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Numerical Study of the Shear Behavior of Ultra-High-Performance Concrete Beams

Estudio numérico del comportamiento a cortante de hormigones de muy alta resistencia

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ABSTRACT

In the last decades, experimental and numerical studies on steel fiber-reinforced concrete have shown that providing suitable fiber content and distribution in the matrix can improve the post-cracking strength of concrete. Although there is a large database of experimental and finite element model shear tests of steel fiber-reinforced concrete beams, there are not profuse test data and finite element models available for steel fiber-reinforced concrete beams with traditional transverse shear reinforcement (stirrups). In this work, the shear behavior of ultra-high-performance fiber-reinforced concrete beams with three different types of reinforcement is analyzed. For this purpose, a comparative study has been previously carried outo validate the finite element model with conventional rebars. From the results, it was observed that the maximum shear load increased by 39% to 48% depending on the type of steel fibers used, with respect to concrete without fiber reinforcement. The length and number of fibers had a direct effect on crack initiation and propagation.

KEYWORDS: shear, fracture, steel fibers, beam, ultra-high-performance concrete, fiber-reinforced concrete, finite element model.

RESUMEN

En las últimas décadas, los estudios experimentales y numéricos, sobre el hormigón reforzado con fibras de acero, han demostrado que un contenido y una distribución adecuados de las fibras en la matriz pueden mejorar la resistencia del hormigón tras la fisuración. Aunque existe una amplia base de datos de ensayos experimentales y numéricos a cortante de vigas de hormigón reforzado con fibras de acero, no se dispone de profusos datos de ensayos y modelos de elementos finitos para vigas de hormigón reforzado con fibras de acero con armadura transversal tradicional a cortante (estribos). En este trabajo se analiza el comportamiento a cortante de vigas de hormigón de ultra altas prestaciones reforzado con fibras con tres tipos diferentes de refuerzo. Para ello, previamente se ha realizado un estudio comparativo para validar el modelo de elementos finitos con armaduras convencionales. A partir de los resultados, se observó que la carga máxima de cortante aumentaba entre un 39% y un 48%, en función del tipo de fibras de acero utilizadas, respecto al hormigón sin refuerzo de fibras. La longitud y el número de fibras tenían un efecto directo sobre el inicio y la propagación de las fisuras.

PALABRAS CLAVE: cortante, fractura, fibras de acero, viga, hormigón de muy alta resistencia, hormigón reforzado con fibras, modelo de elementos finitos.

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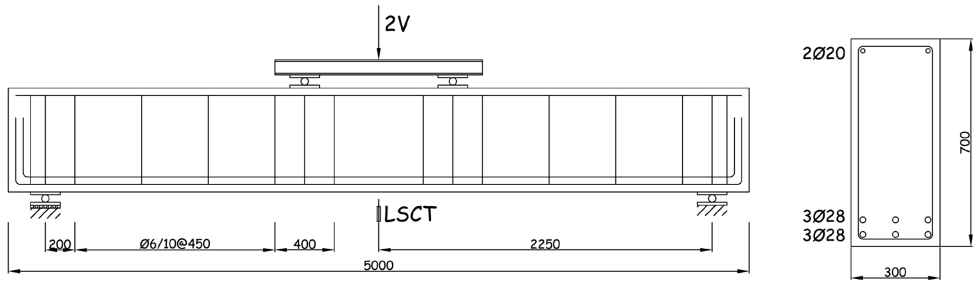
1. INTRODUCTION

The flourishing experienced in recent years by steel fiber-reinforced concretes (SFRC) is well known, both in the study of their properties and applications [1][2]. On the other hand, the development has also reached in ultra-high-performance fiber-reinforced concretes (UHPFRC), although not so much in their applications. This kind of concrete achieves compressive strengths above 200 MPa [3][4] or flexural strengths above 30 MPa [5]. Nevertheless, there is a need to transfer the acquired knowledge, based on all the research effort developed, by applying it in usual structures. To this end, concrete standards have been adapted to facilitate the use of these new materials. This is the case of the Spanish structural concrete standard EHE-08 [6], which already contained an annex 14 with recommendations for the use of concretes with fibers, or the Structural Code [7] or the German [8] and Italian [9] standards. The ACHE association itself published in 2000 a manual to aid in the design of concrete structures with steel fibers [10].



