

An experimental study on the shear behaviour of reinforced concrete beams with macro-synthetic fibres

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A B S T R A C T

Shear behaviour in reinforced concrete (RC) elements can improve with an adequate amount of fibres. Research has recently determined how fibres affect shear strength, but has barely focused on macro-synthetic fibre-reinforced concrete (PFRC). This paper presents the experimental results of 16 full-scale beams (eight RC, eight PFRC), 12 without transverse reinforcement. Polypropylene fibres (10 kg/m^3) were included. Mode of failure (MOF) in shear and behaviour throughout the loading process were studied. The results obtained with fibres showed significantly improved shear strength in the RC beams with/without transverse reinforcement. A synergy between transverse reinforcement and fibres was observed in some cases.

1. Introduction

The shear behaviour of structural concrete elements is a research topic that is being continuously debated by researchers. Shear behaviour is influenced mainly by: effective depth (d), compressive concrete strength, the longitudinal reinforcement ratio, coarse aggregate size, the presence or absence of prestressing, load conditions, and the shear span/depth ratio (a/d). Bresler-Scordelis [1], tested 12 reinforced concrete (RC) beams in 1963 at the University of Berkeley in order to investigate critical shear behaviour. This beams series covered a wide range of transversal reinforcement and span conditions. The shear research community has considered this classical beam series to be a reference for calibrating numerical models. At the University of Toronto, Vecchio-Shim [2] reproduced classical Bresler-Scordelis beams in 2004 to test the repeatability of the results obtained by Bresler, particularly for load capacity and mode of failure (MOF).

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Research into shear has also been applied by some authors to fibre-reinforced concrete (FRC) structural elements, in which the most important variables were: amount [3], shape, material and slenderness (aspect ratio, l/d) of fibres [4,5], as well as the presence [6,7] or absence [8–15] of stirrups, or the combination of stirrups and fibres [7,16,17].

Design guidelines have recently allowed fibres to be used as shear reinforcement; e.g., Model Code 2010 [18] and the ACI Building Code [19]. In particular, Model Code 2010 [18] provides two different formulations to properly evaluate the shear strength of FRC elements. The ACI Building Code [19] allows steel fibres to be used in volume fractions that exceed or equal 0.75% as a mini-mum shear reinforcement in normal-strength concrete beams.

According to the experimental results, it is well-known that steel fibres are used to enhance concrete shear capacity and post-cracking tensile strength since FRC is characterised by enhanced toughness due to the bridging effects provided by steel fibres [20,21]. Steel fibres also provide substantial post-peak resistance and ductility [11,20,22], and can transform brittle MOF into ductile ones [22–26]. Cuenca and Serna [16] also proved the

Notation

a	shear span	h	beam depth
A_s	longitudinal reinforcement area	L	beam length
A_{sw}	transversal reinforcement area	P_u	peak load
b	beam width	s	distance between transverse reinforcements
CMOD	crack mouth opening displacement	v_u	nominal shear strength
d	effective depth	V_f	fibre volume fraction
E_c	modulus of elasticity of concrete	V_u	shear force on the considered section
f_{ck}	characteristic value of compressive strength of concrete	v_c	contribution of concrete to shear strength
f_{cm}	mean value of compressive strength of concrete	v_s	contribution of steel to shear strength
f_{ctm}	mean tension strength of concrete	v_f	contribution of fibre to shear strength
f_{ctk}	characteristic value of tensile strength of concrete w/o fibres	w_f	flexural crack width
f_L	limit of proportionality	w_s	shear crack width
f_{Rj}	residual flexural tensile strength corresponding to CMDO 1–4	Z	internal lever arm
f_{Rjk}	residual flexural tensile characteristic strengths corresponding to CMDO 1–4	δu	deflection at peak load
f_u	value of the ultimate strength of reinforcement	ϵ_c	longitudinal strain measured in the compression zone
f_y	value of the yield strength of reinforcement	ϵ_t	longitudinal strain measured at longitudinal reinforcement
		ρ_s	longitudinal reinforcement ratio
		ρ_w	transverse reinforcement ratio

beneficial effect of steel fibres as shear reinforcement in prestressed elements in self-compacting concrete. Presence of steel fibres alone, or combined with conventional reinforcement, has led to enhanced shear strength and specimens ductility. In this study, no clear differences according to the post-peak behaviour between the prestressed beams reinforced only with stirrups or those reinforced only with steel fibres were observed.

The use of steel fibres can also offer a clear advantage in structural elements where it is difficult, or even impossible, to place transverse reinforcements, such as hollow core slabs [27].

To date, the vast majority of the research conducted on the shear behaviour of FRC has focused on steel fibres [5,16,27–34] as very few studies on macro-synthetic fibres are found in the literature, such as [7,9,10,35,36]. Macro-synthetic fibres have significantly improved in the past decade, and can now be used in structural applications, as long as fibre long-term behaviour is guaranteed [37,38]. In fact macro-synthetic fibres are currently able to fulfil the Model Code 2010 requirement [4] for structural applications, and experimental studies have shown their suitability as shear reinforcement in beams [7,9,10,39], prestressed double tees [40], flat suspended slabs [41] and as a reinforcement in precast tunnel segments [42–44]. Regarding shear reinforcement, Altoubat et al. [9] tested 17 full-scale beams without (w/o) stirrups, but with straight macro-synthetic fibres. Compared to the reference samples, the increment in shear strength with a volume fraction of fibres, which varied from 0.5 to 1.0%, fell within the 14–30% range. Based on two experimental programmes on 14 wide-shallow beams and 19 deep beams reinforced by polypropylene fibres, Conforti et al. [7] showed that macro-synthetic fibres can be used as a shear reinforcement in these structural elements. Similar results have also been obtained by Sahoo et al. [10]. Guray et al. [36] studied the influence of polypropylene fibres on the shear behaviour on 11 beams w/o transversal reinforcement by varying the shear span-effective depth ratio from 2.5 to 4.5, and the volume fraction of fibres. Their tests showed that strength and ductility had improved by adding synthetic fibres and, in certain cases, the MOF has changed depending on the shear span-depth and the volume fraction of fibres.

Even though these studies can certainly be considered to represent the good progress made in knowledge about the shear behaviour of elements reinforced by macro-synthetic fibres, a limited number of experimental results, and only a few factors that affect

shear strength, have been studied in the presence of macro-synthetic fibres.

2. Research significance

The shear behaviour of steel fibre-reinforced concrete (SFRC) has been more extensively investigated than macro-synthetic fibre-reinforced concrete (PFRC). In the last few years, several authors have organised experimental campaigns to determine the shear contribution provided by synthetic fibres in slender beams w/o transversal reinforcement. The objective of the present paper is to determine firstly the benefits of macro-synthetic polypropylene fibres used as a shear reinforcement in structural slender beams both with and w/o transversal reinforcement (stirrups), and secondly the synergy that exists between fibres and stirrups when both are used together as a transversal reinforcement. For this propose, the classic test beams series by Bresler and Scordelis in 1963 [1] was reproduced, and a new series of beams was incorporated to cover a wide range of reinforcement and span conditions and, hence, a range of influencing factors and MOFs.

3. Experimental programme

3.1. Test specimens

The research by Bresler-Scordelis [1] consisted of 12 beams (four series of three beams) with a different cross-section geometry, an amount of longitudinal reinforcement, transverse reinforcement, span length and concrete compressive strength. Most beams, except those of maximum length, failed by shear, specifically due to diagonal tension (D-T) or shear-compression (V-C). The ICITECH beams are somewhat inspired by these two classic series of reinforced concrete beams. In fact the reproduced beams are A1 (305 × 552 × 3660 mm), A2 (305 × 552 × 4570 mm), B1 (229 × 552 × 3660 mm), B2 (229 × 552 × 4570 mm), OA1 (A1 w/o stirrups) and OA2 (A2 w/o stirrups). Those beams with a span length of 6400 mm, “Series 3”, and with a failing flexure-compression (F-C), were excluded from the experimental programme, as were the “C” series beams with a cross-section of 155 × 552 mm. Two new beams were added: OB1 (B1 w/o stirrups) and OB2 (B2 w/o stirrups). Thus the whole series of RC beams consists in eight beams, as shown in Fig. 1 and Table 1.

