THROUGH-THICKNESS DISTRIBUTIONS OF WELDING RESIDUAL STRESSES IN AUSTENITIC STAINLESS STEEL CYLINDRICAL BUTT WELDS

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ABSTRACT

The purpose of this paper is to present a general prescription for as-welded residual stress distributions in austenitic butt welds of arbitrary diameter and thickness. This has been obtained by interpolation of finite element model results. The derived residual stress distributions are compared with recommended 'bounding' distributions from other sources. The distributions derived here are rather more detailed than previously available bounding distributions. In typical cases the weld material overmatches the parent in terms of tensile properties. This is shown to lead to residual stresses in the heat affected zone which can exceed the parent 1% proof stress substantially. It is intended that the general prescription for the residual stress distributions derived here should be of use to the engineer in performing structural assessments.

INTRODUCTION

British Energy's Advanced Gas Cooled Reactors make extensive use of austenitic stainless steels. These materials commonly entered service without post-weld heat treatment, and hence contain yield magnitude residual welding stresses. A detailed knowledge of these residual stress distributions is of central importance to structural integrity assessments, and hence to nuclear safety cases. In recent years British Energy has used finite element techniques to model residual stresses in a range of plant geometries. The results, in the geometrically simple case of cylindrical butt welds, show a consistent trend against welding heat input per unit thickness (q). This permits a general prescription for as-welded residual stress distributions in austenitic butt welds to be devised using 'q' as the controlling parameter.

DEFINITION OF HEAT INPUT PARAMETER, q

'q' is defined as the heat input per unit length of one weld bead, divided by the section thickness. No allowance for welding efficiency is included in the definition of 'q' (although the finite element models do make allowance for efficiency). Hence, $q = VA/St$, where V is the closed circuit welding voltage, A is the welding current (amps), S is the arc speed (mm/sec) and t is the section thickness (mm), giving q in units of J/mm^2.

THE MODELS ANALYSED

Eight cases were analysed using ABAQUS. The geometries, welding procedures and heat input parameters are summarised below.

Weld	R^{mean} mm	t mm	R/t	q J/mm^2	Weld Type
S5	184	64	2.9	21	MMA
S6	203	26.2	7.75	56	MMA
Spine	261	19	13.7	56	MMA
R4C3	161	18	9.0	65	MMA
Weld C(1)	398	15.9	25.0	65	SA
Weld 7.03	152	21.5	7.06	89	TIG
SW1	159	12.7	12.5	89	MMA
Weld C	398	15.9	25.0	167	SA

(1) This is a sensitivity study for Weld C which considered a reduced heat input.

All these welds were made from a single-sided weld prep (outer-V) with the exception of Weld C which comprises internal MMA runs together with external submerged arc welding, the latter being dominant as regards the resulting residual stresses.

The modelling procedure in all cases was to build the weld bead-by-bead, calculating the heat transfer during and after each weld bead deposition. For thick weldments, a 'lumped bead' approximation was employed (each modelled bead representing 2 or 3 actual beads). For each time step, the elastic-plastic stresses and strains were solved. The material in all cases was 316H stainless steel. Modelling the different tensile data and hardening responses of the weld and parent materials was found to be important.

TENSILE DATA AND NORMALISATION OF RESIDUAL STRESSES

For 316H, a reasonable approximation is to equate the weld 1% proof stress with the virgin parent 10% proof stress. This was adopted throughout, with perfect plasticity in the parent at strains greater than 10% and perfect plasticity in the weld at strains greater than 1%. This was found to lead to stresses which varied smoothly over the fusion boundary. All residual stresses presented below are normalised by the parent 10% (= weld 1%) proof stress.

GENERAL PRESCRIPTION FOR RESIDUAL STRESS DISTRIBUTIONS

Figures 1 and 2 show idealised distributions through the thickness for the axial and hoop residual stresses respectively. Comparison of the individual curves in Figures 1 and 2 shows how the residual stresses vary with the heat input parameter (q). Distributions for intermediate values of 'q' may be derived as follows;

<u>Axial Stress Distributions</u>: Define a dimensionless position parameter, x, such that x = +1 on the outside surface, x = 0 at the middle of the section, and x = -1 on the inside surface. Define a function f(x) by,

For $-2x_o < x < +2x_o$, $f(x) = \sin[\pi(x/x_o + \phi)/2]$
For $x > +2x_o$, $f(x) = \pi(2 - x/x_o)/2$
For $x < -2x_o$, $f(x) = -\pi(2 + x/x_o)/2$

The normalised axial residual stress is then given by,

$$\sigma_{axial}/\sigma_{10\%(parent)} = A\,[\,f(x) + \xi\,] \qquad \textbf{(1)}$$

In the above formulation, x_o, ϕ and ξ are fitted parameters. The values of these parameters for the five different modelled values of 'q' are as follows;

Heat Input q, J/mm²	x_o	ϕ	ξ	σ_1	**A**
21	0.72	0.28	0.43	-	0.65
56	0.50	0.46	0	-	0.82
65	0.38	0	0	1	0.72
89	0.35	0	0	1.35	0.49
167	0.1	0	4	12.6	0.030

For any value of 'q' between 21 J/mm^2 and 167 J/mm^2, the x_o, ϕ, ξ parameters may be found by linear interpolation. The amplitude factor, A, can be found from the bounding line for the peak axial residual stress, see Figure 3. Thus the value for A is chosen so that the maximum of Equ.(1) agrees with Figure 3. This is achieved as follows;

