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A State-of-the-Art Review of Synthetic Fibres as Shear Reinforcement in Concrete Elements

Revisión del estado del arte sobre el uso de fibras sintéticas como refuerzo a cortante en elementos de hormigón

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ABSTRACT

Shear failure is considered one of the most critical modes of failure in concrete structures, especially for those elements without shear reinforcement. In the last sixty years, the research community has shown much interest to solve this problem. In fact, since the 80's, the use of fibres as shear reinforcement has been explored as an alternative to traditional reinforcement. Several investigations have shown that the addition of fibres in correct proportions, enhances the shear behaviour in concrete elements with and without shear reinforcement. Most of this knowledge has been built using steel fibres. However, synthetic fibres have also been introduced for structural applications in concrete. Some recent publications have reported the success of synthetic fibres to be used as shear reinforcement in structural elements. Within this framework, the present paper aims to review the existing literature about the use of synthetic fibres as shear reinforcement in structural concrete elements..

KEYWORDS: synthetic fibres; shear; fibre-reinforced concrete; state-of-the-art.

RESUMEN

La rotura por cortante se considera uno de los modos de fallo más críticos en las estructuras de hormigón, especialmente para aquellos elementos sin armadura transversal. En los últimos sesenta años, la comunidad investigadora ha mostrado mucho interés por resolver este problema. De hecho, desde los años 80 se ha explorado el uso de fibras como refuerzo a cortante como alternativa al refuerzo tradicional. Es así como varias investigaciones han demostrado que la adición de fibras en las proporciones correctas mejora el comportamiento a cortante en elementos de hormigón con y sin armadura transversal. La mayor parte de este conocimiento se ha obtenido empleando fibras de acero. Sin embargo, en los últimos años se han introducido en el mercado fibras sintéticas que pueden ser empleadas en aplicaciones estructurales en el hormigón. Algunas publicaciones recientes han informado sobre el éxito de las fibras sintéticas para ser utilizadas como refuerzo a cortante en elementos estructurales. En este contexto, el presente trabajo tiene como objetivo revisar y compendiar la literatura existente sobre el uso de fibras sintéticas como refuerzo a cortante en elementos de hormigón estructural.

PALABRAS CLAVE: fibras sintéticas; cortante, hormigón con fibras; estado del arte.

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1. INTRODUCTION

Even though the study of shear behaviour of reinforced concrete elements has been of interest for researchers, the problem how this phenomenon occurs remain in debate. Shear failure is considered one of the most critical failures in concrete elements as it occurs with no warning, especially in those elements with no shear reinforcement. In fact, great advances have been made in the last years specially on theories and models that describe mechanically the shear behaviour of reinforced concrete elements [1–4].

In general, most of the models provide accurate results when applied on reinforced concrete elements, however, in the case of elements without shear reinforcement, do not achieve the same accuracy. This is due to the fact that shear is influenced by several factors like effective depth, concrete compression strength, the shear span to effective depth ratio (a/d), aggregate size, loading conditions, or longitudinal reinforcement ratio, which interact among them. On the one hand, all these factors influence the different shear transfer mechanisms that occur in a concrete member like aggregate interlock, dowel action effect, residual strength, uncracked compression zone and the arching action, which at the same time influence the shear failure mode of the element. In fact, the development of the critical inclined shear crack plays an important role in the shear transfer mechanisms governing the element.

The shear strength can be modified when new materials such as discrete fibres randomly distributed are introduced to the concrete matrix due their capacity to change the different shear transfer mechanisms in an element.

The study of fibre reinforced concrete (FRC) has been one of the main topics studied in the last 40 years since the fresh and hardened properties of concrete could be modified to improve it. The fibres industry has developed a large variety of sizes, sections and shapes of fibres manufactured with different materials, being the steel ones the most commons used worldwide. The common applications of steel fibres in concrete are pavements, tunnelling lining, shotcrete, and structural applications.

Figure 1 shows the evolution of studies about steel fibre reinforced concrete (SFRC) in the last 45 years and a comparison with macro-synthetic fibre reinforced concrete (MS-FRC) and polypropylene fibre reinforced concrete (PFRC).

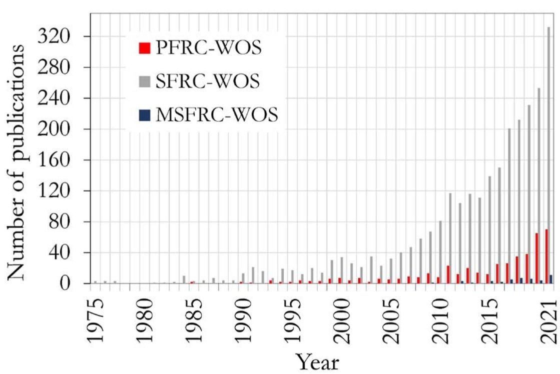

Figure 1. Evolution of studies of FRC in literature.

Although steel fibres were initially employed to control shrinkage in concrete, nowadays, steel fibres are used to improve the flexural toughness, shear strength and ductility of concrete. All these benefits are produced due to the bridge effect of fibres that cross the cracks and sew the crack face holding a residual stress transfer for longer. The impact of fibres in concrete will be influenced mainly by the fibre content, shape, length, aspect ratio, and concrete matrix strength. For structural use, a minimum content of steel fibres must be guaranteed to influence positively on the serviceability limit state (SLS) and the ultimate limit state (ULS).

Similar to steel fibres, the study of synthetic fibre reinforced concrete (SYFRC) has shown a growing increase of interest in the last years as shown in Figure 1. This type of fibre traditionally has been used to control shrinkage cracking since its modulus of elasticity is similar to concrete during the first hours. Types of materials most commonly used as synthetic fibres are polyethylene, polypropylene, acrylics, polyvinyl alcohol, polyamides, or aramid, among others.

Chemical industry in the last decade has improved the polymeric materials used to manufacture fibres being the polypropylene and polyolefin with larger lengths and diameters the most common fibres employed in construction applications. This new generation of fibres, characterized as macro-synthetic fibres, incorporate new treatments over the material to improve the adhesion between the fibre and the concrete matrix.

Some treatments consist of chemical and physical process where the roughness of the fibre is modified chemically or topographically, to increase the adherence of the fibres to the matrix. Modification of material with sodium moieties, colloidal alumina or silica, plasma treatments among others [5,6] result in a better anchorage of fibres in the concrete.