Since the main objective of this research was to study shear-critical fibre-reinforced concrete beams, the experimental programme was extended to the specimens that contained PFRC. The series of PFRC beams had the same geometry as the series of RC beams. The details that correspond to the whole programme of 16 beams are summarised in Table 1. This results in an interesting combination of parameters: (a) two different cross-sections ('A' 305 × 552 mm and 'B' 229 × 552 mm); (b) two span lengths ('1' 3360 mm and '2' 4570 mm); (c) two concrete types: RC and PFRC; (d) repetitions with and w/o transverse reinforcement. It is noteworthy that symbol 'O' was added to the specimen designation in the beams w/o transverse reinforcement, as was 'P' in the macro-synthetic polypropylene FRC beams. The 16 above-described ICITECH beams formed part of an experimental campaign of 24 beams, in which the effect of SFRC was also studied [45].

Longitudinal and transverse reinforcements with similar properties to the traditional beams developed by Bresler et al. were chosen [1]. A large amount of longitudinal reinforcement was used to prevent flexure failure in bending. Steel longitudinal reinforcing bars of diameters of 25 mm and 20 mm were used as the bottom reinforcement. The amount of longitudinal reinforcement was 1.43% to 1.91%, depending on the beam series. Bars of diameters of 12 mm and 10 mm were chosen as the longitudinal top reinforcement, and 8-mm stirrups anchored with 135° bends were used as the transverse reinforcement. In order to prevent either bond failure or the influence of bond failure on other failure mechanisms, length of beams was extended 700 mm away from the supports in order to ensure sufficient anchorage, as shown in Fig. 2. Steel-end plates, like those in the Bresler-Scordelis [1] or Vecchio-Shim[2] beams, were not used.

3.2. Material properties

Portland cement, two types of crushed limestone gravel, three kinds of fine aggregate, water and superplasticiser were used to prepare the concrete. Table 2 lists the dose that was taken into account in the 12 prepared mixtures. Maximum aggregate size

was 20 mm. The employed cement type was CEM I 42.5 N. The water/cement (w/c) ratio was 0.50. To obtain the desired high workability, superplasticiser was dosed in the order of 1%–1.1% (percentage of cement weight) in the RC mix, and of 1.4%–1.5% (percentage of cement weight) in the PFRC mix. The slump flow test was 612 mm on average, according to EN 12350-8:2011. The mix design for RC and PFRC was carried out for a characteristic compressive concrete strength of 35 MPa.

Polypropylene fibres, 48 mm long with a nominal aspect ratio (length/diameter) equal to 57, were used in the PFRC beams. Fig. 3 shows the geometry of the polypropylene fibres used in the experiments. Table 3 indicates the mechanical and physical properties of the macro-synthetic fibres employed in the test. Tensile strength and modulus of elasticity were 400 MPa and 4.0 GPa respectively, according to EN-ISO 6892-1-2009. The RC and PFRC beams were made in a concrete batching plant. Fibres were gradually incorporated into the mixture to not only ensure that fibres were correctly dispersed in the concrete, but to also guarantee the desired workability. Steel formworks were filled with several concrete batches (see Fig. 4) Twelve concrete batches were needed to fill the 16 beams.

In order to determine the mechanical properties of RC and PFRC, samples of concrete from each batch were used to obtain 48 cylindrical specimens of 150 × 300 mm and 24 prismatic (150 × 150 × 600 mm) beam specimens. Both specimens and beams were cured at room temperature under similar conditions.

Cylinder specimens were used to determine both the concrete compressive strength and the modulus of elasticity of the concrete mixture. Uniaxial compression tests were carried out according to EN 12390-3. Increased loading was applied at a rate of 0.6 MPa/s. Four cylinder specimens were tested per cast type. Modulus of elasticity was determined according to EN 12390-13 (see Fig. 6-a). The mean concrete compression strength (f_{cm}) of all the experimental tests resulted in 42.17 MPa, with a coefficient of variation (CV) of 5.04%. The concrete characteristic compression strength (f_{ck}) was 38.30 MPa, calculated with a reliability factor value (K) of 1.80. f_{ck} came close to the desired concrete compression strength of 35 MPa.

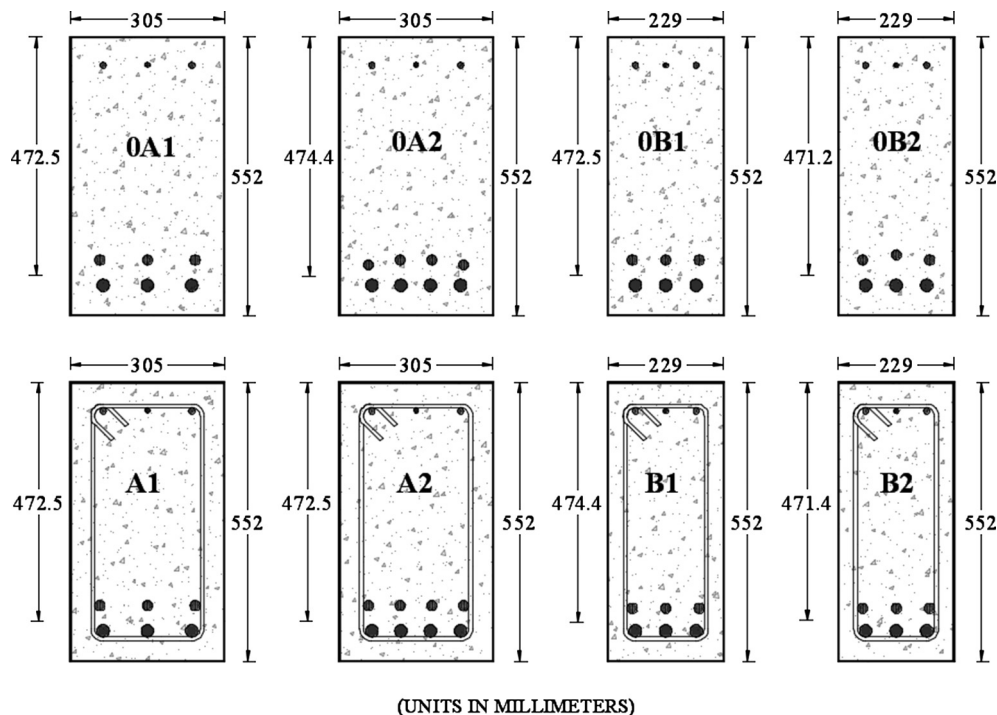
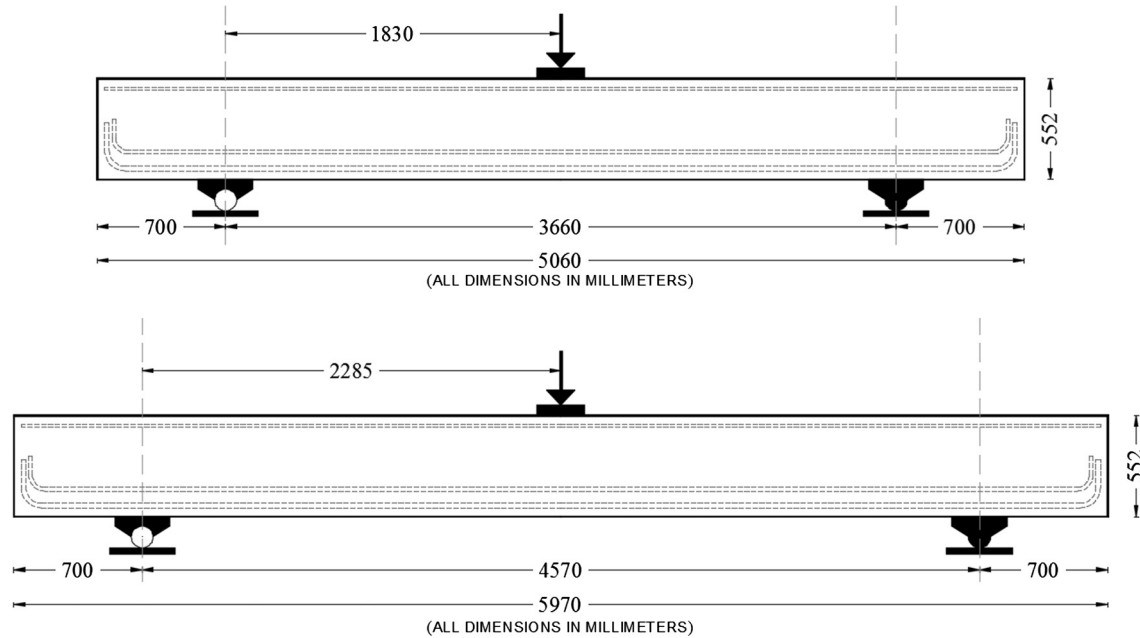


Fig. 1. Cross-section details of the ICITECH Beams.