For $x_o > 0.38$, A = graph maximum / $(1 + \xi)$
For $x_o < 0.38$, A = graph maximum / $(\sigma_1 + \xi)$
where, $\sigma_1 = \pi(^1/x_o - 2)/2$

<u>Hoop Stress Distributions</u>: The residual hoop stress distributions can be described reasonably well by a tri-linear distribution through the thickness (see Figure 4). The parameters x_1, x_2, σ_1 and σ_2, defined in Figure 4, have been chosen as follows;

Analysis	**Material**	**q, J/mm²**	x_1	x_2	σ_1	σ_2
S5	Weld+HAZ	21	0.58	-1.0	1.13	-0.48
S6,Spine	Weld+HAZ	56	0.24	-0.34	1.11	0.1
Weld C* and R4C3	HAZ	65	0.56	-0.25	1.0	0.5
Weld C* and R4C3	Weld	65	0.25	-0.5	1.17	0.6
Weld 7.03 and SW1	HAZ	89	0.1	-0.2	0.98	0.37
Weld 7.03 and SW1	Weld	89	-	-	1.0	1.0
Weld C	Weld+HAZ	167	-	-	0.9	0.9

*reduced heat input.

For values of 'q' between 21 J/mm^2 and 167 J/mm^2 the appropriate values for x_1, x_2, σ_1 and σ_2 may be found by linear interpolation.

FINITE ELEMENT RESULTS: COMPARISON WITH GENERAL PRESCRIPTION

The normalised stress distributions resulting from the finite element models are shown in comparison with the above general prescription in Figures 5 to 16. For each model two sections have been illustrated; one through the weld centre line, and one through heat affected zone (HAZ) material. The general prescription provides a good representation of the FE data. It is generally bounding, especially for HAZ.

COMPARISON WITH SINTAP COMPENDIUM

A Compendium of Residual Stress Profiles has been compiled recently by Barthelemy (1). For pipe butt welds, the residual profiles have been parameterised against section thickness, t. Consequently, a rigorous comparison with the general prescription given here is problematical due to the latter being based on the heat input parameter, q, rather than thickness, t. However, Figures 17 to 20 compare the profiles from the two procedures as applied to two actual geometries (with $q=65$ J/mm^2, $t=18$mm and $q=56$ J/mm^2, $t=26$mm, $R/t=7.75$). Whilst not entirely dissimilar, the profiles show significant differences. In addition, it should be noted that the two sets of profiles are based on different stress normalisations. The present procedure normalises the stresses using the parent 10% (=weld 1%) proof stress, whereas Barthelemy (1) uses the weld 0.2% proof stress for the hoop stress and the parent 0.2% proof stress for the axial stress.

VALIDATION AGAINST MEASUREMENTS

Although beyond the scope of this paper, we note that many of the above FE models have been directly validated against sub-surface residual stress measurements on mock-ups or ex-service plant. This has covered the full thickness range, from relatively thin (16mm and 19mm), see Bouchard et al (2) and Bruno et al (3), through intermediate (35mm) and thick (≥65mm), see Smith et al (4) and Bate et al (5). Good agreement has been reported in all cases. The measured axial peak stress generally exceeds the 0.2% proof stress.

CONCLUSION

A general prescription for welding residual stresses in single-sided, austenitic butt welds has been presented. It is rather more detailed than existing prescriptions, eg. (1), with more complex through-thickness profiles and larger peak axial stresses.

REFERENCES

1. Barthelemy JY, "Compendium of Residual Stress Profiles", Brite-Euram SINTAP report BRPR-CT95-0024, May 1999
2. Bouchard PJ, Hutchings MT, Withers PJ, ICRS-6 *(these proceedings)*
3. Bruno G, Edwards L, Dutta M, Bouchard PJ, Abbott KR, Lin Peng R, ICRS-6 *(these proceedings)*
4. Smith DJ, George D, Bouchard PJ, Watson C, I.Mech.E Seminar "Recent Advances in Welding Simulation", 26 Nov 1999.
5. Bate SK, et al, ICRS-6 *(these proceedings)*

Figure 1: Idealised Residual Axial Stress Profiles [Eqn 1] : Comparison of Different 'q' Values (J/mm^2)

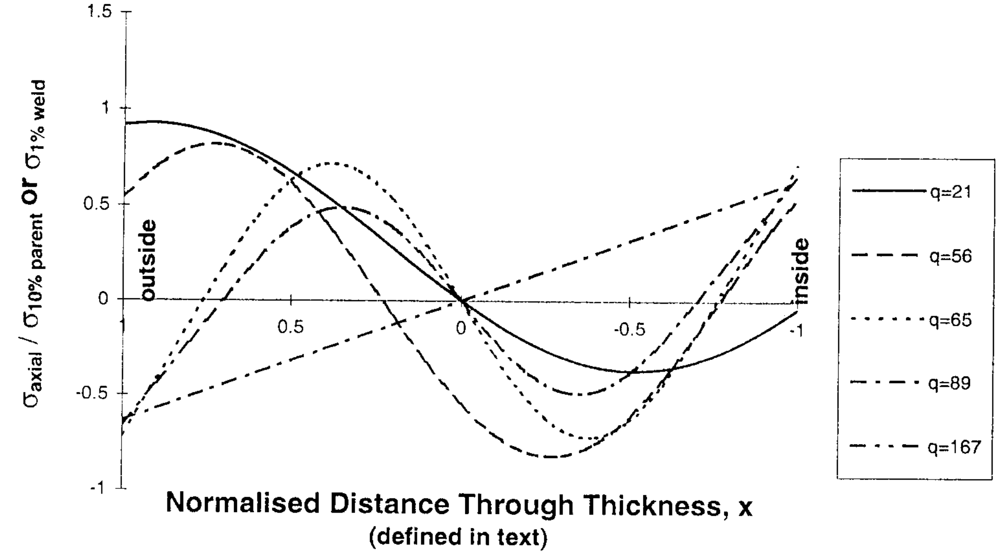


Figure 2: Idealised Residual Hoop Stress Profiles : Comparison of Different 'q' Values (J/mm^2)

