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Shear behavior of prestressed precast beams made of self-compacting fiber reinforced concrete

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HIGHLIGHTS

- A SCFRC is designed and adapted for its daily use in a precast industry.
- Nine precast prestressed beams were tested in shear.
- Deflections, crack widths and shear strengths were analyzed.
- Steel fibers control cracks propagation. Fibers and stirrups have a synergic effect.
- Although Codes are safe, more analysis on the influencing parameters is needed.

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ABSTRACT

Even after many years of in-depth research the shear behavior of concrete structures is still a subject for debate. Current Design Codes need to be adapted to new materials and production methods. This paper discusses some still unresolved doubts, based on an experimental program consisting of nine prestressed I-beams of different flange dimensions. Shear evaluation is analyzed in accordance with the Codes under different conditions: a combination of fibers with stirrups, the possible influence of flange width on shear strength and the interaction of fibers with other important parameters such as flange width and longitudinal reinforcement. The results obtained show that fibers act as additional reinforcement to stirrups and also that the Codes are within the safety limits as regards shear ultimate limit state (ULS).

1. Introduction

Even after many years of in-depth research, the shear behavior of concrete structures has still not been fully explored and is a topic of continuous debate among researchers looking for models and methods to describe and determine the shear capacity of structural concrete members. General shear models are also being extended to other materials such as Fiber Reinforced Concrete (FRC).

The shear behavior of structural elements made of Self-Compacting Concretes (SCCs) has also been studied. Some authors [1–3] claim that SCC elements have a lower shear strength than traditional concretes due to their smaller aggregate size, which affects the shear friction mechanism. On the other hand, other authors such as Cuenca and Serna [4] think that SCC beams have a similar response to those made with traditional concretes in terms on shear behavior. These results were obtained using SCC and traditional concrete with analogous particle size distributions. When concretes of different granular structures are compared, different shear behaviors will obviously be obtained [4]. However, other authors [5] believe that the use of fibers in self-consolidating concrete may combine the advantages of both SCC and FRC.

Some of the main parameters usually thought to influence shear behavior are: element dimensions (size effect), presence (or absence) of axial forces, amount of longitudinal reinforcement, compressive concrete strength, load conditions, cross-section shape, the shear span/depth ratio (a/d) and FRC toughness properties.

Many studies [6–32] have included a number of experimental tests on FRC shear resistance and have advanced our understanding of the shear behavior of FRC beams. The main ideas include: fibers used to enhance concrete shear capacity, or to partially or totally replace stirrups in reinforced concrete (RC) structural members [11,33–35]; FRC is characterized by enhanced toughness due to the bridging effects provided by fibers [35,36]; fibers provide substantial post-peak resistance and ductility [35,37–40]; by adding fibers, brittle shear failures do not take place (e.g. [26–

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28,34,36,41]); test results indicate that when fibers are applied, maximum crack width, average crack width and average crack spacing are reduced [19,36,42]; FRC is suitable for structures when diffused stresses are present. In structures where both localized and diffused stresses are present, the best reinforcement is based on a combination of rebars and fiber reinforcement [35]. Some of the most recent work aims at improving the concrete itself [43–47].

Referring to the Design Codes, the proposal of Committee TC-162TDF of RILEM (*International Union of laboratories and experts in construction materials, systems and structures*) produced pioneer design guidelines [48] in which the fiber contribution to shear is added to that of concrete as a separate term.

A comparison was made [35] of a wide experimental database on the model proposed by the University of Brescia (the expression contained in the final draft of the MC2010 to calculate the shear capacity of FRC beams) [49] and the RILEM formulation [48]. Although the agreement was less promising when dealing with high-strength concrete specimens or prestressed members, the RILEM results [48] were slightly better for small-sized elements than for deep beams [35].

The FRC shear design workshop held in Salò (Italy) [50] proved to be an interesting advance in the development of the Model Code provisions [51,52] and in inspiring future research into these topics. The papers presented are available in a *fib* Bulletin [50]. The approach presented in the final draft of the Model Code 2010 [51,52] to calculate FRC members' shear capacity was proposed by Minelli [49] and is based on the Eurocode 2 equation [53] used to determine the shear contribution to concrete members with no shear reinforcement by adding a factor ($C_2 = (1 + 7.5 \cdot (f_{Ftuk}/f_{ctk})) \cdot f_{ck}$), which includes an FRC toughness that modifies the effect of the longitudinal reinforcement ratio (since $C_2 = (1 + 7.5 \cdot (f_{Ftuk}/f_{ctk})) \cdot f_{ck}$ multiplies the longitudinal reinforcement ratio and, therefore, MC2010 takes into account the positive effect of fibers on the dowel action). Fibers were then included in the concrete contribution to obtain a more representative modeling of their actual effect, which basically make the concrete matrix tougher after cracking by improving both the transfer of residual tensile stresses and the aggregate interlock (the latter, by keeping cracks smaller) [35]. However, it should be noted that the two formulations require toughness properties. When combining fibers and stirrups, both Codes include an additional term to consider the stirrup effect.

