A GENERIC APPROACH FOR A LINEAR ELASTIC FRACTURE MECHANICS ANALYSIS OF COMPONENTS CONTAINING RESIDUAL STRESS

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ABSTRACT

A review of through thickness transverse residual stress distribution measurements in a number of components, manufactured from a range of steels, has been carried out. Residual stresses introduced by welding and mechanical deformation have been considered. The geometries consisted of welded T-plate joints, pipe butt joints, tube-on-plate joints, tubular Y-joints and tubular T-joints as well as cold bent tubes and repair welds. In addition, the collected data cover a range of engineering steels including ferritic, austenitic, C-Mn and Cr-Mo steels. The methods used to measure the residual stresses also varied. These included neutron diffraction, X-ray diffraction and deep hole drilling techniques. Measured residual stress data, normalised by their respective yield stress have shown an inverse linear correlation versus the normalised depth of the region containing the residual stress (up to 0.5 of the component thickness). A simplified generic residual stress profile based on a linear fit to the data is proposed for the case of a transverse residual tensile stress field. Whereas the profiles in assessment procedures are case specific the proposed linear profile can be varied to produce a combination of membrane and bending stress distributions to give lower or higher levels of conservatism on stress intensity factors, depending on the amount of case specific data available or the degree of safety required.

Keywords: Residual stress, linear elastic fracture mechanics, stress intensity factor

1. INTRODUCTION

When components are joined together by fusion welding or deformed mechanically, the resulting non-uniform plastic deformation can lead to a residual stress field being set up across the thickness of the component. Residual stress can be classified as the stresses that exist in a component after all external forces, including dead weight and thermal gradients, have been removed. It is important that such stresses are accounted for in safety assessment procedures such as the British Energy R6 procedure [1] and BS7910 [2]. Since information on residual stress distributions is often not available, compendia with recommended upper-bound residual stress profiles for use in analyses are included in R6 and BS7910. Subsequent to the derivation of the appropriate residual stress in the component, a fracture mechanics analysis is generally required

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to determine the appropriate fracture mechanics parameter to account for the effect of the residual stress on pre-existing or putative cracks.

In this study, rather than developing a definitive residual stress distribution for a particular geometry a generic approach is adopted. The difficulty in determining accurate residual stress profiles is acknowledged and allowed for by assigning an uncertainty to the measured or estimated value. Some judgement will be required by the assessor as to the magnitude of such uncertainty and this will also depend on the level of safety required for the particular operation.

2. MATERIAL AND GEOMETRY SPECIFICATIONS

A range of residual stress data has been examined [3]–[10]. These include MMA welded T-plate specimens, fabricated with high strength ferritic steels SE702 [5] and medium strength low carbon ferritic steel BS EN 10025 S355 [10]. Measurements for welded joints and cold bent tubes [4] have been included to investigate whether it is appropriate to treat mechanical and repair weld-induced residual stresses in the same manner as the rest of the data. Furthermore the range of yield stress of the steels is from 207 MPa (austenitic steel) to 700 MPa (SE702 ferritic steel) which includes a wide range in material properties. In addition it should be noted that the residual stresses have been obtained using a number of techniques, including deep hole drilling, neutron and X-ray diffraction. Schematics of the different geometries are shown in Fig. 1.

3. ANALYSIS OF RESIDUAL STRESS DISTRIBUTIONS

Observations of measured residual stress data in the literature show a wide range of variability both in comparing data obtained using different techniques on the same specimen as well as variation from specimen to specimen. The differences can be attributed to the different distributions for different weld geometries as well as scatter found in measurement techniques and from weld to weld. It is often difficult to distinguish the reasons for the scatter since, given the time and costs involved, few (if any) repeat measurements are made. The collected measured residual stress data are shown in Fig. 2. In this figure the transverse residual stress for a range of geometries and materials and measurement methods is shown. It may be seen that when the measured data are considered up to $y/W = 0.5$ (half of specimen thickness) the stress distributions can be represented as a straight line corresponding to a membrane (uniform) + bending (linear) distribution. The present sets of data contain plate or pipe thicknesses of 5 mm to 60 mm and the crack length of interest for life assessment is generally the short crack region starting at the surface. Hence $y/W = 0.5$ is usually well beyond safety margins that will be considered in any lifing procedure for the range of thicknesses considered.