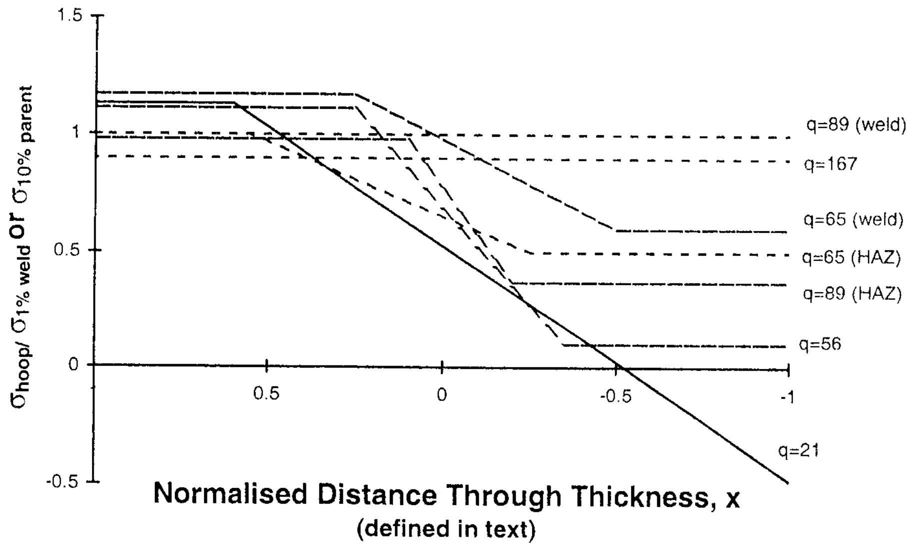


Figure 3: Normalised Peak Axial stress versus Heat Input Parameter, q. (larger of stresses in Weld or HAZ)

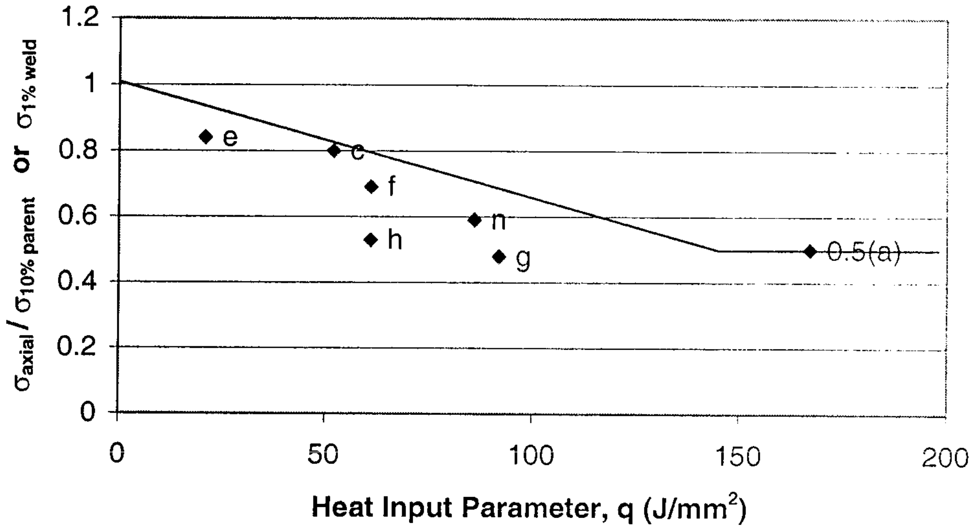
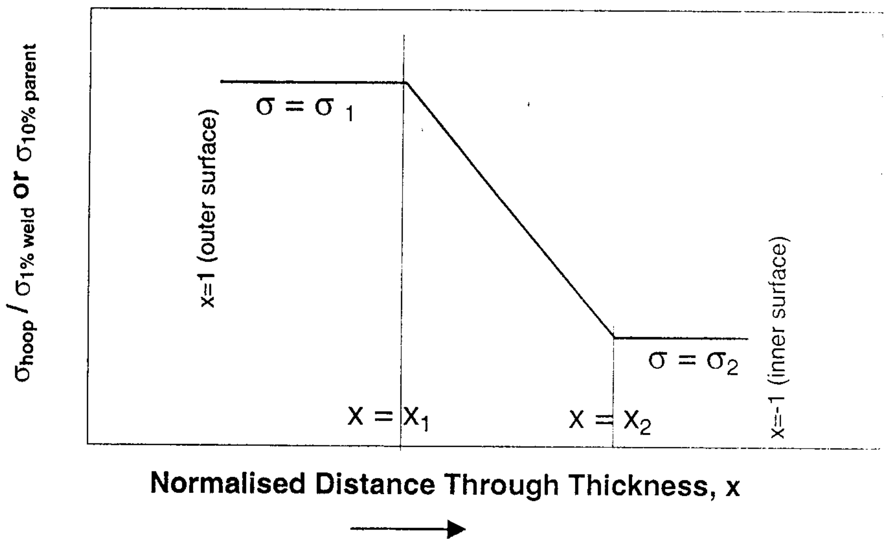


