

Flexural response of SFRC under impact loading

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Abstract

The research presented in this paper deals with the impact behavior of steel fiber-reinforced concrete (SFRC). An experimental campaign on unnotched prismatic specimens has been carried out, covering three types of steel fibers (smooth, hooked and prismatic), two volumetric contents (0.5 and 1%), and companion unreinforced plain concrete specimens. Impact tests have been performed with an instrumented drop weight testing machine recently installed at the Technical University of Madrid (UPM), Spain. According to experimental results, the peak strength and fracture energy of tested SFRC mixes are strain-rate dependent, showing dynamic increase factors (DIF) well larger than 1. On the one hand, the analysis has shown that the DIF of the peak bending strength of SFRC reinforced with smooth and prismatic fibers is higher than the DIF of the tensile strength of plain concrete and increases with the fiber content. SFRC reinforced with hooked fibers presented higher DIF with 0.5% fiber content than with 1.0%. The influence of rate-dependent size effect in the former results is discussed in the paper. On the other hand, the DIF of the fracture energy showed the highest rate sensitivity for plain concrete specimens and decreases with the addition of fibers due to the rate dependence of the mechanisms involved in the fiber-matrix interaction.

Keywords: impact, SFRC, dynamic strength, strain rate, flexural strength.

Notation

E	=	elastic modulus
G_f	=	fracture energy
L	=	span length
P_{\max}	=	peak bending strength

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b = width
 f_c = compressive strength
 f_{ct} = tensile strength
 h = height
 t = time
 v_f = volumetric content of fibers

δ = midspan displacement
 $\dot{\delta}$ = displacement rate
 ε = strain
 $\dot{\varepsilon}$ = strain rate

1. Introduction

The addition of fibers to concrete significantly increases its performance against cracking. In tension, the higher capacity of fiber-reinforced concrete (FRC) is due to the ability of fibers to bridge tensile stresses between crack surfaces. In general, higher tensile strength and much higher capacity for energy absorption is attained in FRC than in plain concrete (PC). It is the energy absorption capacity of FRC which makes it especially attractive to be used in structures subjected to loads in the dynamic domain, like impacts or explosions. Against such loading scenarios, concrete structures have a high tendency to develop brittle failures by shear or punching [1, 2]. The brittleness of PC can be enhanced by FRC owing to its energy absorption capacity. The ACI code [3] has recognized the possibility of using a volume content of at least 0.75% of deformed steel fibers as minimum shear reinforcement in common structural applications under quasi-static conditions. In order to study the applicability of FRC to structures subjected to impacts (e.g. rock-fall protection galleries or airport pavings), it seems necessary to extend the acquired knowledge on FRC behavior to dynamic regime. Since concrete is known to have strain-rate dependence of its mechanical properties, an appropriate characterization of FRC in dynamic regime is first required in order to use it properly at the structural level.

The most extended way of characterizing the strain-rate dependence of concrete materials is through dynamic increase factors (DIF). A DIF represents the ratio between the dynamic and quasi-static value of a material property. For PC, formulations for the DIF of the compressive and tensile strength are available [4-6]. Regarding direct tensile strength (f_{ct}) of PC, a high DIF has been typically reported, especially from strain rates of 1-10 s⁻¹ (refer to Figure 1), which has been typically considered as the impact rate domain [7]. In spite of the small fracture energy (G_f) of PC, many authors [8, 9] have reported a significantly higher DIF of G_f than f_{ct} , but no generally accepted formulations exist.

For FRC, not even a formulation for the rate dependence of tensile strength is available. Firstly, it must be emphasized that the term FRC includes a wide variety of materials according to, among other parameters, the fiber type or the matrix composition. Since both parameters play a big role in the fiber-matrix interaction, which in turn is responsible for the tensile behavior of FRC, it makes sense that no general formulations have been provided. Secondly, measurement of dynamic properties (f_{ct} and G_f) of concrete materials is not easy. Modified Split-Hopkinson Bar (MSHB) devices have been employed by some researchers [8-11], which allow for reaching velocities in the high strain-rate domain (10-10³ s⁻¹). Other authors have employed less complex

set-ups with drop weight testing machines [12-15], where strain rates fall within the impact domain ($1-10 \text{ s}^{-1}$). In general, both testing techniques are useful to study the dynamic performance of PC or FRC, but some specific aspects related to the set-ups are to be taken into account when analyzing experimental results.

Existing experimental results on the dynamic behavior of steel fiber-reinforced concrete (SFRC) have shown that both the tensile strength and fracture energy increase with the strain rate. In direct tension experiments (typically performed with MSHB), it has been observed a smaller DIF of the tensile strength and fracture energy of SFRC than PC [16, 17]. Zanuy et al. [18] have shown that the former is due to the smaller rate sensitivity of the mechanisms involved in the pull-out of the fibers within the matrix than the DIF of the concrete matrix itself. Accordingly, the DIF of the tensile strength and fracture energy of SFRC decreases as the fiber content increases. A general formulation for the DIF of the tensile strength of SFRC cannot be provided because it depends on the particular properties of the fibers, the matrix and their interaction. The type of fiber plays a significant role in the rate dependence of both tensile strength and fracture energy of SFRC. While the pull-out of smooth straight fibers is mainly governed by bond stress-slip mechanism, a big part of the pull-out strength of hooked fibers is provided by the end anchorage which requires the formation of plastic hinges in the curved sections of the hook [19, 20]. The rate sensitivity of pull-out of hooked fibers is dependent on the DIF of the steel strength, which is less rate-sensitive than concrete-related mechanisms. Therefore, SFRC consisting of smooth fibers is supposed to present higher DIF than SFRC with hooked fibers, which also shows higher tendency to fiber fracture in the highly dynamic domain.