Table 1

Cross-section details of the ICITECH Beams.

Beam	b (mm)	h (mm)	d (mm)	L (mm)	Span (mm)	a/d	Bottom Steel (Ratio) ¹	Top Steel (Ratio) ¹	Stirrups (Ratio) ²	Fibres (kg/m ³)
OA1	305	552	472.5	5060	3660	3.87	3Φ20 + 3Φ25 (1.68%)	2Φ12 + 1Φ10 (0.21%)	-	-
OA2	305	552	474.4	5970	4570	4.82	4Φ20 + 4Φ25 (2.23%)	2Φ12 + 1Φ10 (0.21%)	-	-
OB1	229	552	472.5	5060	3660	3.87	3Φ20 + 3Φ25 (2.23%)	2Φ12 + 1Φ10 (0.28%)	-	-
OB2	229	552	471.2	5970	4570	4.85	3Φ20 + 3Φ25 (2.24%)	2Φ12 + 1Φ10 (0.28%)	-	-
A1	305	552	472.5	5060	3660	3.87	3Φ20 + 3Φ25 (1.68%)	2Φ12 + 1Φ10 (0.21%)	Φ8 at 330 mm (0.10%)	-
A2	305	552	472.5	5970	4570	4.84	4Φ20 + 4Φ25 (2.23%)	2Φ12 + 1Φ10 (0.21%)	Φ8 at 330 mm (0.10%)	-
B1	229	552	474.4	5060	3660	3.86	3Φ20 + 3Φ25 (2.22%)	2Φ12 + 1Φ10 (0.28%)	Φ8 at 300 mm (0.15%)	-
B2	229	552	474.4	5970	4570	4.82	3Φ20 + 3Φ25 (2.22%)	2Φ12 + 1Φ10 (0.28%)	Φ8 at 300 mm (0.15%)	-
OAP1	305	552	472.9	5060	3660	3.87	3Φ20 + 3Φ25 (1.67%)	2Φ12 + 1Φ10 (0.21%)	-	10
OAP2	305	552	472.5	5970	4570	4.84	4Φ20 + 4Φ25 (2.23%)	2Φ12 + 1Φ10 (0.21%)	-	10
OBP1	229	552	470.6	5060	3660	3.89	3Φ20 + 3Φ25 (2.24%)	2Φ12 + 1Φ10 (0.28%)	-	10
OB2	229	552	469.2	5970	4570	4.87	3Φ20 + 3Φ25 (2.25%)	2Φ12 + 1Φ10 (0.28%)	-	10
AP1	305	552	475.0	5060	3660	3.85	3Φ20 + 3Φ25 (1.67%)	2Φ12 + 1Φ10 (0.21%)	Φ8 at 330 mm (0.10%)	10
AP2	305	552	474.4	5970	4570	4.82	4Φ20 + 4Φ25 (2.23%)	2Φ12 + 1Φ10 (0.21%)	Φ8 at 330 mm (0.10%)	10
BP1	229	552	481.0	5060	3660	3.80	3Φ20 + 3Φ25 (2.19%)	2Φ12 + 1Φ10 (0.28%)	Φ8 at 300 mm (0.15%)	10
BP2	229	552	474.6	5970	4570	4.81	3Φ20 + 3Φ25 (2.22%)	2Φ12 + 1Φ10 (0.28%)	Φ8 at 300 mm (0.15%)	10

¹ longitudinal reinforcement ratio in brackets. $\rho_s = \frac{A_s}{b \cdot d}$ as a percentage.² Transversal reinforcement ratio in brackets. $\rho_w = \frac{A_{sw}}{b \cdot s}$ as a percentage.**Fig. 2.** Elevation details of the ICITECH Beams.**Table 2**Concrete doses considered (kg/m³).

Materials	Mix proportions (kg/m ³)
Crushed sand type 1	482
Crushed sand type 2	168
Crushed sand type 3	482
Gravel 6/12 mm	591
Gravel 12/20 mm	118
Cement CEM I 42.5 N	350
Polypropylene fibres	0 (RC)10 ($V_f = 1.1\%$) (PFRC)
Water	175
Superplasticiser	3.5-5.25

The residual tensile strengths of PFRC were tested according to EN 14651 (see Fig. 6-b). Three point-bending test setups were chosen. Load was applied at a rate of 0.05 mm/min until CMOD = 0.1. After CMOD = 0.1, the rate was gradually increased to 0.20 mm/

min. It is worth mentioning that after the test, the number of fibres that bridged the crack was determined by visual counts to obtain a truer approximation of PFRC behaviour. Table 4 summarises the number of fibres per square decimetre and the other mean mechanical concrete properties per beam. Fig. 5 presents the graphics of the mean residual tensile strength of PFRC. The mean PFRC residual tensile strengths of all the experimental tests were 2.76 MPa (15.83% CV) and 4.34 MPa (18.16% CV) for f_{R1} and f_{R3} , respectively. The PFRC residual characteristic tensile strengths, after taking account a K value of 1.29, were 2.19 MPa, and 3.32 MPa for f_{R1k} and f_{R3k} , respectively. The material post-cracking strength of PFRC was classified as 2e according to Model Code 2010 [18].

Steel reinforcement samples were taken to determine tensile properties. Tensile tests were carried out according to EN-ISO 6892-1 (see Fig. 6-c), and the results are shown in Table 5.

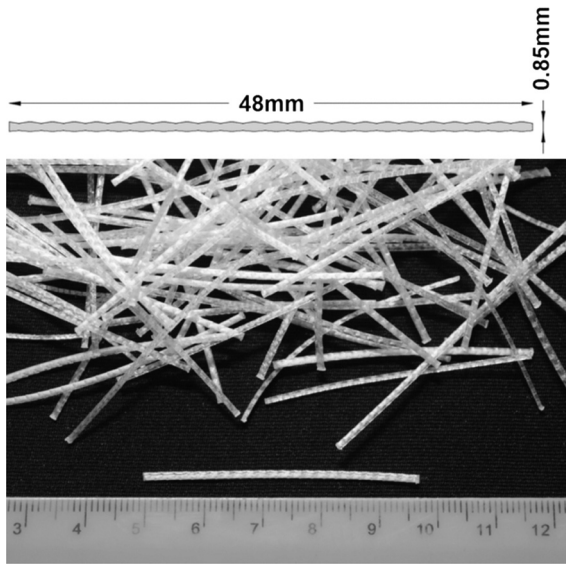


Fig. 3. Polypropylene macro-synthetic fibres.

Table 3

Mechanical and physical properties of the macro-synthetic fibre.

Properties	Value
Material	Polyolefin 100%
Design	Monofilament
Equivalent diameter	0.85 mm
Length	48 mm
Tensile strength	400 MPa
Modulus of Elasticity	4.7 GPa
Water Absorption	Nil
Density	0.91 g/cm ³
Shape	Elliptical
Melting point	160 °C
Ignition point	350 °C

3.3. Beams test setup

The test setup to perform the experiments is shown in Fig. 7. A servo-hydraulic jack of 1000 kN was used, which was connected to a universal testing machine. The test was carried out under the displacement control conditions of deflection at mid-span. Load was applied to all the beams at an average constant deflection rate of 0.30 ± 0.10 mm/min.

