Construction and Building Materials 169 (2018) 888–899

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

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

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HIGHLIGHTS

- Macro-synthetic fibres can substitute transverse reinforcement in slender beams.
- Macro-synthetic fibres provide great shear strength and ductility.
- Diagonal tension MOF was less brittle and more predictable in PFRC than in RC beams.

ARTICLE INFO

Article history:
Received 28 July 2017
Received in revised form 15 November 2017
Accepted 4 February 2018

Keywords:
Slender beams
Macro-synthetic fibres
Shear strength
Polypropylene fibres
Synergy between stirrups and fibres

ABSTRACT

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).

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 minimum 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

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https://doi.org/10.1016/j.conbuildmat.2018.02.023
0950-0618/

Notation

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