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Stress intensity due to residual stresses

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Stress intensity due to residual stresses

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EXECUTIVE SUMMARY

Background

The work in this report is a contribution to Task 4 of the SINTAP collaborative project. It has been performed at TWI under contract to the Health and Safety Executive.

SINTAP Task 4 addresses the treatment of residual stresses in structural integrity assessment procedures. Based on contributions from the SINTAP partners, Dr J Y Barthelemy of Institut de Soudure has compiled a compendium of standard residual stress profiles for a range of welded joint geometries. The purpose of these profiles is to allow the effects of residual stress to be included in engineering critical assessments more accurately and less conservatively than if the residual stresses at welds were assumed to be uniform and of yield magnitude.

In this report, the stress intensity factors corresponding to the SINTAP standard residual stress profiles have been evaluated for a range of common joint geometries and defect types. The recommended profiles are mostly non-linear, so the methods for obtaining stress intensity factors are more complex than for linear distributions such as the membrane or bending stresses due to applied loads. In many cases, it is necessary to apply one or more transformations to the profiles in order to make them suitable for use in conjunction with the solutions given in the SINTAP handbook of stress intensity factor solutions.

Objectives

- To explore the practicalities of applying the available stress intensity factor solution techniques in conjunction with the recommended residual stress profiles.

- To provide example solutions for typical joint and defect geometries.

- To investigate the sensitivity of the calculated stress intensity factors to the assumed residual stress profiles and solution methods.

Conclusions

- Good representation of the SINTAP 6^{th} order profile of transverse residual stresses at butt welds in plate and the SINTAP bilinear profile of transverse stresses at T-butt welds in plate was obtained using fitted 5^{th} order profiles, as required by the SIF calculation procedure for finite surface cracks.

- Fitted 3^{rd} order curves gave a good representation of the SINTAP cosine profile for high heat input butt welds in pipes, but unsatisfactory representation of the 4^{th} order profile for low heat input welds.

- The use of the SINTAP recommended procedures for calculating the stress intensity factors (SIFs) due to residual stresses at infinite and finite surface cracks in plates has been found to be valid by comparison of results obtained using the recommended procedures with those obtained using previously published solutions.

- A closed form solution for the SIF due to a trapezoidal residual stress profile, as recommended for the variation of residual stresses across the weld, is presented in this report.

- The SIFs calculated using the SINTAP recommended profiles were found to be significantly lower than those calculated assuming uniform yield magnitude residual stresses, especially at larger cracks, for the following cases:

  - Infinite surface cracks and at the deepest point of finite surface cracks in butt welds in plate, T-butt welds in plate, and at the inside surface of pipe butt welds with low heat input.

  - Transverse through-thickness cracks at butt welds in plate, for cracks whose length was greater than the width of the weld.

- The normalised SIFs at the surface intersections of longitudinal surface cracks of finite length in plate butt welds and plate T-butt welds were found to remain approximately constant or rise with increasing crack depth, and to exceed the SIF at the deepest point in deeper cracks.

- For the example considered in this report, the use of the SINTAP profile of longitudinal residual stresses acting on long transverse through-thickness cracks gave lower SIFs than the assumption of a reduced level of uniform residual stresses following a proof load.

- The SIFs corresponding to the SINTAP recommended polynomial profile for transverse residual stresses at the toe of T-butt welds in pipe are up to 33% greater than those corresponding to the SINTAP recommended bilinear profiles for T-butt welds in plate.

Recommendations

- Consideration should be given to harmonising the format of the SINTAP recommended residual stress profiles with that required by the SINTAP recommended stress intensity factor solutions.

- Further consideration should be given to the SINTAP recommended profiles for pipe butt welds with respect to the transverse stresses at the outside surface.

- If the SIF due to residual stress is calculated to be negative, it should be assumed to be zero.

NOMENCLATURE

a	=	crack size (depth of surface cracks, half-length of through-thickness cracks)
b	=	half-width of weld
c	=	half-length of surface cracks
c	=	half-width of tensile zone (in Eq.[9])
K_I	=	stress intensity factor
K_o	=	$\sigma_Y \sqrt{\pi a}$
q	=	weld power, J/s
r_o	=	radius of tensile zone in thick plate
R_i	=	inside radius of pipe
t	=	thickness of plate or pipe, mm
u	=	depth from cracked surface
v	=	weld velocity, mm/s
W_1	=	maximum width of weld metal
y_o	=	half-width of tensile zone in thin plate
z	=	depth from surface
σ_R^L	=	longitudinal residual stress
σ_R^T	=	transverse residual stress
σ_Y^*	=	least of σ_{YP} and σ_{YW}
σ_{YP}	=	parent metal yield strength
σ_{YW}	=	weld metal yield strength
s_R^m	=	membrane component of residual stress
s_R^b	=	bending component of residual stress
σ_b	=	bending stress
σ_m	=	membrane stress
$\sigma_R^{T,O}$	=	transverse residual stress at outside surface
σ_Y	=	σ_Y^* for transverse residual stresses, σ_{YW} for longitudinal residual stresses

ABBREVIATIONS/GLOSSARY

SINTAP	Structural Integrity Assessment Procedures for European Industry (BRITE EURAM Project BE95-1426)
SIF	Stress intensity factor
SAQ	SAQ Kontroll AB
TPI	Tada, Paris and Irwin (3)
Longitudinal	Parallel to weld
Transverse	Transverse to weld

1. INTRODUCTION

The work in this report is a contribution to Task 4 of the SINTAP collaborative project. It has been performed at TWI under contract to the Health and Safety Executive.

SINTAP Task 4 addresses the treatment of residual stresses in structural integrity assessment procedures. Based on contributions from the SINTAP partners, Dr J Y Barthelemy of Institut de Soudure has compiled a compendium of standard residual stress profiles for a range of welded joint geometries (1). The purpose of these profiles is to allow the effects of residual stress to be included in engineering critical assessments more accurately and less conservatively than if the residual stresses at welds were assumed to be uniform and of yield magnitude.

In this report, the stress intensity factors corresponding to the SINTAP standard residual stress profiles have been evaluated for a range of common joint geometries and defect types. The recommended profiles are mostly non-linear, so the methods for obtaining stress intensity factors are more complex than for linear distributions such as the membrane or bending stresses due to applied loads. In many cases, it is necessary to apply one or more transformations to the profiles in order to make them suitable for use in conjunction with the solutions given in the SINTAP handbook of stress intensity factor solutions (2).

2. OBJECTIVES

- To explore the practicalities of applying the available stress intensity factor solution techniques in conjunction with the recommended residual stress profiles.

- To provide example solutions for typical joint and defect geometries.

- To investigate the sensitivity of the calculated stress intensity factors to the assumed residual stress profiles and solution methods.

3. SCOPE OF ANALYSIS

The stress intensity factors due to the residual stresses acting at cracks in welded joints were calculated for the conditions summarised in paragraphs (i) to (iv) below.

(i) Joint types

The following joint types were considered.

- Butt weld in plate.
- T-butt weld in plate.
- Circumferential butt weld in cylinder (pipe or pressure vessel).

(ii) Crack types and orientations

The following crack types were considered.

- Longitudinal infinite surface cracks.
- Longitudinal semi-elliptical surface cracks.
- Transverse through-thickness crack (at butt weld in plate only).

(iii) Residual stress distributions

The following residual stress distributions were considered.

- The recommended residual distribution for the given weld joint and crack orientation, as specified in the SINTAP compendium of residual stress profiles (1).

- Uniform membrane stresses of yield magnitude. This is the 'default option', i.e. the distribution which would be used if no non-uniform distribution was available, or if the objective was to do a simple and conservative analysis for screening purposes.

- Alternative residual stress distributions were considered for selected cases.

(iv) Stress intensity factor solution procedure

The stress intensity factors due to residual stresses were calculated using the following solution procedures.

- the recommended solution procedure for non-uniform stress distributions for the appropriate structural configurations and crack types as given in the SINTAP handbook of stress intensity solutions (2).

- Solutions for uniform or linear stress distributions given by Tada, Paris and Irwin (3) and Newman and Raju (4). These well-established solutions were used to check the accuracy of the SINTAP handbook solutions.

- A closed form solution was derived from a weight function solution given by Tada, Paris and Irwin (3), for the trapezoidal cross-weld distribution of longitudinal stresses assumed to be acting at a butt in a plate.

> **NOTE**:
> In order to provide specific examples of stress intensities corresponding to the SINTAP or other residual stress profiles, it has been necessary in some cases to make certain assumptions about the residual stress magnitudes or distributions. For example, in Section 4.2.2(a) below it is assumed that the heat input to the weld is such that the width of the tensile zone is equal to five times the width of the weld. Assumptions such as this are purely for illustrative purposes, and should not be assumed to be generally true.

4. BUTT WELD IN PLATE

The full list of cases analysed for butt welds in plates is summarised in Table 1 and described in more detail below.

4.1. DEFECT TYPE, ORIENTATION AND LOCATION

Please note that all orientations are given relative to the welding direction, i.e. longitudinal is parallel to the weld and transverse is across the weld. The following crack types and orientations were considered:

a) Longitudinal infinite surface crack in weld (Cases 1.1 to 1.4).

b) Longitudinal finite surface crack in weld (Cases 1.6 to 1.11). Stress intensity factors (SIFs) are calculated for the deepest point (Point A) and the surface intersection point (Point B) for aspect ratios (crack length/crack depth) 2c/a = 10 and 2c/a = 3.33.

c) Transverse through-thickness cracks across weld (Cases 1.12 to 1.14).

4.2. RESIDUAL STRESS DISTRIBUTION

4.2.1. Transverse Residual Stresses

The following residual stress distributions were considered:

a) SINTAP recommended 6th order polynomial profile

The SINTAP recommended through-thickness profile of transverse residual stress at a plate butt weld is given in Appendix 2 Fig.1d of the SINTAP Residual Stress Compendium (1), as follows:

$$\sigma_R^T / \sigma_Y^* = 1 - 0.917(z/t) - 14.533(z/t)^2 + 83.115(z/t)^3 - 215.45(z/t)^4 + 244.16(z/t)^5 - 96.36(z/t)^6 \quad [1a]$$

where:

σ_R^T	=	transverse residual stress
σ_Y^*	=	lower of (σ_{YW}, σ_{YP})
σ_{YW}	=	weld metal yield strength
σ_{YP}	=	parent metal yield strength
z	=	depth from front face (side welded last)
t	=	plate thickness

b) Fitted 5th order polynomial

The SINTAP recommended SIF solution procedure for finite surface cracks given in Page AI.3 of the SINTAP SIF solution handbook (2) is appropriate for a 5th order polynomial residual stress distribution. Hence the following 5th order polynomial was fitted to Eq.[1a] for use in Cases 1.4 to 1.11:

$$\sigma_R^T / \sigma_Y^* = 1.1027 - 5.2752(z/t) + 29.18(z/t)^2 - 91.954(z/t)^3 + 112.98(z/t)^4 - 44.92(z/t)^5 \quad [1b]$$

The original 6th order polynomial and the fitted 5th order polynomial are shown in Fig.1. It can be seen that there is a reasonable fit over the whole thickness. The greatest discrepancies are at the surfaces. The discrepancy at z/t = 0 can be expected to give a corresponding discrepancy in normalised stress intensity as the crack depth tends to zero.

c) Uniform residual stress

Uniform transverse residual stress equal to a membrane stress of yield magnitude, i.e:

$$\sigma_R^T / \sigma_Y^* = 1 \quad [2]$$

4.2.2. Longitudinal Residual Stresses

The following residual stress distributions were considered.

a) SINTAP recommended trapezoidal profile

The SINTAP recommended surface profile of longitudinal residual stress at a plate butt weld in thin plate is given in Appendix 2 Fig.1a of the SINTAP Residual Stress Compendium (1). The residual stresses are assumed to be equal to the weld metal yield strength, σ_{YW}, within the width of the weld, W_1, and to decrease linearly from σ_{YW} at the edge of the weld to zero at a distance, y_o, from the weld centre. The parameter y_o is calculated as a function of the heat input to the weld. For illustrative purposes, y_o is assumed to be equal to 2.5 W_1 in the present study. It is further assumed that the stresses do not vary through the thickness, and are equal to the surface stresses given in the SINTAP Residual Stress Compendium. Hence, the distribution of longitudinal residual stress assumed to be acting on transverse through-thickness cracks in the present study is as shown in Fig.2, with y_o = 2.5 W_1.

b) Uniform residual stress equal to yield

Uniform longitudinal residual stresses equal to a membrane stress of weld metal yield magnitude were also considered, i.e:

$$\sigma_R^L / \sigma_{YW} = 1 \quad [3]$$

c) Uniform residual stresses equal to 60% of yield

Uniform longitudinal residual stresses equal to a membrane stress of 60% of weld metal yield magnitude were also considered, i.e:

$$\sigma_R^L / \sigma_{YW} = 0.6 \qquad [4]$$

This case was included to illustrate the effect of a reduced level of uniform residual stress, which may be assumed to be acting after the application of a proof load. The assumed value of the reduced residual stresses, $0.6\sigma_{YW}$, is purely illustrative.

