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Bending-shear response of self-consolidating and high-performance reinforced concrete beams

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ABSTRACT

The shear strength and the fracture behavior of self-compacting reinforced concrete (RC) beams were investigated. Beams with and without shear reinforcement (stirrups) made with self-consolidating as well as normal vibrated concrete (both ordinary and high-performance) were tested in four-point bending considering four shear arm ratios (a – shear span/d – distance from extreme compression fiber to centroid of tension reinforcement = 1.5, 2.5, 3.5, 4.5). The response of RC beams was assessed based on the results of crack patterns, load at first cracking, ultimate shear capacity, and failure modes. Comparisons with similar tests on normal vibrated concrete beams show that self-compacting concrete beams exhibit similar shear strength associated with a more brittle behavior. Finally, the code-based shear resistance predictions for RC beams are considered. While Eurocode 2 predictions exhibit, in terms of shear strength, a lower bound of the experimental results, the crack spacing is not accurately predicted by code specification.

1. Introduction

Traditional shear design procedures of reinforced concrete (RC) members are based on equations derived from the results of experimental tests [1–3], nevertheless this approach is often criticized because of its unconservativeness. In particular, experimental evidence has shown that as the size of a beam increases, the intensity of shear stress decreases, especially for lightly reinforced applications [4–6]. Therefore, a significant size effect on the shear strength, that is, for a given concrete compressive strength, the shear strength varies with the characteristic dimension of a beam, needs to be taken into account. Recently, Collins et al. [7] showed that this size effect is instigated by the reduced capability of wide cracks to transfer shear stresses, similarly to what may be detected in fiber-reinforced concrete beams [8].

The problem seems more perceptible in RC beams without stirrups whereas, with stirrups, a mitigated size dependence has been observed [6].

Among recently developed special concretes, a prominent position is attained by self-consolidating concrete (SCC), which is considered to be one of the greatest achievements in concrete technology [9–13]. The basic feature of SCC is its ability to be poured into formworks without using vibration and maintaining good stability (i.e., no segregation). Although SCC consists basically of the same components as normal vibrated concrete (NVC), its composition is quite different in order to achieve self-compacting properties. While the coarse aggregate fraction is usually limited, the powder volume is higher in a SCC. This different concrete composition leads to different mechanical properties. On one hand, the higher powder and the lower coarse aggregate content changes the granular skeleton and affects strength, modulus of elasticity and volume stability. On the other hand, in SCC there is an improvement of the grain-size distribution and of the interfacial transition zone (ITZ), which becomes denser with respect to a normal concrete [14,15].

In general, the shear strength of RC beams is supplied by different contributions such as the aggregate interlock mechanism, the compression shear zone, and the dowel action of longitudinal reinforcement [1,7,16,17]. Given the different properties of SCC in comparison to the NVC, the problem is to determine the response of RC beams under bending and shear actions [18–21].

In this paper, the shear strength of SCC RC beams with and without shear reinforcement is investigated. Four shear span–depth ratios (1.5, 2.5, 3.5 and 4.5) were considered. Overall, 16 SCC and 18 NVC beams were tested, and the outcomes of the research are compared to standard design equations. Finally, some considerations on the suitability of these equations to SCC are provided.

2. Experimental research

The experimental program involved two different groups of RC beams: in the first one, specimens were cast with NVC designed for a cubic compressive strength at 28 days, R_{ck}, of about 40, 75 and

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90 MPa (NVC40, NVC75, NVC90); in the second group, SCC designed for a compressive strength of about 40 MPa (SCC40) was used. The mix-design and the average compressive (R_{cm}), splitting (f_{ctsp}) and flexural (f_{cfm}) strength at the time of the tests are shown in Table 1.

The mechanical properties were determined in terms of compressive cubic strength, R_{cm} (side 150 mm), bending strength, f_{cfm} (beam 100 mm height × 100 mm width × 400 mm length), elastic modulus E_{cm}, and splitting strength, f_{ct} (cylinder diameter 150 mm, height 300 mm) according to European Standards [22–25].

High strengths were obtained by adding different mineral admixtures (fly ash and microsilica for R_{ck} equal to 75 and 90 MPa, respectively). The SCC was a powder-type obtained with limestone filler. The maximum aggregate size was 15 mm. Beams were cured in environmental condition (of about 20 °C) and covered with wet tissue (for one week).

The fresh state properties of SCC (namely workability, filling and passing ability) were evaluated with slump-flow, V-funnel, L-box, U-box and J-ring tests according to Italian Standards [26–31] and with sieve segregation tests according to European Guidelines [32]. The obtained results are shown in Table 2.

The investigation on NVC focused on beams with three different shear arm ratios:

- S: 15 × 30 × 240 cm tested with shear span $a/d = 1.5$;
- M: 15 × 30 × 290 cm tested with shear span $a/d = 2.5$;
- L: 15 × 30 × 340 cm tested with shear span $a/d = 3.5$.

