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RESIDUAL STRESSES IN HOT ROLLED MEMBERS

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ABSTRACT

The distribution of residual stress in I-sections due to uneven cooling after hot-rolling has been examined. A survey covering a large number of previous measurements has been made in order to establish typical patterns for subsequent inelastic buckling strength calculations. Measured residual stresses in some commonly used British UB and UC sections are in good agreement with these results. When compared with the results of the general survey, American residual stress assumptions are seen to be unrealistic both as to magnitude and distribution.

Patterns of residual stress for different I-section geometries have been selected which are about the worst likely to be encountered in British rolled sections. Buckling strength calculations for I-sections can therefore be based with confidence on residual stress distributions which are representative of the real situation.

1. INTRODUCTION

Residual or "locked-in" stresses have a significant effect on the brittle fracture, fatigue, stress corrosion and buckling strength of structural steel sections. In recent work at Cambridge and Sussex attention has been confined to their particular effect on buckling.

A combination of applied and residual stresses will promote inelastic behaviour in a member cross-section at levels of applied stress less than yield. Since plastic material which does not subsequently unload elastically can make no contribution to resist bending, a knowledge of the effective cross-section stiffness under load is essential for buckling calculations. When buckling is not a consideration, the fully plastic load carrying capacity is not impaired, but deformations will be greater than in a corresponding initially stress free member.

Longitudinal residual stresses arise from uneven heating or cooling of the cross-section during the manufacturing process. Such stresses are thus encountered in hot-rolled sections as well as those fabricated by welding and flame-cutting. Attention here will be restricted to residual stresses in I-sections induced by hot-rolling.

A hot-rolled I-section starts life as an ingot at a temperature of about 1250°C. During the rolling process the section shape is formed. By the time the cooling bed is reached, the average temperature will be down to 600°C to 900°C depending on the section's thickness.

During the final stages of rolling, the flange toes and the centre of the web which are the more exposed parts of the section, have cooled more than the shrouded web to flange junction. The contraction in the cooler material is resisted in the hotter regions where compressive plastic flow takes place at a low value of yield stress associated with the high temperature. The cooler material has now extended in relation to the hotter core and as this latter region contracts on cooling to ambient temperature, a reversal in stress takes place. The material which cools first is now in residual compression, whilst the region which cooled last is in residual tension. The longitudinal stresses must give rise to a system of forces in the cross-section which is in equilibrium.

Considerations of member strength have prompted the investigation of residual stresses by both direct measurement and analysis. References to residual stress measurement are numerous and will be given in connexion with a survey of results

in a later section. Alpsten (1) has recently developed a sophisticated computer analysis to predict residual stresses in hot-rolled steel sections of different geometries. Although the analysis is theoretically sound, in practice the many variations in rolling technique can produce quite different residual stress patterns in identical sections. This tendency is aptly illustrated by M. J. Baker's work at Imperial College (2). It therefore appears that the most satisfactory way of arriving at an estimate of residual stresses in structural sections is by making a study of published results and thereby inferring typical stress patterns for various section geometries.

The magnitude of residual stresses is largely independent of material properties (3,1) and can therefore be considered as a function of section geometry for identical cooling conditions. If the residual stresses are expressed as a proportion of the yield stress their significance is seen to reduce as the material yield stress increases.

We are concerned here only with residual stresses in thin sections, that is to say, those sections for which the stress variation through the thickness can be ignored. Attention at Lehigh University (1,4) has recently turned to thick sections where large variations in residual stress can occur through the thickness. Residual stresses increase in severity for geometrically similar shapes as the size of the section increases.

2. MANUFACTURE OF HOT-ROLLED SECTIONS

The processes involved in the manufacture of hot-rolled sections are generally well known. Techniques however, tend to vary slightly from country to country and details of British practice are given in Ref. 5. In particular, British mills cool sections spaced well apart with the web vertical. In American mills it appears that sections are close packed on the cooling bed. This may account for the fact that webs of American sections end up with tensile residual stresses (3) while the more exposed webs of British sections are in compression.