4.3. SIF SOLUTIONS

4.3.1. Infinite Surface Crack in Plate

The following SIF solutions were used.

a) SINTAP recommended procedure

The recommended solution for an infinite surface crack, as given in the SINTAP SIF handbook (2), page AI.8.

This solution is available for any residual stress distribution, $\sigma(u)$, and is expressed as a function of depth, u, from the surface, using geometric constants f_i (a/t) (i = 1 to 5), which are tabulated for values of crack depth, a/t, from 0 to 0.9 in steps of 0.1.

b) Published solution for uniform membrane stress

A standard solution for infinite surface cracks under uniform membrane loading from Tada, Paris and Irwin (3), page 2.10 and 2.11 namely:

$$K_1 = \sigma\sqrt{(\pi a)}\sqrt{\left\{\frac{2t}{\pi a}\tan\frac{\pi a}{2t}\right\}}\cdot\frac{0.752 + 2.02\,(a/t) + 0.37\left\{1-\sin\left(\pi a/2t\right)\right\}^3}{\cos\left(\pi a/2t\right)} \qquad [5]$$

This solution was used in Case 1.3 for comparison with the results obtained in Case 1.2 using the SINTAP recommended solution.

4.3.2. Finite Surface Crack in Plate

The recommended solution for a finite surface crack was used, as given in the SINTAP SIF handbook (2), page AI.3. This solution is available for a residual stress distribution, $\sigma(u/a)$, which is expressed as a 5^{th} order polynomial function of the depth to crack depth ratio (u/a), for $0 \le (u/a) \le 1$. The recommended residual stress profiles are usually expressed as a function of the depth to thickness ratio, (u/t), and hence they have to be transformed as follows:

Given:

$$\sigma(u/t)=\sum_{i=0}^{i=5}\sigma_i\,(u/t)^i \qquad [6]$$

Then:

$$\sigma(u/a)=\sum_{i=0}^{i=5}\sigma_i\,(a/t)^i\,(u/a)^i \qquad [7]$$

The solution is expressed as a function of geometric constants f_i (a/t, 2c/a) (i = 1 to 5), which are tabulated for crack depths, a/t, from 0 to 0.8 in steps of 0.2 and aspect ratios, 2c/a, equal to 2, 2.5, 3.33, 5, 10 and infinity.

4.3.3. Through-Thickness Crack in Plate

In the absence of any solutions for non-linear stress distributions in the SINTAP SIF handbook (2), the following solutions were used.

a) Solution for trapezoidal distribution

A solution for the trapezoidal stress profile shown in Fig.2 was obtained by integrating the weight function solution given on page 5.11a of Ref.(3) for a symmetrical point load, p, at a distance, y, from the centre of a crack length, 2a, in an infinite plate. For a transverse crack subjected to longitudinal stresses, $\sigma_R^L(y)$, the point load, p, is equated with the force, $\sigma_R^L(y)\,dy$, acting on an infinitesimal length, dy, of the crack. Then:

$$K_1=\frac{2}{\sqrt{\pi a}}\int_o^a\frac{\sigma_R^L(y)\,dy}{\sqrt{1-(y/a)^2}} \qquad [8]$$

The solution for the trapezoidal distribution shown in Fig.2 is as follows:

Let b = $W_1/2$ and c = y_o

For a ≤ b

$$K_1=\sigma_{YW}\sqrt{\pi a} \qquad [9a]$$

For b < a ≤ c

$$K_1=\sigma_{YW}\sqrt{\pi a}\,(2/\pi)\left\{(\pi/2)-\left[\left(a^2-b^2\right)^{1/2}-b\pi/2+b\sin^{-1}(b/a)\right]/(c-b)\right\} \qquad [9b]$$

For:

a > c

$$K_1 = \sigma_{YW}\sqrt{\pi a}\,(2/\pi)\left\{\sin^{-1}(c/a) - \frac{\left[\left(a^2-b^2\right)^{1/2} - \left(a^2-c^2\right)^{1/2} - b\sin^{-1}(c/a) + b\sin^{-1}(b/a)\right]}{(c-b)}\right\}$$

[9c]

b) Standard solution for uniform membrane stress

For uniform stresses, the standard stress intensity solution for a through wall crack in an infinite plate was used:

$$K_1 = \sigma\sqrt{\pi a} \qquad [10]$$

4.4. RESULTS AND DISCUSSION

The stress intensity factors were calculated for the cases listed in Table 1 using Mathcad software.

All results are presented in non-dimensional form. The stress intensity factors are normalised with respect to K_o, where $K_o = \sigma_Y \sqrt{\pi a}$, and σ_Y is the normalising stress used in the residual stress profile, i.e. σ_{YW} for longitudinal residual stress, and σ_Y^* (the lower of σ_{YP} and σ_{YW}) for transverse residual stresses. For surface cracks, the crack depth, a, is normalised with respect to plate thickness, t. For through-thickness cracks, the crack length, 2a, is normalised with respect to the weld width, W_1.

4.4.1. Longitudinal infinite surface cracks

a) Comparison of solution methods for polynomial profiles

The normalised SIF, calculated as a function of crack depth for the recommended SINTAP profile for transverse stresses at a butt weld in plate, is plotted in Fig.3 using two analysis methods:

- Case 1.1, using the SINTAP recommended procedure for infinite surface cracks (see Section 4.3.1(a) above) in conjunction with the SINTAP recommend 6th order polynomial residual stress profile (Eq.[1a]).
- Case 1.4, using the SINTAP recommended procedure for finite surface cracks (see Section 4.3.2 above), for a crack of aspect ratio, 2c/a, equal to infinity, in conjunction with the fitted 5th order polynomial residual stress profile (Eq.[1b]).

The two solutions were found to agree with 10% at a/t = 0 and 0.8, and within 1% at intermediate values. This was considered to provide confirmation of the self-consistency of the recommended solutions and to validate both the solutions in

Mathcad and the use of the fitted 5th order polynomial for all but the extreme crack depths. The 10% discrepancy at zero crack depth can be attributed to the poor fit at zero depth (Fig.1).

b) Comparison of residual stress profiles

Normalised SIFs calculated using the SINTAP recommended procedure (see Section 4.3.1(a) above) are plotted in Fig.4 for two stress profiles.

- Case 1.1, the SINTAP recommended 6th order polynomial distribution (Eq.[1a])
- Case 1.2, assuming uniform residual stresses equal to the yield strength σ_Y^*

It can be seen that the solutions are identical as crack depth tends to zero (where the residual stress equals yield in both cases), but the solution for uniform stress becomes increasingly conservative with crack depth. This demonstrates the benefits to be obtained using the SINTAP profile, especially for deeper cracks.

c) Comparison of analysis methods for uniform stresses

Normalised SIFs for uniform yield magnitude stresses are plotted in Fig.5 for two analysis methods:

- Case 1.2, using the SINTAP recommended procedure (see Section 4.3.1(a) above).
- Case 1.3, using the published solution by Tada, Paris and Irwin (3).

It can be seen that the results are virtually identical, providing additional evidence of the validity of the SINTAP procedure.

4.4.2. Longitudinal Finite Surface Cracks

a) Effect of aspect ratio

The normalised SIF for the deepest point of finite surface cracks of aspect ratio, 2c/a, equal to 10 (Case 1.6) and 3.33 (Case 1.8) and for the surface intersection points of the same cracks (Cases 1.7 and 1.9) are plotted in Fig.6. These are compared with the SIF for an infinite surface crack (Case 1.4). All solutions were obtained using the fitted residual stress profile (Eq.[1b]) and the recommended solution procedure for finite surface cracks (see Section 4.3.2 above).

The normalised SIF rises for a/t > 0.2 for the infinite surface crack, but falls continuously with crack depth for the deepest point of the semi-elliptical cracks. The stress intensity is always positive, despite the fact that the residual stress is negative for crack depths between 0.5 and 0.8 of the plate thickness. The stress intensity at the surface intersection point is greater than that at the deepest point for a/t > 0.5 for a crack aspect ratio of 10, and for a/t > 0.1 for aspect ratio 3.33.

b) Comparison of residual stress profiles

The normalised SIFs for the deepest point of a crack of aspect ratio 2c/a = 3.33 for the fitted 5^{th} order polynomial profile (Eq.[1b]) and a uniform yield magnitude residual stress (Cases 1.8 and 1.10, respectively) are plotted in Fig.7, and for the surface intersection point (Cases 1.9 and 1.11) in Fig.8. The normalised SIF for the deepest point is generally much lower for the polynomial residual stress profile, than for the yield magnitude profile. This is particularly so at deeper crack depths, where the residual stresses are compressive (Fig.7). However, as mentioned above, the highest stress intensity for $a/t > 0.1$ is at the surface intersection point (Fig.8), where the reduction in SIF for the polynomial profile compared with yield magnitude residual stress is smaller. It is interesting to note that the normalised SIF for the polynomial profile is approximately uniform, and always less than 0.8.

4.4.3. Transverse Through-Thickness Cracks

The normalised SIF for transverse through-thickness cracks at butt welds in plates are presented in Fig.9 for the following cases:

- Case 1.2, for the SINTAP recommended profile of longitudinal residual stresses (see Section 4.2.2(a) and Fig.2), using the SIF solution given in Eq.[9] above;

- Case 1.13, for uniform longitudinal residual stresses equal to the weld metal yield stress (see Section 4.2.2(b)) using the standard SIF solution for through-thickness cracks in infinite plates (Eq.[10]).

- Case 1.14, for uniform longitudinal stresses equal to 60% of the weld metal yield strength (see Section 4.2.2(b)), again using the standard SIF solution (Eq.[10]).

The normalised SIF has a constant value of 1 for residual stresses equal to yield and of 0.6 for residual stresses equal to 60% of yield. For the SINTAP profile of longitudinal residual stresses, the normalised SIF is equal to 1 inside the width of the weld ($a/W_1 \leq 1$), where the residual stress is equal to the weld metal yield strength, but subsequently decreases to 0.34 at the edge of the tensile zone (at $a/W_1 = 2.5$ in this example), and continues to decrease thereafter, though still remaining positive. The use of the SINTAP profile removes the conservatism inherent in the assumption of residual stresses equal to weld metal yield strength for cracks whose length is greater than the weld width.

It is interesting to compare the SIFs corresponding to the SINTAP profile (Case 1.12) with those corresponding to a uniform level of residual stress lower than yield, which may be assumed to occur after the application of a proof load (Case 1.14). In the example shown in Fig.9, the use of the reduced uniform stresses gives a lower SIF for crack half lengths up to about $a/W_1 = 1.6$, but the SINTAP profile gives lower SIFs for longer cracks.

4.5. PRACTICALITY OF SOLUTION PROCEDURES

In some cases, the application of the SINTAP solution procedures in conjunction with the SINTAP residual stress profiles is somewhat tortuous. It is often necessary to curve fit the recommended profile to transform it to the form required by the solution procedure, and then to transform it from a function of plate thickness to a function of crack depth. For a crack located at the reverse face of the plate, it would also be necessary to perform a further transformation of the position reference variable.

Hence, it is recommended that in any future developments of the SINTAP procedures, consideration should be given to improve the ease of use of the residual stress profiles by harmonising their format with that assumed in the SIF solution procedures. However, it should be noted that the expression of the profiles with a lower order of polynomial may involve some loss of accuracy.

4.6. CONCLUSIONS FOR CRACKS IN BUTT WELD IN PLATE

- Good representation of the SINTAP 6^{th} order profile of transverse residual stresses at butt welds in plate was obtained using a fitted 5^{th} order profile, as required by the SIF calculation procedure for finite surface cracks.

