collaboration, the Barcelona test would underestimate the residual strength capacity of the structure, obtaining more conservative results. For instance, this could be the case of centrally cast slabs made of self consolidating/compacting fibre reinforced concrete. In this case, fibres are mainly oriented orthogonal to the radial flow (Fig. 9a), and the cracking pattern is known to be radial [18], as shown in Fig. 9b. In this situation, the crack would take place orthogonally to the main fibre direction (Fig. 9c), with a high orientation number and, therefore, a relatively elevated residual strength. If the Barcelona test was performed in a core extracted from the slab, the test will fail through a plane co-linear with the fibres (Fig. 9d), i.e. a low orientation number in the plane of rupture and, therefore, a relatively low residual strength value.



**Figure 9.** a) Fibre orientation in centrally cast slabs; b) Typical crack pattern in slab; c) Detail of crack pattern; and d) crack pattern of core under Barcelona test.

It is suggested here that the residual strength obtained by the Barcelona test can be corrected using the information obtained by the inductive test. The correction would be necessary only in the case where anisotropy SFRC is tested and if it is known that the load direction of the structure would be different to the direction of minimum residual strength in the Barcelona test.

The residual strength in the loading direction of the structure ( $L_{TCOD,L}$ ) can be obtained from the residual strength obtained with the Barcelona test ( $L_{TCOD,R}$ ) using a *direction correction factor* ( $K_\eta$ ), as shown in Eq. (1).

$$L_{TCOD,L} = K_{\eta} * L_{TCOD,R} \quad (1)$$

The direction correction factor ( $K_{\eta}$ ) is defined through Eq. (2), based on the results that show that the residual strength has a directly proportional relationship with the orientation number.

$$K_{\eta} = \eta_{Load} / \eta_{Rupt} \quad (2)$$

Where  $\eta_{Load}$  is the fibre orientation number in the load direction of the structure, and  $\eta_{Rupt}$  was already defined as the orientation number in the direction orthogonal to the main crack.

## 5. CONCLUSIONS

An experimental campaign based on the Barcelona test and the inductive test was conducted to evaluate the residual mechanical properties of sprayed SFRC. Results confirm the fibre anisotropy, with the preferential orientation plane being orthogonal to the spraying direction, and with different residual strengths being obtained in the different directions.

The main crack direction in the Barcelona test is highly influenced by the fibre orientation, and takes place orthogonally to the direction where the orientation number is minimum, mainly, when the sample tested presents a high fibre anisotropy. Furthermore, the fibre orientation number in the direction orthogonal to the main crack is directly proportional to the residual strength value obtained with the Barcelona test.

The Inductive test and the Barcelona test can be used together to predict SFRC residual strengths in any in-plane direction, and by testing a single core. Finally, a correction factor is proposed, which can be applied if the loading direction does not correspond with the minimum reinforcement direction.

Further investigation of the correlations herein presented is required, in particular for other fibre distributions, with orientation numbers ranging from 0,5 to 0,8. In addition, it would be interesting to validate the results using a directional oriented test, such as the DEWS test [5].

## ACKNOWLEDGMENTS

The authors would like to thank the Spanish Ministry of Science and Innovation for the economic support received through Research Project IPT F-00339 FIBHAC.

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