While the rate-dependent behavior of SFRC in direct tension can be understood as explained in the previous paragraph from the conclusions by [18], the flexural response under impact still presents many research challenges. On the one hand, the quasi-static behaviors of SFRC in bending and tension are already defined as different [21]. On the other hand, there seems to be more difficulties in comparing experimental dynamic results from different authors in bending than in direct tension in terms of DIF. Suaris & Shah [22] obtained higher DIF of the peak strength with SFRC than with the corresponding unreinforced mortar and they stated that it was likely due to the multiple cracking of the matrix observed in SFRC specimens. Naaman & Gopalratnam [23] obtained rather high values of the DIF of the peak strength of SFRC, with increasing DIF for larger fiber content. More moderate DIF was obtained for the fracture energy, also higher for larger fiber fractions. The two former studies were carried out on unnotched specimens. Gopalratnam & Shah [12], now on notched specimens, also obtained higher DIF of peak strength and fracture energy with SFRC than with the corresponding unreinforced matrix. They concluded that it was probably due to additional transverse cracking

of the matrix and interfacial debonding in SFRC specimens. Mindess et al. [24] obtained extremely high values of the DIF of the peak strength in notched PC specimens and they attributed the results to the test configuration.

Bindiganaville et al. [25] have obtained very high values of the DIF of the peak strength (11-14) with unnotched specimens of SFRC reinforced with flat-end fibers. Regarding the fracture energy, it decreased with the loading rate (impact heights from 0.2 m to 1.0 m) due to higher sensitivity to fiber fracture than full pull-out of the fibers as the strain rate increases. Zhang & Mindess [26], with the same fiber type, also unnotched specimens, and impact heights until 1.5 m, observed that the fracture energy decreased when the fiber volume increased from 0.5 to 1.0%. Zhang et al. [13] have found high values of the DIF of the tensile strength (7) and the fracture energy (38) in notched high-strength PC specimens subjected to rather moderate impact heights (0.36 m). The same authors [14] have observed smaller DIF (3.5 for the peak strength and 2.5 for the fracture energy) in SFRC reinforced with hooked fibers under the same testing conditions.

A common result of the former experimental findings is that DIF values were higher than those theoretically obtained with available formulations for the DIF of the tensile strength of concrete (drawn in Figure 1). John & Shah [27] explained that the DIF of the peak strength in bending should theoretically fall somewhere between the DIF of the tensile strength and the DIF of the compressive strength, which seems logical. They concluded that the observation of a higher DIF in bending than in tension should be due to size effects involved in flexural tests. Only in rather large bending specimens (span length of 3.0 m), they obtained the same DIF in bending as the corresponding DIF in direct tension. These interesting conclusions suggest that comparisons between dynamic bending experiments in terms of DIF may be insufficient if the specimen size is not provided.

According to the review of existing experimental results, there is no clear understanding of the impact behavior of SFRC in bending. Many factors may play an influence, like quality of the matrix, fiber type, fiber content or dimensions of specimens. Unfortunately, existing experimental campaigns are not comprehensive enough to include all or some of such influencing parameters. The present paper provides an experimental research on the impact performance of SFRC covering three types of steel fibers and two values of the fiber content, in addition to unreinforced PC specimens. Impact tests have been carried out with a recently installed instrumented drop weight testing machine at the Laboratory of Structures at UPM. The results are analyzed in terms of the peak strength and fracture energy. A discussion is provided

in order to understand the impact flexural behavior and the influence of the testing methodology on experimental results.

2. Experimental approach

2.1. Test overview and configuration

An experimental campaign comprising impact tests of SFRC prismatic specimens has been carried out. The dimensions of specimens were 600 x 150 x 150 mm, tested in a three-point bending configuration with a span length between supports of 500 mm. The overview of test set-up is given in Figure 2. Impact tests were carried out with the instrumented drop weight testing machine recently installed in the Laboratory of Structures at UPM. The machine has an impact capacity of 3.92 kJ. It is possible to drop a mass ranging from 100 to 200 kg from a height up to 2.0 m. The mass is dropped through a guided tower upon releasing the brakes which initially fix the mass at the desired height. The mass is guided through vertical rails by frictionless devices which ensure its free fall. The machine can be used to test linear specimens of span length up to 2.0 m by adjusting the distance between supports. The stability of the machine is ensured by four prestressed steel columns which join the head of the tower with a stiff concrete slab foundation. The supports have a cylindrical shape with a 29 mm radius which allows the free rotation in longitudinal direction. Two load cells of 190 kN (HBM CFW-190) are installed at the supports to measure reaction loads. The impact or tup load is measured with a load cell of 700 kN (HBM CFW-700) installed in the striker. The striking face has a cylindrical shape with a 29 mm radius. The position of the tup is registered with a digital reader. Employed load cells are specifically suited for high dynamic requirements, consisting of piezoelectric force washers with a sensitivity of 4.3 pC/N. They were calibrated by HBM. Due to the high energy capacity of the machine and the brittleness of concrete specimens, it may occur that once the specimen has failed, the dropped mass may still have a considerable kinetic energy. In order to ensure that the equipment does not suffer any damage, an auxiliary brake is placed below the specimen to stop the falling mass. The auxiliary brake is composed of high energy-absorbing elastomeric and wooden plates.