- The use of the SINTAP recommended procedures for calculating the stress intensity factors (SIFs) due to residual stresses at infinite surface cracks in plates has been found to be valid by comparison of results obtained using the recommended procedures with those obtained using previously published solutions.

- A closed form solution for the SIF due to a trapezoidal residual stress profile, as recommended for the variation of residual stresses across the weld, is presented in Section 4.3.3.

- The SIFs calculated using the SINTAP recommended profiles were found to be significantly lower, particularly for larger cracks, than those calculated assuming uniform yield residual stresses for the following cases:

    - Longitudinal infinite surface cracks.
    - The deepest point of longitudinal surface cracks of aspect ratio, 2c/a, of 3.33 and 10.
    - Transverse through-thickness cracks whose length was greater than the width of the weld.

- The normalised SIFs at the surface intersections of surface cracks of finite length were found to remain approximately constant with crack depth, and to exceed the SIFs at the deepest point in deeper cracks.

- For the example considered in this report, the use of the SINTAP profile of longitudinal residual stresses acting on a long transverse through-thickness crack gave lower SIFs than the assumption of a reduced uniform level of residual stress following a proof load.

5. T-BUTT WELD IN PLATE

The full list of cases analysed for T-butt welds in plates is summarised in Table 2 and described in more detail below.

5.1. DEFECT TYPE, ORIENTATION AND LOCATION

The following defect types, locations and orientations were considered:

a) Longitudinal infinite surface crack in base plate at toe of T-butt weld.
b) Longitudinal finite surface crack in base plate at toe of T-butt weld.

5.2. RESIDUAL STRESS PROFILES

The following residual stress profiles were considered.

a) SINTAP bilinear profile

The SINTAP recommended through-thickness profile of transverse residual stress at the toe of a T-butt weld, as shown in Fig.2d of the SINTAP Residual Stress Compendium (1) and in Fig.10 of this report was used. The residual stress are assumed to decrease linearly from σ_Y^* at the toe to zero at a depth r_o below the toe, and to remain at zero over the remainder of the thickness. σ_Y^* is defined as the lower of σ_{YW} and σ_{YP}. r_o is defined as a function of the weld heat input and the parent yield strength in Eq.[A] of Appendix 1 of the Compendium.

The variable part of the profile can be expressed as the sum of a membrane and bending component of residual stresses:

for $0 \le z/r_o \le 1$

$$\sigma_R^m = \sigma_Y^* \left(1 - t/(2r_o)\right) \qquad [11a]$$

$$\sigma_R^b = \sigma_Y^* \, t/(2r_o) \qquad [11b]$$

In order to illustrate the effect of this profile, SIFs were calculated for the case r_o/t = 0.5. Hence, σ_R^m in Eq.[11a] goes to zero, and $\sigma_R^b = \sigma_Y^*$. In other words, the residual stress in the region $0 \le z/t \le 0.5$ is a pure bending stress of yield magnitude.

b) 5th order curve fitted to bilinear profile

The SIF solution procedure for finite surface cracks given in Page AI.3 of the SINTAP SIF handbook (2) is appropriate for a 5th order polynomial residual stress distribution. Hence a 5th order polynomial was fitted to the SINTAP bilinear distribution, for the case r_o = t/2, as shown in Fig.11. The polynomial profile has the following equation:

$$\sigma_R^T / \sigma_Y^* = 0.97308 - 1.06062(z/t) - 6.32076(z/t)^2 + 12.76276(z/t)^3 - 6.38138(z/t)^4 + 0.0(z/t)^5 \quad [12]$$

c) SINTAP polynomial for T-butt welds in pipes

Figure 4d of the SINTAP Compendium (1) gives the following profile for the through-wall distribution transverse residual stresses in the chord member at the toe of a T-butt weld in tubular construction:

$$\sigma_R^T / \sigma_Y^* = 0.97 + 2.327(z/t) - 24.15(z/t)^2 + 42.485(z/t)^3 - 21.087(z/t)^4 \quad [13]$$

This equation is a fitted upper bound to measured residual stress distributions in tubular T and Y nodes and at pipe-on-plate welds, for chord-to-brace thickness ratios in the range 1.375 to 2.0. The profile is illustrated in Fig.12. For thickness ratios less than 1.375, a uniform yield tensile stress is recommended, and for thickness ratios greater than 2, the bilinear distribution for T-butt welds in plates (see (a) above) is recommended.

There is clearly a strong similarity between T-butt welds in plates and pipes, and it could be argued that the same profiles are applicable for both geometries. SIFs have been calculated for both profiles for infinite and finite toe defects at T-butt welds in pipes. This enables a comparison to be made between the different approaches.

d) Transformation of profiles

The SIF solutions for finite surface cracks are expressed as a function of position over crack depth, (z/a). Hence, the profiles had to be transformed from functions of (z/t) to functions of (z/a), where (z/t) = (z/a)(a/t).

e) Uniform residual stress

The default profile of uniform residual stresses of yield magnitude was also considered, namely:

$$\sigma_R^T / \sigma_Y^* = 1 \quad [13]$$

5.3. SIF SOLUTIONS

All the SIF solutions used in this chapter are for cracks in plane plates. They do not allow for any increase in SIF due to the stress concentration at the weld toe. This approach is consistent with the provision of British Standards document PD6493:1991 (5) and its planned replacement BS 7910:1999 (6), in which the SIF due to primary and thermal stresses are increased by the factor M_k in the presence of stress concentrations, but the SIF due to residual stresses are not so increased. The

SINTAP procedure does not provide specific recommendations for the effect of stress concentrations at weld toes.

5.3.1. Longitudinal Infinite Surface Crack

a) SINTAP recommended procedure

The solution given on page AI.8 of the SINTAP SIF handbook (2) was used, as described in Section 4.3.1(a) above.

b) Published solution for uniform membrane stress

A standard published solution for the SIF at a long surface crack in a plate subject to uniform membrane loading was used, as described in Section 4.3.1(b) above.

c) Published solutions for bending stress

Solutions published by Tada, Paris and Irwin (3) for long surface defects in plates were used. The solution for bending stresses was as follows:

$$K_1 = \sigma_b \sqrt{(\pi a)} \sqrt{\left\{ \frac{2t}{\pi a} \tan\left(\frac{\pi a}{2t} \right) \right\}} \frac{0.923 + 0.199\{1 - \sin(\pi a / 2t)\}^4}{\cos(\pi a / 2t)} \qquad [14]$$

5.3.2. Longitudinal Finite Surface Crack

a) SINTAP recommended solution

The solution procedure for finite surface cracks recommended in the SINTAP SIF handbook (2), page AI.3, as described in Section 4.3.2(a) above, was used.

b) Published solution

The well-known solution by Newman and Raju (4), for the stress intensity due to a semi-elliptical surface crack in an infinite plate subject to membrane and bending stresses, was used.

5.4. RESULTS AND DISCUSSION

5.4.1. Longitudinal Infinite Surface Cracks

a) Comparison of analysis methods

The normalised SIF corresponding to the SINTAP recommended bilinear profile (Fig.10), with the depth of the tensile zone taken as r_o/t = 0.5 for illustrative purposes, is plotted in Fig.13, for the following solution procedures.

- Case 2.1, using published solutions for membrane and bending stresses (see Section 5.3.1(c)), for crack depths up to a/t = 0.5.

- Case 2.2, using the SINTAP recommended solution procedure (see Section 5.3.1(a)), with the polynomial fit to the bilinear residual stress distribution (Fig.11).

- Case 2.5, using the SINTAP recommended solution procedure for a finite surface crack, using the solution for crack aspect ratio 2c/a equal to infinity.

It can be seen that the SIFs are identical for all crack depths considered (Fig.13). This demonstrates that the SINTAP solutions for an infinite surface crack, used in combination with a fitted polynomial version of the recommended bilinear residual stress profile, is consistent with results obtained using a published solution for the linear part of the distribution; and that the two SINTAP solution procedures are consistent with each other.

b) Comparison of residual stress distributions

The SIFs corresponding to the SINTAP bilinear distribution recommended for T-butt welds in plate (see Section 5.2(a) above) and the SINTAP polynomial distribution recommended for T-butt welds in pipes are plotted in Fig.14. It can be seen that stress intensity corresponding to the T-butt in pipe profile is up to 33% greater than that corresponding to the T-butt in plate profile.

The SIFs corresponding to the bilinear residual stress profile (Case 2.1) and a uniform residual stress of yield magnitude (Case 2.4) are plotted in Fig.15. The SIFs are equal as the crack depth tends to zero, but diverge as the crack depth increases, such that the SIF for uniform stresses becomes significantly over-conservative compared with the more realistic bilinear distribution.

5.4.2. Longitudinal Finite Surface Cracks

a) Effect of aspect ratio

Normalised stress intensities for the deepest point of cracks of aspect ratios 2c/a = infinity, 10 and 3.3 are shown in Fig.16 and for the surface point in Fig.17. In Fig.16 it can be seen that the stress intensity at the deepest point of the crack rises as the crack depth increases for an infinitely long crack, but falls for cracks with aspect ratio 10 or 3.33. However, the stress intensity at the surface intersection points of the finite surface cracks rise with crack depth, as shown in Fig.17, such that initiation from the surface intersections may be the limiting factor at deeper cracks.

b) Comparison of solution methods

SIFs calculated using the SINTAP solution method (see Section 5.3.2(a)) and a published solution (see Section 5.3.2(b)) are plotted in Fig.18 to 21 for the deepest point and surface intersection points in finite surface cracks of aspect ratios 10 and 3.33. It can be seen that there is good agreement between the SINTAP and published solution procedures in all cases.

c) Comparison of residual stress profiles

Normalised SIFs corresponding to the bilinear residual stress profile recommended for T-butt welds in plates and the polynomial profile recommended for T-butt welds in pipes for surface cracks of aspect ratio 2c/a = 3.33 are plotted in Fig.22 for the deepest point of the crack and in Fig.23 for the surface intersection point. As previously observed for infinite surface cracks, the SIF is higher for the polynomial profile, particularly at the deepest point.

The normalised SIFs corresponding to the bilinear profile and a uniform membrane stress σ_R^T / σ_{YP} = 1 at a surface crack of aspect ratio 2c/a = 3.33 are compared in Fig.24 for the deepest point of the crack, and in Fig.25 for the surface intersection points. The normalised SIFs rise with crack depth for the uniform residual stress profile; they fall rapidly at the deepest point for the bilinear profile, but remain approximately constant at the surface intersection point, which is the controlling location for crack depths a/t > 0.1.

5.5. CONCLUSIONS FOR CRACK IN T-BUTT WELD IN PLATE

- Good representation of the SINTAP bilinear profile of transverse stresses at T-butt welds in plate was obtained using a fitted 5th order profile, as required by the SIF calculation procedure for finite surface cracks.

- The use of the SINTAP recommended procedures for calculating the stress intensity factors due to residual stresses at finite surface cracks in plates has been found to be valid by comparison of results obtained using the recommended procedures with those obtained using previously published solutions.

- The SIFs calculated using the SINTAP recommended profiles were found to be significantly lower, particularly at deeper cracks, than those calculated assuming uniform yield residual stresses, for infinite surface defects and for the deepest point of surface defects of aspect ratio 3.33 and 10.

- The normalised SIFs at the surface intersections of surface cracks of finite length increased with crack depth, and to exceed the SIFs at the deepest point in deeper cracks.

- The SIFs corresponding to the SINTAP recommended polynomial profile for transverse residual stresses at the toe of the T-butt welds in pipes are up to 33% greater than those corresponding to the SINTAP recommended bilinear profile for T-butt welds in plate.

6. CIRCUMFERENTIAL BUTT WELD IN CYLINDER

The full list of cases analysed is listed in Table 3 and described in more detail below.

6.1. DEFECT TYPE, LOCATION AND ORIENTATION

The following defect types were considered.

a) Fully circumferential surface crack on inside or outside surfaces.
b) Part circumferential surface crack on inside or outside surfaces.

