

*Discussion on Paper No. 6583**

Residual stresses in rolled I-sections

by

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Mr P. Jory (Senior Job Engineer, Caltex Services Ltd) wrote that on reading the Paper his attention was at once drawn to Fig. 19. That photograph showed a stub column after testing, and clearly indicated cracking of the resin where compressive residual stresses occurred. In a contribution to the Discussion on Paper No. 6529 he had included a photograph of an H-section wharf pile pulled after some years' service (see *Proc. Instn. civ. Engrs*, vol. 24, Feb. 1963, pp. 288-290, Fig. 9). This showed a corrosion pattern presumed to be due to lines of high stress locked in the section during the manufacturing process. This presumption appeared to be confirmed by the Paper. In those photographs a distinct similarity was noted in the patterns of resin cracking and corrosion. Those patterns seem to indicate that, say, along the extremity of a flange, the residual compressive stresses varied, being maxima at lines of resin cracking or corrosion. Was the Author able to offer any explanation of this pattern which was generally at 45° and 90° to the longitudinal axis of the I-sections? Further, how was the presence of 45° lines compatible with the Author's patterns of residual stresses having been arrived at from specimens cut from 90° cross-sections?

40. The corroded pile, referred to above, came from a wharf designed to absorb a vessel's energy by deflexion of the whole structure. Thus the main duty of the piles was as cantilever beams rather than as columns. One therefore assumed that residual stresses were of no significance in view of the Author's remark that the influence of residual stresses on the behaviour of beams in bending was not critical. However, in many marine structures piles were acting primarily as columns and the Author had indicated that in compression members, residual stresses might be significant. She went on to say that, although reductions in carrying capacity were unlikely to occur in actual structures, they were a warning. This warning would appear to be especially significant in the case of marine structures, as it had been shown that, unless protected, corrosion could rapidly occur where residual compressive stresses were highest, thus further weakening already weak points. He wondered whether the removal of metal by corrosion released residual stresses to any extent, thus slowing down the process of corrosion.

41. In § 27 the Author had set out the maximum reductions of column strength for I-sections containing residual stresses. Looking at this in conjunction with § 26, Mr Jory was not clear whether she was advocating the use of reduction factors in design; or had such factors generally been considered when drawing up standards such as B.S.449:1959.

42. Finally, he would like to pose a question that might possibly be beyond the scope of the Author's work. If so, perhaps Mr Wright could comment. The photograph of the corroded wharf pile showed flange corrosion generally occurring only over the outer half of the flanges, that is, where the Author had shown residual stresses

* *Proc. Instn. civ. Engrs*, vol. 23, November, 1962, pp. 361-378.

to be impressive. He therefore wondered whether stress corrosion showed a preference for areas of high compressive stress rather than of tensile stress.

Dr Lambert Tall (Research Assistant Professor of Civil Engineering, Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania) wrote that the Author was to be commended on her careful study of residual stresses in four structural rolled I-sections. This work corroborated very extensive theoretical and experimental studies conducted by many investigators since 1950.^{3, 5, 8-14}

44. Since the work of the Author followed closely the lines of the previous investigations, in particular that of reference 5, interesting comparisons might be made. For completeness, additional information was also presented, mainly on recent work conducted at Lehigh University. The details of the discussion were enumerated according to the paragraph sequence of the original Paper.

45. § 4. Reference 9 summarized the results of the Lehigh study on residual stresses and column strength for rolled shapes. Results were presented for a wide range of structural shapes of ASTM Designation A7 steel. Although the residual stress distribution varied from shape to shape, and even in the same shape, sufficient experimental data was collected to be able to estimate, to a sufficient accuracy, the residual-stress distribution in a rolled shape. Supplementary studies on a low-alloy high-strength steel¹⁵ (ASTM A242) indicated that the residual-stress distribution depended very little on the material properties, but to a great extent on the shape of the cross section. This fact was also shown in studies of welded plates, although the yield point did play a much greater role for residual stresses in welded shapes.¹⁶⁻¹⁸

46. § 6. Studies of the pinned-end, initially straight, axially-loaded column were necessary as a basis for the general column study, although such columns did not exist in practice. The strength of a column was defined by its ultimate load; in the case of rolled shapes, the increase of the ultimate load above the bifurcation load (given by the tangent modulus concept) was comparatively small and was neglected. For rolled shapes, then, the tangent modulus bifurcation load resulted in a conservative estimate of column strength.⁹ For this reason, the (U.S.) Column Research Council in 1952 issued a memorandum¹⁹ stating that the tangent modulus formula was a proper basis for the establishment of working-load formulas for both ferrous and non-ferrous metals. For welded columns, however, recently completed studies^{13, 16, 20} has indicated that the increase of the ultimate load over the tangent modulus load was substantial, so that the tangent modulus load was not a proper basis for the prediction of the strength of welded columns. Moreover, for welded columns, it was shown that the effect of initial out-of-straightness was approximately equal to the effect of the residual stresses in reducing the column strength for the medium slenderness ratios.