In addition to the sensors installed in the drop weight machine, the vertical acceleration at the midspan of specimens was measured with an accelerometer PCB 353B14 (calibrated by PCB, with a 5 mV/g sensitivity). As well, a 50 mm-long strain gage was bonded on the compression side (at 14.1 mm from the top of the specimen) of a cross-section at 47 mm from the midspan section. The strain gage was not placed at the midspan section in order to avoid its early

breakage during the tests. All measurements were taken at a sampling rate of 40 kHz, except for those of strain gages which could only be sampled at 9.6 kHz.

Tested specimens were subjected to an impact of a 100 kg mass dropped from heights between 0.50 and 1.75 m, which correspond to loading rates ranging from 3.1 to 5.9 m/s. Resulting strain rates were within the typically assumed impact domain, i.e. 1-10 s⁻¹ (refer to section 3.4). Moreover, the strain rates achieved in the present research have been larger than significant experimental campaigns published so far, as those analyzed in section 3.4. At least 6 specimens were tested for each series. Seven series have been tested according to the SFRC mixes described in section 2.2. The specimens were placed on the supports at a distance of 500 mm. Since it could be expected some uplift of the specimens from the supports upon being impacted by the dropped mass, two steel yokes were used at the supports to restrain the vertical displacement and still allowing free rotation. Nevertheless, it was observed that the steel yokes resulted in undesired reaction loads just after the impact because of a somehow fixed support formation (refer to Figure 3). Once the specimen has started to crack, large support rotations occur, as shown in Figure 3(a). The center of rotation of the testing specimen is located in D as the contact point at the supports moves from E to F, as shown in Figure 3(b). Meanwhile steel yokes center of rotation is located at A, and as it rotates the contact point moves from B to C. The geometric configuration of steel yokes should not create a fixed support condition as they move from C towards the midspan. Although this movement is restrained by friction forces caused by the prestressing force steel yokes and the additional prestressing due to the specimen slip, it is observed the formation of fixed support conditions. Moreover, such fixed support formations may cause the development of a second crack at the support cross-section of the specimen. The problem was solved by placing a thin foam layer between the top face of the specimen and the bottom face of the yoke in contact with the specimen, thereby avoiding uplift and undesired reaction loads. The comparison of reaction loads measured with both supporting systems is represented in Figure 3(c) for specimens of series A (PC) and C (SFRC with 0.5% hooked fibers): undesired post-failure reactions are removed with the use of intermediate foam layer.

Also quasi-static tests were carried out for each series in order to have the reference quasi-static flexural behavior. Quasi-static tests were performed with a servo-hydraulic actuator with a three-point bending scheme equal to the one plotted in Figure 2(a). The specimens were subjected to an imposed displacement at the midspan at a loading rate of 0.1 mm/s. The applied load was measured with a built-in load cell of the actuator. Instrumentation consisted of an LVDT measuring the vertical displacement of the midspan section with respect to supports, an

LVDT measuring the crack width at the midspan, and a strain gage with the same configuration as in impact tests.

2.2. Materials

Seven series have been tested, each corresponding to a different material mix. Series A has consisted of a plain concrete mix which serves as a reference for the six SFRC mixes studied. Three types of steel fibers (smooth, hooked and prismatic) were employed, as well as two volume fractions (0.5 and 1.0 %) for each fiber type. Modest values of the fiber amount have been chosen because of its better workability for structural applications. Moreover, selected values (0.5 and 1.0%) lie close to the fiber content required by the ACI code as acceptable minimum shear reinforcement in structural applications (0.75%). It is interesting to analyze whether a significant different behavior is obtained for a fiber content a little smaller and larger than 0.75%. An overview of tested series is listed in Table 1. Prismatic fibers consist of low-carbon steel, 60 mm long straight fibers with two small paths at the ends, and 0.78 mm² rectangular cross-section of 1 mm equivalent diameter. A picture of studied fibers is given in Figure 4. Fiber aspect ratios range from 60 to 80, common for commercially available fibers. The fiber types cover the mobilization of different mechanisms during the pull-out from the matrix. While smooth fibers mainly work by bond and friction, hooked fibers activate an additional force provided by the anchorage. Prismatic fibers, which have two small paths at the ends, are considered an intermediate situation between smooth and hooked fibers. A discussion of the performance of such fiber types in impact regime is carried out in section 3.