As far as residual stresses are concerned an important part of the manufacturing process is cold straightening. This acts beneficially as a form of mechanical stress relief (6). The amount of redistribution of residual stress during roller straightening depends on the operator's setting of the rollers. It can easily happen that no change in the original cooling residual stress pattern is made. Gaging operates only on a short length of the member. To straighten the whole length, it is necessary to pass the member through the gag-press several times. It is possible that after leaving the press, portions of

the length may still contain the original stresses. Alpsten (1) reports undisturbed cooling residual stress patterns in nominally straightened sections. The present measurements (Section 3) confirm this. Basing member strength calculations on the full cooling residual stress pattern rather than the more favourable pattern produced during cold straightening is thus a sensible precaution.

3. PRESENT RESIDUAL STRESS MEASUREMENTS

A large proportion of the work on residual stresses and their measurement has been carried out in the United States. As a result, information is biased towards American sections and rolling practice.

To obtain further information on residual stresses in typical British sections a small programme of measurements was undertaken at Cambridge. As a secondary investigation the effect of cold straightening was examined by making residual stress measurements on two lengths of the same bar, one length having been cold straightened and the other left untouched.

Residual stresses will be relieved completely by cutting the bar longitudinally into thin strips. Extensometer readings made before and after cutting will determine the strain relaxation in the strip and hence the original magnitude of residual stress. This 'sectioning' method as it is called provides the most useful means of measuring residual stresses. With thick members, sectioning may be followed by 'slicing' to obtain the stress variation through the thickness (4).

When long gauge length extensometers are used, an automatic averaging of the stresses is obtained. A 250 mm gauge length has been used at Lehigh University (3). A 200 mm gauge length Demec extensometer was used for the present tests. Measurements made by Jez-Gala (7) at Cambridge using a 20 mm gauge length were unsatisfactory because only local values of residual stress were measured. A similar criticism can be levelled at other well-known methods of measurement such as trepanning, hole drilling and X-ray diffraction.

The present residual stress measurements were carried out on seven lengths of five commonly used Universal Column and Beam sections. Five lengths were not cold straightened (NCS) and two lengths were (CS). The section sizes are shown in Table I. All material was to BS 4360 Grade 43A ($\sigma_y = 250 \text{ MN m}^{-2}$) and was supplied by courtesy of the British Steel Corporation's Lackenby and Cargo Fleet Iron Works, Middlesbrough.

TABLE I PRESENT RESIDUAL STRESS MEASUREMENTS

No.	SECTION	$\frac{Bt}{DT}$	RESIDUAL STRESS: MN m ⁻²		
			σ_f	σ_{fw}	σ_w
1	6x6x14.7 lb - NCS ^(a)	0.89	+122	-100	+110
2	8x8x31 lb - NCS ^(b)	0.67	+122	- 90	+100
3	8x8x31 lb - CS ^(b)	0.67	+ 10	- 75	+120
4	10x5 $\frac{3}{4}$ x21 lb - NCS ^(a)	0.41	+ 55	-125	+260
5	12x6 $\frac{1}{2}$ x31 lb - NCS ^(a)	0.31	+ 38	-150	+340
6	16x7x36 lb - NCS ^(b)	0.31	+ 68	-144	+220
7	16x7x36 lb - CS ^(b)	0.31	+ 45	-133	+216

Source: a) Cargo Fleet Iron Works, b) Lackenby Works

The sectioning method was used to determine the residual stress distribution. A number of specimens parallel to the longitudinal axis were selected from both web and flange. Preparation of each specimen consisted of drilling a pair of 1 mm diameter holes, 1 mm deep and 200 mm apart. The change in strain on a 200 mm gauge length was determined by comparing Demec extensometer readings before and after sectioning. Each specimen after cutting was 12 mm wide and some 220 mm long. Readings were made on both faces of each specimen except for that at the centre of each flange where a reading could only be made on the outside face. The number of specimens per section ranged from thirteen for the 6 in x 6 in x 15.7 lb section to nineteen for the 16 in x 7 in x 36 lb section.