3.1. Analysis of the measured data

Figure 3 shows the data of Fig. 2 re-plotted over the region $0 \leq y/W \leq 0.5$. It may be seen that the normalised residual stress data (σ/σ_y) can be conveniently described by a linear variation with a relatively wide range of scatter. For simplicity, the regression line treats all data equivalently and no allowance has been made for outlying points. Figure 3 shows that within the range of scatter the stress distributions can be represented as linear up to $y/W = 0.5$ (half of specimen thickness). In this work, the linearised stress distribution is separated into a bending and membrane stress, as illustrated schematically in Fig. 4. This is consistent with the representation of mechanically induced stresses in BS7910 [2] and ASME XI [12]. With this definition, the normalised stress distribution is written as

$$\hat{\sigma} = \hat{\sigma}_m + \hat{\sigma}_b(1 - 2x), \quad (1)$$

where $\hat{\sigma} = \sigma/\sigma_y$ and $x = y/W$. In previous work, [9], a linear distribution was considered to represent the distribution of residual stress data, with, for further conservatism, any compressive region of stress taken to be at zero stress. In this work compressive stresses are considered and the interpretation of membrane and bending stresses is slightly different.

Least square linear fits have been obtained for each of the data sets examined as well as for the full set of data. It has been found that for the cases examined the uncertainty in the slope (bending stress $\hat{\sigma}_b$) is small and therefore the uncertainty in the residual stress distributions for these geometries can be quantified through a variability, $\Delta\hat{\sigma}_m$, in the mean stress.

Figure 3 shows the mean line for all the data and upper/lower bound lines at one and two standard deviations (2SD). The corresponding values of the mean slopes and one standard deviation (1SD) for the datasets are provided in Table 1. Analysis of the individual data sets shows that the pipe-butt has the lowest bending stress and the pipe-on-plate has the highest bending stress. The data for the cold bent tube shows the lowest value of standard deviation since these were results from a large number of specimens and thus less scatter is observed. The normalised linear mean line, for all the data, shown in Fig. 3 is given by:

$$\hat{\sigma}(x) = -0.31 + 0.88(1 - 2x). \quad (2)$$

3.2. Stress intensity factors

Following the ASME XI or BS7910 procedures, given a stress composed of a membrane and bending component, the stress intensity factor, K , for a two dimensional crack of length a , normal to the transverse stress, in a plate/pipe of thickness W , can be written as:

$$K = (\sigma_m f_m(a/W) + \sigma_b f_b(a/W))\sqrt{a}, \quad (3)$$

where f_m and f_b are geometry factors which may be obtained from existing fracture mechanics solutions, finite element or weight function analyses. It was shown in [5] that for a sufficiently deep crack in a T-plate geometry the solution for a smooth plate can be used to determine the stress intensity factors. In this paper, however, solutions are presented for f_m and f_b which have been obtained from finite element analysis for the relevant geometry.

The sensitivity of the stress intensity factor to changes in mean or bending stress can also be obtained from Eq. (3). For example, for an increase in membrane stress $\Delta\sigma_m$, the increase in K , ΔK is given by,

$$\Delta K = \Delta\sigma_m f_m(a/W)\sqrt{a}. \quad (4)$$

3.2.1. Stress intensity factor solutions

As seen from the previous section, if the functions $f_m(a/W)$ and $f_b(a/W)$ are known the stress intensity factors and their sensitivity to variation in stress can be obtained. The stress intensity factors (SIF) have been obtained for T-plate and tubular T-joints using finite element (FE) analysis in conjunction with the superposition method as discussed in [5] and [9]. For the T-plate the width of the plate and the attachment are the same. The tubular joint is a three dimensional geometry, but here is represented by an axisymmetric, “tube on plate” FE mesh.