6.2. RESIDUAL STRESS PROFILES

The following residual stress profiles were considered. Residual stress directions are referred to the weld, such that the transverse direction is the pipe axial direction.

a) SINTAP low heat polynomial profile

The through-thickness profile of transverse residual stress at a circumferential butt weld in ferritic steel with heat input per unit thickness, q/(vt) < 60J/mm^2, as given in Fig.3d of Appendix 2 of the SINTAP Residual Stress Compendium (1), was used, namely:

$$\sigma_R^T / \sigma_R^{T,O} = 1.0 - 3.29(z/t) - 26.09(z/t)^2 + 73.16(z/t)^3 - 45.72(z/t)^4 \qquad [14a]$$

$$\sigma_R^{T,O} / \sigma_Y^* = -0.5 - 0.0083\, q/(vt) \qquad [14b]$$

z is measured from the outer surface. For the present study, a heat input per unit thickness of q/(vt) = 60J/mm^2 was assumed, to give the limiting case of $\sigma_R^{T,O} / \sigma_Y^* = -1$.

b) SINTAP high heat cosine profile

The through-thickness profile of transverse residual stress at a circumferential weld in ferritic steel with heat input per unit thickness, q/(vt) > 60J/mm^2, as given in Fig.3d of Appendix 2 of the SINTAP R6 Compendium (1), was used, namely:

$$\sigma_R^T / \sigma_R^{T,O} = \cos(\pi z/t) \qquad [15a]$$

$$\sigma_R^{T,O} / \sigma_Y^* = -1 \qquad [15b]$$

c) Low heat fitted 3rd order polynomial

The SIF solutions for part circumferential cracks described in Section 6.3 below require the residual stress profile to be expressed as a third order polynomial. Hence, the following 3rd order polynomial was fitted to the SINTAP low heat profile (Eq.[14a]):

$$\sigma_R^T / \sigma_Y^* = -1.64923 + 16.3333(z/t) - 32.6733(z/t)^2 + 18.28(z/t)^3 \qquad [16]$$

The SINTAP and fitted profiles are plotted in Fig.26. The fit is not very good, especially at z/t = 0, where the discrepancy is 65%.

d) High heat fitted 3rd order polynomial

The following 3rd order polynomial was fitted to the SINTAP high heat residual stress profile (Eq.[15a]):

$$\sigma_R^T / \sigma_Y^* = -0.991053 - 0.266177(z/t) + 6.74485(z/t)^2 - 4.496565(z/t)^3 \qquad [17]$$

The SINTAP and fitted profiles are plotted in Fig.27. The fit is virtually perfect.

e) Transformation of profiles

All the above profiles are expressed as a function of distance from the outside surface, z. The SIF solutions are expressed as a function of depth from the cracked surface, u. Hence, for cracks at the inside surface, the profiles had to be transformed from functions of (z/t) to functions of (u/t), where (u/t) = 1 – (z/t).

The SIF solutions for part circumferential defects are expressed as a function of depth over crack depth, (u/a). Hence, the profiles had to be further transformed from functions of (u/t) to (u/a), where (u/t) = (u/a)(a/t).

f) Uniform residual stress

The default profile of uniform residual stress of yield magnitude was also considered, namely:

$$\sigma_R^T / \sigma_Y^* = 1 \qquad [18]$$

6.3. SIF SOLUTIONS

All the SIF solutions used in this chapter for circumferential cracks in cylinders were taken from the SINTAP SIF handbook (2). The solutions in the handbook were collated by Dr S Al Laham of British Energy Generation Ltd, based partly on previous work by SAQ. The four solutions used here are referred to by their number in Appendix I of the SINTAP SIF handbook (2).

a) Fully circumferential outside surface crack

SIF handbook page AI.38.

b) Fully circumferential inside surface crack

SIF handbook page AI.30.

c) Part circumferential outside surface crack

SIF handbook page AI.32.

d) Part circumferential inside surface crack

SIF handbook page AI.25.

The solutions for fully circumferential cracks (a) and (b) above, are expressed as integrals of the product of the through-wall stress distribution, $\sigma(u)$, and a geometric function Σf_i:

$$K_1 = \frac{1}{\sqrt{(2\pi a)}} \int_o^a \sigma(u) \sum_{i=1}^{i=3} f_i (a/t, R_i/t)(1-u/a)^{i-3/2} \, du \qquad [19]$$

Values of f_i are given for a/t = 0 to 0.6 in steps of 0.1, and for R_i/t = 2.33, 5 and 10. This expression can be evaluated for any stress profile $\sigma(u)$, where u is the distance from the cracked surface.

The solutions for part circumferential cracks, (c) and (d) above, are expressed as summations of the products of the through wall stress profile, $\sigma(u)$, the global bending stress, σ_{bg}, and geometric functions, f_i and f_{bg}. The stress profile is expressed as a 3rd order polynomial:

$$\sigma(u) = \sum_{i=0}^{i=3} \sigma_i \, (u/a)^i \qquad [20]$$

In the present study, global bending stresses are not considered, and the stress intensity solutions is:

$$K_1 = \sqrt{(\pi a)} \sum_{i=1}^{i=3} \sigma_i \, f_i \, (a/t, l/a, R_i/t) \qquad [21]$$

The geometric function f_i is given for a/t = 0 to 0.8 in steps 0.2, for 2c/a = 2, 4, 8, 16 and 32, for R_i/t = 5 and 10, and for the deepest point and surface intersection points of the crack. In accordance with Eq.[20], the residual stress profile must be expressed as a third order polynomial.

Solutions for part circumferential cracks were obtained for the deepest point of a crack of aspect ratio 2c/a = 4. All solutions were obtained for a cylinder with internal radius to wall thickness ratio R_i/t = 10.

6.4. RESULTS AND DISCUSSION

6.4.1. Fully Circumferential Crack at Outside Surface

The normalised SIFs for fully circumferential cracks at the outside surface in a circumferential butt weld in a pipe with $R_i/t = 10$ are plotted in Fig.28, for three residual stress profiles:

- SINTAP, low heat input (see Section 6.2(a) above).
- SINTAP, high heat input (see Section 6.2(b) above)
- Uniform yield stresses (see Section 6.2(f) above).

In Fig.28, it can be seen that the normalised SIF for uniform yield magnitude residual stress starts at 1.12 as the crack depth tends to zero, and then rises gently with crack depth. This is as expected. However, the SIF corresponding to the SINTAP profiles starts at –1.12; it stays negative for the high heat profile, but becomes positive at (a/t) > 0.3 for the low heat profile. The negative SIFs are caused by the negative residual stresses at the outside surface in the SINTAP profiles (see Fig.26 and 27).

It is the understanding of the author that the SINTAP profiles were generated with particular reference to the stresses near the inside surface, and with a particular concern to ensure that they were conservative with respect to defects at the root of circumferential butt welds made from the outside. The recommended profiles imply that the residual stress at the outside tends to a compressive value between $-0.5\sigma_Y^*$ and $-\sigma_Y^*$, i.e. that they are always large and compressive. Some cases have been reported where the transverse residual stress at the outside surface is tensile (7,8). The currently recommended profiles would be unconservative for these cases. Hence, it is recommended that further consideration should be given to the SINTAP profiles for transverse stresses at the outside surface at circumferential butt welds in ferritic steel.

Even if there are cases where the residual stresses can be assumed to be compressive, then it needs to be considered whether it is appropriate to include a negative SIF due to residual stress in defect assessments. A negative SIF cannot exist per se, as it would be prevented by crack closure. However, it is possible that negative residual stresses could make a negative contribution to the total SIF under a positive applied load, although the total SIF cannot be negative.

In general, it is possible that any initially negative residual stresses may be reduced during pressure testing or service life. Hence, it is recommended that whenever the SIF due to residual stresses is calculated to be negative, it should be taken as zero.

6.4.2. Fully Circumferential Cracks at Inside Surface

The normalised SIFs for fully circumferential cracks at the inside surface are plotted in Fig.29, for the three residual stress profiles described in the previous section. The residual stress equals the yield strength at the inside surface for all three profiles, and the normalised SIF equals approximately 1.1 as the crack depth tends to zero for all three cases. It then rises for uniform yield residual stress, stays about level for the SINTAP high heat input cosine profile, and falls rapidly for the SINTAP low heat input profile. This demonstrates the benefit which can be obtained using the SINTAP profiles.

6.4.3. Part Circumferential Crack at Outside Surface

The normalised SIF for the deepest point of a part circumferential surface crack of aspect ratio 2c/a = 4 at the outside surface in a circumferential butt weld in a pipe with $R_i/t = 10$ are plotted in Fig.30 for the following three residual stress profiles.

- 3^{rd} order polynomial profiles fitted to SINTAP low heat input profile (see Section 6.2(c) above).
- 3^{rd} order polynomial profile fitted to SINTAP high heat input profile (see Section 6.2(d) above).
- Uniform yield stress (see Section 6.2(f) above).

The normalised SIFs for the 3^{rd} order curves fitted to the SINTAP profiles are strongly negative at low crack depths, due to the assumed negative residual stresses in this region. The recommendations concerning these negative stresses and SIFs given in Section 6.4.1 apply here also.

The normalised SIF for uniform yield residual stress start at about 0.85 as the crack depth tends to zero, and then rises gently with crack depth. As expected, these SIFs are lower than for fully circumferential cracks, because a short crack opens less than a long crack.

6.4.4. Part Circumferential Crack at Inside Plate

The normalised SIFs for part circumferential cracks at the inside surface are plotted in Fig.31 for the same sets of conditions as in the previous sub-section.

The normalised SIF for the SINTAP low heat profile starts at a low value of about 0.3 as the crack depth tends to zero, and then falls with increasing crack depth to minimum at a/t = 0.23, and then rises as the crack tip reaches the tensile zone nearer the outside surface (see also Fig.26, noting that the stress profile is referred to the outside surface). The normalised SIF corresponding to the high heat SINTAP profile starts at a higher value, about 0.9, and then falls with depth as the crack tip reaches the compressive zone in the outer half of the thickness. The normalised SIF for uniform yield residual stresses also starts at about 0.9, but then rises gently for crack depths up to a/t = 0.6, and steeply to a/t = 0.8. The graph illustrates the benefits to be gained using the SINTAP profiles.

6.5. CONCLUSIONS AND RECOMMENDATIONS FOR CIRCUMFERENTIAL CRACKS IN BUTT WELDS IN PIPES

- Fitted 3rd order curves gave a good representation of the SINTAP cosine profile for high heat input welds, but unsatisfactory representation of the 4th order profile for low heat input welds.

- The SIF at finite or infinite circumferential cracks at the inside surface of pipe butt welds, when calculated using the SINTAP recommended profile for welds with low heat input, were significantly lower than when calculated assuming uniform yield stresses, especially for deeper cracks.

- The SIFs at cracks at the inside surface, when calculated using the SINTAP recommended profile for high heat input welds, were somewhat lower than those calculated assuming uniform yield residual stresses.

- It is recommended that further consideration be given to the SINTAP recommended profiles for pipe butt welds with respect to the transverse stresses at the outside surface.

- It is recommended that it should be assumed that, if the SIF due to residual stresses is calculated to be negative, it should be assumed to be zero.

7. CONCLUSIONS

- Good representation of the SINTAP 6th order profile of transverse residual stresses at butt welds in plate and the SINTAP bilinear profile of transverse stresses at T-butt welds in plate was obtained using fitted 5th order profiles, as required by the SIF calculation procedure for finite surface cracks.

- Fitted 3rd order curves gave a good representation of the SINTAP cosine profile for high heat input butt welds in pipes, but unsatisfactory representation of the 4th order profile for low heat input welds.

- The use of the SINTAP recommended procedures for calculating the stress intensity factors (SIFs) due to residual stresses at infinite and finite surface cracks in plates has been found to be valid by comparison of results obtained using the recommended procedures with those obtained using previously published solutions.

- A closed form solution for the SIF due to a trapezoidal residual stress profile, as recommended for the variation of residual stresses across the weld, is presented in this report.

- The SIFs calculated using the SINTAP recommended profiles were found to be significantly lower than those calculated assuming uniform yield magnitude residual stresses, especially at larger cracks, for the following cases:

- Infinite surface cracks and at the deepest point of finite surface cracks in but welds in plate, T-butt welds in plate, and at the inside surface of pipe butt welds with low heat input.

- Transverse through-thickness cracks at butt welds in plate, for cracks whose length was greater than the width of the weld.

