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Shear strength of high-strength concrete beams: Modeling and design recommendations

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ABSTRACT

In the present paper, the flexural and the shear resistance of high strength reinforced concrete (HSC) beams with longitudinal bars, in the presence of transverse stirrups is analyzed both theoretically and experimentally. The experimental researches here presented are parts of previous researches carried out by the author. Researches refer to HSC beams with high percentages of steel bars failing in shear and in flexure. From the analytical point of view, a model based on the evaluation of the resistance contribution due to beam and arch actions including bond splitting and concrete crushing failure modes is developed and presented. The model was verified against available experimental results and those recently obtained by the author. Some of the more recent analytical expressions able to predict the shear and the flexural resistance of concrete beams were mentioned and design considerations are made referring to a ductile design of HSC beams. Finally, design recommendations were derived with the proposed model and compared with expressions given in most common codes.

1. Introduction

High Strength Concrete (HSC) has high compressive strength in the range of 50–100 MPa. The widespread use of HSC in reinforced concrete constructions takes origin in its obvious advantages with respect to normal strength concrete, in term of both strength and durability. HSC, in fact, is characterised by increased modulus of elasticity, chemical resistance, freeze thaw resistance, lower creep, lower drying shrinkage and lower permeability. Although high-strength concrete does not give benefits in increasing flexural resistance, shear resistance is increased. However with higher strengths the failure will be through aggregates as the paste is very strong. Therefore there is a reduction in aggregate interlock action.

A complete knowledge of HSC properties is essential for evaluating the structural response in flexure and shear under monotonic and cyclic loads. Beam flexural strength may be greatly influenced by the contemporary presence of shear and particularly reduced with respect to the pure flexure case. Failure mechanisms characterized by the shear–moment interaction may be dangerous occurring in a brittle way without any warning sign [1]. The complexity of the phenomenon has led many researchers to firstly investigate the resisting mechanisms of reinforced beams without stirrups [2,3]. The strength provided by transverse steel reinforcement is generally taken into account by adding the contribution of the truss mechanism to that of the concrete mechanisms [4]. Some other codes [5,6] give, for the bearing capacity in shear, analytical expressions for shear strength based on mechanical approach reflecting more recent research project developments (variable inclination truss model, modified compressed field theory). A formula for the shear strength of HSC beams with stirrups is presented depending on the following variables: – geometric steel ratio of the longitudinal reinforcement; – depth-to-shear span ratio; – resistance of materials; – crack spacing; – tensile stress in main bars; – residual bond resistance; – size effect. The model was verified against available some experimental results and those recently obtained by the author. Considering that design procedures proposed for regulatory standards should be safe, conceptually correct and simple to understand, and should not necessarily add to either design or construction costs, the most effective procedures are based on relatively simple conceptual models rather than on complex empirical equations [4]. Therefore, the proposed equations are verified comparing the results of existing shear tests on RC beams with stirrups and predicted values obtained with the current model. In fact, the comparison with experimental data shows that, in almost all cases, the aforementioned expressions accurately predict the shear strength of HSC beams and the proposed model is able to provide the most conservative results.

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List of symbols

A_s	section of longitudinal steel
a	shear span
b	width of beam
d	effective depth of beam
h	height of beam
f'_c	cylinder compressive resistance
f_y	yielding stress of longitudinal reinforcement
M	bending moment
V	shear force
q_{res}	residual bond resistance of bar

Finally, starting from the proposed model some design considerations are suggested dealing with the upper and lower limit on section of shear reinforcement and geometrical ratio with the variation of concrete compressive strength and span to depth ratios.

2. Brief description of previous experimental study

Two experimental researches carried out by the author [8–10] are here mentioned and utilised as data bank.

The first one [8,9] refers to beams having rectangular cross-section with base $b = 100$ mm, height $H = 125$ mm and length $L = 1000$ mm. The beams were reinforced with longitudinal steel reinforcements consisting in two deformed bars having diameter $\phi = 16$ mm, and the concrete strength f_c was 70 MPa. Beams were also reinforced with stirrups made of deformed bars having a 6.35 mm diameter and placed at a spacing of 198 or 98 mm. Two additional longitudinal bars in the upper part of the beams having a 6.35 mm diameter were utilised. They essentially had the function of forming a framework maintaining the steel position during concrete casting. Beam tests were carried out with shear span to depth ratios (a/d) equal to 2.25. Steel bars had yielding stress values 275 MPa for longitudinal bars and 510 MPa for stirrups.

