Cross-section behaviour and ductility in composite beams

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The Authors' method of computing moment-curvature curves for positive moment regions of composite beams is shown (Table 1) to give reliable predictions of ultimate moments of resistance of simply supported beams found in two series of tests. For every beam in Table 1, $M_{\max}$ given by the theory exceeds M_p , which is presumably the value that would be used by a designer. However, it appears (§ 18) that there are beams of compact section that fail to reach M_p .

53. This finding need cause no concern unless it relates to beams of proportions likely to be used in practice, and can be verified by tests. The reason is that the flexural behaviour of composite beams found in tests is almost always better than that predicted by simplified design rules (e.g. all beams in Table 1 except one). This is not just because the design rules are based on conservative approximations; of more relevance is that conventional computer analyses of cross-sections do not model the three-dimensional behaviour and finite size of plastic hinges in composite members.⁷ Is the conclusion of § 18 supported by the results of tests on practicable members of compact section?

54. The discrepancies between theory and tests are even more significant in continuous members, where the applicability of simple plastic theory depends⁷ on the relationship between moment-rotation curves for hogging and sagging hinges, the ratios of the lengths of adjacent spans, the incidence and location of loads concentrated over short lengths, and on the inelastic behaviour of the negative moment regions, where the effects of local buckling,²⁰ method of construction, vertical shear,²¹ and slip may all be relevant. This is shown by many tests, particularly those discussed in §§ 50-53 of reference 7. In all of these the ultimate load was much higher than the initial prediction, even though the proportions and loadings of the beams were chosen (from the results of a parametric study) to provide particularly severe tests of the applicability of simple plastic theory.

55. The Authors' computer studies, being limited to midspan cross-sections, are therefore thought to provide insufficient basis for their recommendation that the use of cross-sections with $\chi \geq 1$ (Fig. 22) should be a necessary condition for the use of plastic theory.

56. It is accepted that the higher the value of χ , the greater will be the midspan curvature at maximum load of a simply supported beam. However, this has little relevance to continuous beams for buildings, where plastic behaviour usually occurs first at internal supports. When the steel section is suitable for plastic design (compact) and the slab reinforcement is of high yield steel (as is usual), strain hardening is likely to begin when the midspan moment is well below M_p , and the design ultimate load will be

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reached with higher support moments and lower midspan moments than those calculated. In this situation, the shape of the moment-curvature curve at midspan at large curvatures is irrelevant, and no requirement for strain-hardening behaviour in this region is needed.

57. The proposed restriction ($\chi \leq 1$) should not be placed on designers in absence of clear evidence that it is necessary. This can be obtained only from tests on beams that satisfy existing criteria for plastic design (§ 66 of reference 7), have one or more midspan cross-sections with $\chi < 1$ and are of a type that may be expected to occur in practice.

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Professor Johnson states that the more relevant reasons why tests on composite beams show strengths almost always higher than those predicted by simplified design rules are the three-dimensional behaviour and the finite size of plastic hinges. We disagree. We believe that strain hardening is the paramount cause of the increased strength. The latter is recognized in research work on steel^{11,15} and reinforced concrete,^{2,3} and emerges clearly from Table 1 and the figures in the Paper. Indeed, the marked improvement in predictions given in § 49 and table 2 of reference 7, when some account was taken of strain hardening, also shows that it is the principal cause of the greater strength. However, we recognize that strain hardening results in plastic hinges of finite size, and moreover that, under moment gradient, plastic hinges are possible only under such circumstances.¹⁵

59. Sagging hinges in composite beams have usually been characterized as strain-softening^{6,7} although in fact most practical beams are strain-hardening with $\chi > 1$. Nevertheless, the designer should guard against strain-softening behaviour which may arise in practice with the use of thin slabs and/or steels of higher strength. In statically determinate beams, ductile hinges lead to large deflexions before collapse and give warning of failure. Our concern is not that M_p may not quite be reached, but that ductility will be lacking.

60. In continuous beams, the sagging hinge is not always the last to form, and the sequence of hinge formation can easily be affected by relative settlement of supports, construction loading and the shrinkage of adjacent concrete (e.g. in columns). Thus a guarantee of sagging hinge ductility is most valuable. Professor Johnson does not dispute that the criterion $\chi > 1$ gives such a guarantee.

61. The Paper examines most of the parameters relevant to behaviour at sagging moment regions of composite beams. A ductility test has been advanced which is easy to apply, rationally based and not unduly restrictive. We remain convinced that the test is superior to the requirement that the plastic neutral axis should lie above the web of composite beams.

62. Experiments are in hand to obtain further information on the behaviour of continuous beams, some of which should provide more severe tests of the applicability of simple plastic theory than are at present found in the literature.

References

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