In order to measure displacements, nine potentiometric displacement transducers (SDLs) were used as shown in Fig. 7. One was uti-

lised for measuring deflection at mid-span and two as supports for capturing undesired vertical movements. Two horizontal devices were located at mid-span to measure the average strain in the compression and tension chords. Another set of two potentiometric displacement transducers was placed with some inclination on the shear span to record the diagonal cracking induced by shear (see Fig. 8-a). Finally, two other devices were placed at the top of the specimen, between the loading application point and the supports. In order to allow the horizontal displacements of beam due to bending and shearing deformations, one of the used supports was a roller support (see Fig. 9), while the other was a pinned support.

Four high-resolution digital cameras were employed to take pictures of the beams every 10 s during the loading process, and a video camera recorded all the specimen failures (see Fig. 8-b). These digital devices are used to study crack propagation and to measure crack openings. A 100×100 mm grid was painted on one of the lateral faces of the beam to facilitate further digital image correlations.

4. Test results and observation

This paper presents the state of the beams upon failure and at maximum load. Table 6 lists all 16 beams, experimental peak load P_u , peak experimental shear capacity, including self-weight V_u , shear strengths v_u , mid-span deflection δ_u when the beam reaches P_u , the mid-span deformation at the top (ϵ_c) and bottom (ϵ_t) of the section, shear crack width (w_s) and flexural crack width (w_f) upon peak load. Shear capacity was determined as half the resisted maximum load and self-weight of each beam, calculated at a distance equal to the effective depth (d) from the bearing plate edge. Mid-span deflection was corrected using the vertical reading obtained with the LVDTs placed on the bearing plates (see Fig. 7). The tensile and compression deformation at the mid-span were obtained with LVDTs 7 and 6, respectively (see Fig. 7). Three well-known and accepted MOFs in slender beams were addressed: *Diagonal – tension (D-T)*, which is a brittle failure that takes place in slender beams with no or very little shear reinforcement; the *Shear – compression (V-C)* MOF presents many inclined cracks, which grow and reduce the compression zone, with the beam failing at the end by splitting in the compression zone; The *Flexure-compression (F-C)* MOF, which is a ductile failure that occurs when flexural cracks progress until they reach the compression zone and concrete starts crushing after yielding the longitudinal reinforcement.

Fig. 10 shows the load-deflection response for all the tested beams. For simplicity sake, the results are organised in four graphs, and each corresponds to the same cross-section (A or B) and the same span length (1 or 2). This makes it easier to study the effect of fibres and transverse reinforcement on shear behaviour in each case.

Since many photographs were taken of each specimen, it was possible to study the crack pattern evolution during the loading

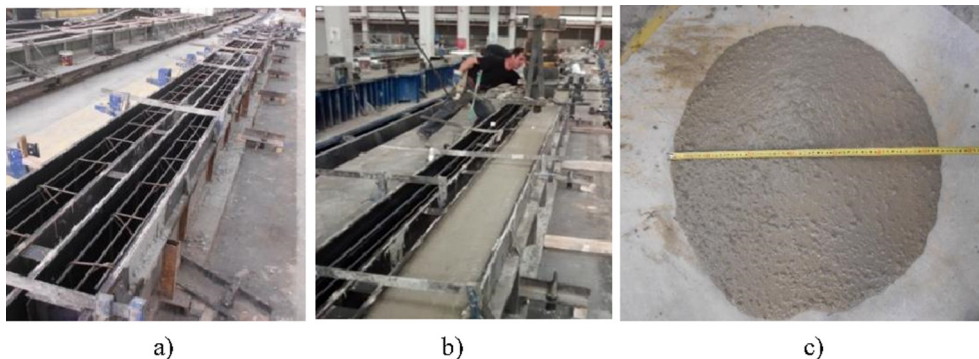


Fig. 4. a) Formworks, b) Full casted beam, c) Slump Flow test.

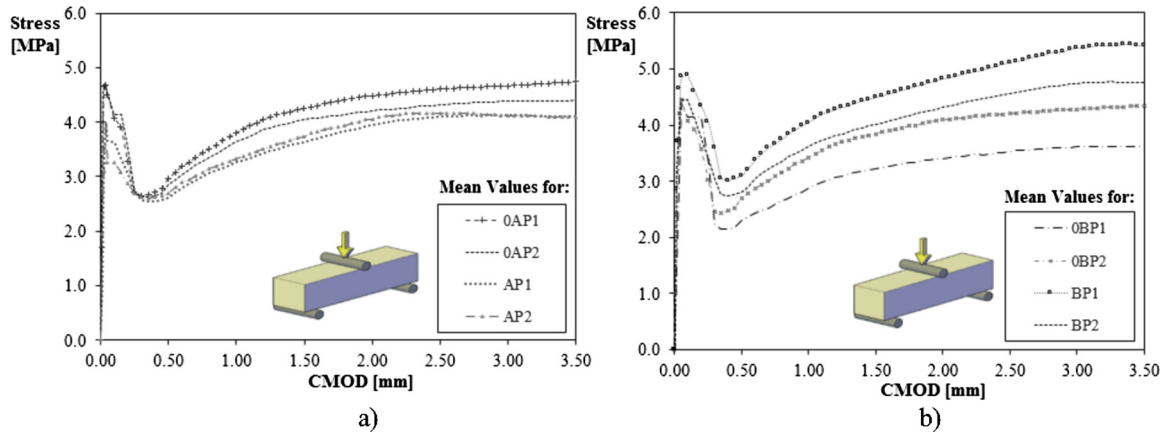


Fig. 5. a) Series A, b) Series B, Beam Average Residual Tensile Strength.

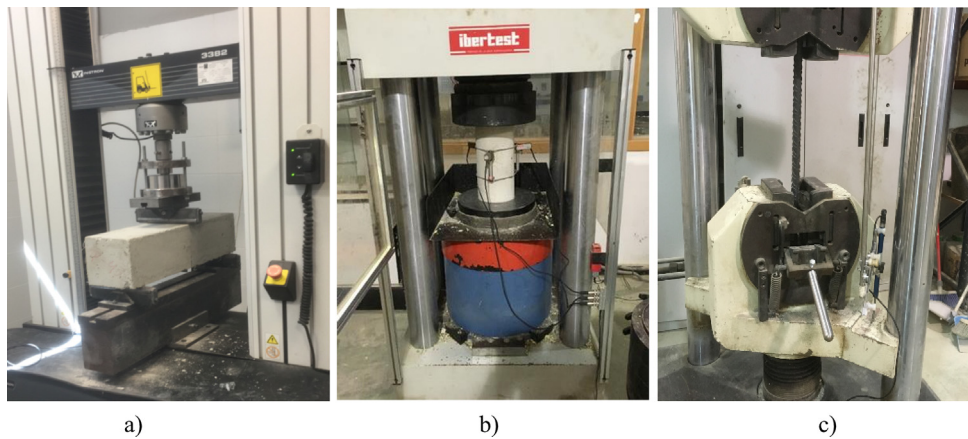


Fig. 6. Test material setup: (a) Residual tensile strength, (b) Compression testing, (c) Reinforced tensile strength.

Table 4
Mechanical properties of beams.