Figure 4: Idealised Residual Hoop Stress Profiles: Definition of (x_1, σ_1), (x_2, σ_2)



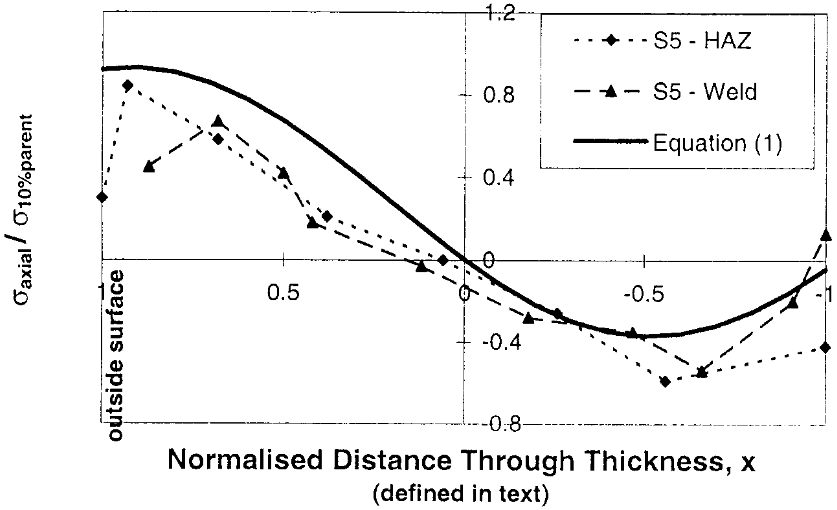


Figure 5: FE Axial Residual Stresses compared ʼh Equation (1) (q=21 J/mm²)

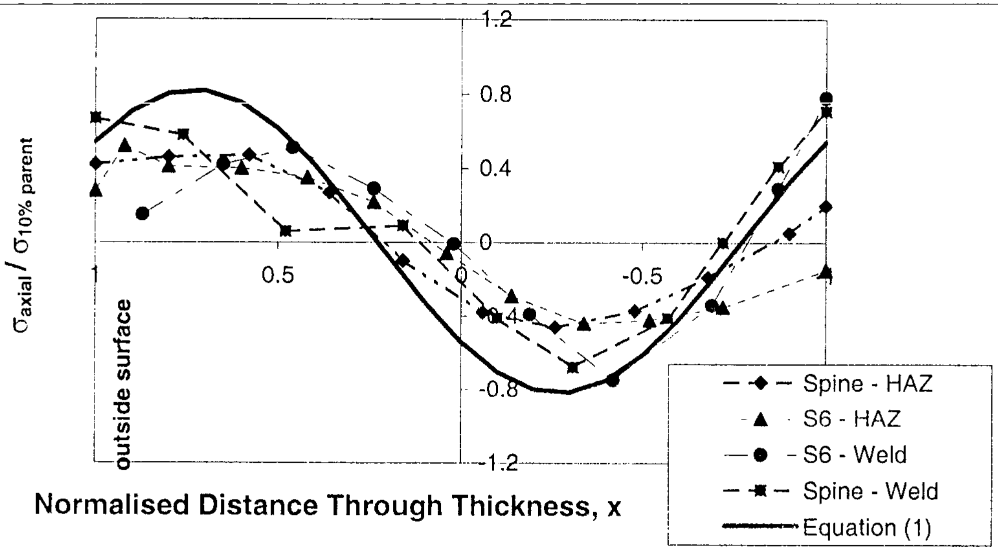


Figure 6: FE Axial Residual Stresses compared with Equation (1) (q = 56 J/mm²)

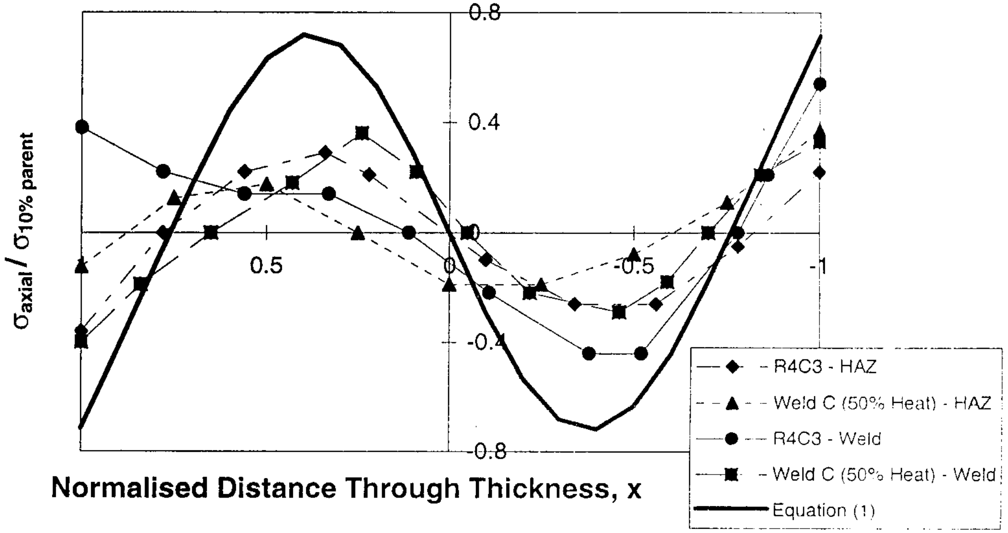


Figure 7: FE Axi ʼesidual Stresses compared with Equation (1) (q=65 J/mm²)