The measured residual stresses are plotted in Figures 1a to g. The simple theoretical distribution, flange toes and web in compression and web to flange junction in tension is confirmed. Severe cold straightening is seen to have redistributed flange stresses for the 8 in x 8 in x 31 lb (CS) section although the web is largely unaffected. Cold straightening by rotorising in the 16 in x 7 in x 36 lb section has had no effect. Peak residual stress values from Figure 1 appear in Table I, where σ_f , σ_{fw} , and σ_w are respectively the stresses at flange toes, flange to web junction and centre of web. Compressive stresses are positive.

Tensile tests were made on two coupons cut from each section, one coupon coming from a flange and one from the web. The non-

waisted coupons were pulled in a 100 kN Instron machine. The strain rate at yield was maintained at $8.3 \times 10^{-6} \text{s}^{-1}$ which was as close to the zero strain rate condition which could be attained without stopping the machine altogether. Tensile yield stress values appear in Table II below together with the mill test results.

TABLE II TENSILE COUPON TESTS

SPEC. No.	POSITION	σ_y MN m ⁻²	y (MILL TEST) MN m ⁻²
1	Flange	291	-
	Web	310	386
2	Flange	296	-
	Web	303	345
3	Flange	300	-
	Web	332	334
4	Flange	273	-
	Web	366	352
5	Flange	256	-
	Web	338	357
6	Flange	273	-
	Web	340	357
7	Flange	281	-
	Web	335	341

4. PREVIOUS RESIDUAL STRESS MEASUREMENTS

The theoretical work by Alpsten (1) has shown that the magnitude and disposition of residual stresses in hot-rolled sections are governed mainly by section geometry and cooling conditions. Whilst the first of these parameters is well behaved, the second may vary considerably from mill to mill. A survey of published residual stress measurements shows a wide variation of residual stresses in geometrically similar shapes. The results of this survey are given in Table III. Many of the results shown in the Table are averaged from several tests. In general the material was ordinary structural mild steel having a yield stress in the region of 250 MN m^{-2} . A few results are included for high strength steel to BS 4360: Grade 55, ($\sigma_y = 450 \text{ MN m}^{-2}$).

It is difficult to describe the geometry of an I-section in a single parameter, but Ketter (8) has suggested the non-dimensional grouping Bt/DT . B and D are the breadth and depth of