Beam	Type	Mix	f_{cm} (MPa)	E_c (MPa)	f_{ctm} (MPa)	Fibres ^a (U)	f_l (MPa)	f_{R1}^b (MPa)	f_{R2} (MPa)	f_{R3}^b (MPa)	f_{R4} (MPa)
OA1	RC	4-5	41.78 (3%)	29,440 (5%)	3.30 (2%)	-	4.71 (2%)	-	-	-	-
OA2	RC	4	42.21 (2%)	30,071 (4%)	3.30 (4%)	-	4.71 (4%)	-	-	-	-
OB1	RC	6	38.30 (3%)	29,273 (2%)	3.00 (9%)	-	4.29 (9%)	-	-	-	-
OB2	RC	5-6	39.83 (5%)	28,908 (3%)	3.15 (7%)	-	4.50 (7%)	-	-	-	-
A1	RC	1	39.75 (2%)	30,275 (1%)	3.25 (8%)	-	4.65 (8%)	-	-	-	-
A2	RC	1-2	40.79 (4%)	30,182 (1%)	3.17 (6%)	-	4.53 (6%)	-	-	-	-
B1	RC	3	40.12 (5%)	30,949 (2%)	3.00 (3%)	-	4.29 (3%)	-	-	-	-
B2	RC	2-3	40.97 (4%)	30,495 (2%)	3.05 (4%)	-	4.35 (4%)	-	-	-	-
OAP1	PFRC	7-8	43.12 (5%)	29,361 (3%)	3.34 (5%)	48	4.77 (5%)	2.97 (15%)	4.26 (14%)	4.60 (15%)	4.74 (15%)
OAP2	PFRC	7	44.91 (1%)	30,164 (1%)	3.38 (8%)	49	4.83 (8%)	2.85 (22%)	4.05 (21%)	4.32 (23%)	4.40 (22%)
OBP1	PFRC	9	42.67 (1%)	29,112 (6%)	3.10 (1%)	45	4.43 (1%)	2.30 (6%)	3.22 (10%)	3.53 (11%)	3.62 (10%)
OBP2	PFRC	8-9	42.00 (2%)	28,835 (4%)	3.20 (4%)	46	4.58 (4%)	2.70 (18%)	3.85 (20%)	4.21 (20%)	4.35 (21%)
AP1	PFRC	10-11	43.96 (2%)	30,432 (4%)	2.98 (5%)	44	4.26 (5%)	2.61 (17%)	3.64 (20%)	4.10 (19%)	4.10 (21%)
AP2	PFRC	10	44.62 (3%)	30,178 (2%)	3.08 (6%)	40	4.40 (6%)	2.70 (27%)	3.74 (32%)	4.16 (32%)	4.10 (35%)
BP1	PFRC	12	44.96 (3%)	30,571 (4%)	3.42 (13%)	55	4.89 (13%)	3.09 (7%)	4.49 (4%)	5.10 (13%)	5.42 (12%)
BP2	PFRC	11-12	44.22 (3%)	30,628 (4%)	3.16 (13%)	53	4.51 (13%)	2.80 (13%)	4.02 (14%)	4.57 (16%)	4.75 (18%)

Coefficients of variation are shown in brackets (%).

^a Fibres per square decimetre.

^b Residual flexural-tensile strength (f_{R1}): 0.5 mm for CMOD and (f_{R3}) and 2.5 mm for CMOD.

process. Figs. 11 and 12 represent a panoramic view of all four pictures taken with each digital camera. Distortion was corrected before merging pictures.

In all the beams series, and as seen in Fig. 10, the same stiffness was initially observed, which changed according to new crack propagation. The first crack observed during the test appeared

upon an average load of 73 kN for series A1, 78 kN for series A2, 60 kN for series B1 and 55 kN for series B2.

Diagonal tension failure was observed in all the beams (RC and PFRC) that had no web reinforcement. The RC beams w/o stirrups showed a single main critical diagonal crack between 0.2 mm and 0.5 mm in width before collapsing, which produced an

Table 5
Reinforcement properties.

Diam. (mm)	Area (mm ²)	f _y (MPa)	f _u (MPa)
8	50.27	518	660
10	78.54	526	670
12	113.10	529	640
20	314.16	579	662
25	490.87	579	662

instantaneous brittle-like failure with no ductility when the peak load was reached. Vertical flexural cracks began to inflect towards the load point at about 41% of the peak load on average. After the main critical diagonal crack had formed, it began to propagate quickly (45° slope) through the web of beams until longitudinal compression reinforcement took place, and then propagated rapidly as a large horizontal crack up to the beam-bearing plate.

Conversely, the PFRC w/o stirrups showed larger cracks, in the order of 0.25 mm, on both sides of the beam, and several main cracks over 6 mm before collapsing, which also produced reduced loads and instantaneous failure, but they were less brittle-like than their corresponding RC beam. The vertical flexural cracks began to inflect towards the load point at 24% of the peak load on average. The main diagonal tension cracks were formed at approximately 71% of the peak load on average, and presented a more direct inclination between the load point and the support.

The RC and PFRC beams with stirrups failed to shear-compression, except for BP2, which presented a flexion MOF. However, beam AP2 displayed major longitudinal reinforcement deformations upon peak load, which exceeded the yield steel limit (2.8×10^3).

The RC beams showed several diagonal-tension cracks with a crack width of around 3–5 mm upon peak load. Diagonal cracks extended upwards and downwards while load increased. Failure



Fig. 9. Roller Support.

occurred when one of the diagonal cracks reached the compression chord and caused the concrete to crush.

The PFRC beams with stirrups exhibited a much greater cracking pattern than the RC beams, with less separated cracks, and initially with a narrower width. The vertical flexural cracks began to inflect towards the load point at about 25% of the peak load. Several diagonal tension cracks opened gradually to 1 mm in the peak load as load increased. Failure started when the diagonal tension cracks reached the compression chords and began to split the concrete below the load application point.

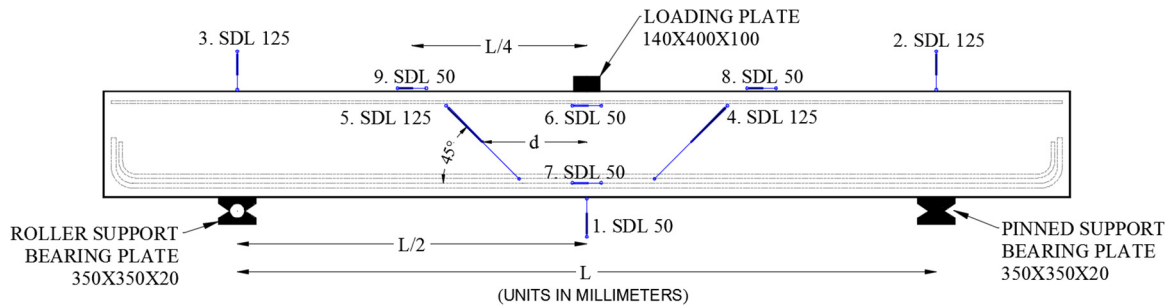


Fig. 7. Beams Test Setup.

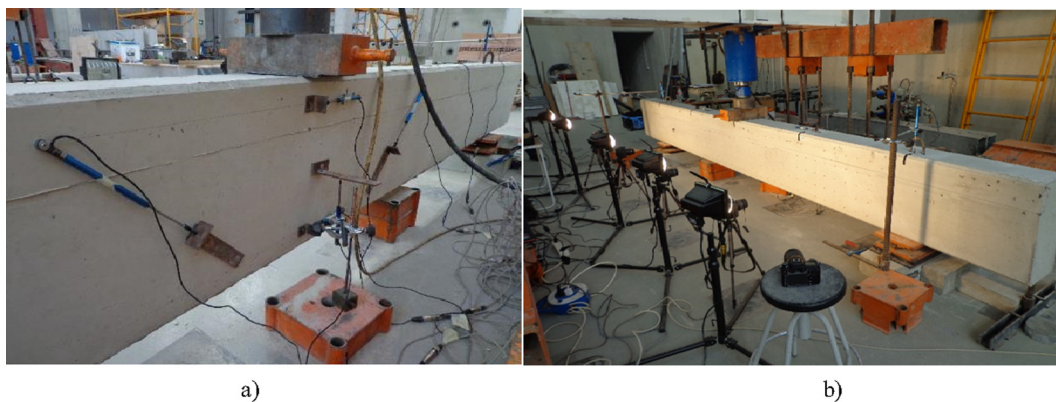


Fig. 8. a) Shear Inclined LVDTs and b) Cameras Setup.

Table 6
Test beam results.