- The normalised SIFs at the surface intersections of longitudinal surface cracks of finite length in plate butt welds and plate T-butt welds were found to remain approximately constant or rise with increasing crack depth, and to exceed the SIF at the deepest point in deeper cracks.

- For the example considered in this report, the use of the SINTAP profile of longitudinal residual stresses acting on long transverse through-thickness cracks gave lower SIFs than the assumption of a reduced level of uniform residual stresses following a proof load.

- The SIFs corresponding to the SINTAP recommended polynomial profile for transverse residual stresses at the toe of T-butt welds in pipe are up to 33% greater than those corresponding to the SINTAP recommended bilinear profiles for T-butt welds in plate.

8. RECOMMENDATIONS

- Consideration should be given to harmonising the format of the SINTAP recommended residual stress profiles with that required by the SINTAP recommended stress intensity factor solutions.

- Further consideration should be given to the SINTAP recommended profiles for pipe butt welds with respect to the transverse stresses at the outside surface, which are assumed to be compressive in all cases.

- If the SIF due to residual stress is calculated to be negative, it should be assumed to be zero.

9. REFERENCES

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Table 1 Butt weld in plate, surface and through thickness cracks

Weld joint geometry	Defect orientation	Defect type	Variable	Residual stress distribution	Analysis method	Aspect ratio and point of initiation	Case No.	Comment
Butt weld in plate	Longitudinal	Long surface defect	$0 \le a/t \le 0.9$ $\Delta(a/t)=0.1$	SINTAP Fig.1d (polynomial)	SAQ AI.8	N/A	1.1	
				$\sigma_R^T = \sigma_Y$*	SAQ AI.8	N/A	1.2	Check conservatism
				$\sigma_R^T = \sigma_Y$*	TPI 2.10	N/A	1.3	Check vs SAQ AI.8
		Short surface defect. A = deepest point B = surface intersection	$0 \le a/t \le 0.8$ $\Delta(a/t)=0.2$	SINTAP Fig.1d (polynomial)	SAQ AI.3	Infinity, A	1.4	Check vs SAQ AI.8
						10, A	1.6	
						10, B	1.7	
						3.33, A	1.8	
						3.33, B	1.9	
				$\sigma_R^T = \sigma_Y$*	SAQ AI.3	3.33, A	1.10	Check conservatism
						3.33, B	1.11	
	Transverse	Through-thickness	$0 \le 2a/W_1 \le 10$ $\Delta(a/W_1)=0.1$	SINTAP Fig.1a, thin plate, $y_0=2W_1$	TPI 5.11a	N/A	1.12	
				$\sigma_R^L = \sigma_{YW}$	TPI 5.1a	N/A	1.13	Check conservatism
				$\sigma_R^L = 0.6\sigma_{YW}$	TPI 5.1a	N/A	1.14	Effect of BS7910 Eq 14b (e.g.)

KEY
TPI means Tada, Paris and Irwin (3)
SAQ refers to solution methods from the SINTAP SIF handbook (2), taken from solutions collated by SAQ
SINTAP refers to stress profiles from the SINTAP Residual Stress Compendium (1)

Table 2 T-butt weld, surface cracks

Weld joint geometry	Defect orientation	Defect type and location	Variable	Residual stress distribution	Analysis method	Aspect ratio and point of initiation	Case No.	Comment
T-butt weld	Longitudinal	Long surface defect at toe	$0 \le a/t \le 0.9$ $\Delta(a/t)=0.1$	SINTAP Fig.2d $r_0/t=0.5$	TPI 2.13	N/A	2.1	
					SAQ AI.8	N/A	2.2	Check vs TPI
				SINTAP Fig.4d (polynomial)	SAQ AI.8		2.3	Compare with SINTAP 2d
				$\sigma_R^T = \sigma_Y$*	TPI 2.10	N/A	2.4	Check conservatism
		Short surface defect at toe. A = deepest point B = surface intersection	$0 \le a/t \le 0.8$ $\Delta(a/t)=0.2$	SINTAP Fig.2d $r_0/t=0.5$	SAQ AI.3	Infinity, A	2.5	Check vs SAQ AI.8
						10, A	2.17	
						10, B	2.18	
						3.33, A	2.11	
						3.33, B	2.12	
			$0 \le a/t \le 0.5$ $\Delta(a/t)=0.1$		Newman and Raju	10, A	2.7	Check vs SAQ AI.3
						10, B	2.8	
						3.33, A	2.9	
						3.33, B	2.10	
			$0 \le a/t \le 0.8$ $\Delta(a/t)=0.2$	SINTAP Fig.4d (polynomial)	SAQ AI.3	3.33, A	2.13	Compare with SINTAP 2d
						3.33, B	2.14	
			$0 \le a/t \le 0.8$ $\Delta(a/t)=0.1$	$\sigma_R^T = \sigma_Y$*	Newman and Raju	3.33, A	2.15	Check conservatism
						3.33, B	2.16	

KEY
TPI means Tada, Paris and Irwin (3)
SAQ refers to solution methods from the SINTAP SIF handbook (2), taken from solutions collated by SAQ
SINTAP refers to stress profiles from the SINTAP Residual Stress Compendium (1)

Table 3 Circumferential butt weld in pipe, surface cracks

Weld joint geometry	Defect orientation	Defect type and location	Variable	Residual stress distribution	Analysis method	Point of initiation	Case No.	Comment
Circ. butt weld in pipe, $R_i/t = 10$	Circ., i.e. longitudinal	Long surface defect, outside	$0 \le a/t \le 0.6$ $\Delta(a/t)=0.1$	SINTAP Fig.3d low heat	SAQ AI.38	N/A	3.1	
				SINTAP Fig.3d high heat	SAQ AI.38	N/A	3.2	
				$\sigma_R^T = \sigma_Y$*	SAQ AI.38	N/A	3.3	Check vs 3d
		Long surface defect, inside	$0 \le a/t \le 0.6$ $\Delta(a/t)=0.1$	SINTAP Fig.3d low heat	SAQ AI.30	N/A	3.4	
				SINTAP Fig.3d high heat	SAQ AI.30	N/A	3.5	
				$\sigma_R^T = \sigma_Y$*	SAQ AI.30	N/A	3.6	Check vs 3d
		Short surface defect, outside. 2c/a = 4 A = deepest point	$0 \le a/t \le 0.8$ $\Delta(a/t)=0.2$	SINTAP Fig.3d low heat	SAQ AI.32	A	3.7	
				SINTAP Fig.3d high heat	SAQ AI.32	A	3.8	
				$\sigma_R^T = \sigma_Y$*	SAQ AI.32	A	3.9	Check vs 3d
		Short surface defect, inside. 2c/a = 4 A = deepest point	$0 \le a/t \le 0.8$ $\Delta(a/t)=0.2$	SINTAP Fig.3d low heat	SAQ AI.25	A	3.10	
				SINTAP Fig.3d high heat	SAQ AI.25	A	3.11	
				$\sigma_R^T = \sigma_Y$*	SAQ AI.25	A	3.12	Check vs 3d

KEY
SAQ refers to solution methods from the SINTAP SIF handbook (2), taken from solutions collated by SAQ
SINTAP refers to stress profiles from the SINTAP Residual Stress Compendium (1)

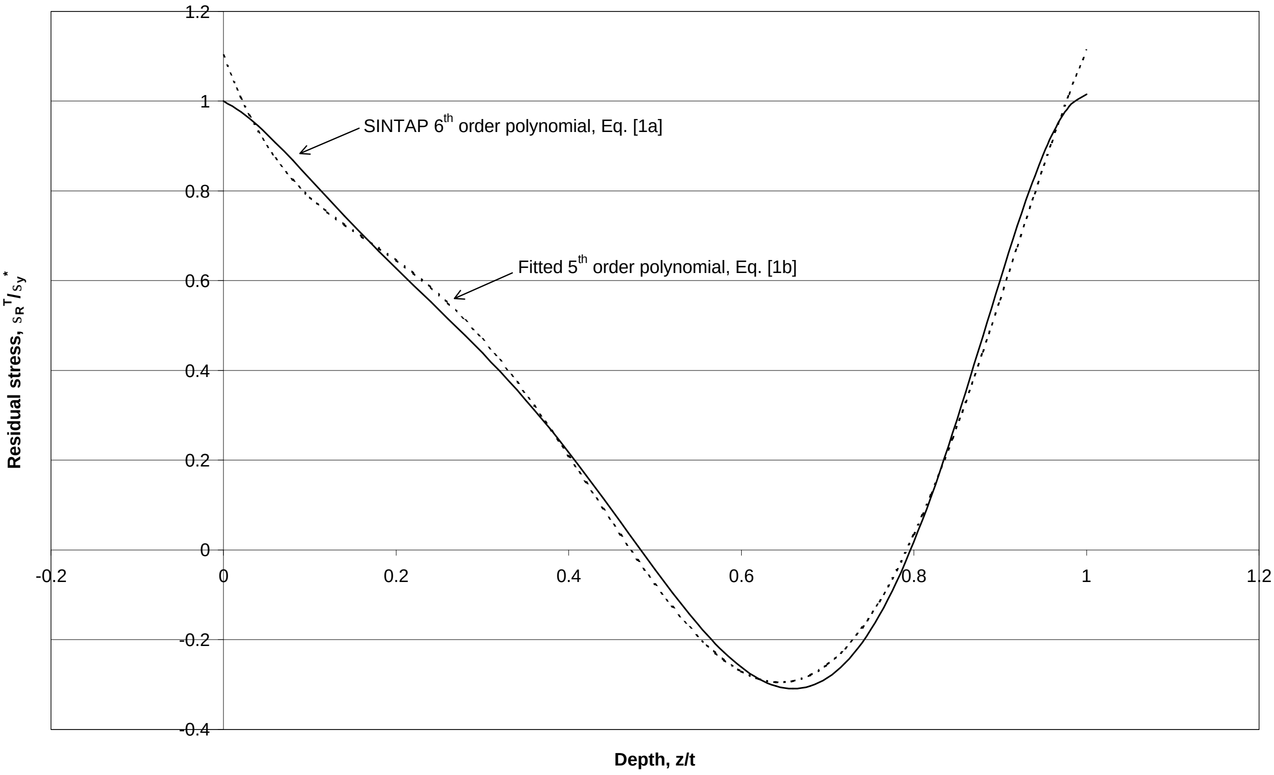

Fig. 1. Through thickness profiles of transverse residual stress at butt weld in plate.

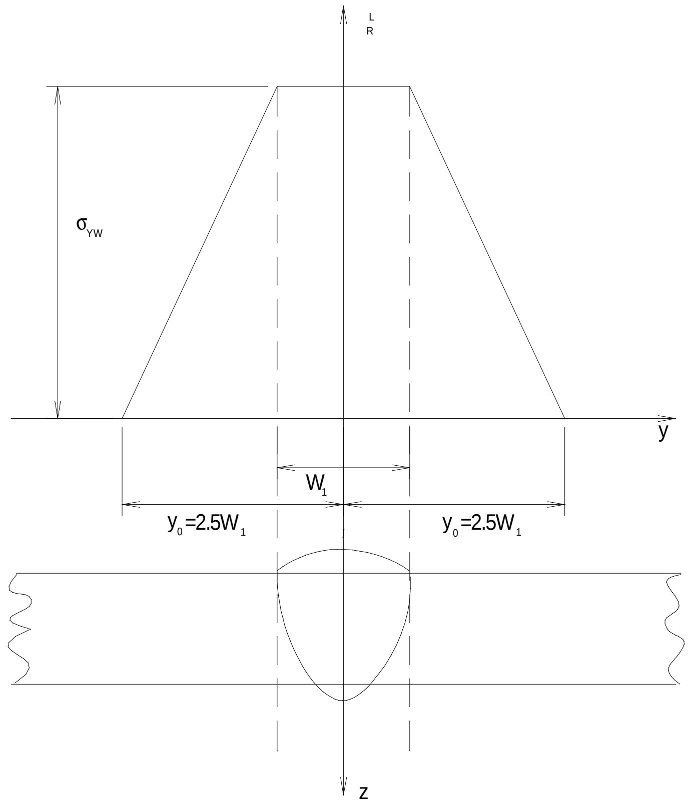

Fig. 2. Profile of longitudinal residual stresses at butt weld in plate.