TABLE III RESIDUAL STRESS MEASUREMENTS

SECTION	Bt DT	ORIGIN	REF.	RESIDUAL STRESSES: MN ⁻²			SECTION	Bt DT	ORIGIN	REF.	RESIDUAL STRESSES: MN ⁻²		
				σ_f	σ_{fw}	σ_w					σ_f	σ_{fw}	σ_w
12x6½x27 lb	0.31	Aust.	9	- 34	-117	+207	8x4 RSJ	0.28	Aust.	11	0	- 70	+168
12x6½x27 lb	0.32	Japan	"	- 7	-117	+155	12x5x25 lb	0.27	G.B.	12	+ 42	-135	+148
16x7x50 lb	0.26	Aust.	"	- 7	-158	+103	8 WF 31	0.67	U.S.A.	13	+ 85	- 35	- 56
16x7x50 lb	0.20	Japan	"	0	-165	+172	8 WF 31	0.67	"	"	+ 78	- 8	-105
10x10x49 lb	0.53	Aust.	"	-	-	+ 90	8 WF 31	0.67	"	"	+ 80	- 28	- 33
10x10x49 lb	0.61	Japan	"	0	- 55	+103	8 WF 31	0.67	"	"	+102	- 62	+ 25
27x10x102 lb	0.24	Aust.	"	+ 35	-124	+160	IAP 150	0.34	Belg.	14	+ 45	-115	+100
27x10x102 lb	0.22	G.B.	"	0	-193	+262	IPE 200	0.34	"	"	+ 25	- 90	+230
12x6½x31 lb	0.32	Aust.	10	+ 17	-172	+307	DIE 20	0.68	"	"	+130	- 48	+ 30
16x7x50 lb	0.26	"	"	+ 15	-188	+250	DIR 20	0.60	"	"	+ 70	+ 8	- 60
16x7x50 lb	0.27	"	"	+ 13	-152	+230	DIE 20	0.68	"	15	+128	- 95	+ 42
10x10x89 lb	0.60	"	"	+117	-110	+138	6x6x20 lb	0.68	G.B.	7	+ 80	- 75	+ 82
12x12x190 lb	0.53	"	"	+122	- 98	+147	8x8x31 lb	0.66	"	"	+ 77	- 75	+ 93
27x10x102 lb	0.23	"	"	0	-193	+276	10x10x49 lb	0.61	"	"	+138	-138	+138
12 WF 50	0.37	U.S.A.	8	+ 37	- 72	+120	12x12x92 lb	0.61	"	"	+120	-102	+110
12 WF 65	0.64	"	"	+135	-105	+110	8 WF 67	0.57	U.S.A.	1	+ 82	- 70	+ 38
14 WF 426	0.55	"	"	+155	- 90	- 98	10x4½ RSJ	0.27	Aust.	16	+ 25	-200	+142
4 WF 13	0.80	"	"	+ 98	- 22	- 67	8x4 RSJ	0.35	"	"	+ 18	-160	+215
8 WF 24	0.50	"	"	+ 75	+ 22	-127	6x5 RSJ	0.66	"	"	+ 53	- 70	+ 98
8 WF 31	0.67	"	"	+112	- 37	+ 22	*6x6x20 lb	0.68	G.B.	17	+ 10	- 30	+ 54
8 WF 67	0.57	"	"	+ 60	+ 37	-112	*8x8x58 lb	0.60	"	"	+ 10	- 19	+ 25
14 WF 43	0.33	"	"	+ 67	-145	+190	*8x5½x17 lb	0.50	"	"	+ 5	- 31	+ 70
36 WF 150	0.22	"	"	+ 52	- 82	+ 60	*12x6x19 lb	0.23	"	"	- 30	-102	+140
6 M 15.5	0.89	"	"	+112	- 75	+ 15	12x5x32 lb (A)	0.25	"	2	0	- 92	+118
12 J 14	0.20	"	"	+ 30	-	-	" (B)	"	"	"	0	-155	+147
4 WF 13	0.80	"	11	+ 90	- 30	- 30	" (C)	"	"	"	0	-145	+147
8 WF 31	0.67	"	"	+ 90	- 37	+ 37	18x7½x66 lb (A)	0.24	"	"	0	- 38	+ 42
12 WF 65	0.64	"	"	+ 82	- 82	+ 98	" (B)	"	"	"	+ 25	-182	+180
14 WF 426	0.55	"	"	+112	- 30	- 60	" (C)	"	"	"	0	-115	+100

*High Yield Steel (Grade 55)

the section and T and t are respectively the flange and web thicknesses. It would be wrong to attach too much authority to this simple parameter, but it does have the virtue of separating I-sections into Universal Column and Beam shapes. Values of Bt/DT are included in Tables I and III.

To examine the trend in residual stress magnitudes with section geometry, the values of residual stresses in Table III together with the results of the present measurements given in Table I are plotted against Bt/DT in Figure 2a, b, and c.

Typical patterns of residual stress found for the tests reported in Table III were parabolic in both flange and web (Figure 3(a)). Certain American results for column sections showed a tendency towards a bilinear stress distribution in the flange accompanied by a tensile uniform stress level in the web (Figure 3(b)). The present measurements on column shapes also showed this type of flange distribution but the web stresses were found to be predominantly compressive with a parabolic distribution (Figure 1a and b).