Beam	MOF	P_u (kN)	V_u (kN)	v_u (MPa)	δ_u (mm)	$\epsilon_c \times 10^3$	$\epsilon_t \times 10^3$	w_s (mm)	w_f (mm)
OA1	D-T	312.11	160.96	1.12	5.74	-0.33	1.40	0.30	0.25
OA2	D-T	339.03	176.29	1.22	12.06	-0.65	2.92	0.50	0.30
OB1	D-T	274.97	141.17	1.30	7.48	-0.65	0.79	0.20	0.15
OB2	D-T	226.37	118.28	1.10	10.01	-0.51	1.29	0.30	0.25
A1	V-C	472.71	241.25	1.67	16.31	-0.27	2.15	4.00	0.25
A2	V-C	478.39	245.97	1.71	25.96	-1.79	1.93	5.00	0.40
B1	V-C	468.01	237.67	2.19	17.69	-2.12	2.50	3.50	0.30
B2	V-C	439.57	224.86	2.07	31.62	-3.00	2.47	3.00	0.40
OAP1	D-T	446.68	228.24	1.58	15.81	-0.43	2.19	6.00	0.25
OAP2	D-T	486.26	249.91	1.73	28.02	-1.93	2.57	6.00	0.20
OBP1	D-T	361.73	184.55	1.71	15.30	-0.72	2.04	7.00	0.20
OBP2	D-T	295.60	152.90	1.42	18.02	-1.28	2.02	6.00	0.25
AP1	V-C	695.30	352.54	2.43	29.78	-3.96	2.20	2.50	1.00
AP2	V-C	678.60	346.07	2.39	35.49	-3.54	4.29	2.00	0.30
BP1	V-C	555.56	281.43	2.56	18.60	-1.61	2.62	1.50	0.20
BP2	F-C	487.37	248.77	2.29	32.37	-0.82	3.73	1.00	0.30

* All the measurements were taken at peak load.

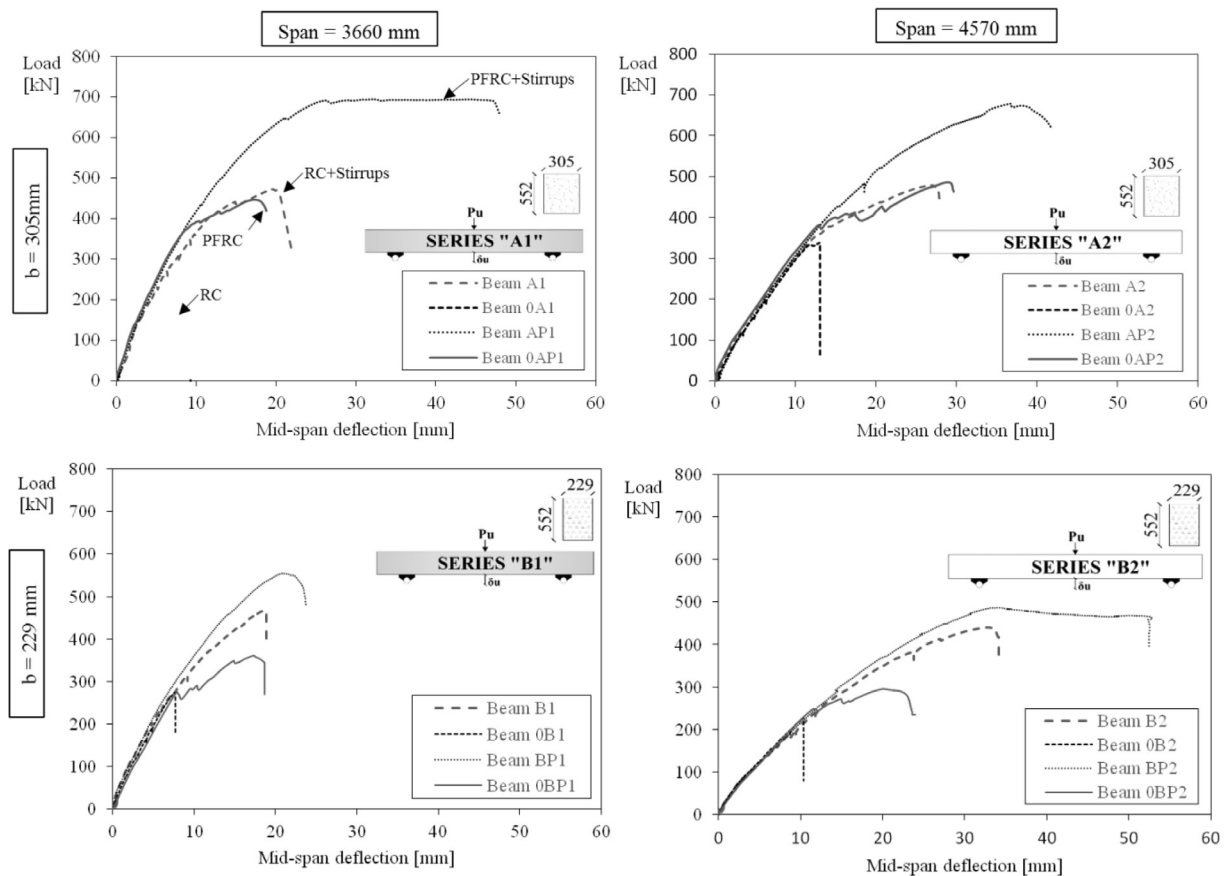


Fig. 10. Load-deflection response. RC vs. PFRC fibres.

5. Analysis of the results

5.1. Comparison of the Bresler-Scordelis, Toronto, and ICITECH beams

The experimental programme run in the present research used six beams, which had been previously tested by Bresler-Scordelis [1] and Vecchio-Shim [2]. Fig. 13 includes the graphical comparisons made of the six beams.

A similar trend in the load-deflection responses was observed, as was a similar MOF to those observed in the corresponding Bresler-Scordelis and Vecchio-Shim et al. beams, despite there being certain differences in the material properties. Table 7 shows the comparisons of all three tests. The ratio of the peak load between the ICITECH and Bresler [1] beams was in the order of 0.91 to 1.07, with a 6.1% coefficient of variation, which generally achieved greater deflection upon peak load compared to the

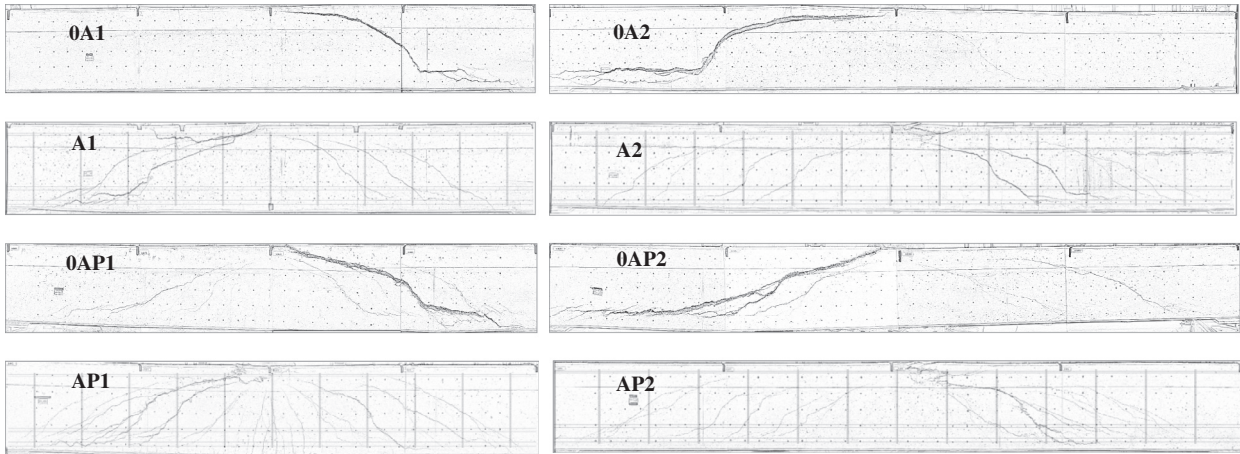


Fig. 11. ICITECH Beams upon failure. Series A.