Singh *et al.* [7] studied a new method to improve the bond of fibres by means of mechanical indentations of fibres, i.e. changing the topography of the fibre surface. Authors determined an optimum level of indentations to maximize the bond strength and interface toughness of fibres. Results showed that fibre bond strength increased threefold the bond strength of smooth fibres. These improvements of behaviour in synthetic fibres probably are the cause that nowadays macro-synthetic fibres provide comparable fracture properties to steel ones.

All these modifications have resulted to go beyond the original fibre applications (mainly on fresh concrete) to structural applications where the flexural toughness, and impact strength of concrete is improved. In fact, one of the applications of synthetic fibres is to enhance the shear behaviour of concrete elements.

Within this framework, the present paper aims to review and collet the existing literature about the use of synthetic fibres as shear reinforcement in structural concrete elements. For this, a bibliographic review from the first attempts to use synthetic fibres to improve the shear strength of concrete up to the most recent studies is carried out.

2.
FIRST STUDY ON SHEAR USING SYNTHETIC FIBRES

In 1985 Barr *et al.* [8] described the experimental results for Mode II fracture (shear stress acting parallel to the plane of the crack) of synthetic and steel fibre reinforced concrete. Barr *et al.* used double-notched beams of 100 x 100 x 200 mm as seen in Figure 2a. Fibres used were fibrillated polypropylene of 12 000 denier (700 m/kg) cut into 50 mm single size strands length added in concrete at 0, 0.05, 0.10, 0.15, 0.20, 0.25 and 0.30 % by weight. Steel fibre used was 0.4mm diameter straight fibre cut into 40 mm single size length dosed at 0.2,0.4,1.0, 2.0, 3.0 and 4.0 % by weight.

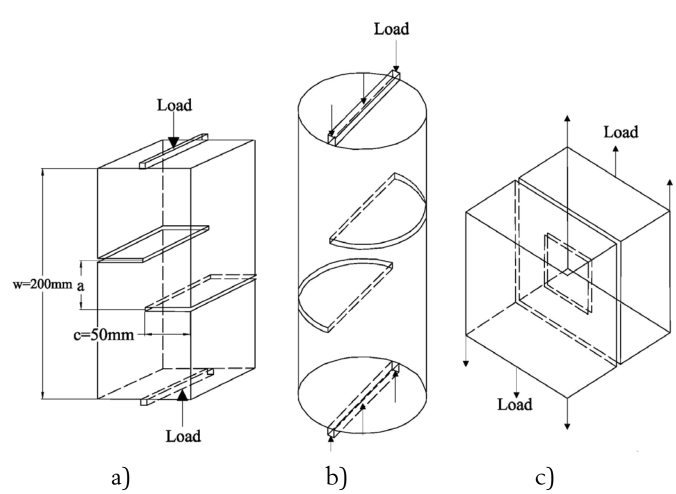

Figure 2. Shear test specimens used by Barr *et al.* [8] a) double-notch beam specimen, b) cylinder double-notch specimen and c) compact cube specimen.

Barr *et al*. continued the study on shear of FRC, and extended the study using two new types of shear specimens [9], cylinders and notched compact cubes, as can be seen in Figure 2b and c. All the specimens were tested with a loading rate of 0.5 mm/min. The main objectives of the study were to determine the most appropriate FRC specimen in order to study the effect of the relationship between the depth of the specimen and the notch separation to compare the effect of fibre content on the shear toughness.

Authors concluded that the shear strength of SYFRC decreased when the fibre amount was increased. Moreover, when toughness of SYFRC in Mode I (stress acting normal to the plane of the crack), and Mode II were compared, both results were similar, whereas when steel fibres with same dosages were investigated, shear strength and toughness in Mode II increased with increasing fibre content. These results probably were influenced by the effect of the fibres in the compression strength of concrete since with the increment of fibre concrete, the compression strength was reduced passing from 38.5 MPa with 0% of fibre content to 21 MPa with 0.5% of fibre content.

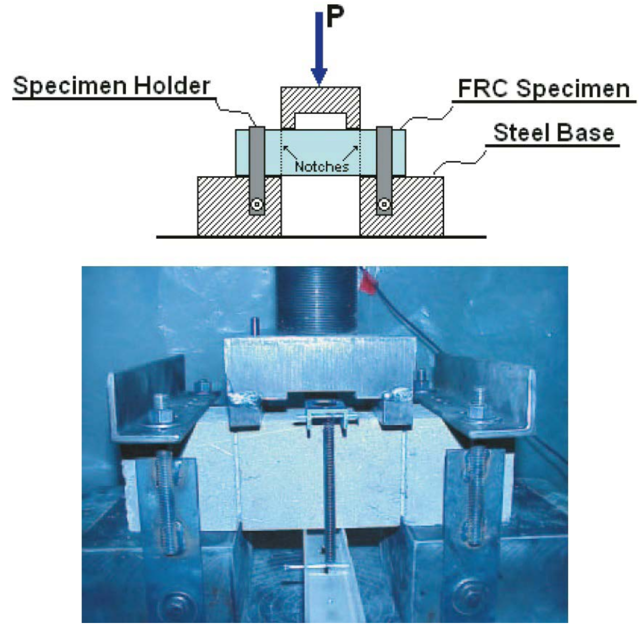

Figure 3. Test setup for direct shear tests performed by Majdzadeh *et al*. [10].

3. DIRECT SHEAR TESTS USING SYFRC

Usually, shear stress acts combined with other stresses such as normal stresses. To decouple and isolate the effect of shear from other mechanisms, concrete scaled specimens have been reported in the literature. These specimens also have been used to evaluate the contribution of the different type of fibres to the shear strength of concrete.

In 2006, Majdzadeh *et al*. [10] conducted an experimental campaign where two types of synthetic fibres and one type of steel fibre were used on slender beams under four-point bending test to evaluate their shear behaviour. As a part of the experimental campaign, prismatic specimens of 100 mm × 100 mm × 350 mm manufactured with SYFRC and SFRC were tested to characterize their shear strength. The synthetic fibres were self-fibrillating of 54 mm length and 0.15 mm of equivalent diameter (aspect ratio equal to 360) with a 675 MPa tensile strength and 3.5 GPa of elastic modulus. The second synthetic fibre was a polypropylene straight fibre of 50 mm length, 0.58 mm of equivalent diameter, 620 MPa of tensile strength and 9.5 GPa of elastic modulus. Both types of fibres presented a density of 0.9 g/cm3. The fibre volume fraction used were 0.5, 1.0 and 1.5%. In total six tests (one specimen for each volume fraction studied and for each fibre type). JSCE-SF6 [11] test was employed (see Figure 3) as direct shear test. The compression strength of the concrete used ranged from 40.9 to 47.1 MPa.