(a) (b)

Figure 1. Test setup. (a) longitudinal section, (b) cross section.

Some studies have demonstrated as following the development of the initial diagonal crack, the fibers regulate crack propagation and permit significant internal plastic stress redistribution to boost the specimens' shear strength [11–13] The addition of fibers can increase the tensile and shear strength of the concrete matrix [14,15]. It may be possible to ease the congestion of reinforcing by reducing the quantity of shear reinforcement in RC deep beams. Steel fibers also offer concrete reinforcement in several directions, clutter-free detailing, and improved post-cracking residual strength and ductility. Lee *et al.* [16] indicated that the steel fibers are more effective in improving the strength and ductility capacity than the stiffness and energy capacity of the specimens.

Regarding shear behavior, some standards have assigned a part of the strength capacity to the fibers, as is the case of the ACI-318 (2008) [17] or the 2010 Model Code [18], although with some inconsistencies, as Amin and Foster [19] refer. Following the guidelines set out in the latter reference, in this work is numerically studied the shear strength mechanisms of beams designed with ultra-high-performance concretes such as those developed in the Structures Laboratory of the School of Engineering of Seville. For this purpose, the commercial software Abaqus [20] has been used to develop the finite element model, and in particular its concrete damage plasticity model.

2.
METHODOLOGY

The procedure followed is analogous to that developed in the work of Amin and Foster [19]. That is, first, the experimental results of the test of a real beam are used as a reference to validate the results of the numerical model of the beam. Subsequently, using this numerical model, in the same way as Amin and Foster, similar beams are modeled with the mechanical properties of the concretes developed in the Structures Laboratory of Seville, whose data can be found in the paper published by Ríos *et al.* [21]. The two most significant differences between the work of Amin and Foster and the one presented here are that, on the one hand, Amin and Foster used ATENA [22], and now Abaqus [20] is used; and on the other hand, the study carried out in this work is extended to the behavior of other novel UHPFRC.

2.1. Experimental test

The experimental test is that already performed by Amin and Foster [19]. Figure 1, adopted from the reference [19], shows the dimensions of the four-point bending tested beam. In this work, it has been assumed the data and experimental results of the beam named B25-10-450 by Amin and Foster. The setup and more details of the test can be consulted in the referenced bibliography, although for the reader's convenience, we remind that the paper indicates that it is concrete with 25 kg/m^3 of fibers, transverse reinforcement formed by stirrups of 10 mm diameter, and the separation of the stirrups is 450 mm. The mid-span deflection was measured by a longitudinal transducer.

2.2. Finite element model

In this work has been used the concrete damaged plasticity model developed by Abaqus. This plastic damage model in concrete reproduces the inelastic behavior of concrete based on an isotropic elastic damage theory in combination with isotropic tension and plastic compression.

The model considers tensile softening when tensile strain exceeds that corresponding to the tensile strength of the concrete. It also allows considering the unloading process through a damage variable, which reduces the stiffness of the material. Damage variables can be defined for both compressive and tensile behavior. In compression, the model uses the plasticization function of Lubliner [23] with the modifications proposed by Lee and Fenves [24]. For plastic flow, the Drucker-Prager hyperbolic function is used.

Figure 2 shows an image of the finite element model that is built with 8-node linear hexahedral elements type C3D8I from the Abaqus library, to simulate the concrete, and two-node linear elements with axial behavior only, for the reinforcing bars, T3D2 from the Abaqus library.

The mesh sensitivity of results of the FEA has been checked. For this purpose, the beam was analyzed using two different FE meshes (quadrilateral elements limited to 50mm and 100mm). The difference between results of the analyses was negligible [25].

The finite element mesh has a characteristic dimension of 50 mm, and 300x200 mm pads with the same stiffness characteristic of the concrete, but without plastic behavior. This behavior is implemented in the support and load application areas to eliminate the problem derived from the application of concentrated loads.