All finite element analyses were carried out using the FE software package, ABAQUS 6.3 [14]. Only the crack surface stresses need to be considered as the calculation of the SIF is based on the superposition principle [5, 13]. The transverse residual stress is considered as the crack driving force and the Mode I SIFs have been evaluated using a path independent integral. The values of $f_m(a/W)$ and $f_b(a/W)$ have been obtained by applying a unit membrane and bending stress respectively to the crack face. A similar approach has been used to obtain the stress intensity factor for surface cracked plates and the values obtained were almost identical to handbook solutions (see [5] for details). Figure 5 shows the solution for f_m and f_b for a T-plate and tubular T-joint.

3.3. RESIDUAL STRESS PROFILES

The recommended through-thickness transverse residual stress distribution available in R6 for the T-plate consists of an upper bound bilinear profile. The peak stress is at the weld toe, equal to the parent material yield stress and reduces linearly to zero at a distance r_o from the weld toe, where r_o is an estimate of the plastic zone size. A typical value of plastic zone size for the specimens

examined in [5], [9] is about 25 mm and $r_o/W \approx 0.5$. Thus for this case, the R6 distribution is given by $\hat{\sigma}_m = 0$; $\hat{\sigma}_b = 1$. Alternatively, given that for the T-plate the mean values from Table 1 for $\hat{\sigma}_m$ and $\hat{\sigma}_b$ are -0.44 and $+0.93$, respectively, this distribution is equivalent to the Table 1 mean values with $\Delta\hat{\sigma}_m = +0.44$ and $\Delta\hat{\sigma}_b = +0.07$. The tubular T-joint residual stress profiles in R6 depend on the ratio of the chord thickness (W) to the brace thickness (t). For $W/t < 1.375$, a uniform tensile residual stress is assumed, *i.e.* $\hat{\sigma}_m = 1$; $\hat{\sigma}_b = 0$ (or $\Delta\hat{\sigma}_m = +1.33$ and $\Delta\hat{\sigma}_b = -0.38$, based on the mean values in Table 1). For $W/t > 2$, the profiles for T-butt plate welds are recommended. For cases $1.375 < W/t < 2$, the same equation as BS7910 is applied (see below).

3.3.1. BS 7910 distributions for T-plate and tubular T-joint

BS7910 provides two transverse residual stress distributions for T-plate joints. The first transverse residual stress distribution is a polynomial function representing an upper bound fit to experimental data and is given by Eq. (5).

$$\hat{\sigma} = 0.97 + 2.3267x - 24.125x^2 + 42.485x^3 - 21.087x^4, \quad (5)$$

where $\hat{\sigma} = \sigma/\sigma_y$ and $x = y/W$ as in Eqn. (1). If this equation is linearised then for $a/W = 0.5$ the membrane and bending stresses are almost identical to the R6 equation for the geometries considered, $\hat{\sigma}_m = 0$; $\hat{\sigma}_b = 1$. For all other crack lengths the value of $\hat{\sigma}_m$ and $\hat{\sigma}_b$ will depend on the relative crack depth, a/W .

The second distribution in BS7910 follows that in R6, with the distribution dependent on the size of the plastic zone. However, in BS7910, if the plastic zone is determined to be greater than the plate width, the stress is taken to be equal to the yield strength across the whole specimen thickness ($\hat{\sigma}_m = 1$; $\hat{\sigma}_b = 0$). The recommended BS7910 transverse residual stress profile for the tubular T-joint is the same polynomial function as that provided for T-plate welds (Eqn. (5)). It should be noted that for the current geometry BS7910 provides a more conservative residual stress profile than R6 for the T-plate while the R6 distribution is more conservative for the tubular T-joint as shown in Figure 6.