All mixes were designed with ordinary Portland cement I 42.5 R/SR, siliceous aggregates with a maximum size of 12.5 mm, limestone filler and Viscocrete 20HE superplasticizer. The mixing proportions are reported in Table 2. The amounts of steel fibers were 39 and 79 kg/m³ for volume fractions of 0.5 and 1.0%, respectively. The average compressive strength and indirect tensile strength (Brazilian test) on cylinders (150 x 300 mm) at the age of testing are listed in Table 1. Manufacturing of specimens was completed by the Section for Special Concretes of Torroja Institute, a specialized research section on concrete and other construction materials of Spanish Research Council (IETCC-CSIC, Spain). A low rotation speed mixer with a capacity of 125 l was employed for all the mixes. The mixing procedure was as follows: The aggregates were firstly mixed in dry conditions. Next, the 15% of the total amount of water was mixed with the aggregates. Thereafter, 2 minutes were waited to allow water absorption by the aggregates. Cement and filler were then added, and they were mixed with the gradual addition of the rest of the water and the additive for 5-7 minutes. The fibers were finally added slowly to ensure a

uniform distribution. All specimens were cured for 28 days at controlled constant temperature and humidity conditions (23 °C, 95%).

2.3. Results

A summary of results of quasi-static tests is listed in Table 3 in terms of peak load and fracture energy. The fracture energy was calculated as the area below the load-midspan deflection diagram divided by the surface of the cracked section. All specimens failed by formation and development of a single crack at the midspan. A ligament of less than 10 mm remained unbroken after the tests. The crack was examined after testing, showing fracture of the aggregates and pull-out of the fibers. No fiber ruptures were found. In specimens consisting of hooked fibers, straightened hooks were observed at the cracked section showing full pull-out development. The complete load-midspan deflection diagrams of quasi-static tests are provided later on in comparison with results of impact tests.

Impact tests were completed by dropping the mass weight (100 kg) from a given height. In all cases, specimens failed by the formation and full development of a transverse crack at the midspan, resulting in the division of the specimens into two fragments. The crack surfaces were examined after the tests in order to detect failure modes. In general, aggregate fractures were observed in all impact tests. Regarding the fibers, both fiber pull-out and fiber fracture were found in the tests. Some details are given in the photographs of Figure 5. In general, sensitivity to fiber rupture was found to be mainly dependent on fiber type. In addition, it was observed some higher sensitivity to fiber rupture with increasing loading rate. Among the fibers tested, it was observed that prismatic fibers were more sensitive to fiber rupture, as all specimens of series B and E presented fiber rupture. Hooked fibers presented some fibers rupture, while most fibers remained unbroken and the hooked end was straightened. In the case of smooth fibers, very few fiber ruptures were observed.

The typical evolution of measured parameters over time is represented in Figure 6 for a specimen of series C subjected to an impact from a height of 1.75 m. As it can be noted, the impact force measured at the tup showed a high peak at a very short time. A time delay between the beginning of the impact force and the reaction forces of 0.2 ms was measured, which could be due to the time required by the impact wave to travel from the impact point to the supports. The measurements taken by the load cells at both supports were rather symmetrical and, therefore, only the total reaction force is represented. The total reaction force developed a smaller peak than the impact force and it consisted of a lower-frequency half wave. The

difference between impact force and total reaction shows the presence of inertial forces, which should have followed a shape over time similar to the acceleration measured at midspan.

Strains measured with strain gages showed interesting results (Figure 6). The strain experienced a first stage in compression followed by a second stage in tension. The change of both stages should correspond to the instant when the crack has propagated so that the depth of the unbroken ligament is smaller than 28.2 mm (the double of the distance from the strain gage to the top of the specimen).

By post-processing the measurements taken with the sensors, the parameters represented in Figure 7 were obtained. On the one hand, the strain rate at the point where the strain gage was placed was calculated by derivation of the measured strain. This is a relevant parameter to understand the dynamic regime mobilized by the impact load and to establish comparisons with available formulations for dynamic increase factors (Figure 1). On the other hand, the midspan deflection was calculated by double integration of the acceleration. This method for obtaining displacements has been successfully used by [14, 28, 29]. According to Banthia et al. [28] and Zhang et al. [13], an appropriate comparison between quasi-static and impact tests can be done in terms of load-midspan deflection curves when the load is represented by the total reaction force rather than by the impact force. By the former way, the effect of inertial forces in dynamic tests is removed. In addition, the fracture energy of impact tests can be calculated by considering the area below the reaction force-midspan deflection curve.

Figure 8 shows the reaction force-midspan deflection diagrams for tested series. Each graphic includes the quasi-static reference behavior and the results of impact tests at different loading rates. In general, the curves consisted of a first ascending branch up to the peak load (peak strength) and a subsequent softening branch. The most irregular results were obtained for PC specimens (series A), where some oscillations were observed for impact heights of 1.00 and 1.75 m. A common observation of all series is that the peak load and the softening capacity under impact were larger than the corresponding quasi-static values and both increased with the impact height. The former results indicate, in general, DIF values of the peak strength and the fracture energy larger than 1.0, and growing with the impact height. The same cannot be concluded with regard to the pre-cracking stiffness.