The bilinear distribution of stress in the flange implies a discontinuity over the junction with the web which is unnatural in view of the continuously varying conditions which produce these stresses in the first place. It therefore seems more reasonable to assume a rounding of this sharp corner giving the residual stresses in the flange more of a parabolic distribution. All beam shapes included in Tables I and III had residual stress patterns which conformed with Figure 3(a).

The present residual stress measurements are shown as open circles on Figure 2. They agree well with values from the general survey (plotted as solid circles).

5. ADOPTION OF CHARACTERISTIC RESIDUAL STRESS PATTERNS FOR HOT-ROLLED UNIVERSAL SECTIONS

To simplify the subsequent treatment of residual stresses in column and beam shapes a parabolic distribution in both flange and web is assumed as in Figure 3(a). The magnitudes of the peak stresses are deduced from the plots in Figure 2. A simple calculation to balance longitudinal forces in the cross-section will show the effect of the ratio of web to flange area on the residual stress values in a particular cross-section.

Taking a pessimistic view of the possible residual stresses in a column section ($A_w = 0.3A_f$) we obtain

$$\begin{aligned} \sigma_f &= + 125 \text{ MN m}^{-2} \text{ from Figure 2(a)} \\ \sigma_{fw} &= - 100 \text{ MN m}^{-2} \text{ from Figure 2(b)} \\ \text{and } \sigma_w &= + 175 \text{ MN m}^{-2} \text{ by balance of longitudinal forces} \end{aligned}$$

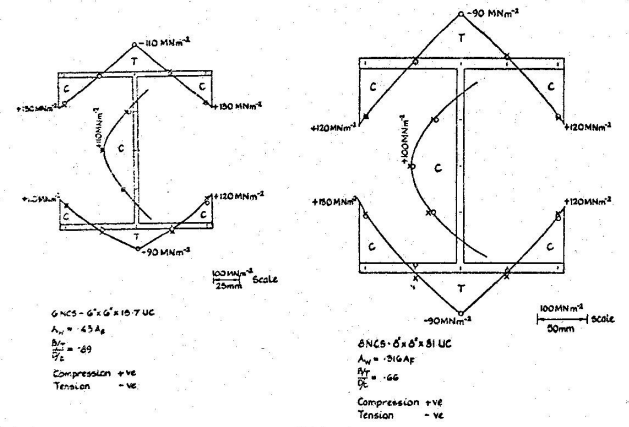
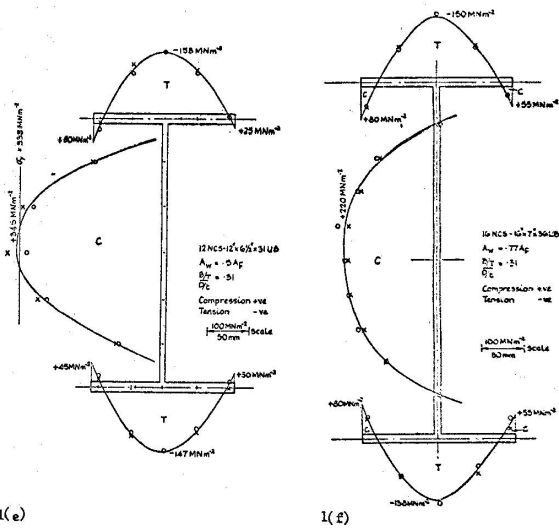
where A_w is the web area ($= dt$)
 A_f is the total flange area ($= 2BT$)
 σ_f is the stress at the flange toes
 σ_{fw} is the stress at the web to flange junction
and σ_w is the stress at the centre of the web.

Characteristic residual stress patterns for beam sections having A_w equal to $0.75 A_f$ and $1.2 A_f$ are also deduced in this way. Use is made here of the empirical observation that as the ratio A_w/A_f increases, σ_f decreases and σ_{fw} increases. This change is assumed to take place linearly, with σ_f for very deep beams ($A_w/A_f = 1.2$) being zero.