Majdzadeh *et al*. determined that the shear strength increased when the volume fraction of synthetic fibres incremented. In fact, not only the peak strength was increased, but also the residual shear strength providing considerable toughness and ductility in comparison with plain concrete. Nevertheless, not much difference in shear strength was found, between 0.5 and 1% of fibre volume.

Similar results were obtained by Mostafazadeh *et al*. [12,13] in 2016 who studied box culverts of MSFRC. For this, the authors performed 30 shear tests using the Japanese direct shear test [11] as Figure 4 shows. Specimens for shear test were 150 mm x 150 mm x 500 mm. The synthetic fibre was an embossed polypropylene fibre of 54 mm length, 0.80 mm of equivalent diameter, 585 MPa of tensile strength and 6.9 GPa of modulus of elasticity. The concrete mixes included volume fractions of fibres in ratios of 0, 0.26, 0.52, 0.78 and 1.0%. ASTM C1609 [14] was used to characterize the flexural behaviour of FRC. Authors concluded that fibres increased both the shear strength and flexural strength. In fact, with ratios of 0.52% of synthetic fibres, an increase of 25% in shear strength was obtained compared with control beams (without fibres). Finally, authors modelled the behaviour of the small specimens by finite element modelling and observed that synthetic fibres increased the shear strength of box culverts by 67% compared to plain concrete, and suggested the use of this type of fibres as an alternative to reduce the transverse reinforcement and the thickness of the elements.

Figure 4. Test setup for direct shear tests performed by Mostafazadeh *et al*. [12,13].

In 2019, Picazo *et al.* [15,16] evaluated the shear behaviour of MSFRC by means of push-off tests (see Figure 5). The fibres used were straight polyolefin of 48 and 60 mm length and 0.90 mm of equivalent diameter. Fibres presented a tensile strength of 400 and 500 MPa, and modulus of elasticity of 6 and 9 GPa, respectively. Four types of concrete were manufactured, two moderate compression strength concretes, with 6 kg/m³ and 7.5 kg/m³ of 48 mm fibre length, one self-compacting concrete with 10 kg/m³ and one vibrating conventional concrete with 10 kg/m³ of fibres. The compression strength of concrete varied from 21.7 to 39.7 MPa. Authors characterized the residual flexural tensile strength of concretes under EN14651 [17].

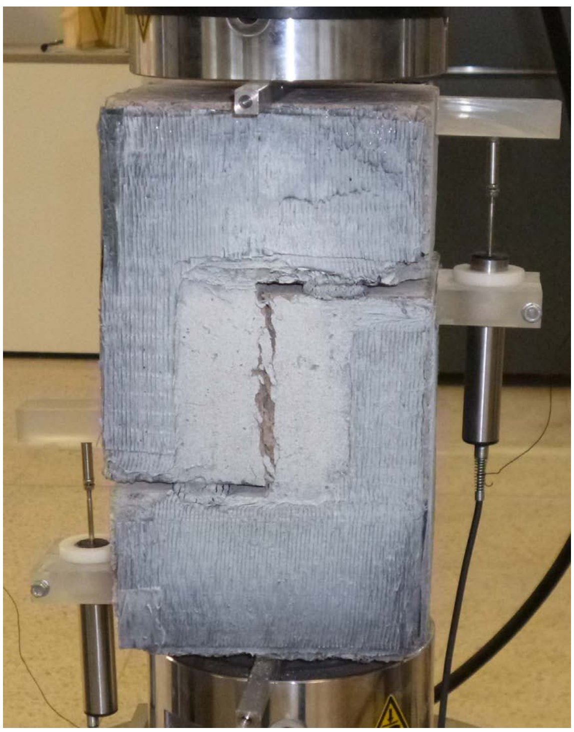

Figure 5. Test setup for direct shear tests performed by Picazo *et al.* [15,16].

The results showed that the shear strength increased as the compression strength of each concrete did. However, shear post-cracking behaviour was similar for all concrete types. This could be due to the significant importance of the aggregate interlock and the fact that the same maximum aggregate size of 12.7 mm was used in all the concretes. Considerable toughness was obtained in the macro-synthetic fibre reinforced concrete specimens compared to the control ones.

4.
SHEAR STRENGTH OF UNIAXIAL ELEMENTS

In 1997, Furlan and Hanai [18] tested fourteen beams of 100 x 100 x 1000 mm manufactured with seven concrete mix proportions where the volume of fibre was varied (see section details in Figure 6). The fibres used were multifilament polypropylene fibres of 42 mm length and 0.05mm of diameter, and crimper steel fibres with rectangular section of 0.2 x 2.3 mm² and 25.4 and 38.1 mm length. Authors did not characterize the residual strength of concrete provided by fibres. Only two of the fourteen beams were manufactured using SYFRC, one with stirrups and one without stirrups. Both beams included fibres dosed at 0.5% of volume fraction.

Although, authors gave no conclusions about the use of synthetic fibres, based on the results, synthetic fibres improved slightly the ultimate load of the beam. Thus, in the case of the SYFRC beam with stirrups the load was increased by 12% while in the beam without stirrups the load was incremented by 9%. However, the mode of failure in the beam with stirrups changed from diagonal tension to flexural failure, whereas in beams without stirrups the mode of failure (MOF) remained the same than in plain concrete (PC). It is worth mentioning that the results may not be conclusive due to the small number of SYFRC beams tested.

Furlan and Hanai [18] continued studying this type of polypropylene fibres on another type of beams such as prestressed I section beams, and obtained quite similar results to the ones described previously (Figure 6).

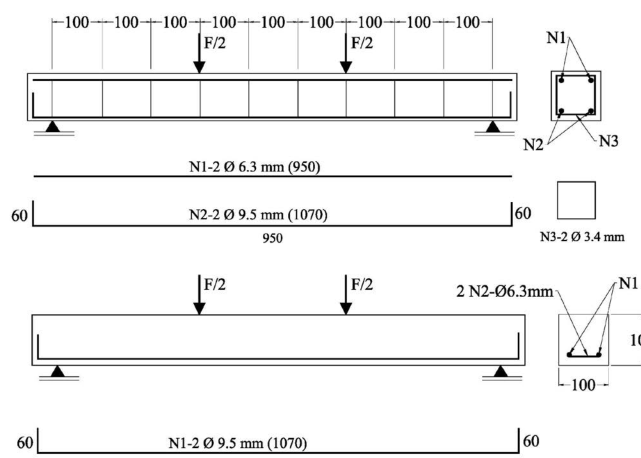

Figure 6. Geometry and reinforcement details of Furlan and Hanai [18] beam with stirrups (a) and without stirrups (b).