The peak strength (P_{\max}) and fracture energy (G_f) are plotted in Figure 9 for each fiber type over the impact height. It must be noted that the results obtained for series A (PC) are plotted in all graphics, so that each graphic can be used to study the influence of the fiber content. For all fiber types, larger values of P_{\max} were obtained as the fiber content increased (except for smooth

fibers under impact height of 1.5 m). The former cannot be generally stated regarding G_f . Even though fiber-reinforced specimens had higher fracture energy than corresponding PC specimens, the results with $v_f = 0.5\%$ were in many cases larger than with $v_f = 1.0\%$. This may be explained by fiber rupture.

A similar study can be done by representing the results for a given value of the fiber content, in order to study the influence of the fiber type (Figure 10). For a fiber content of $v_f = 0.5\%$, the largest peak strength was obtained with prismatic fibers up to an impact height of 1.0 m. Thereafter, the highest peak strength was obtained with hooked fibers. In terms of fracture energy, very similar results were obtained without regard of the fiber type up to an impact height of 1.5 m. For the tests with a height of 1.75 m, the largest fracture energy was obtained with hooked fibers, followed by smooth fibers.

For a fiber content of $v_f = 1.0\%$, the highest peak strength was obtained with hooked fibers, except for impact heights of 0.5 m and 1.0 m, where prismatic fibers demonstrated higher strength. The largest fracture energy was obtained in specimens with hooked fibers from an impact height of 1.25 m. For shorter heights, smooth fibers provided the largest fracture energy for an impact height of 0.5 m, while prismatic fibers did the same for a height of 1.0 m.

3. Analysis of results and discussion

3.1. Dynamic increase factors

It is clear from the results presented in the previous section that a comparison between the impact performance of specimens with different fibers is difficult in terms of absolute values of peak strength and impact energy. In order to analyze the rate sensitivity, the results are studied in this section in terms of dynamic increase factors (DIF). The results of quasi-static tests are taken as reference to calculate DIF. The DIF of P_{\max} and G_f are represented over the loading rate (in logarithmic scale) in Figure 11. Significant rate sensitivity is obtained for both parameters. DIF values range between 2.2 and 5.5 for the peak strength of fiber-reinforced specimens and they are somewhat smaller for PC specimens. The contrary occurs for the DIF of the fracture energy: very high values were obtained for PC (of about 30) and more moderate values for fiber-reinforced mixes (smaller than 7). Such values are in agreement with other researches [12-14].

According to Figure 11, the DIF of peak strength increases with the fiber content for specimens reinforced with smooth and prismatic fibers. For specimens reinforced with hooked fibers, the

DIF of peak strength was higher with 0.5% fiber content than with 1.0%. Regarding the DIF of the fracture energy, it decreases with the fiber content for all tested fiber types.

The influence of the fiber type on the dynamic behavior can be studied with the help of Figure 12. For a fiber content of 0.5%, the highest rate sensitivity regarding peak strength was obtained with hooked fibers. Specimens reinforced with prismatic and smooth fibers presented approximately the same DIF of P_{max} . In terms of fracture energy, the highest DIF is obtained with smooth fibers, followed subsequently by prismatic and hooked fibers. For a fiber content of 1.0%, the highest rate sensitivity of the peak strength is obtained with prismatic fibers. Regarding fracture energy, the highest rate sensitivity is obtained again with smooth fibers, having the other fiber types smaller DIF.

3.2. Rate sensitivity of fracture energy

A general result obtained from the study of Figure 11 and Figure 12 is the smaller rate sensitivity of the fracture energy as the fiber content increases. This result is in agreement with previous analyses carried out by Zanuy et al. [18], who proposed an analytical model to study the dynamic performance of SFRC as a function of the rate dependence of the mechanisms governing the interaction between matrix and fibers. In particular, such an interaction is a result of mechanisms mobilized during progressive pull-out of the fibers with respect to the matrix as a crack opens in the SFRC. Zanuy et al. [18] concluded that the rate sensitivity of bond-slip mechanism is smaller than the rate dependence of concrete in tension. Therefore, the addition of fibers whose pull-out is governed by bond-slip mechanism (fibers without anchorage details) leads to reduction of the rate sensitivity of the composite material. That conclusion is in agreement with results obtained for specimens reinforced with smooth fibers in the present paper.

Moreover, Zanuy et al. [18] also studied the strain rate dependence of SFRC including hooked fibers. In such a case, the pull-out behavior of fibers with respect to the matrix is influenced by the strength provided by the hook at the anchorage. The resistance of the hook against straightening requires the formation of plastic hinges at the curved portions of the hooked end, which means that the resistance of the anchorage end depends on the yield strength of the fiber. The yield strength of the steel has shown to be much less rate-dependent than the mechanical properties of concrete [30][31], which in turn results in lower rate sensitivity of SFRC reinforced with hooked fibers. Zanuy et al. [18] demonstrated that such smaller rate dependence of steel-governed fiber-matrix interaction may induce fiber fracture of the fibers at a smaller loading rate than in fibers whose fiber-matrix interaction is governed by concrete-related

mechanisms. The previous description explains the smaller rate sensitivity of the fracture energy shown by specimens reinforced with hooked fibers in the present research. It also agrees with the broken fibers observed at crack surfaces in series C and F (Figure 5(c)).

