Discussion Forum

Shear behaviour of steel fibre reinforced concrete beams with low shear span to depth ratio

This has reference to the paper titled 'Shear behaviour of steel fibre reinforced concrete beams with low shear span to depth ratio' by N. Lakshmanan, T.S. Krishnamoorthy, K. Balasubramanian, B.H. Bharathkumar, and S. Gopalakrishnan published in the The Indian Concrete Journal.

The behaviour and design of reinforced concrete beams under shear loading is an area of concern, as it is not yet fully understood. Generally, the shear failure of a reinforced concrete beam is directly related to the diagonal tensile cracking that develops in the direction perpendicular to the principal tensile stress axis. Once tensile crack occurs, the tensile stress at the crack surfaces rapidly softens, which significantly reduces the shear strength of the beam. Provisions in design codes for shear loading are continually changing and generally becoming very stringent. Still there is a need to establish design and analysis methods that provide realistic assessments of the strength, stiffness, and ductility of structural members under shear loading. This is reflected in the number of papers internationally published on this topic[1]. Though different codes adopt different formula for accessing the shear strength of concrete, there is a wide scatter in the results obtained using this formulae. Hence research in this field is being conducted continually all over the world.

The addition of fibres to concrete effectively improves the shear strength of concrete, as the fibres transfer tensile stresses across crack surfaces (which are called the crack-bridging stress). Due to these characteristics of the steel fibres, the shear strength of a fibre reinforced concrete (FRC) beam increases. Moreover, the failure mode of the beam is changed to be more ductile[2]. Generally fibre-reinforced concrete (FRC) is classified as conventional FRC and high performance FRC (HPFRC), according to their tensile behaviour. Conventional FRC retains a fraction of tensile strength after tensile cracking occurs, but shows tension softening behaviour like other quasi-brittle materials. However, HPFRC exhibits strain hardening response after tensile cracking. Addition of fibres also improves the fire resistance of concrete elements.

The use of fibre-reinforced, high performance concrete (FRC or FRHPC) is gaining considerable attention in recent years, especially when crack propagation control is of primary importance, such as in slab-on-ground applications or in beams where shear reinforcement is partly or totally absent[3-6]. They are also used in repair and retrofitting applications. In India there is a scope for using fibres instead of transverse reinforcement (provided the cost of fibres are reduced considerably and the fibres are mixed properly in the field), as in many cases the required cover is not provided for stirrups and hence they are vulnerable to corrode. From a practical standpoint, however, current design codes do not include any provision on fibre-reinforced concrete sections. Hence, design engineers are not able to incorporate fibrous reinforcements in their structural designs. This situation is surprising, since extensive research has been conducted on fibrous concrete and its material properties are well known[7].

The fibre resistance contribution should be included with the concrete contribution, whereas many researchers suggest a separate fibre shear contribution[8]. The primary parameters that affect the shear strength of FRC beams are the volume ratio, aspect ratio and shape of the steel fibre, the compressive strength of concrete, the ratio of flexural reinforcement, and the shear span-to-depth ratio. Many researchers have proposed design equations that are defined as functions of the primary design variables[9-13]. Existing shear models, however, do not accurately predict the strength of both normal strength FRC and high strength FRC beams[10]. It is interesting to note that ACI committee 544 recommends Sharma's model[7,12].

With this background, the authors' paper is a welcome addition the literature on shear strength of normal-strength FRC beams. Though the authors have discussed about the modified compression field theory, originally developed by Collins and his co-workers, they have not used it to calculate the shear capacity of FRC beams (Figure12 of the paper is reproduced from Ref. 1). This theory, though more rigorous than the available empirical methods to calculate the shear strength of beams, is not suitable for design applications, unless some more simplifications are made. With such simplifications it has been adopted in the Canadian code(in fact the code gives three different procedures for determining the factor β and the angle θ. For beams not exceeding 250 mm in depth, the Canadian code allows $\beta = 0.21$ and $\theta = 42^{o}$, which will result in designs comparable to the designs made using the ACI code)[14]. The compression field theory has recently been extented to FRC beams also[8].