In 1999, Campione *et al.* [20] used four types of fibres (polyolefin, carbon, crimped steel and hooked-end steel fibres) to enhance the shear behaviour of fibre reinforced concrete beams combined with traditional transverse reinforcement. Dimensions and reinforcement details can be seen in Figure 7. A total of twenty specimens were tested under four point monolithic and cyclic loading, and four of them were manufactured using synthetic fibre reinforced concrete. The polyolefin fibres (dosed in 2% of volume fraction) were a straight fibre of 25 mm length, 0.8 mm of equivalent diameter, 375 MPa of tensile strength and 12 GPa of elastic modulus. The compression strength for fibre reinforced concrete elements ranged from 53.02 MPa to 78.48 MPa. The residual strength of PFRC measured by splitting tensile strength of cylindrical concrete specimens was 1.30 MPa measured at 2 mm of diametric deformation. Authors concluded that the polypropylene fibres increased the shear strength by 14% compared with beams without any type of fibres, while in the case of steel fibres the increment was over 25%.

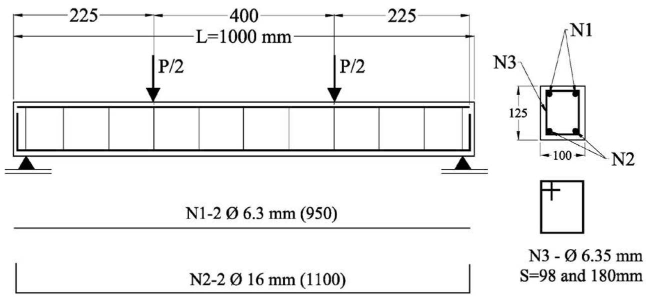

Figure 7. Campione's beams geometry and reinforcement details [20].

In 2006, Majdzadeh *et al.* [10] investigated the influence of three types of fibres (steel and two types of polypropylene fibres) on the shear capacity of reinforced concrete slender beams (a/d = 3.02) with and without stirrups. A total of fourteen beams were manufactured, and eight of them were PFRC beams (two with stirrups and six without stirrups). Dimensions and reinforcement details are presented in Figure 8. Two types of synthetic fibres were employed, self-fibrillating of 54 mm length and 0.15 mm of equivalent diameter (aspect ratio equal to 360) with 675 MPa of tensile strength and 3.5 GPa of elastic modulus. The second type of fibre was a polypropylene straight fibre of 50 mm length, 0.58 mm of equivalent diameter, 620 MPa of tensile strength and 9.5 GPa of elastic modulus. Both types of fibres presented a density of 0.9 g/cm³. The fibre volume fraction used in beams as well as in small specimens for SFRC and PFRC were 0.5, 1.0 and 1.5%. Authors did not characterize the residual strength of concrete provided by fibres. Beams were 800 mm length with a cross section of 150 x 150 mm. The compression strength ranged from 37.8 to 44.8 MPa. Similar than in previous studies, Majdzadeh *et al.* observed that both types of synthetic fibres enhanced the shear capacity, ductility and shear toughness compared to reinforced concrete beams. On the other hand, results showed that that steel fibres were more efficient than both synthetic fibres used in the study. In all fibre cases, the optimum volume fraction was 1%, and after this percentage, no great benefits were found. Finally, results evidenced a synergetic effect to improve shear strength when fibres are combined with stirrups.

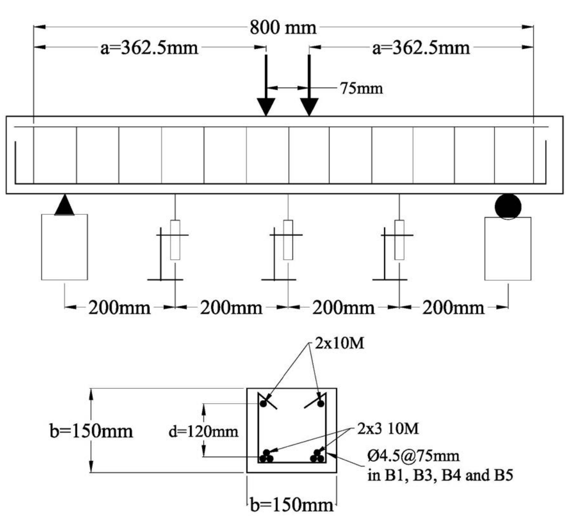

Figure 8. Beams set up, geometry and reinforced details of beams performed by Majdzadeh *et al* [10].

In 2009, Altoubat *et al.* [21] conducted an experimental campaign of twenty-seven full scale beams to study specifically the shear behaviour of macro-synthetic fibres. The beams were tested under three-point loading scheme covering a shear span ratio of 3.5d (slender) and 2.3d (short). Section of beams were 280 x 460 mm, 230 x 390 mm while length varied from 1.9 to 3.2 m. The synthetic fibre used was made of polypropylene and polyethylene, with 40mm length, with rectangular section of 1.4 x 0.105 mm, aspect ratio equal to 90, tensile strength of 620 MPa and 9.5 GPa of elastic modulus. Eighteen beams included fibres at 0, 0.50, 0.75 and 1.0%. At least two specimens were tested for each amount of fibres in short and slender beams. The compression strength of the experimental campaign ranged from 35.6 to 41.9 MPa. Altoubat *et al.* characterized the residual strength of fibre concretes using JSCE-SF4[22] at 3 mm of deflection. Author reported that synthetic fibres increased the load at which the first crack appeared in 10, 18 and 12% for 0.50, 0.75 and 1.0% in slender beams, respectively, while in I short beams the load was incremented by 7 and 14% for 0.50 and 0.75% of fibre volume fraction, respectively. On the other hand, the peak load was incremented in 14, 23 and 30% for 0.5, 0.75 and 1.0 % in slender beams, and over 20 and 28% in short beams with 0.50 and 0.75% of fibres. In addition, authors observed a change in the MOF of beams passing from a brittle to a ductile failure. In the case of short beams, fibres could change the MOF from a web failure in RC beams to a flexural one in PFRC.

