Discussion on papers published in

Magazine of Concrete Research

Volume 22, Number 73: December 1970

Limit-state design for shear in rectangular and T beams*

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Dr Regan and Dr Placas are to be commended for discussing at length, for the first time, the problem of shear transfer across the vertical interface between the flange and web of a reinforced concrete T beam. This problem can be more acute in composite steel-concrete beams, and Parts I and II of CP 117⁽¹⁾, the Code of Practice for composite beams in building and bridges, give clauses stipulating: (1) the amount of transverse reinforcement required, (2) the minimum amount of transverse reinforcement which must be provided, and (3) the maximum amount of longitudinal shear in the concrete which may be permitted irrespective of the amount of transverse reinforcement. The requirement of transverse reinforcement in CP 117, Part I, is based upon the assumption that at failure the longitudinal shear is resisted by the cohesion in concrete ($= 2.8\sqrt{u_w}$) and a frictional resistance equal to the force at yield in the transverse reinforcement.

The CP 117 value for cohesion ($= 2.8\sqrt{u_w}$) can be obtained by substituting $f_c' = \frac{2}{3}u_w$ in the ACI-ASCE recommendation⁽²⁾ that the ultimate diagonal tension in an unreinforced web should not exceed $3.5\sqrt{f_c'}$ where f_c' is the cylinder strength. However, the analogy between the transfer of longitudinal shear in the flange of a composite beam and of vertical shear in the web of a rectangular reinforced concrete beam is not direct.

Dr Regan and Dr Placas assume that the resistance to longitudinal shear is provided by cohesion ($= 0.1u_w$)

and friction equal to the force in the transverse reinforcement at yielding. The value of cohesion ($= 0.1u_w$) taken by them will be greater than the CP 117 value ($= 2.8u_w$) for all values of u_w greater than 784 lb/in² and, in the light of results of experiments on composite beams with varying amounts of transverse reinforcement now available⁽³⁾, it seems that a higher value may be justifiable. In this respect the higher value used in the paper ($= 0.1u_w$) looks attractive and I would be grateful if the authors would produce some evidence in support of this value.

A major difference between the CP 117 approach and that used in the paper is that Dr Regan and Dr Placas consider both shear and in-plane bending across the shear plane, and take cohesion to exist only where there is compression in concrete due to in-plane bending, whereas CP 117 neglects in-plane bending and assumes cohesion over the entire shear-span.

It appears that equation 23, which is the condition for longitudinal equilibrium, is erroneous. The correct form is:

$$K_c \left(c + K_r f_{yt} \frac{K_s}{K_c} \right) \geq \frac{F}{at} \dots \dots \dots (23)$$

Similarly, equation 25 should be:

$$(r_t f_{yt})_{\min} = \frac{F}{at} \frac{1}{(1 - 0.5K_c)} \left(1 - \frac{cat}{F} K_c \right) \dots \dots (25)$$

Consequently, one of the two sets of curves in the

*Pages 197 to 208 of *Magazine* No. 73.

Figure 1: Corrected design chart for transverse flange reinforcement.

design chart (Figure 10 of the paper) has to be redrawn; the corrected version is shown here (Figure 1).

Although the set of curves corresponding to equation 24 in original Figure 10 is correct, the equation

itself has a printing error. It should read:

$$(r_t f_{yt})_{\min} = \frac{F}{at} K_f \left(\frac{b - b_f}{a} \right) / \left(1 - \frac{K_c}{2} \right)^2 \dots (24)$$

Reply by the authors

We wish to thank Dr Sen for his interest in our paper and his corrections to equations 23, 24 and 25 and to Figure 10. In each case, his version is correct and ours was in error.

The remainder of his contribution raises the problems of the magnitude of the 'cohesive' strength of concrete at cracked surfaces and the distributions of stresses along web-flange junctions.

The cohesion is, of course, not a true material property in the soil mechanics sense, but a property dependent upon a number of characteristics of the crack in question, amongst which the most important are probably the type of cracking and the width of the crack. With regard to the first, there is a basic distinction between cracking due primarily to shear and cracking due to direct tension. Data from tests⁽⁴⁾ of specimens with transverse reinforcement and involving

shear cracking are compared with our 'cohesion + friction' equation in Figure II, and it can be seen that the correlation is satisfactory, subject to an upper limit on shear resistance irrespective of the reinforcement provided. This is the third condition of CP 117 referred to by Dr Sen and is undoubtedly rational. However, in practice, it is extremely unlikely to be a governing criterion in reinforced concrete members. The assumption that cohesive strength is directly proportional to the concrete's cube strength is questionable but should not cause any serious errors within the practical range of concretes.

When the cracking is due to direct tension and a direct separation occurs, the post-cracking shear resistance is reduced, as can be seen from Figure III, which gives results of tests of specimens⁽⁴⁾ similar to those of Figure II but pre-cracked along their shear

Figure II: Results of tests on specimens without initial cracks.⁽⁴⁾

Figure III: Results of tests on specimens with initial cracks.⁽⁴⁾

planes. The reduction is essentially confined to the cohesive component, whilst the friction effect is almost unchanged.

The influence of crack widths upon shear resistance cannot easily be studied in reinforced specimens because the crack width is a function of the behaviour of the reinforcement and cannot be controlled externally. Using unreinforced specimens of the type shown in Figure IV, pre-cracked in tension, Bara⁽⁵⁾ obtained the results shown in the same Figure. In the tests with external compression, the axial load was applied before the shear loading was begun. It can be seen that shear resistance is markedly dependent upon the crack width at the start of the shear loading, from which stage the width remains more or less constant until failure.

Our approach does not take direct account of the effect of crack widths but assumes that, in the region of which the shear resistance is taken into consideration, the crack widths should be similar to those obtained in the tests of reinforced specimens which involved considerable variation in reinforcement details.

The design shear resistance is limited to the length of the junction subject to transverse compression because, once plasticity of the transverse reinforcement is assumed, there is no theoretical control over the widths of cracks along the remainder of the junction. The most reasonable view of the behaviour of the latter length is that the concrete is free from transverse stresses and that its shear resistance should correspond to Bara's results for specimens without axial loads. This would give ultimate shear strengths of $0.02u_w$ with a crack width of 0.1 mm and only 0.005 with a width of 0.4 mm. Such resistances are negligible in comparison with that of the compressed region. The

Figure IV: Results of tests on specimens with initial cracks and without transverse reinforcement.⁽⁵⁾

use of a relatively high cohesive strength in the compressed region is justified by the fact that it is also the region where the cracking is of the shear and not the tension type, and by Bara's and Mattock's results, which show that reduction in strength caused by tensile cracking is not very significant when the concrete is restrained by reinforcement or subsequent compression.

Finally, with regard to the provisions of CP 117

referred to by Dr Sen, it seems to us that, although a rather crude analysis is acceptable, it is illogical to consider only the shear and not the direct transverse forces for two reasons. Firstly, if the transverse effects are neglected, the force system is not in equilibrium and the errors involved can be appreciable. Secondly, as shown above, shear resistance is affected by transverse stresses in its cohesive as well as its frictional component.

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