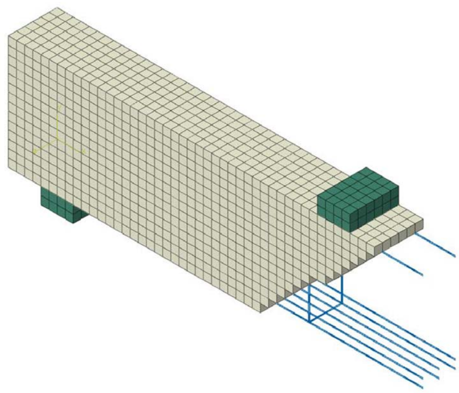


Figure 2. Image of the finite element model.

The model only considers half of the beam, applying symmetry conditions in the central section. On the other hand, the vertical and lateral displacement of the center of the bottom face of the support is prevented, and the model is analyzed by applying an increasing displacement of the central node of the top face of the load pad in a downward direction.

Tie-type displacement constraints are defined between the different parts of the model, i.e., the displacements in all degrees of freedom of the nodes of the contacting faces are made compatible.

On the other hand, it has been defined the condition of the truss type elements to be embedded in the concrete elements, which makes compatible the movements in the translation degrees of freedom of the nodes of the bars, in an interpolated way, with those corresponding to the concrete elements in which they have been inserted.

The mechanical properties of the different materials are particularized for the different models, being common to all of them those corresponding to the longitudinal reinforcement, which maintains the properties of the referred article [19].

3. COMPARATIVE MODEL

A finite element model has been performed to verify the numerical tool, in order to compare the results with the experimental data and the numerical model of Amin and Foster.

It is a replica of the B25-10-450 model. The reference article contains the complete characteristics of this model, of which, for the present study, in addition to those already indicated in section 2.1, we will highlight as the most relevant, those that characterize its behavior in traction.

$$f_t = \begin{cases} E_c\epsilon & \textit{pre-craking} \\ 1.75 - 22.4\omega & \textit{post-craking } \omega < 0.04mm \\ 0.85 - 0.11\omega & \textit{post-craking } \omega \geq 0.04mm \end{cases}$$

Figure 3 shows a comparison of the results of the experimental test, those corresponding to Amin and Foster [13], and those obtained with the Concrete Damage Plasticity model in Abaqus carried out in this work.

A very similar result is observed for the shear behavior that the beam can withstand in the three models, with differences below 3% in both FE models, and a higher stiffness of the finite element models than the real test, which is something more noticeable in the model of our work.

There is a higher difference between the displacement results after the maximum shear force, which has not been considered relevant in order to study the shear strength and could be explained based on different phenomena after cracking.

Based on this result, we justify the study of the behavior of ultra-high-performance fiber-reinforced concretes developed at the Structures Laboratory of the University of Seville.

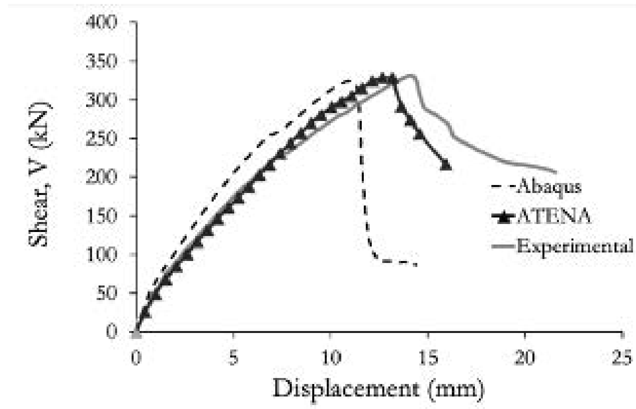


Figure 3. Shear results of the comparative analysis of beam.