In 2012. Altoubat *et al* [23] extended the first experimental campaign to beams containing minimum amount of transversal reinforcement required by ACI-318 [24], and combined them with fibres. Several levels of shear reinforcement were evaluated: without any reinforcement, reinforced by 0.5% (volume fraction) of polypropylene fibres, minimum amount of stirrups required by ACI-318 and combining the minimum amount of stirrups and 0.5% of polypropylene fibres. Slender beams (a/d=3.5) as well as short beams (a/d=2.3) were evaluated under three-point loading scheme. In contrast to previous campaigns, only one type of cross section was evaluated, which corresponded to a rectangular section of 230 mm x 390 mm. Authors concluded that 0.5% of fibres combined with stirrups could improve the shear strength over 40% compared to the control beam with only stirrups. This behaviour was observed in both, slender and short beams. Additionally, authors observed that fibres modified the crack pattern of beams improving the post-cracking behaviour and ductility. Similar than [21] a synergy effect between fibres and stirrups was reported.

From 2010 to 2014, Conforti *et al.* [25–27] studied the applicability of polypropylene fibres on deep and wide-shallow beams subjected to shear (see Figure 9). For this purpose, fourteen wide shallow and nineteen deep beams were manufactured covering three levels of shear reinforcement. The first level corresponds to any type of reinforcement (plain concrete beams), the second level to reinforced by crimped polypropylene fibres dosed at 13 kg/m³, and the third level correspond to the minimum shear reinforcement required by Model Code 2010 [28]. Section of wide-shallow beams were 430 x 250 mm, 770 x 290 mm, 510 x 290 mm, 650 x 250 mm and 890 x 330 mm while length varied from 2076 to 2476 mm. On the other hand, deep beams depths were 600 and 800 mm, width 150 and 300 mm, while length varied from 4310 to 4480 mm. For each section and reinforcement level, two specimens were tested under four-point loading scheme with a shear span ratio (a/d) of 2.5. The mean concrete compression strength ranged from 26 to 34.3 MPa. The polypropylene fibres employed were 40 mm length with a diameter of 0.75 mm, tensile strength of 338MPa and elastic modulus of 4.8 GPa. Authors characterized the residual flexural tensile strength of concrete by EN 14651[17].

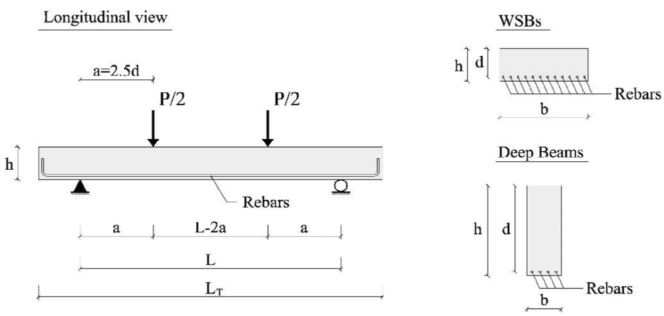

Figure 9. Test set up of wide-shallow and deep beams performed by Conforti *et al.* [25–27].

Conforti *et al.* observed that polypropylene fibres with 13 kg/m³ could provide the shear reinforcement required by equilibrium in wide-shadow beams. In fact, when the beams are compared with minimum amount of reinforcement and PFRC beams, both presented similar shear behaviour and mode of failure (flexural failure). Nevertheless, fibres could develop several progressive cracks during the loading, which lead more ductile behaviour than plain beams. On the other hand, in deep beams, fibres could enhance the shear strength and provide the double of ductility than their counterparts in plain concrete. When PFRC and minimum steel reinforcement deep beams were compared, both presented very similar ultimate shear strength. However, minimum steel reinforcement beams presented a flexure MOF while PFRC beams showed a shear MOF.

In 2012, Parmentier *et al.* [29] tested twenty-eight short and slender beams under a four point loading scheme in order to study their shear performance. Beams section was 200 x 300 mm and 2500 length. The shear span ratio (a/d) explored ranged from 0.5 to 2.5. Beams contained two levels of shear reinforcement, the first one without any type of reinforcement (plain beams) and the second one using three types of fibres (two types of steel and one macro-synthetic) dosed at different volume fractions. Nevertheless, only four beams were manufactured using macro-synthetic fibres, dosed in 4.5 kg/m³ (0.49% of volume fraction), and tested under a shear span ratio (a/d) of 1.5 and 2.5. The macro-synthetic fibre was a fibrillated fibre, manufactured using polypropylene and polyethylene of 50 mm length with 600 MPa of tensile strength and 5 GPa of elasticity modulus. The compression strength was 54.5 MPa. Authors characterized the residual flexural tensile strength of concrete by EN 14651[17].

Parmentier *et al.* observed that PFRC beams tested with a scheme a/d equal to 2.5 presented a 74% of extra shear strength compared to their counterparts in plain concrete. In addition, PFRC beams presented similar shear behaviour than SFRC beams with similar fibre volume fractions that synthetic ones.

In 2015, Sahoo *et al.* [30] studied the effect of synthetic, steel and a combination between both fibres in shear behaviour. A total of seven beams (150 x 200 x 2000 mm) were tested under three-point loading test with a shear span ratio of five. The control RC beams included stirrups of 8 mm spaced at 300 mm in one of the halves of the beams while in the other half stirrups of 8 mm were spaced at 150 mm. With reference to the PFRC beams, only one beam was tested using polypropylene fibre, while the other six beams were manufactured with steel fibres and a combination of synthetic and steel at different dosages. The synthetic fibre employed was made of polypropylene of 12.5 mm long, 0.5 mm of equivalent diameter, 460 MPa of tensile strength and 5.0 GPa of elasticity modulus. Concrete compression strength ranged from 28.1 to 37.6 MPa. Even though the author performed flexural tensile strength tests for all concretes using prismatic specimens, the residual strength of FRC concretes were not characterized. The polypropylene was dosed at a rate of 1% of volume fraction. PFRC beams exhibited the lowest shear strength amount the entire campaign. In fact, Sahoo *et al.* observed that the shear strength and ductility were reduced by 70% and 50% respectively, when polypropylene fibres were added to the beams. However, this comparison was made taking the RC beams with stirrups (8mm@300mm) as a reference beam, which probably resulted not directly comparable. On the other hand, steel fibre dosed at 1% presented similar behaviour than RC beams with stirrups.