On the other hand, the ACI 318-11 Code [54] does not contain a formula to calculate the shear strength of SFRC beams, and only assumes the minimum shear strength withstood by fibers. Parra-Montesinos et al. [42] ensured that hooked steel fibers in a 0.75% volume fraction can be used in lieu of minimum stirrup reinforcement in beams. Evidently, a limit based on FRC toughness properties (that does not depend solely on the quantity of fibers) would be a better criterion to justify the substitution of transverse reinforcement.

Other countries have drawn up design guidelines [35], including France (AFGC-SETRA, 2002), Sweden (Stälfiberbeton, 1995), Germany (DAfStb, 2007), Austria (Richtlinie Faserbeton, 2002), Italy (CNR, 2006) and Spain (EHE: 14th Annex [55]); the latter is based on RILEM.

Kim et al. [38] recently presented a new shear model which considers the fiber-concrete bond mechanism.

The main objective of the research described in this paper is to analyze the shear behavior of real mass-produced prestressed beams made with high-strength self-compacting fiber reinforced concrete (SCFRC). The main goals of the study were to:

- Propose a consistent SCFRC mix design adapted for continuous use in the precast industry.
- Evaluate the possibility of replacing all the transverse reinforcement and secondary rebars by steel fibers.
- Analyze the theoretical shear strength values according to the safety margins of current international Codes, which are obtained as the experimental-to-theoretical shear strength ratio.
- Check the possible influence of flange size on shear behavior.

2. Concrete mix designs

Reference SCC and a SCFRC with 60 kg/m^3 (V_f = 0.75%) of steel fibers, a nominal slump flow of 600 mm and an average compressive strength of about 60 MPa at 28 days were used in the study. This performance was chosen to obtain self-compacting concretes with good compressive strength at an early age which could be poured without vibration, in line with precast prestressed beam production demands.

The materials used were: cement CEM I 52.5R and calcareous crushed aggregates based on filler, sand and 7/12 mm size coarse aggregates. The steel fibers (RC 65/40 BN) were low carbon with hooked-ends (40 mm long, 0.62 mm diameter and a nominal aspect ratio (length/diameter) equal to 65) and a tensile strength of 1225 MPa.

The water/cement ratio and superplasticizer dosage were determined to reach the required strength and slump flow, respectively.

SCC mix design criteria [56], most of which are based on laboratory tests, suggest an increase in fines content. The final application needs experimental verification under working conditions, as when SCC contains fibers the fines content must be higher.

Based on the authors' previous research work [57], the concrete mix design was determined by adapting solid grading (including cement) to the theoretical Bolomey particle size distribution curve [58], defined as:

$$p = a + (100 - a)(d/D)^{1/2} \tag{1}$$

where "p" is the percentage passed through a "d" sieve, "D" is the concrete's maximum aggregate size and "a" is the Bolomey parameter [58], which depends on the desired workability of the concrete and aggregates properties.

For the concretes in this study, the "a" values used were: a = 16 for SCC and a = 20 for SCFRC. The relatively low "a" parameter was due to the inclusion of well graded sand.

Table 1 shows the mix design for both concretes. The theoretical and actual particle size distribution curves are plotted in Fig. 1.

3. Concrete properties and production control

Fig. 2 shows SCFRC concrete being poured into a beam formwork with no compacting process. A consistent mix design was used, suitable for continuous precast production processes.

In order to analyze the mix robustness, an exhaustive production quality control took place in the experimental program and a 2 m^3 mix was used to cast all nine beams. The following tests

Table 1
Concrete mix designs (kg/m^3).

kg/m^3	SCC	SCFRC
7/12 aggregate	846	721
Sand	924	985
Filler	41	50
Cement	440	460
Water	198	205
Fibers (RC 65/40 BN)	0	60
Superplasticizer	11.1	12.8
W/C ratio	0.45	0.45