4. ANALYSIS PERFORMED

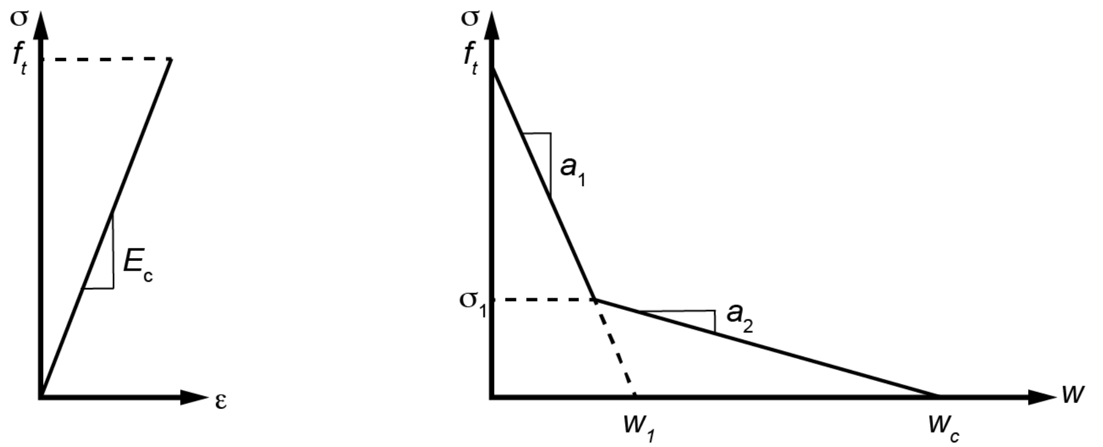
The shear behavior of four ultra-high-performance concretes is analyzed in this section. The UHPFRC mechanical properties can be found in more detail in the paper published by Ríos *et al.* [21].

The main difference among the four UHPFRC is the type of fibers they contain, with the rest of the parameters of their dosage being invariant. Two different types of fibers, called micro-fibers and macro-fibers, have been used in this study. The micro-fibers are straight 13 mm long and 0.2 mm in diameter, while the macro-fibers are shaped at the ends and have a length of 30 mm and 0.38 mm in diameter.

With these two types of fibers, four types of UHPFRC have been manufactured, which are designated as D0, DS, DL and DSL. The D0 mix is a non-reinforced concrete, the rest of the mixes contain 196 kg/m³ of steel fibers in all cases, using only micro-fibers in the DS mix, only macro-fibers in the DL mix, and 50% of each type in the DSL mix. Table 1 shows the mechanical properties of the UHPFRC that have been performed in this way, whose tests have been described in [21].

TABLE 1.
Mechanical properties of the four UHPFRC.

Property	D0	DS	DL	DSL
E_c (GPa)	44.5	43.4	49.2	47.8
fc (MPa)	131.4	154.6	150.2	153.7
f_t (MPa)	4.5	11.7	9.1	10.4
σ_1 (MPa)	0.2046	2.9	3.1	3.6
w_1 (mm)	0.0119	1.7	1.4	3.0
w_c (mm)	0.0694	6.2	12.1	9.9



(a) (b)

Figure 4. Response of UHPFRC in tension: (a) pre-cracking stress-strain response, (b) post-cracking cohesive law.

The response of UHPFRC in tension is represented in Figure 4. The pre-cracking stress-strain response is shown in Figure 4a and the bilinear cohesive law after the tensile first-cracking is presented in Figure 4b.

For the definition of the plastic behavior of concrete in compression, the same behavioral laws are used as those proposed in the work of Amin and Foster [19], which in turn coincide with the formulation of the model code [18] or at least, in the load branch with those proposed by Ruiz *et al.* [26], this part of the compression behavior curve being the most relevant in this study.

The analysis of the shear behavior of the beams carried out with each of these UHPFRC has been performed using a finite element model similar to the one used in the comparative analysis, i.e., the same geometry is used, with the same conventional reinforcement, the same support conditions and the same loading conditions, changing only the mechanical properties that define the behavior of the beam material, according to the parameters shown in Table 1.

5. RESULTS AND DISCUSSION

As a result of the analyses carried out, the load-deflection curves have been obtained for each of the models, which are shown as a group in Figure 5.

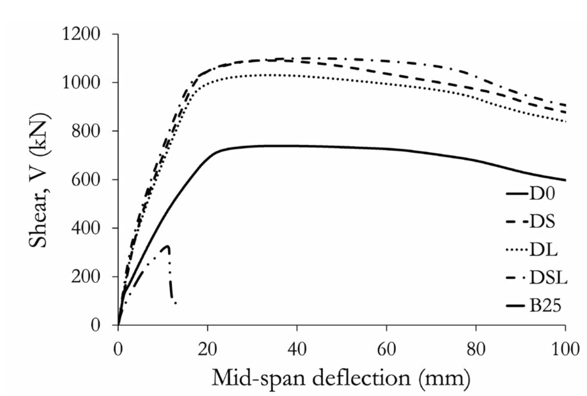


Figure 5. Comparison of FE results against conventional reinforcement.