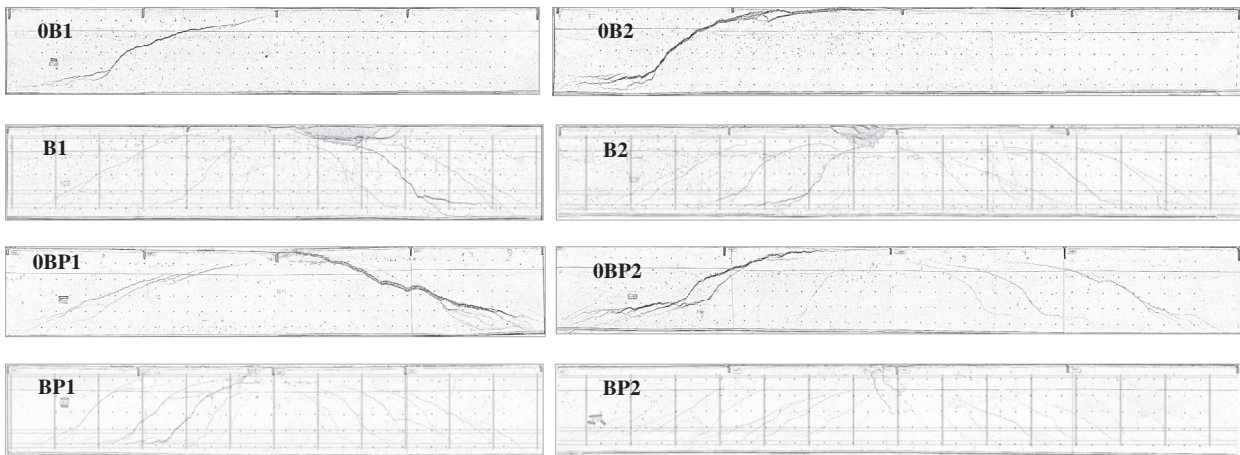


Fig. 12. ICITECH Beams upon failure. Series B.

respective Bresler beams. The Vecchio-Shim beams generally reached less loads and more deflection than the present experimentation beams. Despite the amount of transverse reinforcement being the same as that used by Bresler (0.1–0.148%). Bresler et al. used a diameter of 6.4 mm and spacing between 190 mm and 210 mm. The ICITECH beams used 8-mm-diameter stirrups and spacing between 300 mm and 330 mm. This meant that spacing was wider than the effective depth used by the Bresler beams. One consequence of increasing the transverse reinforcement spacing was that fewer stirrups crossed the diagonal crack, which changed the stiffness of beams to a small magnitude, but not their resistance, as shown in Fig. 13. The ICITECH beams presented generally lesser stiffness than the corresponding Bresler beams, but greater stiffness than the Vecchio ones.

Another modification made to the material that influenced beam behaviour, compared with the Bresler beams, was the small difference in the amount of longitudinal compression and tensile reinforcement. The Bresler beams contained approximately 4.6% more tensile reinforcement and 17% less compression reinforcement than the respective ICITECH beams.

5.2. Analysis of the PFRC beams

The ductility achieved by the PFRC beams (see Table 6 and Fig. 10) was greater and ultimate load increased significantly compared with the RC beams. This happened in the PFRC beams both with and w/o stirrups. Improvements in ductility and peak load

became more evident in the A-section beams as many fibres crossed the diagonal cracks.

We also observed that the PFRC beams w/o transverse reinforcement (0AP1 and 0AP2) achieved a similar peak load and deflection to their corresponding RC beams (A1 and A2), but their stiffness was maintained for longer than the RC beams as fibres enhanced the aggregate interlocking effect. This behaviour was not observed in the B-section beams because fewer fibres crossed the diagonal cracks as they had a narrower section width than the A series beams.

The distribution of shear cracks was also generally random, and no clear pattern was found between beams. However, the macro-synthetic fibres allowed several diagonal cracks to develop and less localised cracking was observed with the PFRC beams *versus* the RC beams w/o stirrups. The diagonal cracks in the RC beams developed mainly from a shear crack, which came to approximately 41% of peak load, while the main diagonal crack in the PFRC beams appeared as a new crack at approximately 70% of peak load, even though shear cracks began to appear at 24% of peak load. This effect is possibly because macrofibres helped to redistribute shear stresses, and to improve the bridging action between crack faces.

A synergy effect among concrete, steel and fibre was also identified in the PFRC beams. Table 8 shows the experimental synergy of each beam series, in which each resistance was decoupled in concrete, steel and fibre, and was finally normalised according to the corresponding square root of concrete compressive strength. The synergy effect occurred in series A1 and A2. The following

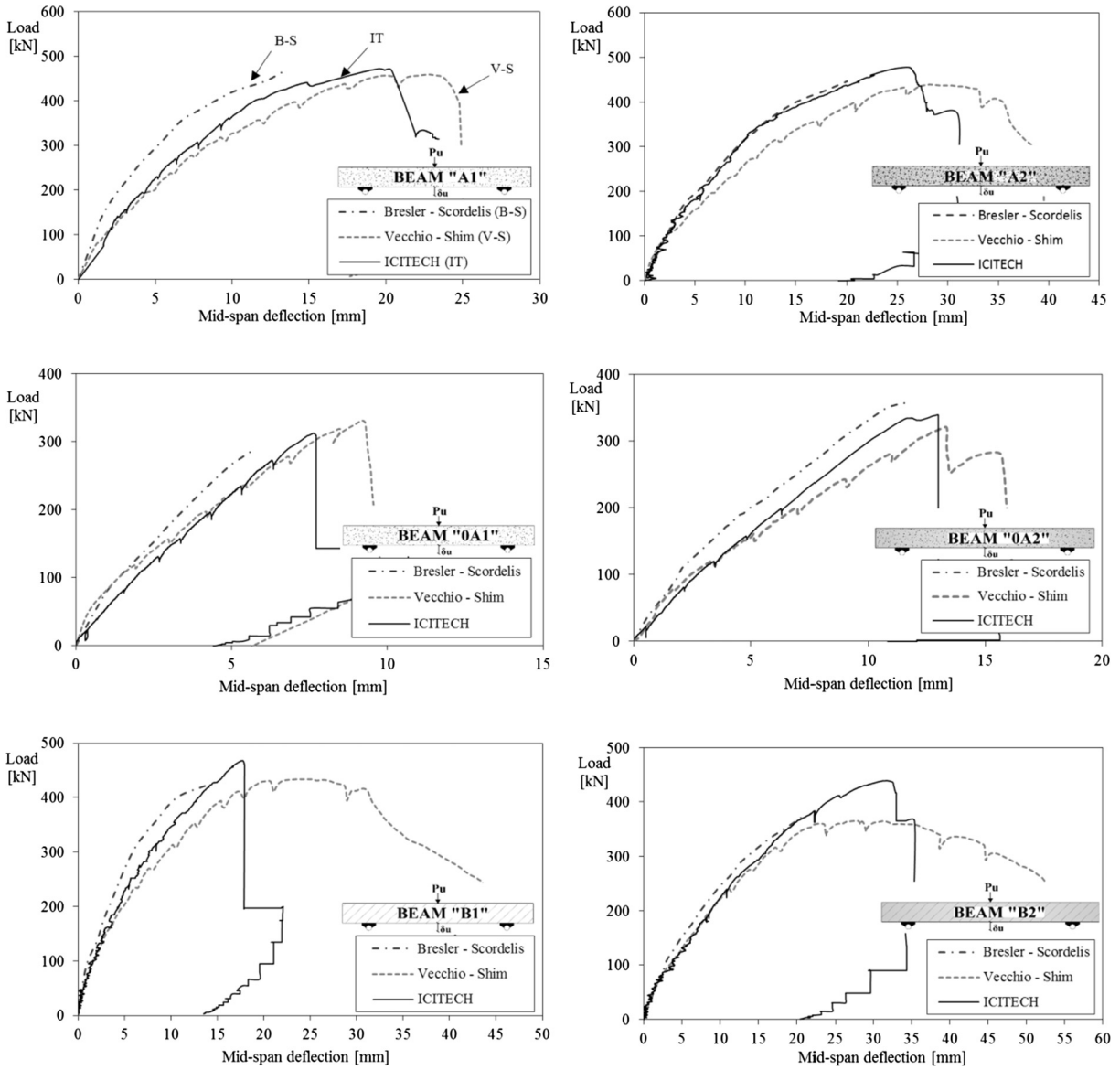


Fig. 13. Comparison of the Bresler-Scordelis, Vecchio-Shim and ICITECH beams.