Weld Geometry	Butt weld in plate	Case Number	1.1	1.4
Defect Orientation	Longitudinal	Residual Stress Distribution	SINTAP Fig 1d	SINTAP Fig 1d
Defect Type	Infinite surface crack	Analysis Method	SAQ AI.8	SAQ AI.3
Initiation Point	A	Aspect Ratio, 2c/a	n/a	Infinity

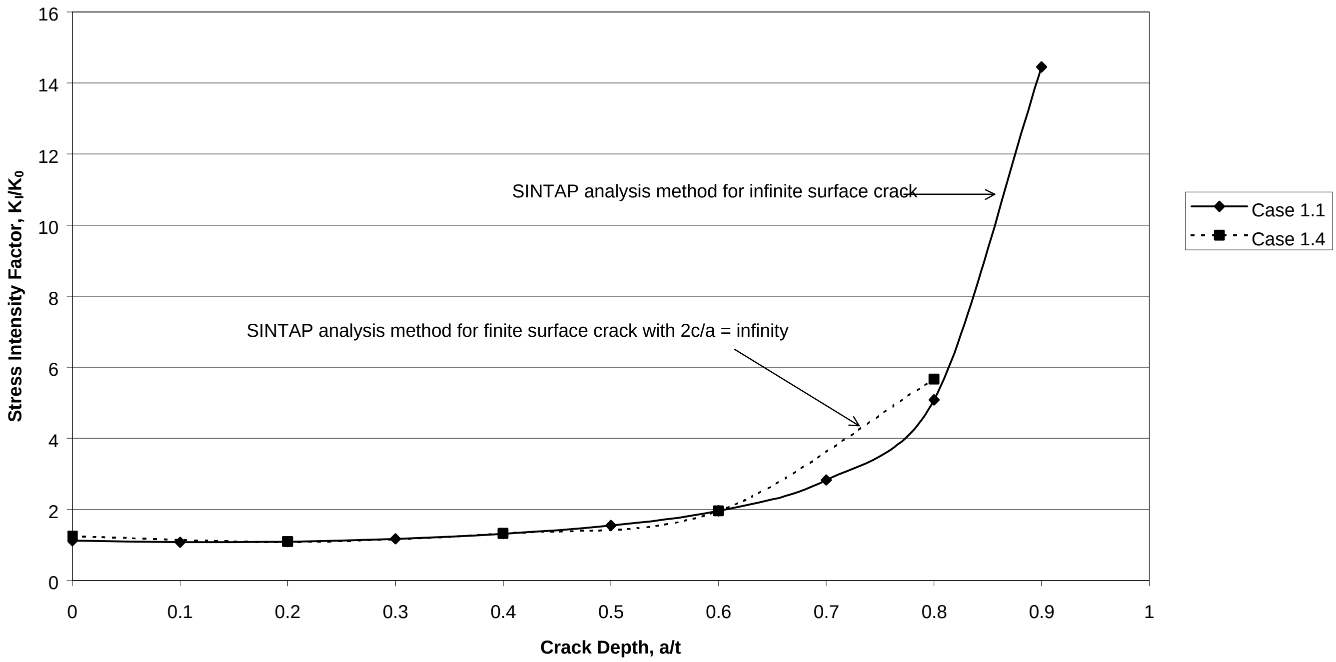

Fig. 3. Normalised SIF at longitudinal infinite surface crack at butt weld in plate. Effect of analysis method.

Weld Geometry	Butt weld in plate	Case Number	1.1	1.2
Defect Orientation	Longitudinal	Residual Stress Distribution	SINTAP Fig 1d	$\sigma_R^T = \sigma_Y^*$
Defect Type	Infinite surface crack	Analysis Method	SAQ AI.8	SAQ AI.8
Initiation Point	A	Aspect Ratio, 2c/a	n/a	n/a

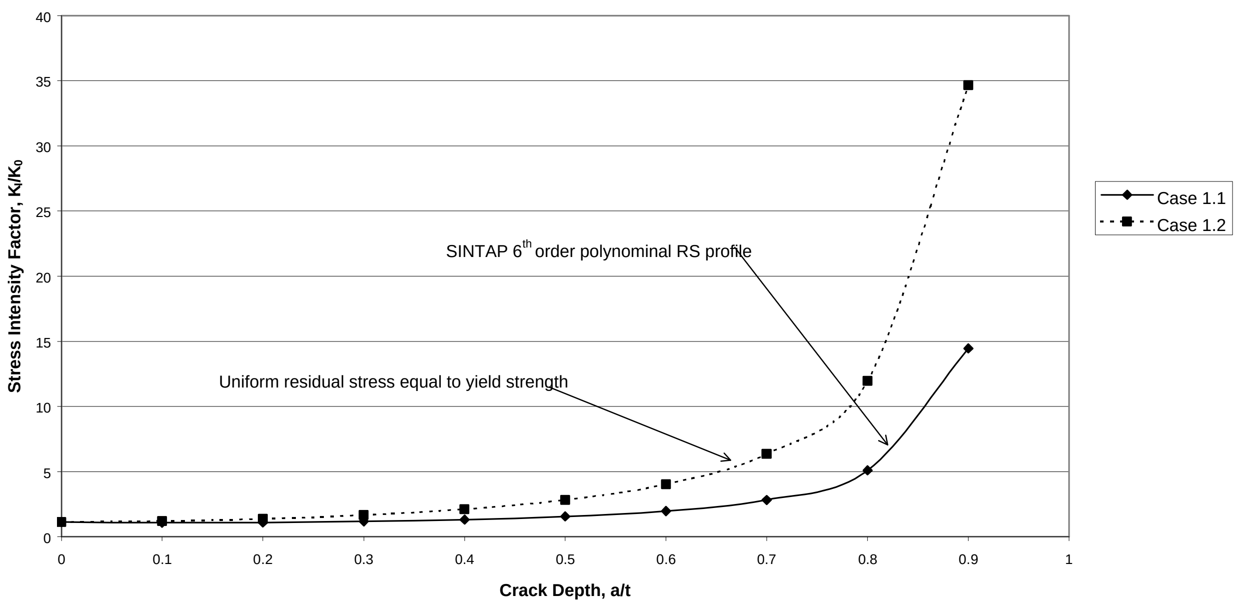

Fig. 4. Normalised SIF at longitudinal infinite surface crack at butt weld in plate. Effect of residual stress profile.

Weld Geometry	Butt weld in plate	Case Number	1.2	1.3
Defect Orientation	Longitudinal	Residual Stress Distribution	$\sigma_R^T / \sigma_Y^* = 1$	$\sigma_R^T / \sigma_Y^* = 1$
Defect Type	Infinite surface crack	Analysis Method	AI.8	TPI 2.10
Initiation Point	A	Aspect Ratio, 2c/a	n/a	n/a

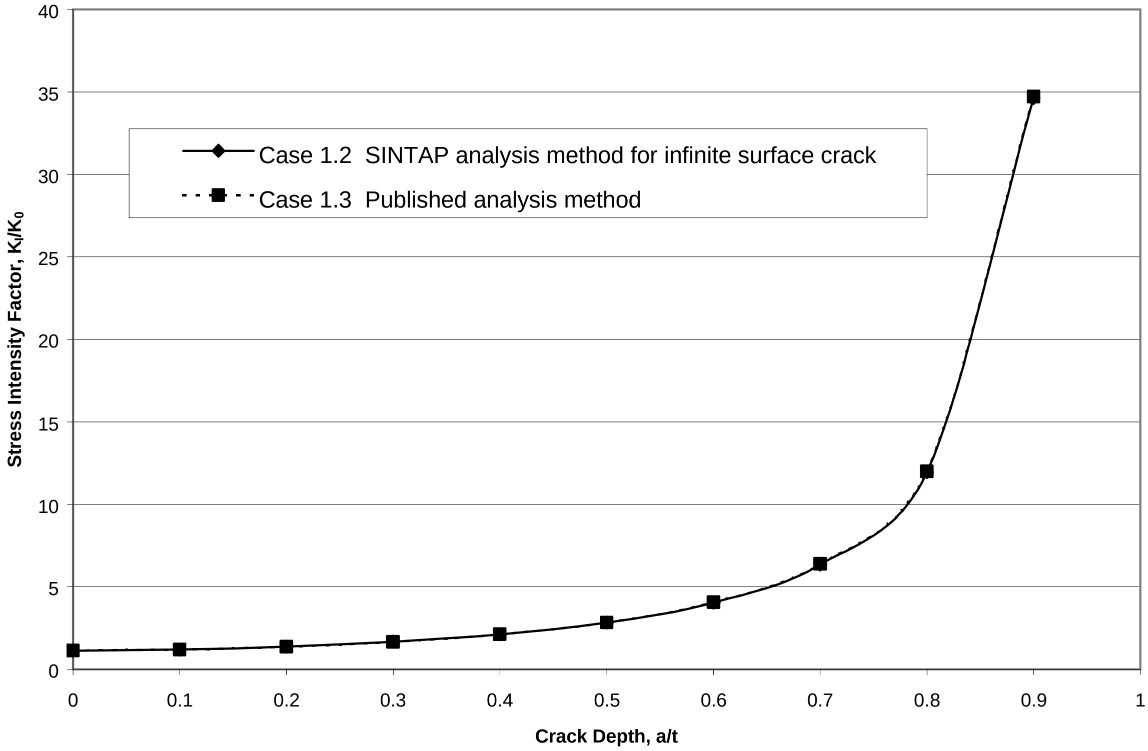

Fig. 5. Normalised SIF at longitudinal infinite surface crack at butt weld in plate.
Effect of analysis method.

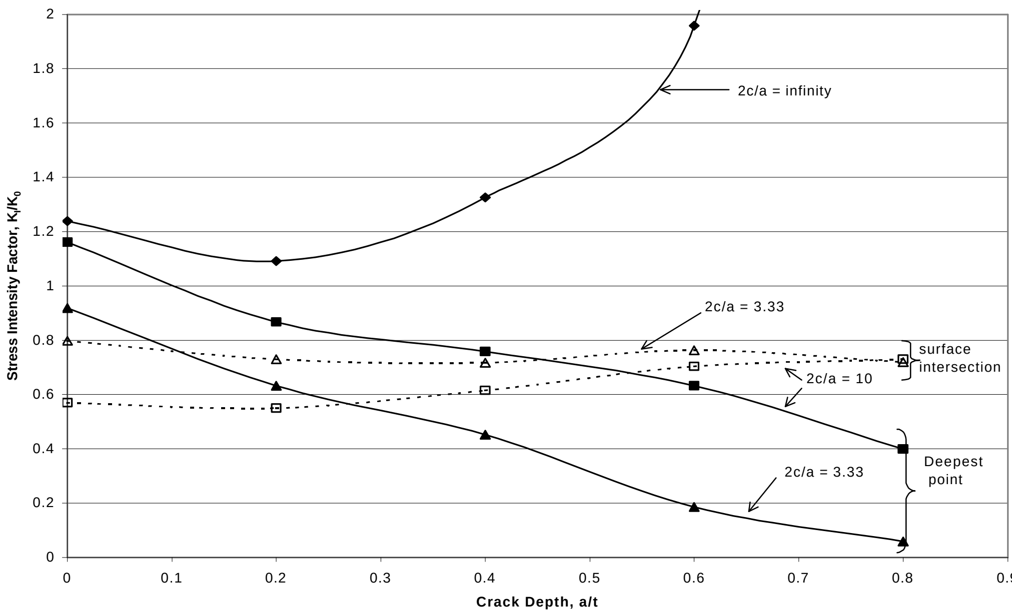

Fig. 6. Normalised SIF at finite surface crack at butt weld in plate.
Effect of crack aspect ratio at deepest point and surface intersection.