The initial part of all curves is very similar because prior to cracking, the parameter that governs the behavior is Young's modulus and its value is very similar in all mixtures.

However, linearity disappears as a consequence of cracking in the matrix, firstly in the concrete without fibers, as corresponds to a lower value of its tensile strength, for an applied shear load of about 135 kN, approximately half (70 kN) in the case of B25 concrete. At this load, the beam continues to accept higher shear stresses, which cause a cracking process, and which is reflected in the finite element model as a process of plastic strains, as shown in Figure 6.

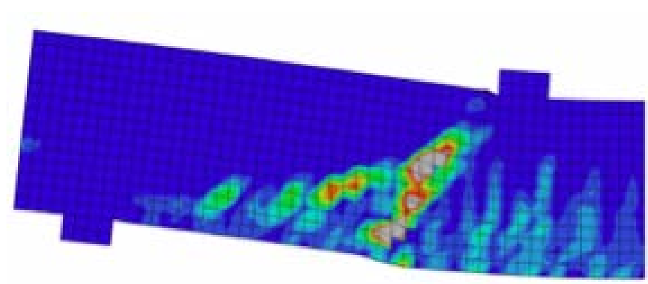


Figure 6. Plastic strains in the FE model.

In the case of the beam without fibers, a maximum shear value of about 740 kN is reached, passing from that point on to a descending branch. This value is 318 kN in the case of B25 concrete, with a subsequent sharp drop.

The behavior of fiber concrete beams is somewhat different, especially from a quantitative point of view, although similar among the three types of fiber mixtures.

The maximum shear values for each model, for ultra-high-performance concretes, i.e., with the same matrix, as well as the percentage increase with respect to this value produced by the addition of fibers, are shown in Table 2.

TABLE 2.
Ultimate shear forces and relative improvement.

	D0	DS	DL	DSL
V_u (kN)	738.87	1090.73	1030.51	1099.79
Δ (%)	-	47.62	39.47	48.85

As can be seen, the addition of fibers considerably increases the shear that the material can withstand, in this case, between 39.5% and 48.9%.

On the other hand, it can also be seen that micro-fibers produce a greater increase in shear than macro-fibers, 47.6% compared to 39.5%. Nevertheless, a curious effect is observed when we compare the behavior of the concrete with micro-fibers with the concrete that mixes both types, and it is that although both mixtures have a very similar behavior, the concrete with micro-fibers develops its greater strength with smaller strains, while the concrete that mixes both types, although it presents less strength to small strains, is able to continue increasing its strength, managing to overcome the concrete with micro-fibers for greater strains, being in the end the most resistant composition.

The explanation is that concrete with macro-fibers has the capacity to develop higher resistance, with larger strains, associated with the greater adherence of these fibers, while in concrete with micro-fibers the lower adherence causes resistance to decay more rapidly. A combination of both types of fibers has the effect of shifting the maximum tensile strength to higher strains, where the conventional reinforcing steel collaborates more to the tensile mechanism.

6. CONCLUSIONS

In this work has been developed a finite element model that has allowed the analysis of the shear behavior of ultra-high-performance fiber-reinforced concrete beams, without incurring the costs of laboratory tests, which is undoubtedly an aid in the investigation of their behavior, although it is not intended to dispense with such experimental models. Four types of ultra-high performance fiber-reinforced concretes have been modeled from experimental characterization based on previous work published by the authors. The improvement against shear forces of applying two types of steel fibers, mixed in three different proportions, has been quantified. The main conclusions derived from the study are as follows:

- The use of plain UHPFRC clearly showed an improvement of 132% in the maximum shear load with respect to conventional concrete.
- The finite element model results show a clear collaboration of the fibers in the tensile strength, which increases the ultimate shear loads between 39.5% and 48.9%, in comparison with the plain UHPFRC, and depending on the type of fiber.
- The highest maximum shear load was obtained with a 50% mixture of micro-fibers and macro-fibers (48.9%), although the greatest response in strains appears in the mixture with exclusive micro-fiber reinforcement.
- However, the lowest maximum shear load was obtained by the mixture only reinforced with macro-fibers because the number of fibers is lower in the matrix and, consequently, hinders the crack coalescence and propagation of a fewer number of cracks.

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