47. § 9. References 1 and 13 had indicated that the web material would normally have had a higher yield strength than that of the flange material due to a combined effect of more rapid cooling rate and increased working of the metal in the web.

48. § 11. Although the use of a 20 mm (1 $\frac{1}{8}$ in.) gauge length was theoretically feasible for the measurement of residual stresses, such a measurement was made on a very localized section of the column and, hence, was not necessarily indicative of the residual stresses existing along the complete length of the column. Although any appreciable variation of residual stresses along the length of a column would not occur, there was a possibility of very localized effects due to deformations, accidental or otherwise. The Lehigh research over the past thirteen years had indicated that a 10 in. gauge length would present average values for residual stresses, and that it was these values which were needed for column strength studies. A longer gauge length would also make the handling and reading easier, leading to higher accuracies.

49. Reference 22 had indicated that complete sectioning was not necessary to obtain a measure of the residual stress. It was shown that partial sectioning gave very good results; an indication of the error was presented.

50. It was stated that "the parts of the cross section which have cooled most rapidly contain compressive residual stresses, the others tensile residual stresses". That statement was not true in all cases. The formation of residual stresses due to cooling was a complex problem,¹⁷ and one of its facets was that equilibrium must exist at all stages of cooling, not only at the end of cooling. Dependent on the shape of the cross section, and due to the requirement of equilibrium, it was possible that the part of the cross section which had cooled most rapidly was in a state of residual tension. Examples of this were given in reference 9 for rolled shapes; however, probably the simplest example of that effect of equilibrium was that of the far end of an edge-welded plate.^{17, 23}

51. § 13. The values of residual stresses for the 10×10 and 12×12 shapes, as given in Table 1, appeared very high when compared to those of the 6×6 and 8×8 shapes, and those of the Lehigh study.⁹ The discrepancy could be due to the peculiarity of the shapes, to the short-gauge length or measuring technique used, or to the small population of results obtained. The average value for σ_{rc}/σ_y in the Lehigh study was approximately 0.35.⁹

52. §§ 14-18. Attention should be directed to the Stub Column Test Procedure,²⁴ of the International Institute of Welding, accepted as a Class C Standard at the Oslo conference, July 1962. The Procedure was developed from the Lehigh study²⁵ which conducted more than 50 stub column tests in the past ten years.

53. The Author did not mention the method of loading the stub column, that is, whether the recorded load was at the zero strain rate (static) or at a strain rate other than zero. Reliable and consistent results could only be obtained from static loads^{9, 21, 24} which corresponded to a zero strain rate and which defined the lower bound of yield strength. Likewise, the strain rate for the tensile coupon results were not given, so that it was difficult to appreciate the comparisons made between the yield stress determined by tensile coupon and by stub column.

54. § 19. References 12, 26 and 27 had considered the effect of cold bending on the residual stress distribution and on column strength. The residual stress had been both calculated and measured. For rolled H-shapes it was found that cold bending residual stresses were no more critical than were cooling stresses.

55. § 22. The tangent modulus concept of column buckling would give the load at which an initially-straight column would bifurcate from the straight position.²⁸ Shanley showed that such a column was able to carry additional load under increasing deflection until the ultimate load was reached.²⁹ The term 'Shanley column strength', as used in § 22, corresponded to no particular load. Further discussion on column stability might be found in reference 30.

56. §§ 23 and 24. An important step in the development of the theories of residual stress and column strength was the recognition by Yang that the yielded portion of the cross section no longer played a role in bending strength, but that column strength was a function of the moment of inertia of that portion which remained elastic. As reported in reference 3, this enabled him to develop equation (3) of the Paper under discussion.

57. § 27. References 5, 9 and 12 presented the results of both theoretical studies and experimental verification for the strength of columns failing about both weak or strong axes, and for the effect of residual stress and the effect of the stress-strain relationship. For the idealized elastic, perfectly plastic straight-line stress-strain relationship, it was shown that the greatest reduction in column strength occurred for the medium slenderness ratios. This finding also applied to the strength of welded H- and box-columns, and to columns of high strength steels.^{13, 15, 16, 20} The reduction in strength for the welded shapes was much greater than it was for the rolled shapes, so much so that present specifications (which were based on rolled shapes) were inadequate for welded shapes in the medium slenderness ratios ($L/r = 60$ to 120).