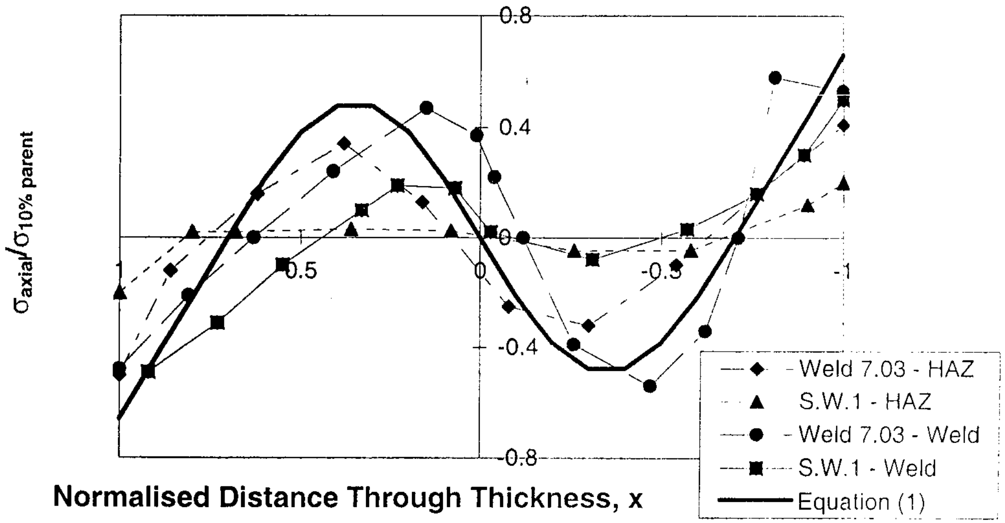


Figure 8: FE Axial Residual Stresses compared with Equation (1) (q = 89 J/mm²)

Figure 9: FE Axial Residual Stresses compared with Equation (1) (q=167J/mm^2)

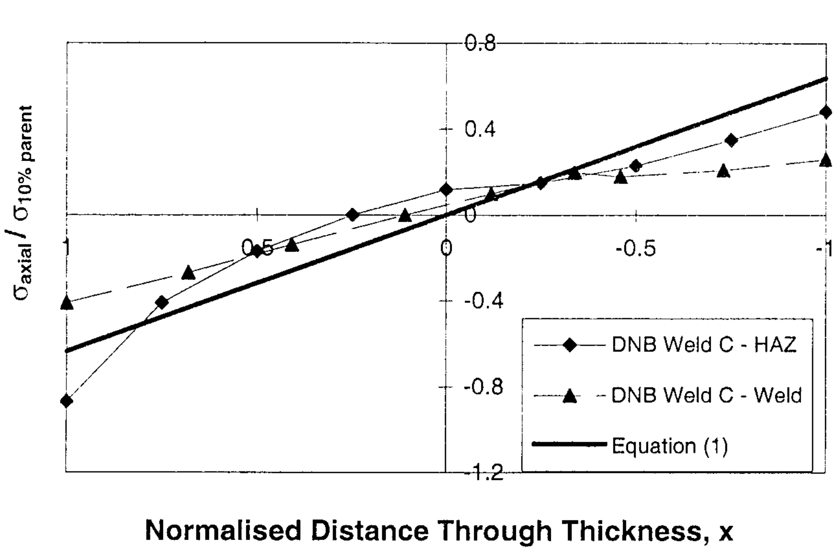


Figure 11 : FE Hoop Residual Stress Compared with Idealised Line (q= 56)

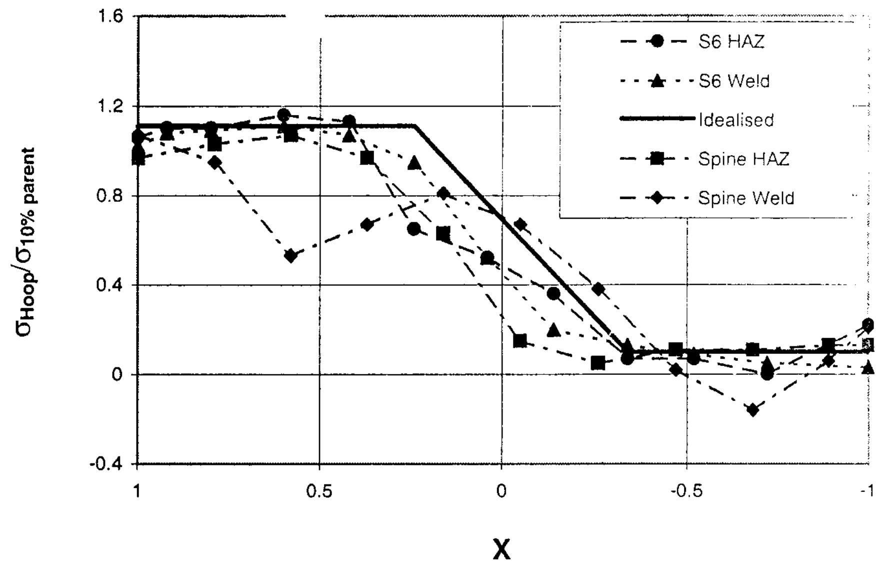


Figure 10 : FE Hoop Residual Stress Compared with Idealised Line (q = 21 J/mm^2)