Weld Geometry	Butt weld in plate	Case Number	1.8	1.10
Defect Orientation	Longitudinal	Residual Stress Distribution	SINTAP Fig 1d	$\sigma_R^T/\sigma_Y^*=1$
Defect Type	Finite surface crack	Analysis Method	SAQ AI.3	SAQ AI.3
Initiation Point	A	Aspect Ratio, 2c/a	3.33	3.33

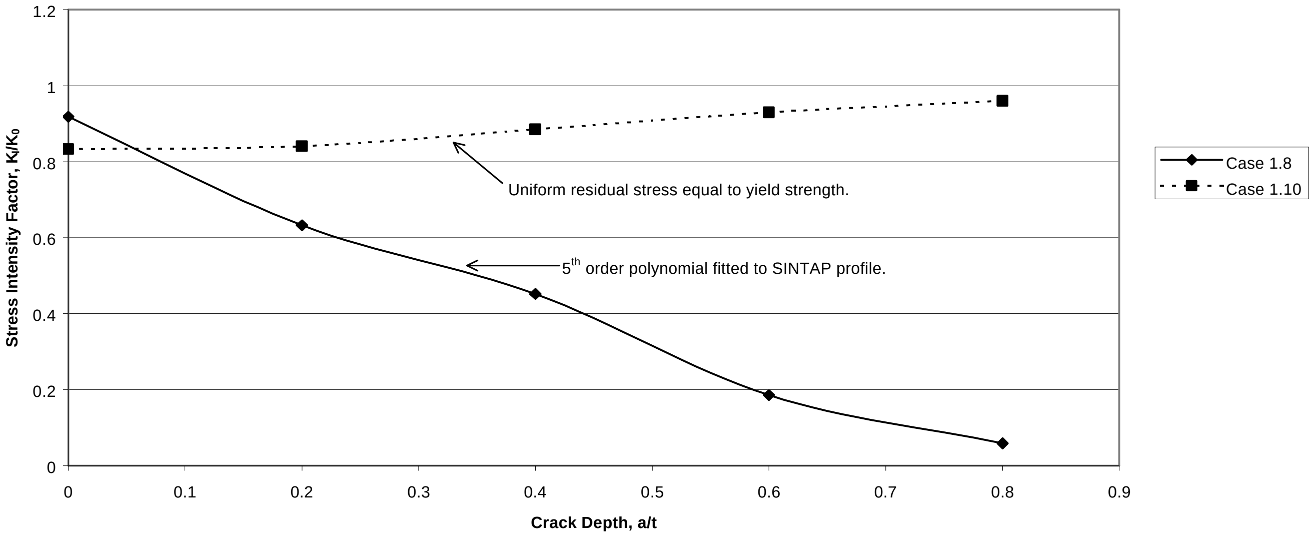

Fig. 7. Normalised SIF at deepest point of finite surface crack at butt weld in plate. Effect of residual stress profile.

Weld Geometry	Butt weld in plate	Case Number	1.9	1.11
Defect Orientation	Longitudinal	Residual Stress Distribution	SINTAP Fig 1d	$\sigma_R^T = \sigma_Y^*$
Defect Type	Finite surface crack	Analysis Method	SAQ A1.3	SAQ A1.3
Initiation Point	B	Aspect Ratio, 2c/a	3.33	3.33

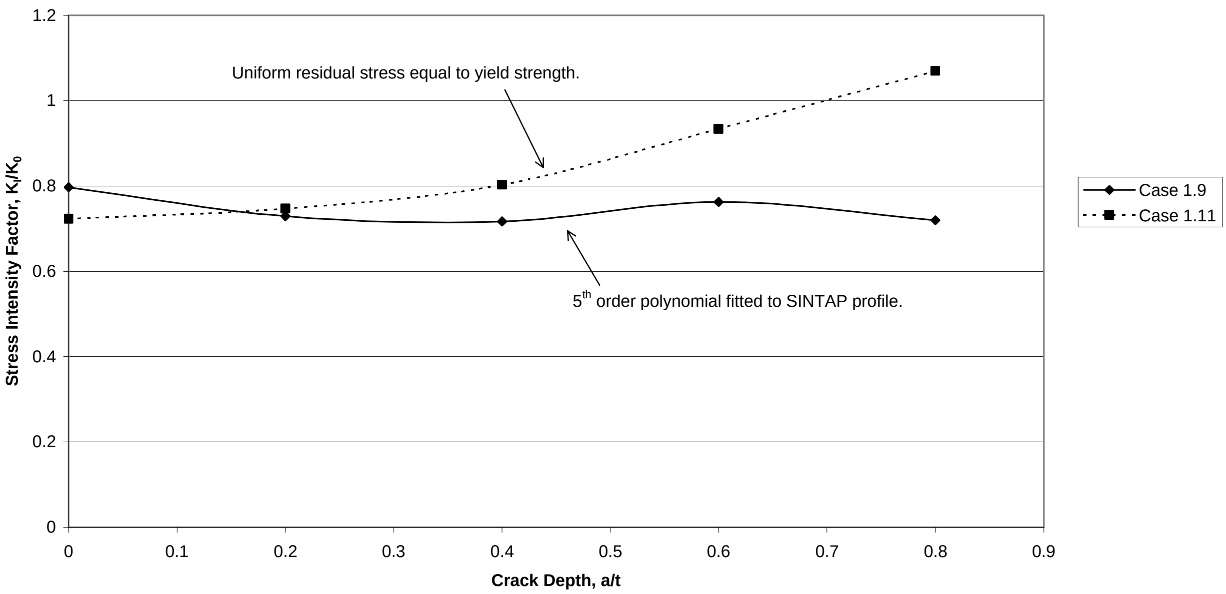

Fig. 8. Normalised SIF at surface intersections of finite surface crack at butt weld in plate. Effect of residual stress profile.

Weld Geometry	Butt weld in plate	Case Number	1.12	1.13	1.14
Defect Orientation	Transverse	Residual Stress Distribution	SINTAP Fig 1a	$\sigma_R^L / \sigma_{YW} = 1.0$	$\sigma_R^L / \sigma_{YW} = 0.6$
Defect Type	Through thickness	Analysis Method	TPI 5.11a	TPI 5.11a	TPI 5.11a
Initiation Point	n/a	Aspect Ratio, 2c/a	n/a	n/a	n/a

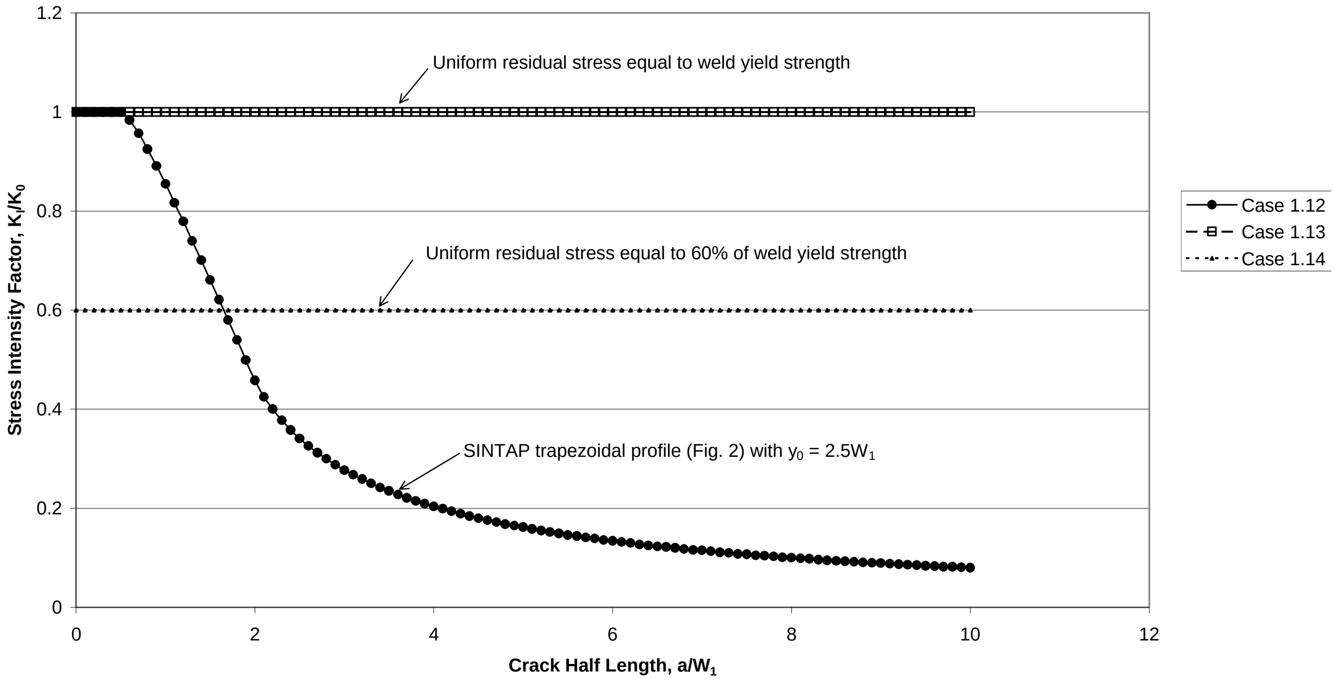

Fig. 9. Normalised SIF at transverse through thickness crack at butt weld in plate. Effect of residual stress profile.

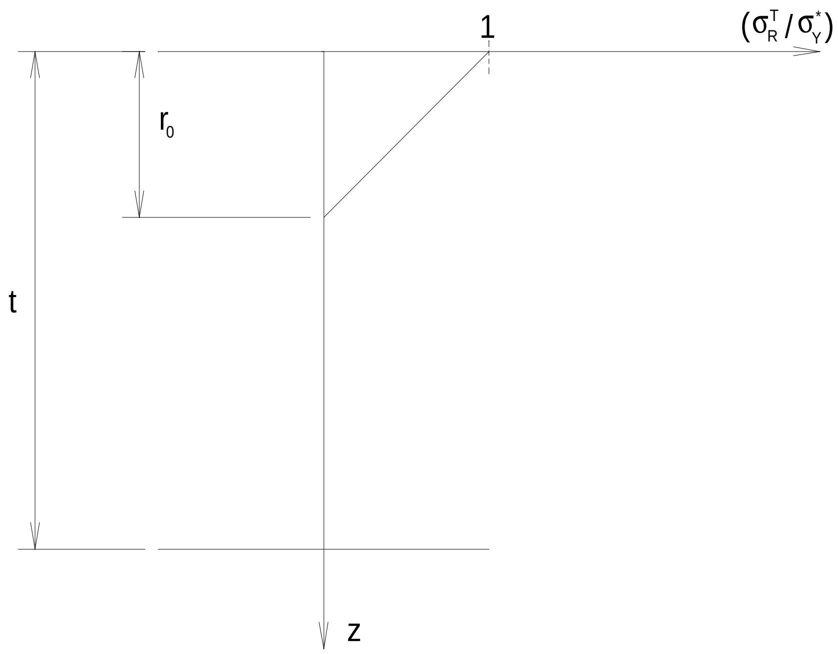

Fig. 10. SINTAP recommended through-thickness bilinear profile of transverse stresses in base plate at toe of T-butt weld.

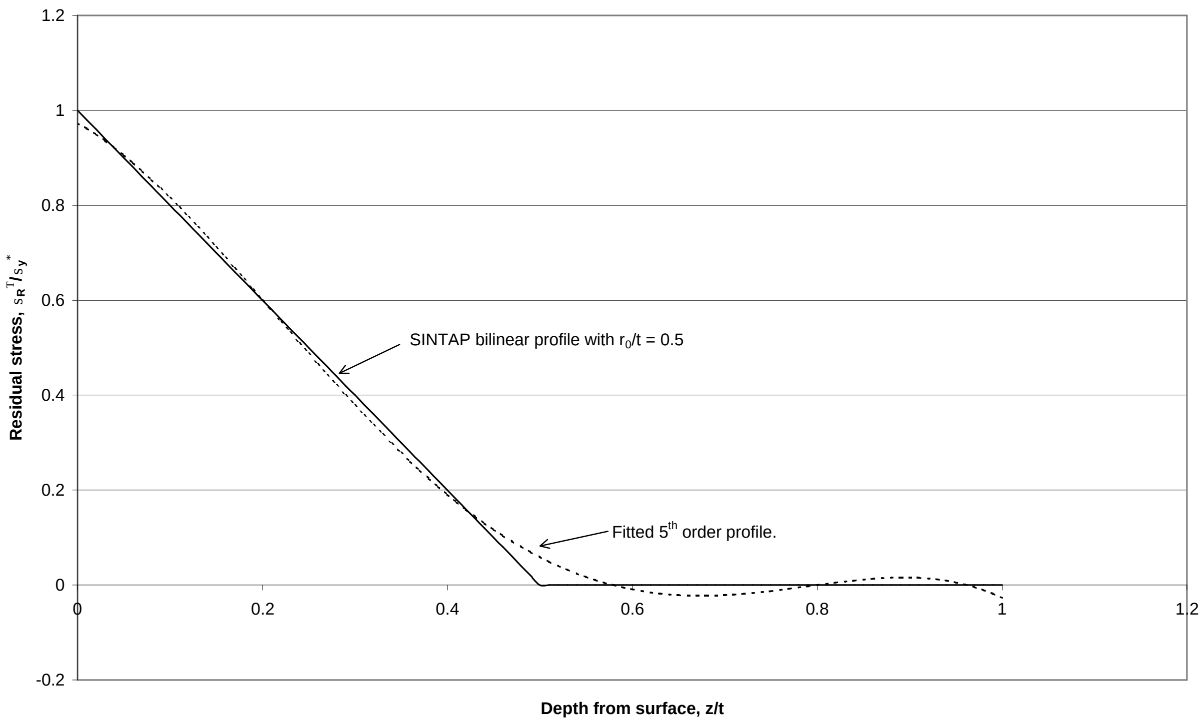

Fig. 11. Through wall distribution of tranverse residual stresses at toe of T-butt weld. Comparison of SINTAP and fitted profiles.