3.3.2. Bilinear distribution

A bilinear distribution has recently been proposed [7] based on residual stress data for a range of T-plate joints in ferritic steels. This distribution, which has been obtained by shifting an approximate mean bilinear fit to the data by a uniform (membrane) stress of $0.25\sigma_y$. For this distribution, the membrane stress defined in Fig. 3 may be obtained by extrapolating the linear part of the curve

beyond $y/W = 0.3$ to give $\hat{\sigma}_m = -0.4$; $\hat{\sigma}_b = 1.4$ (or $\Delta\hat{\sigma}_m = 0.04$; $\Delta\hat{\sigma}_b = 0.51$). However, such an extrapolation may be non-conservative for $a/W > 0.3$.

The available distributions are shown in Fig. 6. It may be seen that of the stress distributions for a T-plate, the BS7910(1) polynomial function distribution is the most conservative followed by the R6 distribution and then the bilinear distribution.

4. RESULTS OF THE ANALYSIS

4.1. Sensitivity study for a residual stress field in a T-plate

It is assumed that the stress distribution may be represented by a mean and bending stress and the uncertainty (standard deviation) in the mean and bending stress is known. The value of the mean K may then be determined directly using the functions in Fig. 5.

Once the stress distribution is represented as a membrane and bending stress with an associated uncertainty the full range of SIFs can be generated using the geometry factors in Fig. 5 without the need for additional FE analysis. As an example, we consider the stress intensity factor for a welded T-plate specimen. As a sensitivity analysis we consider, by using values from Table 1, the following profiles:

- (i) the mean membrane and bending stress values for T-plates
- (ii) the overall mean membrane and bending stress values
- (iii) the mean membrane and bending stress values for T-plates plus 1SD (standard deviation) on $\Delta\sigma_m$;
- (iv) the mean membrane and bending stress values for T-plates plus 2SD on $\Delta\sigma_m$;
- (v) the mean membrane and bending stress values for T-plates plus 1SD on $\Delta\sigma_m$ and $\Delta\sigma_b$
(Here the deviation from the mean is taken as $\Delta\sigma_m = \Delta\sigma_b = 0.4\sigma_y$).

The results are shown in Fig. 7 for a material with yield strength $\sigma_y = 350$ MPa and plate width, $W = 50$ mm. It is seen that the highest distribution for the SIF is obtained for case (iv) which is the case of the mean stress plus two standard deviations, while case (v) gives a lower stress distribution, indicating that for the T-plate the stress intensity factors are more sensitive to $\Delta\sigma_m$ than $\Delta\sigma_b$. A more rigorous approach to the statistical analyses of these data will be provided later.

In Fig. 8 the SIFs obtained from the existing representative residual stress distributions (see Fig. 6) for T-plates using the geometry factors in Fig. 5(a) are presented. The BS7910(2) curve in Fig. 6 has been linearised and the bi-linear curve has been extrapolated to $y/W = 0.5$ to obtain σ_m and σ_b . The strong similarity between the BS7910 (1) curve and the R6 line is noted, with the BS7910(1)

line being slightly line being slightly more conservative. Similar agreement has been seen in [5] when the actual BS7910 curve is used directly in a finite element analysis. As expected the most conservative stress intensity factors are obtained when the residual stress is assumed uniform with $\sigma = \sigma_y$ ($\hat{\sigma}_m = 1.0$). This curve is used when in BS7910 when the estimated plastic zone size is greater than the plate width.

4.2. Application to measured residual stress data

In [5] residual stress data have been presented for welded T-plates of different sizes and two yield strength using neutron diffraction. Measured transverse residual stress data, for two T-plates of different ferritic steels (Grade S355, $\sigma_y = 350$ MPa and Grade SE702, $\sigma_y = 700$ MPa) but both with $W = 50$ mm are illustrated in Fig. 9. In the figure the stress has been normalised by the respective yield stress and distance by plate width. When presented in normalised form the stresses in the medium strength steel plate are somewhat higher than those for the SE702 steel. Note that the measurement error is estimated to be ± 30 MPa for both measurements, which corresponds to $\Delta\hat{\sigma}_m = \pm 0.1$ and ± 0.04 for the medium strength steel ($\sigma_y = 350$ MPa) and high strength steel ($\sigma_y = 700$ MPa), respectively.

