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DISCUSSION ON PAPER 9158 STRUCTURAL ENGINEERING GROUP

Reinforced concrete deep beams: a method of analysis

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Dr Subedi proposes an alternative method for the analysis of deep beams, which raises a number of interesting questions. For example, how were the specimens cast? If they were cast upright, the concrete of the upper portion of the test beams is likely to be weaker, thereby increasing the possibility of crushing the concrete under load. Indeed, Table 4 shows that four of the 19 beams failed at the bearing, and three of the four beams failed at the bearing under load.

86. The analysis method proposed in the Paper requires the determination of the compression zone t_c. By considering the equilibrium of horizontal forces, Dr Subedi suggests that the depth of the compression zone t_c can be calculated by assuming linear strain distribution across the deep-beam section considered (Fig. 12(a)) and using a rectangular stress block (Fig. 12(b)). Although these assumptions simplify subsequent calculations (see Appendix 1 of the Paper), they contradict deep-beam behaviour: the stress and strain distributions across a deep-beam section are non-linear. Extensive elastic analysis, a good summary of which is given in reference 12, has also suggested that the neutral axis of a deep beam is lower than that of a shallow beam and that there is a high peak of compression; for deep beams with high height/span ratio, more than one neutral axis may exist (for example, see Appendix A of reference 12). It would be interesting to know the extent to which Dr Subedi has found the above assumptions (i.e. the use of Figs 12(a) and 12(b)) to remain reasonably valid. Fig. 8 of the Paper seems to indicate that the measured t_c are much larger than the corresponding calculated t_c shown in Table 6: the values of the calculated t_c vary between 30 and 100 mm (i.e. the calculated t_c/h ratios vary between 0·04 and 0·1).

87. In the Introduction to the Paper, Dr Subedi has rightly pointed out that the behaviour of deep beams may be governed by the slenderness effect. Recent tests at Newcastle University[21,22] have demonstrated that the failure mode of deep beams with h/b ratio exceeding 20 is strongly dependent on the eccentricity of the load (i.e. the e/b ratio), the slenderness of the beam (i.e. the h/b ratio) and the web reinforcement arrangement. It was also observed that the transition from the shear or bearing failure mode (i.e. in-plane failure) to the buckling failure mode (i.e. out-of-plane failure) was accompanied by a significant reduction in the failure load. In practice, it is very difficult to be sure that deep beams are truly centrally loaded, even when the drawing shows they are. For stocky deep beams (say, $h/h < 20$), a slight eccentricity will not have serious consequences; for slender deep beams (say, $h/b > 20$), a similar eccentricity, which may be unintentional and not allowed for in the design, could change the failure mode and hence render the design calculations invalid. In practical design, therefore, the load-carrying capacities of deep beams with h/b ratios higher than 20, say, should be based on the

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buckling mode rather than on shear, flexure or bearing. On this basis, I disagree with Dr Subedi that the proposed analysis method is suitable for any section and material properties and loading arrangement (see § 59).

88. In the Paper, Dr Subedi points out that one of the merits of the proposed method is its ability to predict the deep-beam failure mode (see §§ 12–29 and § 59). However, I believe that, for practical design purposes, it is far more important that a method is able to produce safe design against undesirable failure, namely shear failure (owing to the unpredictable and catastrophic nature of deep-beam shear failure), without undue conservatism. In this respect, it has been shown in Table 6 and elsewhere[4,5,21] that the CIRIA Guide[12] is satisfactory. Had the tension reinforcement of the beams 1A1, 1B1, 1D1, 2A1, 2D1, 3E1 been designed in accordance with Clause 2.4.1 of the CIRIA Guide, they would not have failed by flexure. Table 1 shows that the amount of tension reinforcement of the six beams varies between 0·2% and 0·26% of *bh*, which is very close to the minimum allowable limit of 0·13% *bh* given in BS 8110, and to the recommended minimum limit of 2% *bh* given in the Institution of Structural Engineers' Manual.[23]