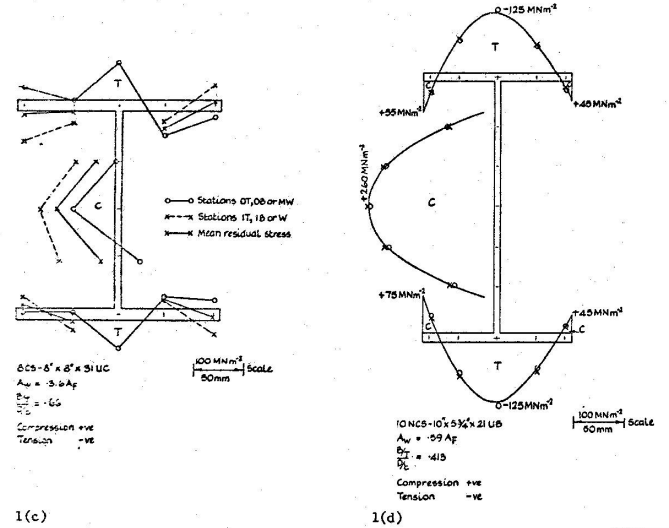
The principle influence of residual stresses on the inelastic buckling length of I-sections will be felt in the flanges. It is essential therefore to take representative values here. The peak web stresses calculated from the balance of residual forces are of secondary importance and may not always agree with typical figures plotted in Figure 2(c). This result is a consequence of assuming the simple parabolic stress distribution in both web and flange.

Although, in general, residual stresses do not depend on the yield stress, it is possible for yielding to occur in the webs of a few deep beams (see the Wyalla results (9,10)). This situation will result in a departure from the assumption of a parabolic web distribution. The consequent redistribution of residual stresses in the section is thus now affected by the magnitude of the material yield stress. Reference to flange stresses as the characteristic parameters will avoid the need to pay particular attention to this effect.

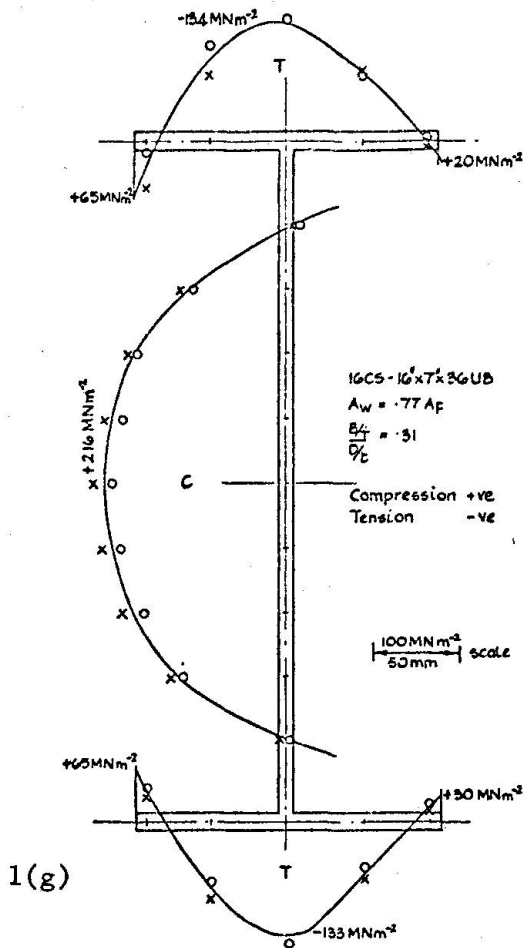
The peak residual stresses assumed in later buckling calculations for the column section and two beam sections are shown in Table IV. The overall distribution is assumed to be parabolic as shown in Figure 3(a). Included in Table IV are the stress values for column shapes that American workers have been using for many years. The stress pattern is that of Figure 3(b). Simple formulae for peak residual stresses appear under Table IV.