Specimens reinforced with prismatic fibers, with two small paths at the ends, have presented an intermediate rate sensitivity between those of SFRC reinforced with smooth and hooked fibers, much closer to that of SFRC reinforced with smooth fibers. According to observations of fracture surfaces (Figure 5(b)), it seems that the paths were enough to induce fiber ruptures at the ends, probably accentuated by the low yield strength of prismatic fibers. Nevertheless, the incidence of such fiber ruptures was not significant due to the negligible pull-out strength gained by adding the paths (on the contrary, the strength gain by hooked ends is rather significant). It seems that the path works as a weak point in the impact domain.

3.3. Sensitivity to fiber rupture

The sensitivity of steel fibers to rupture before developing a full pull-out from the matrix is a result of the mechanisms mobilized during the pull-out. Moreover, such mechanisms may be rate-dependent as studied by Zanuy et al. [18]. Since the contribution of the pull-out mechanisms to the capacity of the FRC depends on parameters like the fiber aspect ratio (fiber length-to-diameter), the yield strength or the presence of anchorage details, a phenomenological description is here provided to observed fiber ruptures in the impact tests. Regarding smooth fibers, rupture in tension can occur if a cross-section yields before the bond strength develops on the embedded fiber-matrix interface. The former does not occur for common fiber aspect ratios of 60-100 and the use of high yield strength. In the present research, very few ruptures of smooth fibers could be detected, which is in agreement with the aspect ratio (62.5) and the high yield strength (3000 MPa). The contribution of hooked fibers to FRC requires the formation of plastic hinges at curved sections of the hook to activate the force provided by the anchorage. Therefore, the yield strength of the fiber is fully utilized at the anchorage, which results in a higher sensitivity to fiber rupture in dynamic regime. The former, together with the lower yield strength (1200 MPa) than that of smooth fibers (3000 MPa), is responsible for the higher number of ruptured fibers found in specimens reinforced with hooked fibers than in FRC mixes reinforced with smooth fibers. In order to decrease the sensitivity to fiber rupture, a higher fiber aspect ratio than smooth fibers is recommended, which was 80 in the present research. Finally, the pull-out behavior of prismatic fibers with small paths at the ends lies between the mechanics of smooth and hooked fibers. Approximately the same aspect ratio (60) as smooth fibers (62.5) was used in the present research. In the impact tests, specimens reinforced with prismatic fibers

presented the highest number of fiber ruptures, which was probably affected by to the smaller yield strength of such fibers (830 MPa).

3.4. Strain-rate dependence of peak strength

Even though the discussion of section 3.2 provides a good explanation for the rate dependence of the fracture energy, a similar conclusion could be drawn regarding the DIF of peak strength. Nevertheless, the experimental results of Figure 11 clearly show that the rate sensitivity of peak strength has been higher for fiber-reinforced specimens than PC specimens, and it increased with the fiber content for specimens reinforced with smooth and prismatic fibers. Since other authors [12, 23] have obtained the same tendency, further analyses are required to understand the rate dependence of the peak strength of flexural specimens.

The measurements taken with strain gages allow for the determination of the strain rate during both quasi-static and impact tests, as explained in section 2.1. Since the estimation of strain rate from derivation of measured strains in impact tests may involve some difficulties, a simplified analysis has been done in order to verify that estimated strain rates make sense. Such simplified analysis has been based on the correlation which exists between the strain the at the most loaded point of a three-point-bent beam (ε) and the midspan deflection (δ). Those parameters can be calculated as follows, respectively:

$$\varepsilon = \frac{3PL}{2Ebh^2} \quad (1)$$

$$\delta = \frac{PL^3}{4Ebh^3} \quad (2)$$

where P is the load applied at midspan, E is the elastic modulus of the material, L is the span length, and b and h are the width and height of the cross-section, respectively. The relationship between Eqs. (1) and (2) leads:

$$\frac{\varepsilon}{\delta} = \frac{6h}{L^2} \quad (3)$$

In terms of velocities:

$$\frac{\dot{\varepsilon}}{\dot{\delta}} = \frac{6h}{L^2} \quad (4)$$

By substituting the geometric properties of tested specimens in Eq. (4), the strain rate (in s^{-1}) results 3.6 times the loading rate (in m/s). After correcting the former relationship to consider the real position of strain gage in the tests, the strain rate at the strain gage (in s^{-1}) should be 2.9 times the loading rate (in m/s). Figure 13 compares the simplified relationship with the experimental results. A good agreement can be seen, which confirms the goodness of estimating strain rates by derivation from measured strains. It is noted that the values obtained for strain rates in impact tests ($1-10 s^{-1}$) fall within the typical range for impact loading [7].

With the strain rate available from impact tests, the DIF of peak strength can be represented over strain rate (refer to Figure 14). The DIF formulation for the tensile strength of plain concrete by Malvar [5] is included in the figure. According to the comparison, the DIF of tested specimens is higher than the theoretical DIF of plain concrete in tension. Moreover, the DIF is higher for fiber-reinforced specimens than for PC specimens. Both results are hardly understandable at first sight. On the one hand, the DIF of bending strength should be smaller than the DIF of direct tensile strength [27]. On the other hand, the addition of fibers should reduce the DIF with respect to the DIF of PC, according to the discussion of section 3.2.