Dr Subedi

In reply to *Dr Wong*'s questions, all the test beams were cast vertically as they would be in practice. Although it is possible to argue that the concrete in the upper portion of the beam may have been weaker, it is unlikely to have been the cause of bearing failure in beams 1C1, 2C1 and 4G3. The likely cause was the multiaxial stresses which resulted in a bursting effect locally. As discussed in § 31, beams 1C1 and 2C1 had no additional reinforcement in the loading area. In the case of beam 4G3, the local strengthening was inadequate. It is clear from these results that whenever load is concentrated over a small area, proper detailing must be carried out in order to prevent premature failure.

90. The depth of the compression zone t_c is determined purely from the equilibrium of forces in the Stage II analysis. This does not assume linear strain distribution. Only in the case of flexural mode of failure is the depth of the neutral axis determined from the strain compatibility method, as is made clear in the examples in Appendix 1. It is suggested, and indeed shown in evidence in Fig. 8, that when flexural mode of failure governs then the strain compatibility is appropriate. Fig. 12 applies to the Stage I analysis. A separate study will be necessary in respect of the precise measurement of the depth of the compression zone, which is at present being investigated at the University of Dundee.

91. In its present form, the proposed analysis applies to reinforced concrete deep beams of rectangular cross-section and a height/thickness ratio of less than 15. This limitation is imposed to make sure that the beam does not fail by out-of-plane buckling. Within this category, the method is versatile; to use it for slender forms, such as those described by Dr Wong, was not the intention. However, the concept can be applied, with appropriate force equilibrium equations, to reinforced concrete flanged beams, I-section,[14] as shown in Fig. 13. In the I-sections, the stability does not depend only on the height/web thickness ratio, but also on other factors such as width of flange, thickness and spacing of stiffeners. At the University of Dundee, we have recently carried out a large number of tests on the slender form of I-section beams, with funding provided by the Science and Engineering Research Council. The results will be published in due course.

92. Dr Wong favours the use of the CIRIA Guide 2[12] on the grounds of practical design purposes and safety. My view about the CIRIA Guide 2 is fully

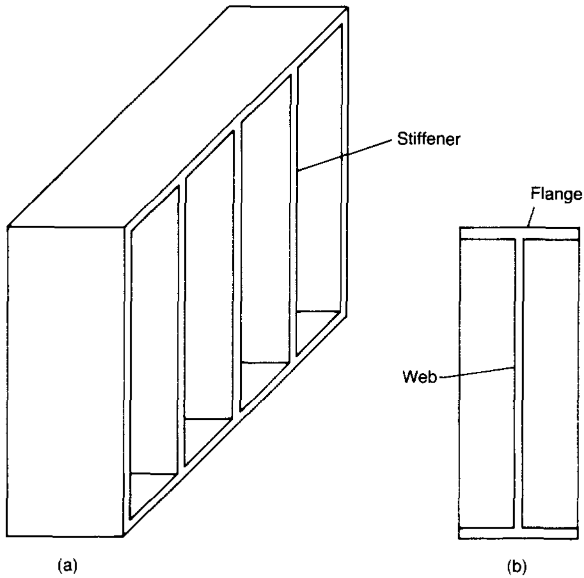

Fig. 13. Flanged beam

discussed in §§ 57–59 of the Paper. It would have been useful to obtain Dr Wong's comments on the points raised in § 58.

93. With reference to Table 6, the CIRIA Guide 2 predictions are inconsistent over the range of parameters examined. In many cases, the predicted ultimate loads are either too high or too low. Without the upper limit set by $v_u bh$, the CIRIA Guide 2 predictions cannot be relied on to give safe results in all cases. The importance of predicting flexural mode of failure in deep beams becomes apparent when the existing structures have to be assessed.

94. The proposed method is a method of analysis which can easily be translated into a design method. Practical application and safety of structures are paramount in suggesting any new method of design, and these points have not been overlooked.

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