1(a) 1(b)
 Figures 1(a) to 1(g) - Present measurements of residual stress in British UC and UB sections



1(c) 1(d)



1(g)

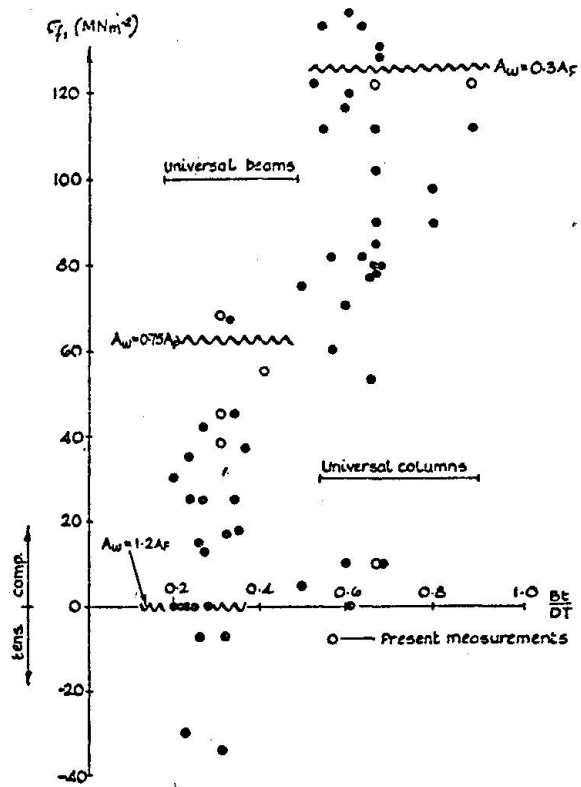


Figure 2(a) Residual stress measurements in I-sections: at the flange toes

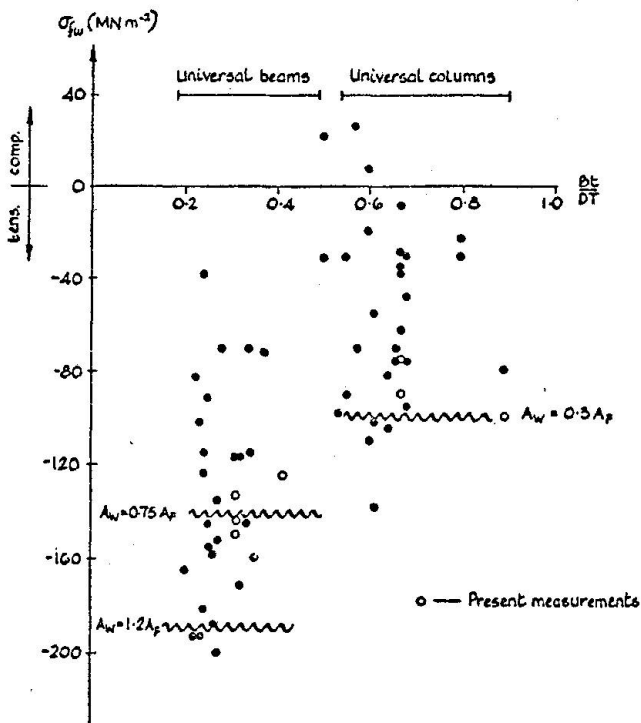


Figure 2(b) Residual stress measurements in I-sections: at the web to flange junction