In 2016, Ensan Navadeh [31] studied the shear behaviour of slender beams with PFRC. Beams were tested under three-point loading scheme with a shear span ratio (a/d) of 2.4. All beams presented the same rectangular section (254 x 381 mm). In total, four types of shear reinforcement were investigated and compared among them, beams without stirrups, beams with the minimum of stirrups required by ACI-318 [24] and beams with polypropylene fibres dosed at volume fractions of 0.5 and 0.75%. The fibre used in PFRC was an embossed polypropylene fibre of 54 mm length, 0.80 mm of diameter and 585 MPa of tensile strength. Concrete compression strength, flexural strength and residual flexural strength were determined following American standards (ASTM C39 [32] and ASTM C1609 [14]). Ensan Navadeh observed that incorporating 0.5 and 0.75% of fibres in the concrete, the shear strength of the beams increased by 17 and 29%, respectively, compared to the plain concrete beams. The increment of shear strength, especially in beams with 0.75% volume fraction of fibres, was relatively similar to the increment of shear provided by the minimum amount of stirrups (31%).

Arslan *et al.* [33,34], in 2016 and 2019, evaluated the shear behaviour of PFRC beams with and without stirrups. In total, twenty-three beams were tested covering different shear span ratios (a/d) 2.5, 3.5 and 4.5. Various levels of transverse reinforcement were tested, beams without stirrups, beams with stirrups in a ratio of 0.34 and 0.45%, polypropylene fibres dosed in 1, 2 and 3% of volume fractions, and a combination between fibres and stirrups. The polypropylene fibre used was a crimped one with a rectangular cross section of 0.93 x 0.50 mm², and 39 mm length. The tensile strength and elasticity modulus were 470 MPa and 3-6 GPa. The concrete compression strength ranged from 13 to 27 MPa, however it should be highlighted that with the increment of fibre volume, the compression strength was considerably reduced. Authors did not characterize the residual strength of concrete provided by fibres.

Arslan *et al.*, like previous studies, observed that polypropylene fibres increased the shear strength and ductility of beams, compared to those in plain concrete. Moreover, fibres could change the mode of failure from a shear failure to a flexure one.

In 2018, Ortiz *et al.* [35] tested 16 full-scale beams, eight manufactured with reinforced concrete and eight with PFRC. Sections, dimensions and reinforcement of beams were inspired on the classic test beams series by Bresler and Scordelis in 1963 [36]. Beams were tested under three-point loading scheme as Figure 10 shows. The main objective of the research was to study the behaviour of shear-critical fibre-reinforced concrete beams using polypropylene macro-synthetic fibres. The concrete compression strength of the experimental campaign ranged from 38.3 to 44.96 MPa. Polypropylene fibres of 48 mm length and 0.85 m of equivalent diameter were included in a ratio of 10 kg/m³ in PFRC beams. Tensile strength and modulus of elasticity of fibres were 400 MPa and 4.0 GPa, respectively. Ortiz *et al* characterized the residual flexural tensile strength of FRC by EN 14651. Results showed that macro-synthetic fibres improved beam behaviour by increasing the ultimate load and improving ductility. This happened in the PFRC beams both with and without stirrups. However, the inclusion of macro-synthetic fibres in reinforced concrete beams without transverse reinforcement was unable to change the MOF although the ductility was significantly incremented. A synergy effect between fibres and stirrups was also reported.

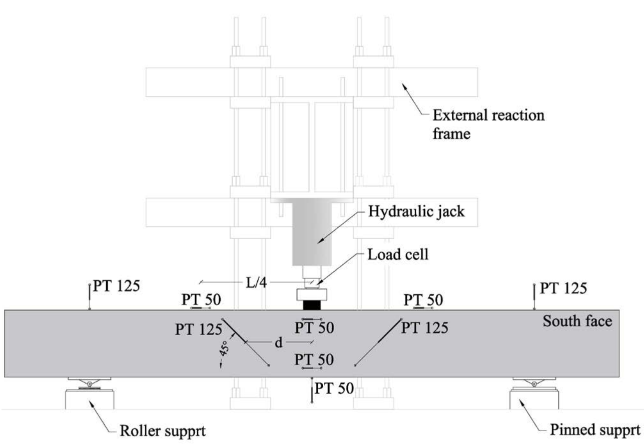

Figure 10. Test set up of beams tested by Ortiz *et al.* [35].

In 2021, Lakavath *et al.* [37] evaluated the shear behaviour of MSFRC prestressed beams of 150 mm x 300 mm cross section and 1600 mm length (see Figure 11). Eight beams were tested at a shear span ratio of 2.4. Four fibre volume fractions were considered, 0%, 0.5%, 1% and 1.5%. The macro-synthetic fibre used was a polyolefin one of 50mm length, 100 aspect ratio, 618 MPa of tensile strength and 10 GPa of elastic modulus. Concrete compression strength of the entire campaign ranged from 52.75 to 54.14 MPa and characterized the residual flexural tensile strength of FRC by EN 14651. Stirrups were placed in one of the shear spans to avoid a not controlled shear failure of the beams. Author evidenced the effectiveness of macro-synthetic fibres to improve the fracture energy when volume fractions of 1% and 1.5% were added. In fact, volume fractions ranging from 0.5 to 1.5% were capable of changing the mode of failure of beams passing from a brittle to a ductile one. Finally, authors observed an improvement of the shear capacity of beams with the increment of fibre volume, and obtained up to 18% of improvement with 1.5% increase of fibre fraction.

Table 1 summarizes the objectives of the different shear test performed on uniaxial elements (beams). It can be seen that all research on shear behaviour of SYFRC is focused only on ULS, and all of them using point-loading schemes. There are no investigations performing distributed loading schemes on the elements. In addition, none of the research have evaluated the influence of fibres on SLS on shear behaviour. Finally, it is important to mention that there are no studies about the long term behaviour of PFRC fibres when used as shear reinforcement.

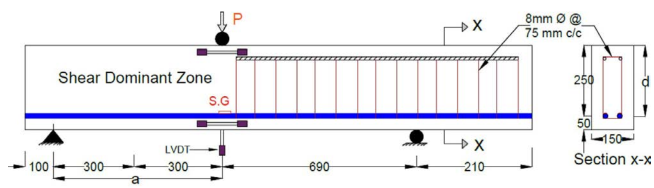

Figure 11. Test set up of prestressed beams tested by Lakavath *et al.* [37].