Table 7

Comparisons made of the ICITECH, Bresler-Scordelis and Vecchio-Shim beams.

Beam	ICITECH		Bresler-Scordelis		Vecchio-Shim		P_u (BS) / P_u (IT).
	P_u (IT) (kN)	δ_u (IT) (mm)	P_u (BS) (kN)	δ_u (BS) (mm)	P_u (VS) (kN)	δ_u (VS) (mm)	
0A1	312	5.74	334	6.6	331	9.1	1.07
0A2	339	12.09	356	11.7	320	13.2	1.05
A1	472	17.03	467	12.2	459	18.8	0.99
A2	478	31.3	489	22.9	439	29.1	1.02
B1	468	17.87	445	13.7	434	22	0.95
B2	439	31.52	400	20.8	365	31.6	0.91

results were obtained when evaluating the synergy in both series: A1 beams 0.03 MPa/MPa, A2 beams 0.02 MPa/MPa. This scenario respectively represents a greater efficiency in fibre resistance of 49% and 28%. This synergy effect did not occur in series B1 and B2, where the synergy was negative (see Table 8): B1 beams -0.02 MPa/MPa, and B2 beams -0.02 MPa/MPa. This finding respectively represents a decreasing fibre resistance of 30% and 54%. This behaviour probably occurred because the width of section B, compared to section A, was narrower, and few fibres bridged

cracks. It is worth noting that this synergy effect occurred when contributions of both fibres and stirrups are similar to one another, which was the case of series A, but not series B where the contribution of fibres was less than half the contribution of steel (see Table 8). The results also indicated that a synergy did not always occur. Further research should be conducted to increase the experience about a synergy effect between fibres and stirrups.

It is important to mention that although the MOF of the PFRC non-stirrup beams remained unaltered compared with their

Table 8
The obtained experimental synergy.

Beam	Pu (kN)	V _u (kN)	v _u (MPa)	$22 \frac{v_u}{\sqrt{f_{cm}}}$	6v _c	5v _s	v _f	Σ ¹	Synergy ²
OA1	312.11	156.06	1.1169	0.17	0.17	–	–	–	
A1	472.71	236.35	1.6741	0.27	–	0.09	–	–	
OAP1	446.68	223.34	1.5824	0.24	–	–	0.07	–	
AP1	695.30	347.65	2.4334	0.37	–	–	–	0.33	0.033
OA2	339.03	169.52	1.2184	0.19	0.19	–	–	–	
A2	478.39	239.19	1.7068	0.27	–	0.08	–	–	
OAP2	486.26	243.13	1.7341	0.26	–	–	0.07	–	
AP2	678.60	339.30	2.3918	0.36	–	–	–	0.34	0.020
OB1	274.97	137.49	1.3047	0.21	0.21	–	–	–	
B1	468.01	234.00	2.1878	0.35	–	0.13	–	–	
OBP1	361.73	180.86	1.7124	0.26	–	–	0.05	–	
BP1	555.56	277.78	2.5550	0.38	–	–	–	0.40	–0.016
OB2	226.37	113.19	1.0962	0.17	0.17	–	–	–	
B2	439.57	219.78	2.0699	0.32	–	0.15	–	–	
OBP2	295.60	147.80	1.4230	0.22	–	–	0.05	–	
BP2	487.37	243.69	2.2890	0.34	–	–	–	0.37	–0.025

¹ $\Sigma = v_c + v_s + v_f$.

² $\text{Synergy} = \frac{v_u}{\sqrt{f_{cm}}} - \Sigma$.

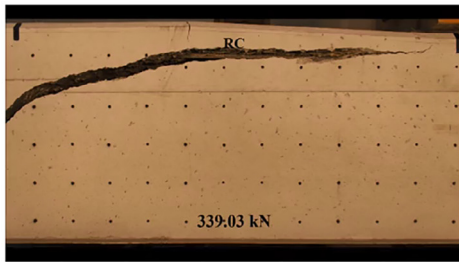
corresponding RC beams, the behaviour of the main diagonal shear crack differed as it was less fragile and more predictable. Thus, it could be classified as a controlled diagonal tension (C-D-T) MOF. The differences between D-T and C-D-T can be watched in Video 1 (the web version paper), which corresponds to the A2 series. The diagonal crack opening measured upon peak load was significantly larger and ranged between 6 mm and 7 mm in the PFRC beams w/o stirrups (OAP1, OAP2, OBP1 and OBP2) versus the RC beams, which were between 0.3 and 0.5 mm. The inclination and shape of the main diagonal cracks also changed compared with the PFRC and RC beams w/o transverse reinforcement (see Figs. 11 and 12). The PFRC diagonal cracks were less curved and more direct from the loading point to the support, while the RC beams clearly displayed a more curved crack.

compression (F-C) MOF because the main shear crack did not clearly progress towards the compression chord.

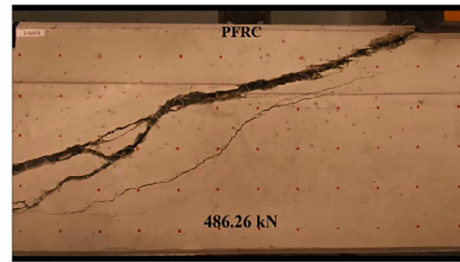
6. Concluding remarks

Sixteen full-scale beams were tested by applying a concentrated load at the mid-span. The main investigated parameters were the influence of macro-synthetic fibres (10 kg/m³, V_f = 1.1%) on shear resistance, and its effect on the MOF. The beams tested by Bresler-Scordelis at the University of Berkeley in the early 1960s inspired the geometry of the present beams, but with certain material differences.

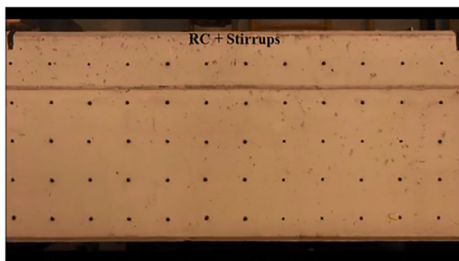
The main conclusions drawn from the present study are as follows:



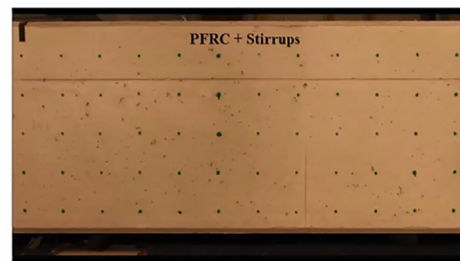
Beam OA2



Beam OAP2



Beam A2



Beam AP2

Video 1.

It is interesting to note that beams AP1, AP2 and BP1 failed in V-C. In the particular case of the AP1 beam, shear-compression failure occurred with the previous yielding of longitudinal reinforcement in tension (see Fig. 10). Longitudinal reinforcement yielding was also observed with the BP2 beam, but ended in a flexure-

- Shear-critical Bresler-Scordelis, Vecchio-Shim and ICITECH reinforced concrete beams showed a similar load-deflection response, a similar ultimate load, and a similar MOF.
- Macro-synthetic fibres significantly improve beam behaviour by increasing the ultimate load and improving ductility.

- c) The inclusion of macro-synthetic fibres in reinforced concrete beams w/o transverse reinforcement is unable to change the MOF, but can change MOF performance by presenting critical diagonal crack openings upon failure within a range of several millimetres, plus less fragile behaviour.
- d) The macro-synthetic fibres added to the beams w/o transverse reinforcement achieved a similar response in some cases to those observed in the reinforced concrete beams with transverse reinforcement.
- e) The macro-synthetic FRC beams, used in combination with transverse reinforcement, achieved a higher ultimate load *versus* the beams w/o fibres. A synergy effect in shear strength terms between the fibres and transverse reinforcement was observed in two of the four beam series, which evidently shows that a synergy does not always occur. In some cases, even yielding longitudinal reinforcement in tension was achieved.
- f) Macro-synthetic fibres can serve as an effective mechanism of shear transfer.

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