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## CHAPTER 6

### *CONCLUSIONS*

In this Chapter, the main conclusions drawn from the work presented in this thesis will be summarized. In general, the principal objectives specified in Chapter 1 have been satisfied.

Regarding the uniaxial tension testing of SFRC, it was shown that the test could be performed with a relatively simple configuration and a standard testing machine. Moreover, the entire test methodology has been presented, using which a complete and stable stress-displacement response can be obtained. The method was successfully applied to normal and high strength concretes and appears to be adequately sensitive to fiber content though there is a large scatter in the results. Toughness measures based on the post-peak tensile response have been defined to characterize the behavior of the SFRC.

The parametric study carried out with the proposed tension test methodology allowed the complete definition of the test configuration, and specimen geometry and dimensions. The study demonstrates that for the analyzed ranges of slenderness and notch depths, the uniaxial tensile test of the molded cylinder is robust and valid, with no significant influence of any of the geometrical parameters and with no problems of instability due to the loss of control in the test.

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The effects of fiber orientation on the tensile response have been studied using cores extracted in different directions from beams compacted by vibration. Since coring constitutes the most frequent quality assessment procedure, it is shown that it is essential to consider such effects when vibration is used for compacting the SFRC element.

Tests of push-off shear specimens demonstrate the energy dissipation capacity of steel fiber reinforced concrete, where significant improvements in the ductility of concrete during shear failure and increases in the shear strength are achieved through the incorporation of steel fibers in both; normal and high strength concretes. Furthermore, the proposed push-off shear test can provide stress-based parameters, including the residual shear stress that can be transferred across an open crack, and also allows the calculation of toughness parameters such as equivalent shear strengths that could be used in structural design.

Even on a structural scale, the benefits due to fiber addition remain substantial. Tests of full-scale rectangular- and T-beams have shown that the incorporation of steel fibers significantly improves the deformation characteristics and shear-load carrying capacity of the both types of beams. The failure modes, load-deflection response and strains have been studied for plain and SFRC beams and the influence of the shape of the cross section on these issues analyzed. The variables considered were the height of rectangular beams, and the width and height of the flange in the case of T-beams.

Also, the experimentally obtained results have been compared with those given by design recommendations for SFRC, contributions to these recommendations are presented and, further, a new approach for design based on tension and shear toughness parameters analyzed.

## **6.1. SPECIFIC CONCLUSIONS OF THE THESIS**

### **6.1.1. Uniaxial Tension Test**

- A stable uniaxial tension test can be performed using notched cylinders and controlling the test by means of the average reading of three extensometers placed across the crack.
- There is significant scatter, in the order of 30%, in the post-peak stress-crack opening response.
- There is no significant effect of the notch depth on the stress-crack width relationship for the analyzed range (10-20 mm). However, the 10 mm deep notch specimens presented slightly lower peak stresses.
- No clear tendency in the stress versus crack width curve is observed when varying the slenderness of the 150 mm diameter cylindrical specimen between 1 and 3.
- There is some relative rotation between the crack faces until the initial part of the post-peak response, which is attributed to the non-symmetric crack propagation in the matrix. However, in most cases, the rotation decreases in the later part of the post-peak regime. Limit values of the relative rotation between the crack faces should be recommended.
- Toughness parameters such as the equivalent post-peak tensile strengths can be obtained from the test.
- The visual observation of the halves of the tested specimen allows defining the effective fibers. The values of the toughness parameters are closely related to the number of effective fibers present at the failure plane.
- When cores need to be tested, the effects of fiber orientation due to the method of compaction must be taken into account.
- Panels extracted/cut from existing elements for obtaining the stress-crack width relation are not useful since the limited thickness reduces the effectiveness of the fibers and leads to high scatter.
- In terms of recommending a 'standard' specimen for further uniaxial tensile testing, a 150 mm long cylinder cut from the middle of a standard 150×300 mm molded cylinder (compacted by tamping to avoid fiber orientation) and having a 15 mm

deep circumferential notch at mid-height seems to be optimum. Regarding the measurement of the displacement,  $\delta$ , when a stiff test set up is used it is sufficient to measure only the average  $\delta$  signal from three displacement sensors placed at  $120^\circ$  to each other around the specimen and across the notch.

- For general material characterization, it is recommended to use the equivalent tensile strength up to 2 mm of crack opening. However, the maximum crack width limit can also be set taking into account serviceability conditions of the particular application.

### 6.1.2. Push-off shear tests

- The direct shear push-off tests were stable for SFRCs. However, all the tests performed on plain concrete specimens presented sudden and uncontrollable failure.
- Tension rather than shear stresses causes the sudden failure in the case of plain concrete specimens. Therefore, the use of this configuration for determining the shear response of plain concrete is not recommended.
- The maximum shear strength of fiber concretes presented a rather low scatter, with the variation not exceeding a 13%.
- The test can give a good estimation of the residual shear stress that can be transferred across an open crack.
- Toughness based parameters, such as equivalent shear strengths, can be obtained for its use in structural design. For the determination of such parameters, it is recommended to consider a slip limit of 2 mm to calculate either residual or equivalent shear strengths.

### **6.1.3. Full-scale Structural Elements Failing in Shear**

- The inclusion of steel fibers results in more distributed cracking and an increase in the ultimate shear load-carrying capacity and first-crack load of both rectangular and T-beams.
- For the range of flange widths studied in this project, increasing the flange width does not seem to affect the ultimate shear load-carrying capacities neither the first-crack load of the beams. However, its existence does result in a substantial increase of the shear capacity.
- Increasing the flange widths of the T-beams does not have any significant effect on the deflections of the beams produced at ultimate or first-crack load.
- Increasing the flange depth of the T-beams over a limit value does results in increased ultimate shear load-carrying capacities and first-crack loads. The same tendency is observed for the case of the respective deflections.
- The RILEM and Dramix<sup>®</sup>  $\sigma$ - $\epsilon$  design methods for prediction the shear load-carrying capacity of a SFRC beam seem to be over-conservative.
- The  $\sigma$ - $w$  design method proposed by Casanova and Rossi appears to be satisfactory for rectangular beams. However, predictions for T-beams can be over-conservative, especially for deep flanges.
- A  $\tau$ - $s$  method that uses the equivalent shear strength from a push-off shear test is proposed; it can predict the shear capacity in the case of rectangular beams satisfactorily.

### **6.2. Recommendations for Further Studies**

Although in the present work the tensile characterization of SFRC by means of the uniaxial tension test has been studied in detail, further studies are still needed to see if the test is valid for concretes of different strength levels and containing different fiber types and dosages. Also, more studies are needed for comparing the results with those obtained from the inverse-analysis of beam data.

Regarding direct shear push-off test, more study is necessary on the number of tests that should be performed and the dispersion to be permitted if the test has to give a parameter to be use in structural design. Another line of further research is an experimental study on the size effect that can influence the test results. Both aspects could be analyzed through a parametric study.

In the case of full-scale structural elements, more test data is required to validate a standard for shear design of SFRC. It will be useful to study further variations in the cross section of beams, especially thin web elements, interrelations between conventional stirrups and fibers, and the influence of the concrete strength.

More research still needs to accomplish for the implementation of the  $\sigma$ - $w$  shear design method since the use of just one residual tensile strength does not seem to be sufficient. The extension of the approach to T-beams also requires more study. The  $\tau$ - $s$  response appears as an attractive alternative for shear design; an application was attempted here with promising results for rectangular beams but must be further analyzed. A way to extend it to T-beams is also necessary and will require more work.