The apparent little sense of the fact that the DIF in bending has resulted larger than the DIF corresponding to direct tension has been also obtained by many authors [12-14, 23]. The result can be explained by size effect and its rate dependence. It is well known that concrete and quasi-brittle materials exhibit size effect, which can be described by the formulation by Bazant & Planas [32]:

$$\sigma_N = \frac{Bf_{ct}}{\sqrt{1 + \frac{h}{h_0}}} \quad (5)$$

where σ_N is the bending strength corresponding to a specimen size h , f_{ct} is the size-independent tensile strength of the material, B and h_0 are constants to be determined empirically. Very few researchers have focused on the rate dependence of the size effect of concrete [33]. From impact tests of concrete cylinders under compression, Elfahal & Krauthammer [34] have observed an increase in the size effect with an increase in the loading rate. The same has been verified by Bindiganaville & Banthia [35] on unnotched concrete prisms tested under bending impact. According to those observations, it is proposed that Eq. (5) can be modified as follows:

$$\sigma_{N,dyn} = \frac{B(\dot{\varepsilon}) f_{ct,dyn}}{\sqrt{1 + \frac{h}{h_0(\dot{\varepsilon})}}} \quad (6)$$

Eq. (6) suggests that the dynamic bending strength of concrete ($\sigma_{N,dyn}$) is a function of not only the dynamic tensile strength ($f_{ct,dyn}$), but also depends on a size effect law which is strain-rate dependent. The rate dependence of size effect can be described by parameters $B(\dot{\varepsilon})$ and $h_0(\dot{\varepsilon})$. According to the empirical observations by [34, 35], the size effect laws for concrete under different strain rates can be represented as sketched in Figure 15(a). This figure shows the tendency of $B(\dot{\varepsilon})$ and $h_0(\dot{\varepsilon})$: both would increase with the strain rate. From the size effect laws of Figure 15(a), the bending strength can be represented over the strain rate for different specimen sizes in Figure 15(b). Finally, the DIF of the bending strength for a given specimen size can be derived by dividing the dynamic strength by the quasi-static strength, which is represented in Figure 15(c). As it can be observed, the reasoning leads to larger DIF with increasing specimen size. Moreover, the DIF of bending strength can be derived from Eq. (6) as follows:

$$DIF(\sigma_{N,dyn}) = \frac{B(\dot{\varepsilon}) DIF(f_{ct,dyn})}{\sqrt{1 + \frac{h}{h_0(\dot{\varepsilon})}}} \quad (7)$$

According to Eq. (7) and Figure 15, the DIF of bending strength can be larger than DIF of tensile strength due to rate-dependent size effect. Appropriate experiments should be carried out to quantify the parameters of Eq. (7), but the presented qualitative development provides a good understanding of the result that the DIF of peak strength in bending is higher than the DIF of the tensile strength, obtained in the tests of this paper and others [12-14, 23]. The estimation of parameters governing Eq. (7) is rather complex because size effect actually depends on the concrete quality and the specimen shape (including the effect of notching). In addition, as observed from Figure 14, the rate dependence of SFRC seems to be higher than that of PC.

A comparison with some results of the literature is given in Figure 16. Zhang et al. [13, 14] performed impact tests on notched PC and SFRC ($v_f = 0.8\%$ of 50/0.75 hooked fibers) specimens and their results are plotted in Figure 16(a) together with the findings of the present paper for series A, C and F (hooked fibers). From the figure, the results with SFRC reinforced with 0.8% fibers, tested with the same size as those of the present paper, seem to fall between

those obtained here for 0.5% and 1.0%, which makes sense. Moreover, their PC specimens had a smaller size than those presented here and resulted in a higher DIF, which shows the importance of size effect.

Naaman & Gopalaratnam [23] tested unnotched SFRC specimens with three volumetric contents (1, 2 and 3%) of smooth fibers. Their results are compared with those from series A, D and G in Figure 16(b). The specimen size was $h = 75$ mm, which is smaller than the specimens tested in the present research. As expected from the discussion of the rate dependence of size effect, their DIF was higher than that of the tendency line of series A, D and G. Moreover, in agreement with the findings of the present paper, the DIF of Naaman & Gopalartanam [23] increased with fiber content.

A last comparison is done in Figure 16(c) with the experiments on notched specimens completed by Gopalaratnam & Shah [12]. Those authors tested SFRC with 0, 0.5, 1.0 and 1.5% of smooth fibers. The size of the specimens was $h = 64$ mm. Even though the loading rate was slower than that employed in the present research, the results show again an increase of the rate dependence as the fiber content increases.

The comparison of Figure 16 confirms the findings derived from the present experiments and the explanations regarding rate sensitivity of size effect.

4. Conclusions

The impact response of flexurally loaded SFRC specimens has been experimentally studied in this paper. According to experimental results, the following conclusions can be drawn:

- The bending strength (P_{\max}) and fracture energy (G_f) of SFRC reinforced with smooth, hooked and prismatic fibers are rate-sensitive. An increase of P_{\max} and G_f has been generally observed in impact tests with respect to quasi-static tests for all SFRC mixes tested in the present campaign, as well as in companion plain concrete (PC) specimens. Moreover, larger values have been obtained by increasing the fiber volume fraction from 0.5% to 1.0%.
- The rate sensitivity of P_{\max} , measured in terms of DIF, has shown to increase by increasing the fiber content for SFRC mixes reinforced with smooth and prismatic fibers, while it has decreased for SFRC reinforced with hooked fibers. This result might be due to the higher tendency to fiber rupture of hooked fibers in dynamic regime. Moreover, the DIF of P_{\max} has

been higher for all SFRC mixes than for companion PC specimens. A discussion of the rate sensitivity of size effect has been included in the paper.