TABLE 1.
Summary of test's objectives on uniaxial elements using SYFRC.

Author	a/d	SLS	ULS	Cracking	MOF
Furlan and Hanai [19]	4.0		•		
Campione *et al.* [21]	2.3		•		
Majdzadeh *et al.* [11]	3.0		•		
Altoubat *et al.* [22]-[24]	2.3-3.5		•	•	•
Conforti *et al.* [26]–[28]	2.5		•	•	•
Parmentier *et al.* [30]	0.5-2.5		•		
Sahoo *et al.* [31]	5		•	•	•
Ensan Navadeh [32]	2.4		•	•	•
Arslan *et al.* [33], [34]	2.5-4.5		•		•
Ortiz *et al.* [35]	2.4		•	•	•
Lakavath *et al.* [37]	2.4		•		•

5. SHEAR STRENGTH OF BIAXIAL ELEMENTS

One of the most critical failures in biaxial elements, such as slabs, is the punching shear failure, which occurs when high localized forces, such as connection column and slab, act in the biaxial element. This failure usually occurs without warming since it is a brittle MOF, and it usually can be avoided increasing the slab depth or adding traditional steel transverse reinforcement or studs. In addition to these traditional methods of strengthening against punching, the use of steel fibres has proved to be an effective alternative. In fact, the position of the critical shear perimeter around the loaded area can be also influenced by steel fibre content. Although the use of steel fibres to improve the punching strength in slabs is well reported [38–40], literature using synthetic fibres results limited.

In 2012, Alani and Beckett [41] performed five different set of tests on ground slabs with different load conditions: slab centre point load, load at 150 and 300 mm loaded from edge, and loaded at corner at 150 and 300 mm from edge. Synthetic fibres were 48mm length with 640 MPa of tensile strength and 10 GPa of elastic modulus. Fibre content was 7 kg/m³. The dimension of the slab was 6000 x 6000 mm and 150 mm thickness. The average compression strength was 32.5 MPa. Authors did not compare punching shear results with a control plain concrete slab, however, a comparison with steel fibre reinforced concrete slab was done. Results evidenced that in all loads cases, synthetic fibres dosed at 7 Kg/m³ presented similar results that slabs manufactured with hooked ended steel fibre dosed at 40 kg/m³.

In 2020, Nassif *et al.* [42] tested six reinforced concrete slabs under monolithic canter-point with simple supports (see Figure 12). Synthetic fibres were dosed in concrete at rates of 0.5 and 1%. Macro-synthetic fibres were 40 mm length with aspect ratio of 90, 9.5 GPa of elastic modulus and 620 MPa of tensile strength. Dimension of slabs were 1500 x 1500 x 100 mm with an effective depth of 75 mm. Two slabs were used as a control specimen while two slabs contained 0.5% of fibre and two slabs 1% of fibre. Compression strength ranged from 28 to 29.45 MPa. Results showed that macro-synthetic fibres improved the punching shear capacity by 30% and 70% with addition of 0.5% and 1% of fibres, respectively. In addition, fibres increased the ductility of the slabs in such a way that the slabs failed in a more ductile manner. This behaviour let the FRC slabs presented more energy absorption than the control slabs. Finally, authors evaluated models for predicting punching strength developed for steel fibre reinforced concrete and observed a good prediction when synthetic fibres were used.

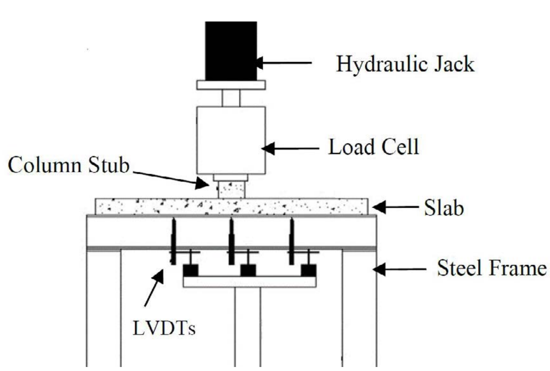

Figure 12. Test set up of slabs tested by Nassif *et al.* in 2020 [42].

6. REAL APPLICATIONS USING SYNTHETIC FIBRE REINFORCED CONCRETE

Conforti *et al.* [43] in 2017 performed a full-scale shear test on six prestressed double tees made of self-compacting concrete and self-compacting polypropylene fibre reinforced concrete. The main objectives of the experimental campaign were to evaluate the possibility of replacing the minimum amount of shear reinforcement by macro-synthetic fibres only and to determine the benefits of using fibres on the end-zones of the elements. Dimensions of test specimens were 6000 mm length, 500 mm depth and 2490 mm width. The cross section was characterized by having a top flange of 50 mm depth and two webs of 120 mm wide. A three-point loading scheme with a/d equal to 3.1 was adopted in all tests (see Figure 13). Polypropylene fibres of 40mm length with an aspect ratio of 53 were incorporated to PFRC elements at 10 Kg/m³ ratio. Residual strength of PFRC was characterized by EN 14651 [17] and classified as Model Code 2010 as a FRC class 2e. Concrete compression strength was 68 MPa on average.

Authors concluded that the minimum amount of shear reinforcement in this type of elements can be substituted by PFRC class 2e. In fact, fibres could increase about 15% the shear strength in the end zones of the elements.

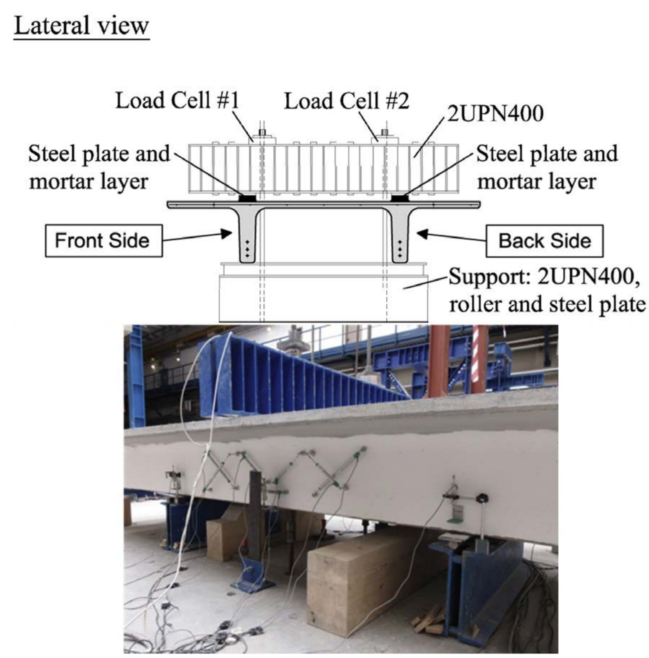

Figure 13. Full-scale double tees tested by Conforti *et al.* [43].