While the investigation on SCC involved beams with four different shear arm ratios:

- S: 17 cm × 30 cm × 250 cm tested with shear span $a/d = 1.5$;
- M: 17 cm × 30 cm × 300 cm tested with shear span $a/d = 2.5$;
- L: 17 cm × 30 cm × 350 cm tested with shear span $a/d = 3.5$;
- XL: 17 cm×30 cm × 400 cm tested with shear span $a/d = 4.5$.

The effective depth of the cross section, d, was 26 cm. For each size, beams with and without stirrups (ϕ6/15 cm) were examined (two specimens of each type for SCC and one specimen of each type for NVC). Overall, 16 SCC and 18 NVC beams were tested. All specimens had the same longitudinal reinforcement (2ϕ16), while 2ϕ8 were used as compression steel in the beams with shear reinforcement. The reinforcement adopted was a grade B450C, with a yielding stress, f_y, equal to 516.5 and 589.6 MPa for NVC and SCC, respectively, and a failure strength equal to 626.5 and 660.5 MPa for NVC and SCC, respectively. The bonded length was chosen according to Eurocode 2 [33] and developed by bending the rebars at 90° to the upper part of the beam (Fig. 1). Each beam was given a proper code in order to identify all the features: namely the type of concrete (NVC40, NVC75, NVC90 or SCC40), shear reinforcement (N = none, S = stirrups), and size (S, M, L or XL). The tests on M, L and XL beams were carried out with an MTS hydraulic jack with load capability of 250 kN, while for the short specimens another MTS hydraulic jack of 1000 kN was used. The tests were displacement controlled, and the beams were monitored with at least 6 LVDTs (±5 mm range) set as shown in Fig. 1. A potentiometer (25 cm gage length) was placed on the middle section to measure the vertical displacement.

Table 1
Mix-design.

	NVC40	NVC75	NVC90	SCC40
Cement CEM II-AL 42,5 R (kg/m^3)	300	//	//	350
Cement CEM I 52,5 R (kg/m^3)	//	380	405	//
Fly ash (kg/m^3)	80	60	//	//
Microsilica in slurry al 50% (kg/m^3)	//	//	90	//
Limestone (kg/m^3)	//	//	//	160
Sand + aggregates (kg/m^3)	1870	1905	1920	1672
Naphthalene sulfonate superplasticizer (l/m^3)	4.5	//	//	//
Acrylic superplasticizer (l/m^3)	//	5.5	10	4.2
Water (l/m^3)	175	150	80	182
R_{cm} (MPa)	64.5	86.7	94.9	53.3
f_{ctsp} (MPa)	4.0	4.5	4.6	3.4
f_{cfm} (MPa)	5.90	6.55	7.05	6.95
Elastic modulus, E_{cm} (MPa)	37,400	39,200	41,500	41,000

3. Experimental results

Different behavior and failure modes were observed depending on the shear reinforcement, shear arm ratio (a/d), and type of concrete. In beams without shear reinforcement, both diagonal and bond failures were typically observed.

3.1. Bond behavior: NVC vs SCC

Bond behavior between concrete and reinforcement is a primary factor in designing reinforced concrete structures. It is well established that bond between a deformed bar and concrete depends on several parameters, such as concrete compressive and tensile strengths, confinement due to transverse reinforcement and bar geometry (diameter, shape of the ribs). Several researchers [15,21,34–39] investigated bond strength in SCC considering pull-out tests on single bars according to CEB/RILEM test method or similar, and considering different shapes of specimens (i.e. walls) to assess the so-called "top bar effect".

In the former test setup, the scatter of the experimental results is significant [11,15], with differences of the bond strength of steel in NVC and in SCC ranging between 0% and 70% [15].

Nevertheless, some studies [14,15,34] showed that the increased bond strength in SCC is due to a more uniform ITZ and a denser cement matrix.

In [35] are presented several results available in literature on pull-out tests on both NVC and SCC short anchorages in terms of ratios between bond strength and concrete compressive strength vs bar diameter.

NVC exhibited a ratio between the bond strength and the compressive strength lower than 0.4, while the results obtained on SCC, showed that, with or without confinement, the same ratio is in the range between 0.3 and 0.6. Confinement modifies the bond strength as a function of diameter: bond strength increases with bar diameter. The same trend for specimens without confinement has been observed by Lorrain and Daoud [37]; they concluded that bond strength becomes insensitive to bar diameter when pull-out failures occur. Furthermore, the SCC specimens used for the experimental research in [35] were casted with the same mix of the tested beams presented in this paper. The bond strength varied between 0.58 and 0.47 of the compressive strength (depending on the bar diameter), and the coefficient of variation varied between 0.92% and 12.23%.

Another crucial issue regarding bond in structures is the top-bar effect, a phenomenon related to bleed-water accumulation under horizontally embedded reinforcing bars. The presence of this water can locally increase the water cement ratio under the bar and weaken the bond strength.

This phenomenon is called top-bar effect because a greater reduction in bond strength occurs in the upper levels of reinforcement.

Studies on the top-bar effect have shown that properly proportioned SCC is less affected by this phenomenon than NVC [38,39].