The SIF solutions for these two stress distributions are shown in Fig. 10 in normalised and non-normalised form. These have been obtained directly from a finite element analysis and were presented in [5]. Note that the K values are higher in the S355 material (Fig. 10b), even though the peak stress for this material is lower (see Fig. 9).

The stress intensity factors shown in Fig. 10 will be compared with values obtained using a range of assumed stress distributions. It has been shown in [5] that the BS7910(2), R6 and bi-linear distributions illustrated in Fig. 6 all give conservative results for both these geometries. It was found that for a crack of length 5 mm at the toe of the S355 T-plate, the conservatism from using the R6 or BS7901 lines was approx. 70 MPa $\sqrt{m}$ and for the bi-linear distribution was 50 MPa $\sqrt{m}$. For a deeper crack (20 mm) the conservatism was even higher, with the R6 and BS7910 distributions over-estimating K by more than 200 MPa $\sqrt{m}$ and the bilinear distribution by more than 100 MPa $\sqrt{m}$. Such a large conservatism is perhaps not surprising since, as discussed in the previous section, these three distributions have significant positive values of $\Delta\hat{\sigma}_m$ relative to the mean line in Fig. 3.

As an alternative to the representative distributions from R6 and BS7910 in Fig. 11 we compare the results for the medium and high strength steels with the five distributions examined previous. It is seen in Fig. 11(a) that all of the distributions (i)–(v) give a conservative prediction for the SE702 T-

plate. This is due to the fact that the stresses in the T-plate are low over a significant portion of the crack face (see Fig. 9). Figure 11(b) shows that both mean distributions (line (i) and (ii)) give a non-conservative result for the S355 T-plate. For shallow cracks, line (iii) (one standard deviation on $\Delta\sigma_m$) gives a conservative estimate of the K values (similar to that achieved using the bilinear upper bound distribution [5]), but overestimates K by about 100 MPa $\sqrt{m}$ in the S355 T-plate at a crack length of 20 mm.

As mentioned previously the uncertainty in the measured residual stress distributions are estimated to be ± 30 MPa or $\Delta\hat{\sigma}_m = \pm 0.1$ for the S355 steel. The effect of allowing for this uncertainty can be seen by adding the contribution from $\Delta\hat{\sigma}_m$ to the K distribution in Fig. 10. This is illustrated in Fig. 12. In this figure, only distributions (i), (ii) and (iii) are included for clarity. It is seen that if the upper bound measured distribution is used (indicated by the square symbols) the mean curve (ii) is non-conservative for all values of crack length. The mean plus one standard deviation curve remains very conservative relative even to the upper bound measured distribution.

4.2.1. Results from surface measurements only

The statistical analysis of the available data has shown that the variation in the measured bending residual stress was low. Thus it may be possible to estimate the residual stress by a fixed bending distribution, $\hat{\sigma}_b = 0.88$, with a superimposed membrane distribution, $\hat{\sigma}_m$. The value of $\hat{\sigma}_m$ can be obtained from a single surface measurement,

$$\hat{\sigma}_m = \left. \frac{\sigma}{\sigma_y} \right|_{y=0} - \hat{\sigma}_b. \quad (6)$$

For the case of the S355 T-plate the value of the stress at the surface is $0.4\sigma_y$ (see Fig. 9) and adding an uncertainty of 30 MPa we get $\hat{\sigma}_b = 0.88$, $\hat{\sigma}_m = -0.38$. (Note that the surface stress is not the peak stress for the T-plate weld). Using these values of stress we obtain the solution shown in Fig. 13. It is seen that the use of the surface stress will underestimate the value of the SIF for the T-plate. The result for the SE702 based on the surface stress is even worse as the surface stress for the SE702 is very low. In this case we obtain $\hat{\sigma}_b = 0.88$, $\hat{\sigma}_m = -0.64$ and the predicted SIFs are negative for $a/W \leq 0.3$.