In 2020, Conforti *et al.* [44] reported a real application where macro-synthetic fibres were employed to improve the shear behaviour of prestressed hollow cores slabs (HCS) as shown in Figure 14. To this end, an experimental program of five full scale HCS (420 mm depth, 1200 mm wide and 6000 mm length), a reference beam without fibres (RC) and four with polypropylene fibres. Three-point loading scheme was used on each test. Two tests were performed on each slab varying the shear span ratio (a/d), i.e. ten shear tests were performed. Thus, one of the end zone of the HCS was tested under a/d=3.5, and the remaining end zone was tested under a/d=2.8 according to EN1168 [45]. Fibres used were macro-synthetic polypropylene fibres of 40 mm length with a nominal aspect ratio (length/diameter) of 53, tensile strength of 400 MPa and 3.63 GPa of elastic modulus. Results showed that polypropylene fibres resulted effective to enhance the shear strength of HCS end zones, providing an extra shear strength capacity of 25% on average, as well as post-cracking resistance. In fact, fibres could improve the bond between the tendon and the concrete, delaying and controlling the development of splitting cracks, and hence, reducing the tendon slip.

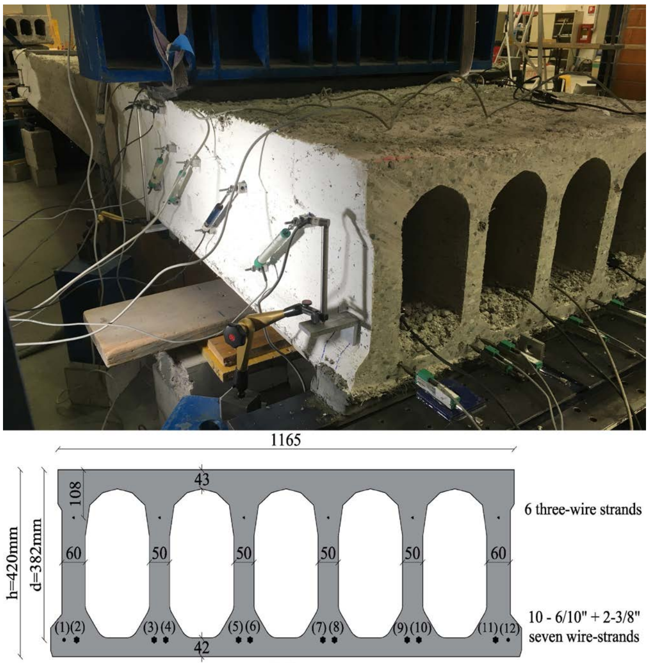

Figure 14. HCS tested by Conforti *et al.* [44].

Diaz and Hamilton [46], after an extensive experimental campaign where FRC was characterized using steel, basalt and synthetic fibres, tested five deep Florida I-Beams girders with 6000 mm of span and a depth of 1981 mm in order to study the effectiveness of fibres to control end-region cracking. Only one of the five beams were manufactured using PFRC including polypropylene fibre dosed at 0.5% of volume fraction. Specimens were all prestressed with fully bonded strands in the bottom and top of the section.

Although Diaz and Hamilton did not directly explore the effect of fibres on shear behaviour of the elements, authors evidenced that fibres were capable of reducing effective crack widths on end regions during the prestress transfer. This result somehow evidences the improvement in shear performance observed by Conforti *et al.* at end zones in HCS.

7. SUMMARY AND CONCLUSIONS

Test results have generally shown that synthetic fibres can enhance the shear strength of concrete. This fact has been evidenced at different test levels starting from small specimens tested under direct shear test up to real applications.

However, the use of synthetic fibres needs to be further investigated since the limited number of experimental tests available. In fact, up to now, only 70 beams and 5 slabs including synthetic fibres have been tested under shear. Figure 15 summarizes graphically two parameters of SYFRC beam elements tested under shear, which were reported in the present paper: the shear span to effective depth ratio (a/d) and the fibre volume (Vf).

As it can be seen, most elements were tested by considering a/d ranging from 2.3 to 3.0, which represents 58% of all the specimens, and only 10 short elements were tested below 2.3. These results show that research on short elements, where shear usually acts without the presence of flexural cracks, is required.

Concerning the volume fraction (Vf), the minimum Vf was 0.49%, while the maximum went up to 3%. The commonest beams were those with Vf ranging from 0.5 to 1.5%.

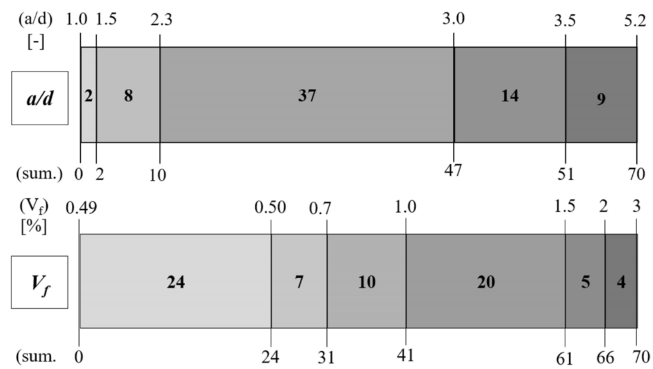

Figure 15. Distribution of parameters in elements tested in uniaxial shear.

Concerning the shear strength of biaxial elements, only two experimental campaigns have included synthetic fibres. In both, fibres were capable of enhancing shear behaviour. However, further investigation to evidence the effectiveness of these fibres is required.

Not all the studies reviewed in this paper made the same characterization of the post cracking fibre performance. It is highlighted that residual flexural tensile strengths were characterised only in 46 of the 74 beams and in none of the biaxial elements. This makes the comparison among works difficult since there is not a uniform criterion to evaluate the real efficiency of synthetic fibre to enhance shear.

Finally, it is worth mentioning that there is a lack of topic that the research community has not studied and can tackle in the future:

- shear on SLS,
- long term behaviour of synthetic fibres when used as shear reinforcement,
- influence of fire on the shear behaviour of SYFRC or
- shear behaviour of SYFRC on elements without flexural cracks.

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