The second experimental investigation here considered [10] refers to beams with two different shear span to depth ratios ($a/d = 2$ and 2.8). The choice of the shear span values was made in such a way that, in the absence of specific shear reinforcement, "shear–compression" failure for $a/d = 2$ or "diagonal-tension" failure for $a/d = 2.8$ is reached. Beams had rectangular cross-section with base $b = 150$ mm, height $H = 250$ mm and length $L = 2500$ mm. The beams were reinforced with two longitudinal deformed bars having diameter $\phi = 20$ mm and stirrups made of deformed bars having a 6 mm diameter and placed at spacing p of 200 or 60 mm. Two additional longitudinal bars in the upper part of the beams having a 10 mm diameter were utilised. Cylindrical compressive strength of plain concrete at 28 days was 41.20 MPa. For steel bars the yielding stress values were 610 MPa for longitudinal bars and 510 MPa for stirrups. Fig. 1 shows geometrical details of tested beams.

Fig. 2 shows load–deflection curves relative to the beams with stirrups tested in [8,9]. In Fig. 2 tick continuous lines refer to lower pitch of stirrups and continuous thin lines to beams without stirrups. In Fig. 3 tick continuous lines refer to lower pitch of stirrups, dashed lines to higher pitch and continuous thin lines to beams without stirrups. From curves it emerges that for higher spacing of stirrups shear brittle failure is attained, while for low spacing of stirrups brittle flexural failure is observed in the compressed zone of the beams. Unloading and reloading the beam the envelope of cyclic response does not follow the monotonic response in the cases of shear failure, while it fits very well when flexural failure is attained.

Fig. 3 shows load–deflection curves tested in [10] relative to the beams with stirrups for $a/d = 2.8$ and $a/d = 2.0$ respectively. From all the curves it emerges that in the absence of stirrups beams fail in shear in a brittle manner and in both cases of $a/d = 2$ and 2.8. With stirrups shear strength increases and reducing the spacing of stirrups the failure modes changes from shear to flexural.

Fig. 4 shows the variation of load P with the axial elongation in the legs of stirrups measured through strain gauges on a gauge length of 5 mm. From the curves it emerges clearly the role of stirrups in bridging the main shear cracks. Up to the load corresponding to failure of shear critical beams, the stirrups are little stressed. Above this load level stirrups reach reaches the yielding.

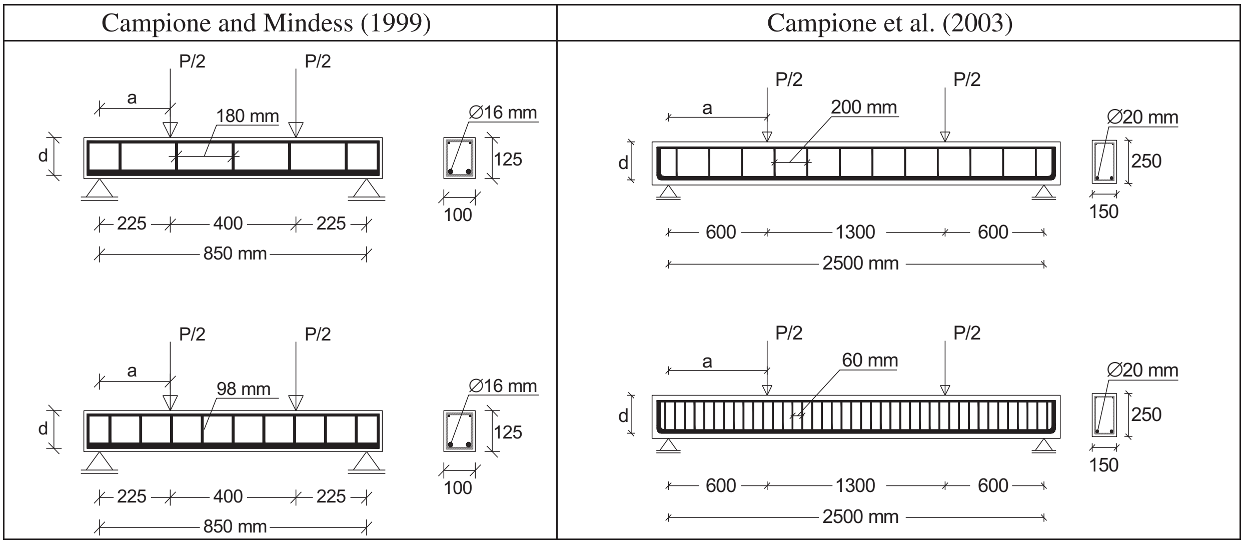

Fig. 1. Geometry of beams tested by Campione and Mindess [8] and Campione et al. [10].