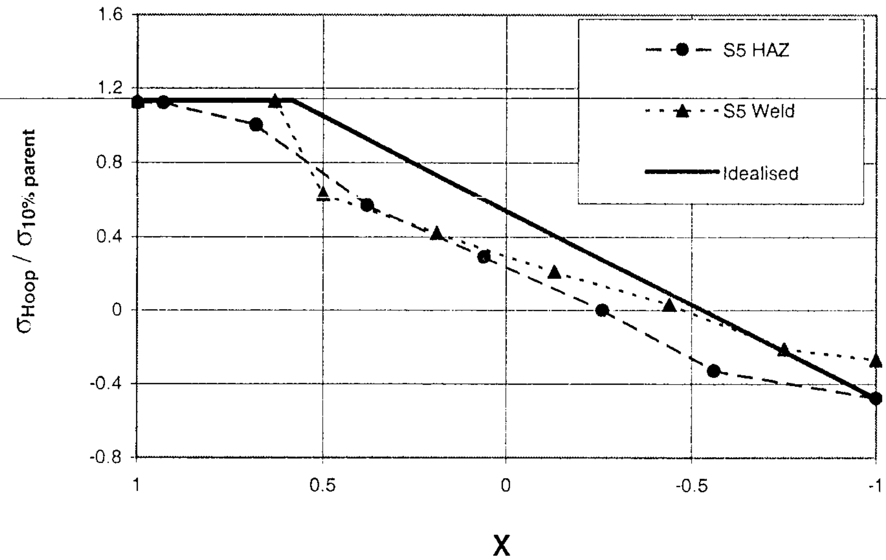


Figure 12 : FE Hoop Residual Stress Compared with Idealised (q = 65, HAZ)

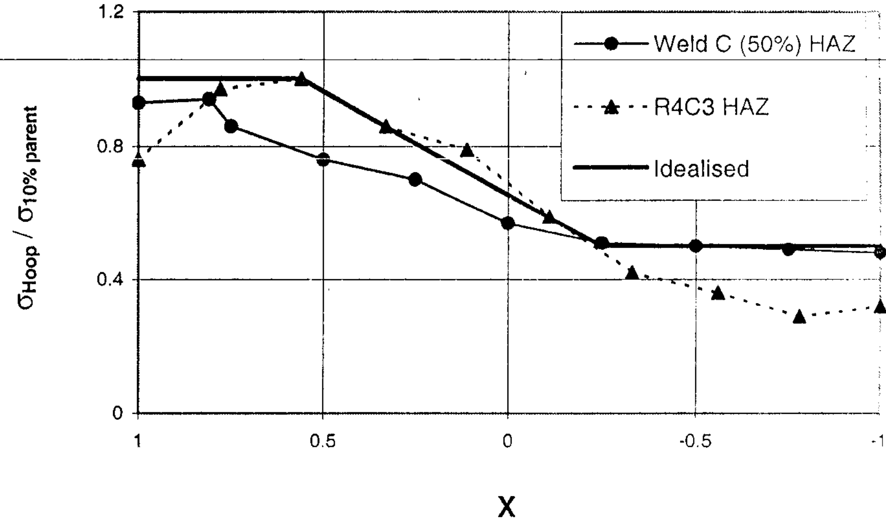


Figure 13: FE Hoop Residual Stress Compa d with Idealised Line (q = 65, Weld)

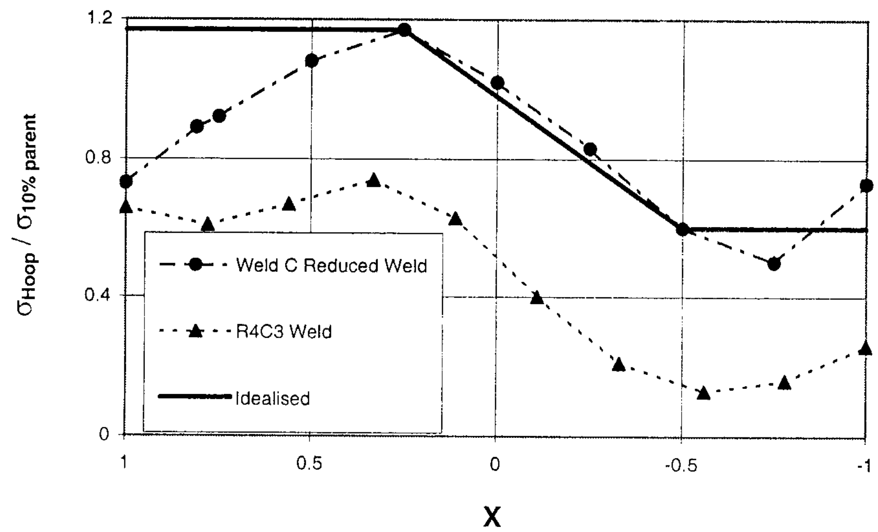


Figure 15 : Hoop Residual Stress Compared with Idealised Line (q = 89, Weld)