58. § 28. Most column curves currently being used for design were based on unrealistic situations such as the use of hypothetical end-eccentricities and co-

efficients of various types to adjust the curve to practical results. The early work conducted at Lehigh University under the guidance of the Column Research Council^{9, 5, 19} showed that the transition in the column curve from the Euler curve to the yield point cut-off was due mainly to the effect of residual stresses. The Column Research Council developed a column curve (the CRC curve) based on the tangent modulus concept of column buckling, taking into account the effect of residual stresses.³¹ In 1961, the CRC curve was adopted by the American Institute of Steel Construction as the basis for the design of columns³² and hence marked the first time that the design of columns reflected actual conditions. Reference 33 had compared the column curves used for design in a number of countries, and also had indicated how residual stresses affected column strength.

59. §§ 30 to 38. Theoretical expressions for the determination of column curves from assumed residual stress distributions in rolled shapes were given in references 5, 8, 12 and 15. Reference 16 presented the ultimate strength analysis of a welded column taking into account the effect of residual stresses. Such theoretical expressions were of great use in evaluating the effect of any particular variable, in this case, residual stresses.

The Author, in reply, wrote that the similarity in the patterns of resin cracking in stub column tests (Fig. 19) and corrosion in the photograph contributed by Mr Jory to the Discussion on another paper, was very interesting. However, the cross-sections (6 × 6 I, 8 × 8 I, 10 × 10 I, 12 × 12 I) tested in compression did not show cold-bend yield lines and the residual stresses were due to uneven cooling during and immediately after the rolling process. It had to be pointed out that rolled sections in real structures were mostly not free from cold-bend yield lines, which, in the Author's opinion, could also be the cause of the corroded wharf piles.

61. The cracking of the resin due to the development of yield lines during the stub column testing gave a good qualitative estimation of the residual stresses. As the compressive residual stresses were the highest at the extremities of the flanges and in the middle of the web, resin cracks appeared there first. The appearance of characteristic directions of yield lines could be explained, to some extent, by the theory of local plastic deformations. Bijlaard³⁴ stated that flow lines appeared in the planes which, according to the yield condition of the limited shearing energy, showed the least resistance to local plastic deformation. Referring to Bijlaard's theory, the yield lines in the thin plate at a linear state of stress formed an angle of 55° with the direction of the principal stress $\sigma_1/\sigma_2=0$. For relatively thin plates, the yielding in the direction of the thickness was not impeded, hence the plastic strain in the direction of yield lines equalled zero. For thick bars, however, the yield lines were inclined at 45° along the wide sides, and were horizontal along the narrow sides of the bar, where yielding was impeded.

62. It was mentioned in the Paper that residual stresses had no influence on the bending carrying capacity, i.e. on the full plastic moment, but they did, of course, affect the load-deflexion relationship. Considering the tangent-modulus bifurcation load for a pin-ended, initially straight, axially loaded column (an idealised case), the reduction of column strength due to residual stresses in different I-sections could be significant. However, column curves used for design in different countries were based on very different assumptions (i.e. end-eccentricities, initially curved axis) and experimental data, and the allowable stresses of compression members, took into account rather different coefficients of safety. B.S.449:1959 dealt with a factor of safety of 2 for a slenderness ratio greater than 80. Fig. 12 would indicate that, considering the influence of residual stresses in the 10 × 10 I-section, the safety factor for buckling about the minor axis would be also less than 2.

63. The last question posed by Mr Jory, about stress corrosion, was beyond the scope of the Author's work, but she would think it essential to take into account whether the wharf pile was cold-bent or not, i.e. the final residual stress pattern due to the rolling process and cold-bending or due only to the rolling process.

64. The Author wished to thank Dr Tall for his most valuable comments which filled a gap in the Paper and enabled the interested reader to learn about the extensive research work in this field conducted at Lehigh University. She was grateful for his list of additional references on recent work, since she had ended her investigations in July 1960 (post-graduate course 1959-60). Considering some points raised in the discussion, it had to be mentioned that the results of stub column tests were obtained from static loads, i.e. the recorded load was at zero strain-rate. She agreed that a longer gauge-length for the measurement of residual stresses gives a better average value. With the applied measurement technique (Schweigerer Setzdehnungsmesser) an accuracy of ± 0.6 tons/sq. in. could be obtained.

65. Finally, the Author wished to point out that the aim of her Paper was to give information about residual stresses caused by the manufacturing process in British rolled I-sections (universal columns) which had not been investigated until that time.

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