5. STATISTICAL APPROACH TO CALCULATION OF SIFs

We have written the SIF as a function of the membrane and bending stress in Eq. 3. If we assume (see Fig. 3) that for a given a/W value the membrane and bending stress may be represented as

random variables with mean values, σ_m , σ_b , and standard deviations, $\Delta\sigma_m$, $\Delta\sigma_b$ we can then infer the corresponding mean value and standard deviation for the SIF. From Eq. 3, we can say that for a given a/W , the mean (expected value) of K is,

$$K_{mean}(\sigma_m, \sigma_b) = (\sigma_m f_m + \sigma_b f_b) \sqrt{a} \quad (7)$$

Similarly, following standard rules for random variables, the standard deviation of the distribution of K , ΔK , is given as,

$$\Delta K(\sigma_m, \sigma_b) = \left(\sqrt{(\Delta\sigma_m f_m)^2 + (\Delta\sigma_b f_b)^2} \right) \sqrt{a} \quad (8)$$

where Eq. (8) assumes that the membrane and bending stress are independent, *i.e.* Covariance(σ_m , σ_b) = 0. Note that Eq. 8 is not a simple sum of the variation in the membrane and bending contributions to the stress. Note further that in the more general case when σ_m and σ_b are not independent variables, Eq. 8 will depend on the covariance of (σ_m , σ_b). In dimensionless form, we obtain from Eqs. 7 and 8,

$$\frac{K_{mean}}{\sigma_y \sqrt{a}} = \hat{\sigma}_m f_m + \hat{\sigma}_b f_b; \quad \frac{\Delta K}{\sigma_y \sqrt{a}} = \sqrt{(\Delta \hat{\sigma}_m f_m)^2 + (\Delta \hat{\sigma}_b f_b)^2} \quad (9)$$

From Fig. 4, it is clear that since both f_m and f_b increase with a/W the deeper cracks will be most sensitive to the variation in membrane or bending stress. If we take the linear regression line for T-plates from Table 1, $\sigma_m = -0.44\sigma_y$; $\sigma_b = -0.93\sigma_y$, $\Delta\sigma_m = 0.4\sigma_y$; $\Delta\sigma_b = 0$ (here $\Delta\sigma_m$ is based on one standard deviations in the data) we can obtain the mean and upper and lower bound distributions for K from Eqs. 7 and 8. The range of K values obtained from the mean and bending lines in Fig. 3 are provided in Fig. 14. (The results for the mean and upper bound lines have already been presented in Fig. 7). For convenience the results are presented here in normalised form. Note that the lower bound of the K distribution is negative for the range of a/W values. It is expected that values between the mean and upper bound solutions will be used in any life assessment analysis. Also included in Fig. 14 are the results obtained if a variation of 1 and 2 standard deviations about the mean membrane stress is included. It may be seen by comparison with Fig. 10a (but note that the K values have been normalised differently) that the mean +1SD distribution provides a conservative upper bound for both of the T-plate distributions examined.

In Fig. 14 the effect of variation in bending stress, σ_b , are examined. Here $\Delta\sigma_b = 0.4\sigma_y$ and $\Delta\sigma_m = 0$. By comparing Figs. 14(b) and 15(b), it is seen that for the T-plate the SIFs are more

sensitive to the variation in σ_m . This is to be expected from the relative magnitudes of f_m and f_b in Fig. 5(a). Finally, in Fig. 16 the sensitivity to a change in both σ_m and σ_b is examined, here $\Delta\sigma_m = \Delta\sigma_b = 0.2\sigma_y$. Thus it is seen that a statistical analysis of the stress intensity factors are easily carried out if the variation in the measured residual stress is known or assumed.