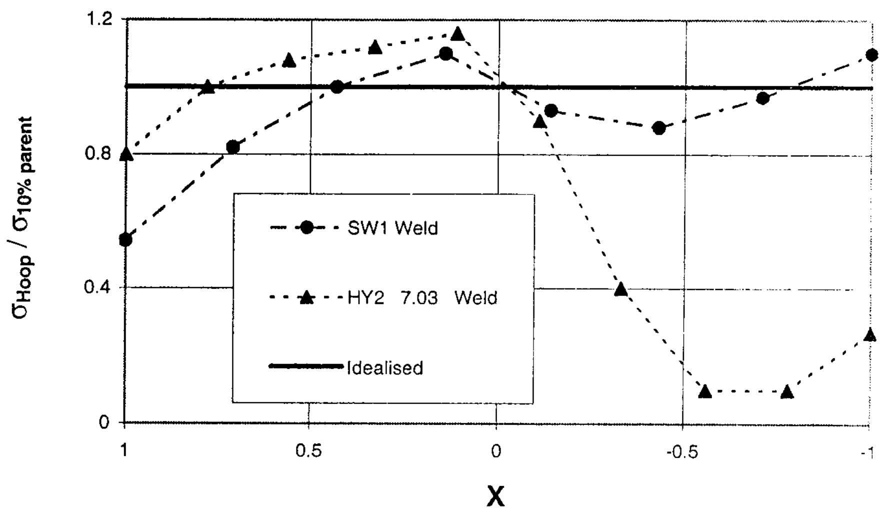


Figure 14: FE Hoop Residual Stress Compared with Idealised Line (q = 89, HAZ)

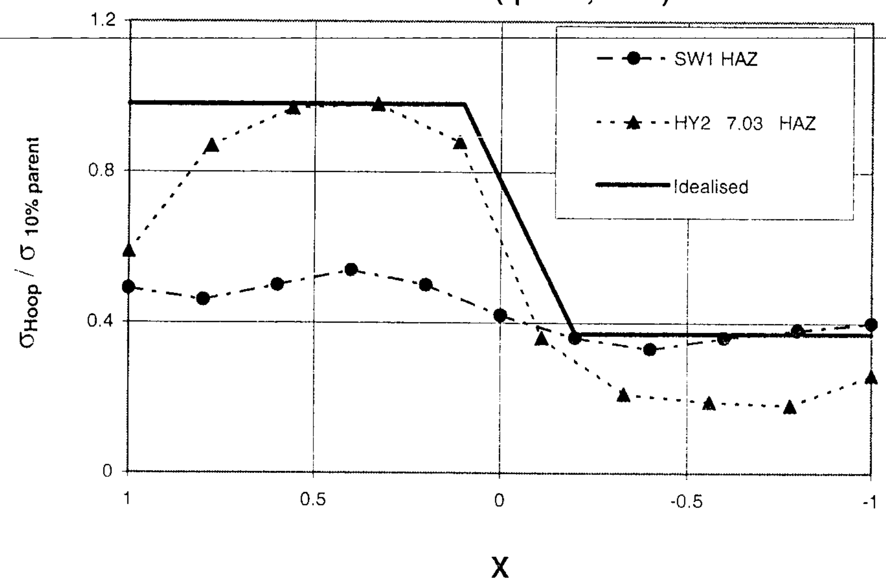


Figure 16: FE Hoop Residual Stress Compared with Idealised Line (q = 167)

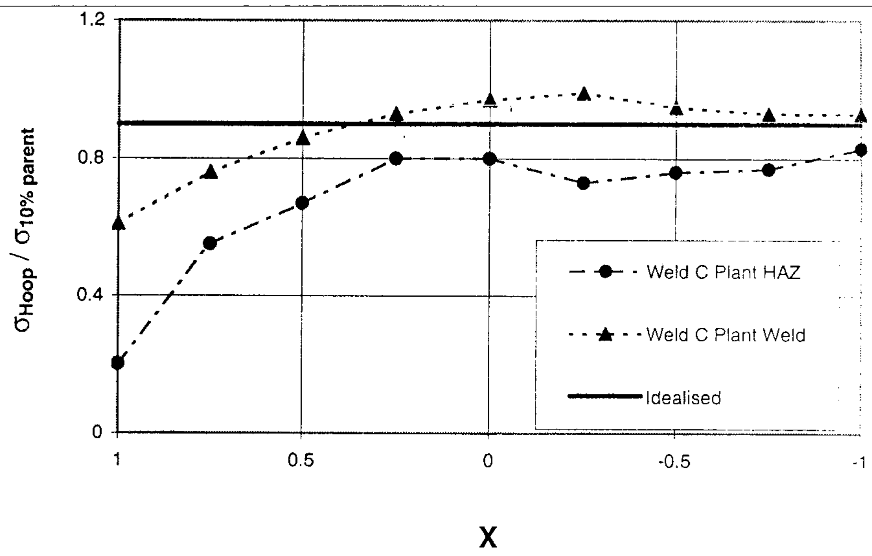


Figure 17: Eqn (1) for Axial Stress with q = 65 compared with SINTAP for t = 18mm.