It is not known how equations 8-10, 12 and 17 of the above paper were derived. The discusser is not sure whether the expression for f , used in equation 17, is the one given in equation 15 or the one that is given in the conclusion. The shear strength of FRC beam, as given in Equation 12 of the paper, considers only the volume fraction of fibres and not the other parameters such as aspect ratio, compressive strength of concrete and amount of tensile reinforcement. Similarly the same equation is used for calculating the shear strength of beams without fibres. Though this matches the experimental results in this case, it is doubtful whether this will be applicable as a general expression to be used in practice. Previous research has shown that the expression given in codes, which is a function of one third power of concrete compressive strength truly represents the shear strength[15]. Hence the latest Eurocode expression given below may be considered as more rational for normal and high strength concretes.

$$V_{uc} = (0.18/\gamma_c)k(100\,\rho_1 f_{ck})^{0.333}\,bd \geq 0.035k^{1.5} f_{ck}^{0.5}bd \quad ......(1)$$

where

$k = 1+(200/d)^{0.5} \leq 2.0$ (d in mm)

γ_c = Partial factor of safety for concrete =1.5

$\rho_1 = A_{st}/bd \leq 0.02$

A_{st} = Area of tensile reinforcement

f_{ck} = cube compressive strength of concrete

b,d = breadth and effective depth of beam, respectively.

Note that the Eurocode expression also considers size effect, which is not considered by the authors. The formula given in the Indian code, which is based on Australian research conducted in 1970's, also considers several of the above parameters.

Similarly, the expression given in Equation 17 considers volume fraction of steel fibres and the compressive strength of concrete only and does not consider the other parameters mentioned earlier (though there is a very good correlation between the test results conducted by the authors and their theory). The discusser tried to compare the other equations as proposed in Ref. 10 -12 and found that the correlation between the authors' test results and these equations is not good. Have the authors checked these aspects? It will be quite useful if they suggest equations to predict the shear strength of normal, FRC and HPFRC concretes which incorporate as many basic parameters and can be universally applied.

Recently, by considering a data base of 1200 beam tests, Brown et al concluded that the following formula given in the ACI 318-05 code for shear capacity of normal concrete beams yield un-conservative results for beams subjected to concentrated loads applied between 2d and 6d from the support (thus showing the importance of incorporating shear span-to-depth ratio in the design equations)[16].

$$V_{uc} = (\sqrt{f_c}\,bd)/6 \quad ......(2)$$

For members in which more than one third of the factored shear at the critical section results from a concentrated load located between 2d and 6d of the face of support, they suggested the following equation

$$V_{uc} = (\sqrt{f_c}\ bd)/12 \qquad ......(3)$$

where, f_c is the cylinder compressive strength of concrete. In practice many beams will be subjected to uniform, or near uniform, loads and their shear strength will be higher than those of beams subjected to concentrated loads.

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The authors' reply

The authors thank the discusser for a well written discussion on a complex topic. When fibre reinforcement is incorporated, it is necessary that they are fully utilised for development of strength and other related parameters. “Fibre pullout” is less efficient. “Fibre rupture” is preferable. Under such circumstances equation (8) has been validated over a large number of beam specimens and has been discussed in a paper presented in the Indo-US workshop [1]. While many researchers accept the presence of dowel action, it is not included in theories because of large scatter. Dowel action on bar would increase the bond length required. Also, the bond length required would decrease with increase in volume of fibres. These two parameters are included in equation (9) and (10). It is a well known fact that V_{uc} of plain concrete is related to split tensile strength. The expressions for split tensile strength may vary, in as much as any parameter related to f_{ck} has variation (including flexural tensile strength, modulus of elasticity, etc.,). Again the expression for V_{uc} in equation (12) is applicable for high strength steel fibres which rupture at failure.

The discusser has stated that the comparison between author’s test results and some of the equation proposed in literature is not good. This is precisely the point the authors are making. The shear capacity is dominated by bond. Hence V_c contribution is significantly restricted, and the crack angle determined by iterative process using equations (15), (16) and (17), leads to reduced Vs. The theme of the paper is to avoid bond failure by suitable detailing to maximize shear capacity.

The last statement “in practice many beams will be subjected to near uniform loads and shear strength will be higher” is to be taken with a pinch of salt. Yes, it may be true that concentrated loads are critical because of shear – moment interaction effects. Maximum moment and maximum shear existing at the same section does not normally happen in simply supported beams. But it does occur in practice over continuous supports.

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