6. CONCLUSIONS

A procedure is provided to calculate the linear elastic stress intensity factors for a range of geometries containing residual stress. A simple linear residual stress distribution which has been determined from a large number of geometries with different conditions was used to derive the stress intensity factors K . It has been shown that for the cases examined, all of which contain tensile surface residual stresses, the residual stress distribution gives an inverse linear stress distribution (normalised with the appropriate yield strength) with respect to the crack length for up to half the plate width. The mean and standard deviation of the dataset is used as the basis to derive a family of stress distribution profiles. Thus the resulting distribution is separated into a bending and membrane stresses which have been used to derive the linear elastic stress intensity factors K for a T-plate and a Tubular T-joint geometry. As an example a statistical analysis is carried out to identify upper and lower bound K solutions based on 1 or 2 standard deviations from the mean of the dataset for the T-plate. The method allows a simplified approach towards the study of residual stress profiles where case specific data are not available. As the dataset covers a comprehensive set of variables it may be possible, in cases where, for example, only surface measurements are available falling within the present dataset, to assume a sufficiently conservative residual stress profile.

ACKNOWLEDGEMENTS

The authors would like to thank British Energy for their financial support and Dr PJ Bouchard of British Energy and Dr. CE Truman of Bristol University for their help and advice and in supplying relevant data. Helpful discussions with Prof. G A Webster are acknowledged.

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Table 1. Analysis of the residual stress data

	Case	$\hat{\sigma}_m$	$\hat{\sigma}_b$	$\Delta\hat{\sigma}_m$ (1SD)
Welds	T-butt	-0.44	0.93	0.4
	Tubular T	-0.44	1.0	0.4
	Tubular Y	-0.34	1.1	0.4
	Pipe Butt	0.09	0.10	0.2
	Pipe on plate	-0.29	1.3	0.4
	Repair weld(Pipe)	-0.11	0.73	0.3
	Cold bent tube	0.08	0.32	0.13
All	All	-0.31	0.88	0.3

(a) T-plate

(b) Tubular-T joint

(c) Tubular-Y joint

(d) Pipe butt weld

(e) Tube-on-plate

(f) Bent pipe

(g) Repair weld

Figure 1 Schematic diagrams of geometries analysed

Figure 2. Transverse residual stress distribution for a range of welded joint types. Here y measures distance through the specimen thickness with $y = 0$ corresponding to the component surface, W is the specimen thickness.

Figure 3. Transverse residual stresses for a range of welded geometries including a mean, $\pm 1SD$ and $\pm 2SD$ upper and lower bound fit to the data.

Figure 4. Representation of membrane and bending stress for a linear stress distribution through a specimen with thickness W .

Figure 5. Geometry factors for T-plate and tubular T-joint

Figure 6. Recommended residual stress distributions for T-plate and tubular T-joint

Figure 7. SIF values for different mean and membrane stress values

Figure 8. Stress intensity factors for T-plate using recommended distributions

Figure 9. Measured residual stress distributions in two T-plates

Figure 10. Stress intensity factors for T-plate using linearised distributions

Figure 11. Comparison of calculated SIFs using the measured distributions and a range of linear distributions (i)–(v).

Figure 12. Comparison of calculated SIFs using the upper bound of the measured distributions (square symbols) the mean of the measured distribution (open circles) and a range of linear distributions (i)–(iii).

Figure 13. Comparison of calculated SIFs using the upper bound of the measured distributions (square symbols) the mean of the measured distribution (open circles) and an estimate of the residual stress based on surface measurements.

Figure 14. Mean, upper and lower bound SIF values obtained from linear stress distribution with variation on $\Delta\sigma_m$ only

Figure 15. Mean, upper and lower bound SIF values obtained from linear stress distribution with variation on $\Delta\sigma_b$ only

Figure 16. Mean, upper and lower bound SIF values obtained from linear stress distribution with variation on $\Delta\sigma_m$ and $\Delta\sigma_b$