- The DIF of G_f has decreased with the fiber content of all studied fiber types. In addition, the DIF of G_f measured in PC specimens was much higher than the one obtained in SFRC specimens. This result can be explained by the smaller rate-sensitivity of fiber-matrix interaction than that of the unreinforced concrete matrix.

Acknowledgement

The financial support provided by the Spanish Ministry for Economy and Competitiveness (Ref. BIA2012-30998) is gratefully acknowledged. In addition, the authors would like to express their gratitude to Bekaert for kindly providing the hooked and smooth fibers used in this study.

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List of tables

Table 1. Overview of test series

Series ID	Volume fraction	Fiber type	Fiber length/diameter [mm]	Fiber yield strength [MPa]	Compressive strength [MPa]	Indirect tensile strength [MPa]
A	0%	-	-	-	48.5	4.8
B	0.5%	Prismatic	60/1	830	59.4	6.1
C	0.5%	Hooked	60/0.75	1200	61.4	6.7
D	0.5%	Smooth	10/0.16	3000	64.0	5.4
E	1.0%	Prismatic	60/1	830	52.1	7.0
F	1.0%	Hooked	60/0.75	1200	61.3	6.8
G	1.0%	Smooth	10/0.16	3000	64.7	6.4

Table 2. Mix proportions of test series.

	A	B	C	D	E	F	G
Cement [kg/m ³]	375	375	375	375	375	375	375
Filler [kg/m ³]	75	75	75	75	75	75	75
Water [kg/m ³]	158	158	158	158	158	158	158
Water/cement [-]	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Gravel 8-12.5 [kg/m ³]	318	318	318	318	320	318	318
Gravel 4-8 [kg/m ³]	302	302	302	302	302	302	302
Sand 0-4 [kg/m ³]	1016	1016	1016	1016	1016	1016	1016
Sand 0.01-0.5 [kg/m ³]	32	32	32	32	32	32	32
Superplasticizer [kg/m ³]	3.3	2.9	2.9	2.9	2.9	3.3	2.9

Table 3. Average results of quasi-static tests.

Series	Peak load [kN]	Fracture energy [kN/m]
A	23.5	0.28
B	38.1	3.14
C	30.4	6.75
D	35.3	1.85
E	36.0	6.65
F	49.9	9.04
G	42.8	4.39

List of figures

Figure 1. Representation of some available formulations for the DIF of tensile strength of PC ($f_c = 40$ MPa).

Figure 2. (a) Schematic set-up of impact tests; (b) Overview of an impact test in the laboratory.

Figure 3. (a) Failure mechanism of specimens; (b) Formation of fixed supports with the steel yokes; (c) Comparison of total reaction force obtained with and without foam placed between specimen and steel yokes.

Figure 4. View of studied fibers. Length in cm and diameter in mm. From top to bottom: Smooth 10/0.16, Hooked 60/0.75 and Prismatic 60/1.

Figure 5. Detailed views of failure development at crack surfaces in impact tests: (a) Aggregate fracture in series A; (b) Fibers pull-out and rupture in series E; (c) Fibers pull-out and rupture in series F; (d) Fibers pull-out in series G.

Figure 6. Impact test of series C (impact height of 1.75 m): Measurements over time.

Figure 7. Impact test of series C (impact height of 1.75 m): Midspan deflection and strain rate over time.

Figure 8. Reaction force-midspan deflection diagrams.

Figure 9. Peak strength and fracture energy over impact height: (a) 60/1 prismatic fiber; (b) 60/0.75 hooked fiber; (c) 10/0.16 smooth fiber.

Figure 10. Peak strength and fracture energy over impact height: (a) $v_f = 0.5\%$; (b) $v_f = 1.0\%$.

Figure 11. DIF of P_{\max} and G_f over loading rate: (a) 10/0.16 smooth fiber; (b) 60/0.75 hooked fiber; (c) 60/1 prismatic fiber.

Figure 12. DIF of P_{\max} and G_f over loading rate: (a) $v_f = 0.5\%$; (b) $v_f = 1.0\%$.

Figure 13. Correlation between strain rate and loading rate.

Figure 14. DIF of P_{\max} over strain rate: (a) 10/0.16 smooth fiber; (b) 60/0.75 hooked fiber; (c) 60/1 prismatic fiber.

Figure 15. Study of rate-dependent size effect: (a) Size effect laws under different strain rates; (b) Bending strength over strain rate for different specimen sizes; (c) DIF of bending strength for different specimen sizes.

Figure 16. Comparison of DIF of peak strength with results from literature: (a) Zhang et al. [13, 14]; (b) Naaman & Gopalaratnam [23], (c) Gopalaratnam & Shah [12].