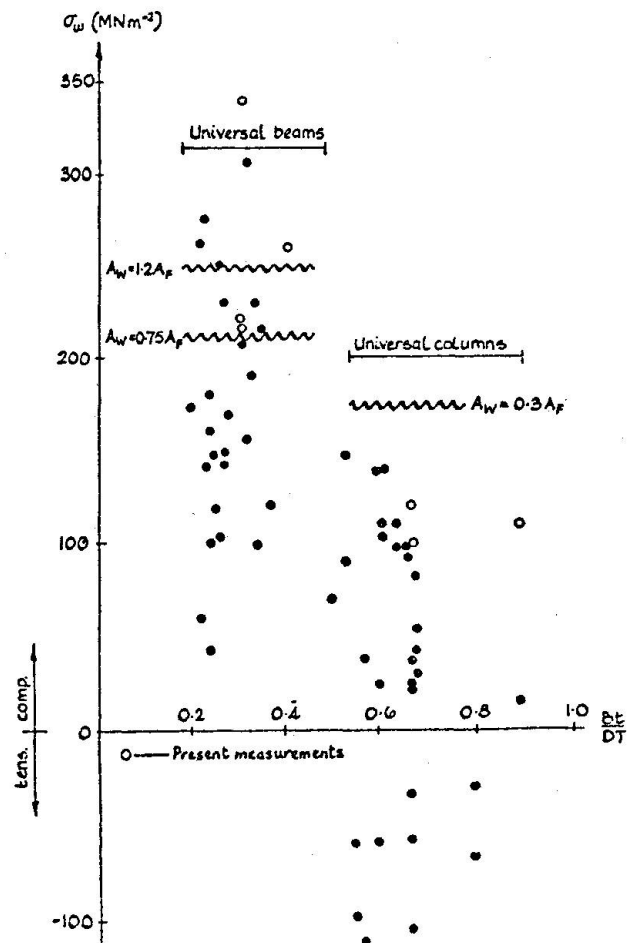


Figure 2(c) Residual stress measurements in I-sections: at the web centre

TABLE IV

SECTION	$\frac{A_W}{A_F}$	σ_f MN m ⁻²	σ_{fw} MN m ⁻²	σ_w MN m ⁻²
COLUMN	0.3	+125	-100	+175
BEAMS	0.75	+ 62	-144	+212
	1.2	0	-188	+250
COLUMN (U.S.A.)	0.3	+ 75	- 50	- 50

Approximate formulae adopted for peak residual stresses in hot-rolled Universal sections:

$$\sigma_f = 165 \left(1 - \frac{A_W}{1.2A_F}\right) \quad \text{MN m}^{-2}$$

$$\sigma_{fw} = -100 \left(0.7 + \frac{A_W}{A_F}\right) \quad \text{" "}$$

$$\sigma_w = 100 \left(1.5 + \frac{A_W}{1.2A_F}\right) \quad \text{" "}$$

A parabolic stress distribution is assumed in both flanges and web.

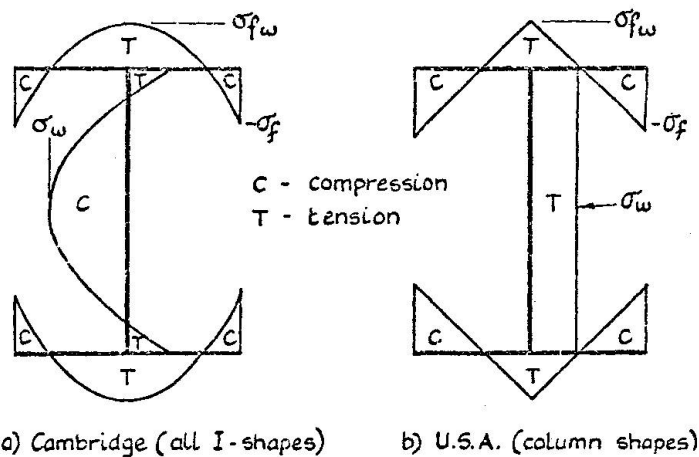


Figure 3. Comparison of assumed residual stress patterns

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Notation

A_F	total flange area (=2BT)
A_W	web area (=dt)
B	flange width
d	web depth
T	flange thickness
t	web thickness
σ_f	residual stress at flange toe
σ_{fw}	residual stress at web/flange junction
σ_w	peak residual stress in web
σ_y	yield stress

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