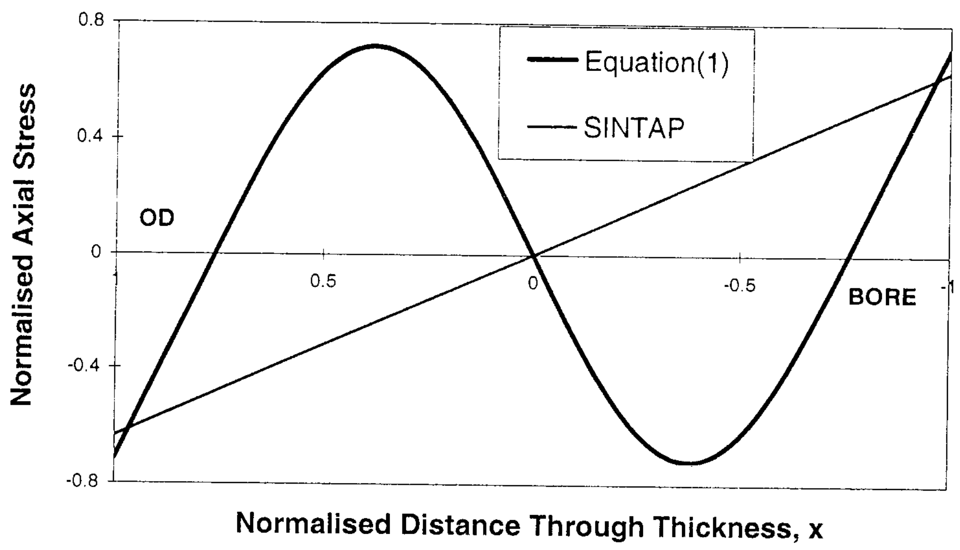


Figure 19: Idealised Residual Hoop Stress for $q = 65\ J/mm^2$ Compared With SINTAP for t=18mm

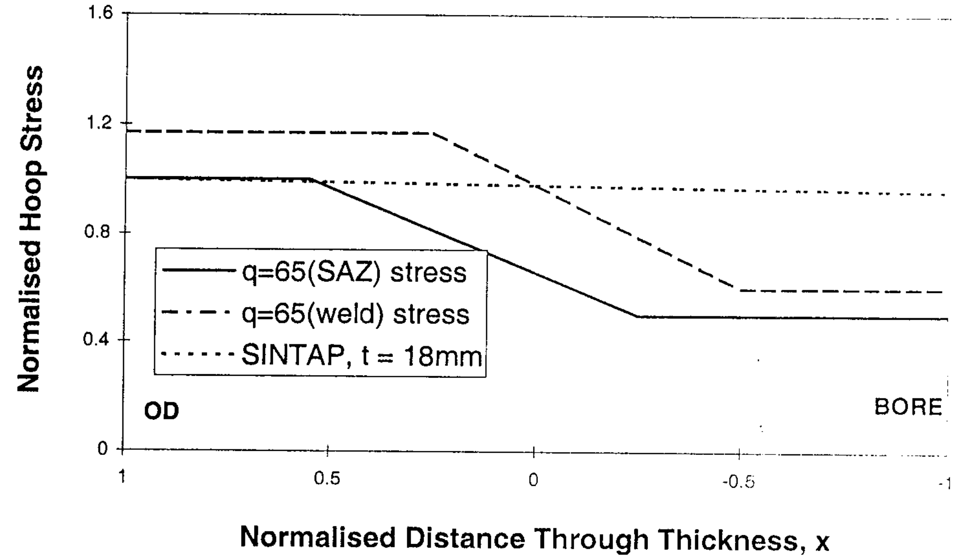


Figure 18: Equation(1) for Axial Stress with q = 56 compared with SINTAP for t = 26mm and R/t = 7.75

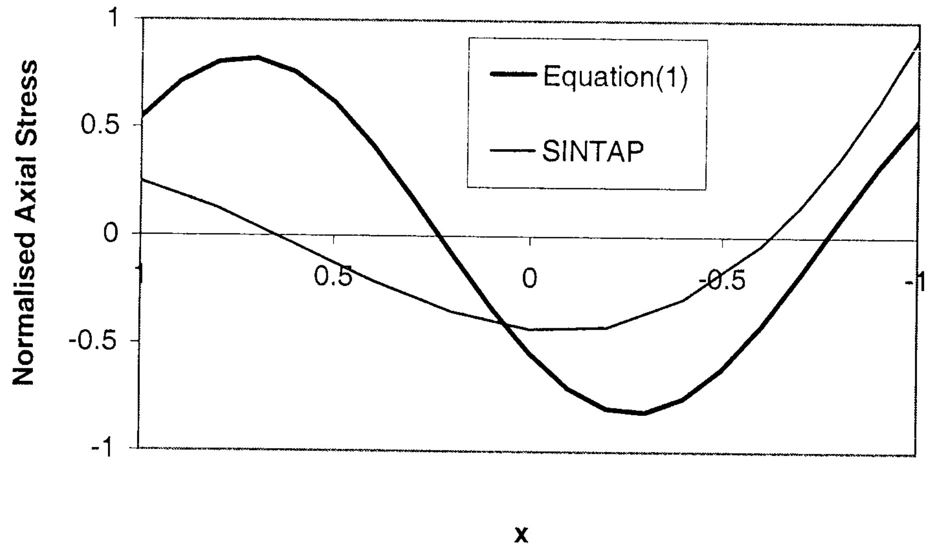


Figure 20: Idealised Residual Hoop Stress for $q=56\ J/mm^2$ Compared With SINTAP for t=26mm