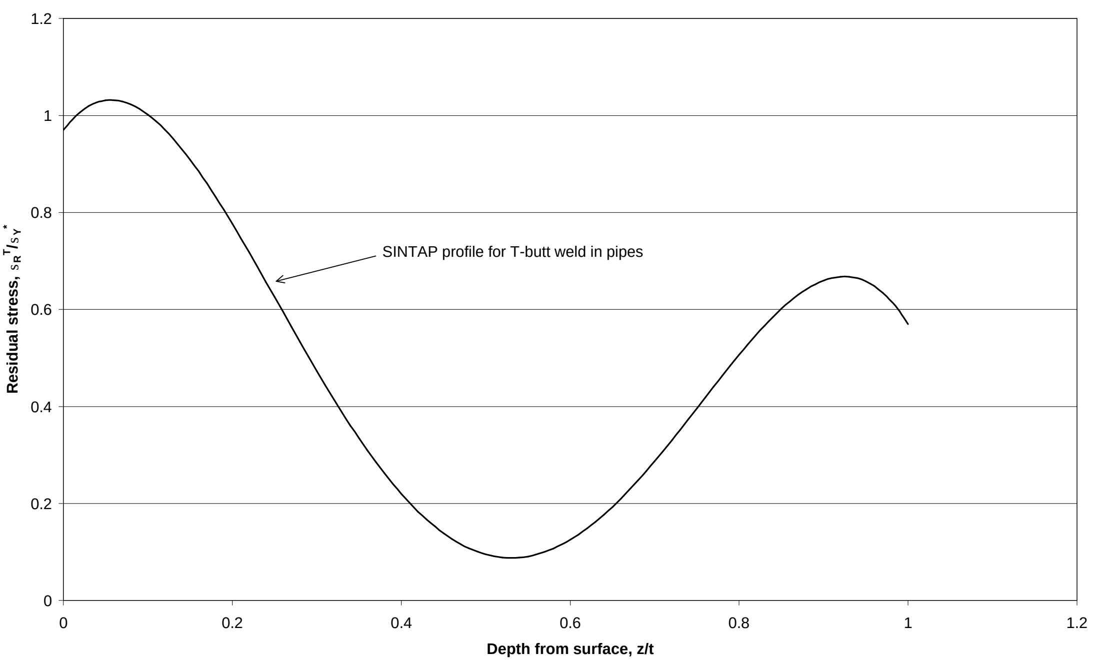

Fig. 12. Through wall distribution of transverse residual stresses at toe of T-butt weld.

Weld Geometry	T-butt weld	Case Number	2.1	2.2	2.5
Defect Orientation	Longitudinal	Residual Stress Distribution	SINTAP Fig 2d	SINTAP Fig 2d	SINTAP Fig 2d
Defect Type	Long surface	Analysis Method	TPI 2.13	SAQ AI.8	SAQ AI.3
Initiation Point	A	Aspect Ratio, 2c/a	n/a	n/a	infinity

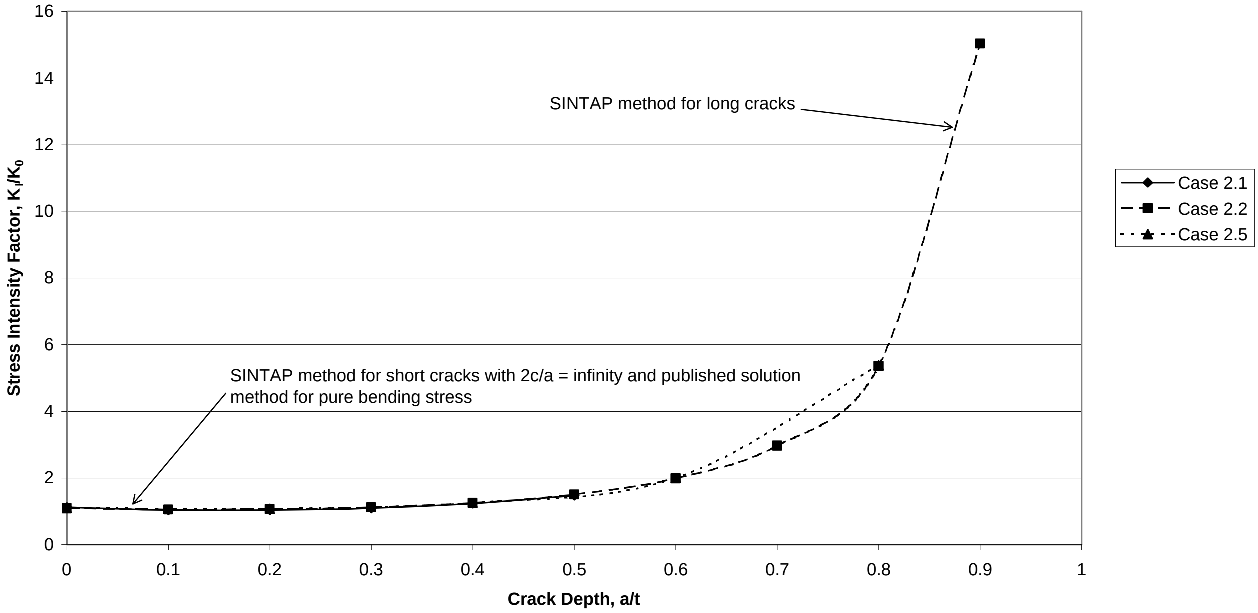

Fig. 13. Normalised SIF at long surface crack at toe of T-butt weld.
Comparison of solution methods.

Weld Geometry	T-butt weld	Case Number	2.2	2.3
Defect Orientation	Longitudinal	Residual Stress Distribution	SINTAP Fig 2d	SINTAP Fig 4d
Defect Type	Long surface	Analysis Method	SAQ AI.8	SAQ AI.8
Initiation Point	n/a	Aspect Ratio, 2c/a	n/a	n/a

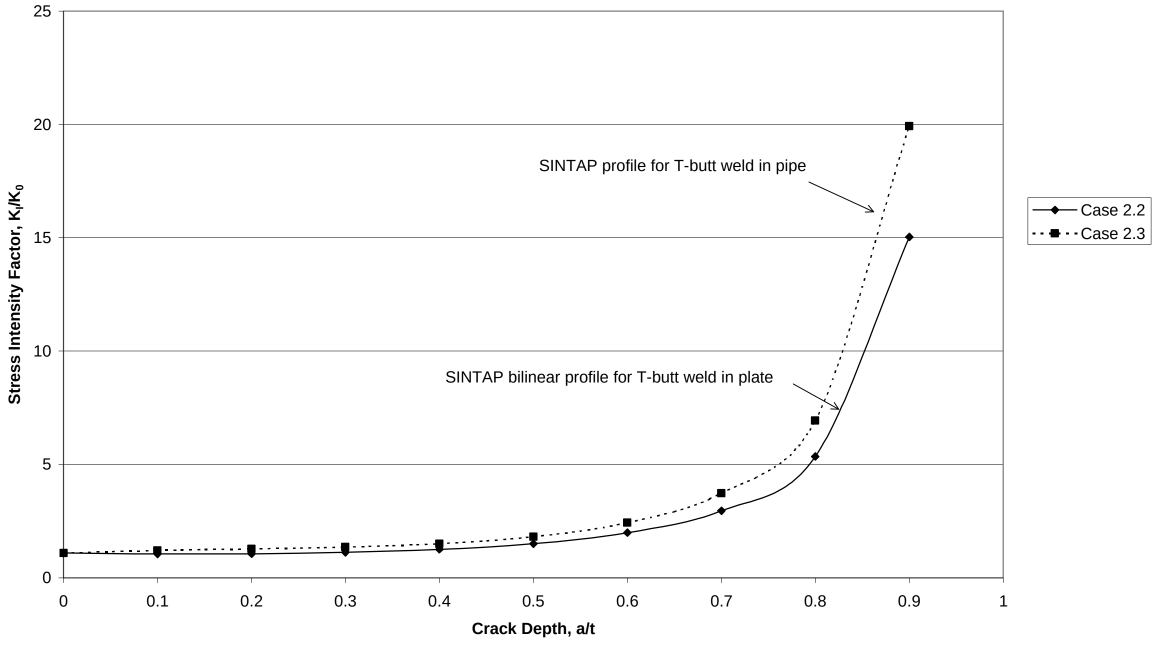

Fig. 14. Normalised SIF at long surface crack at toe of T-butt weld.
Comparison of SIFs for SINTAP profiles for T-butt welds in plate and pipe.

Weld Geometry	T-butt weld	Case Number	2.1	2.4
Defect Orientation	Longitudinal	Residual Stress Distribution	SINTAP Fig 2d	$\sigma_R^T = \sigma_Y^*$
Defect Type	Long surface	Analysis Method	TPI 2.10	TPI 2.10
Initiation Point	n/a	Aspect Ratio, 2c/a	n/a	n/a

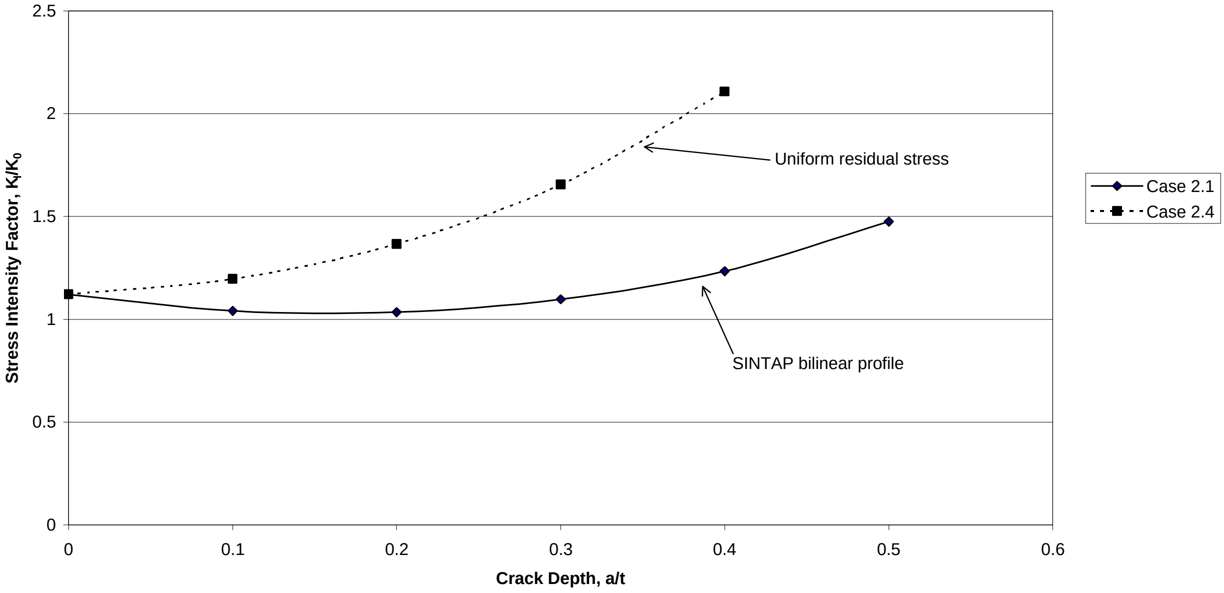

Fig. 15. Normalised SIF at long surface crack at toe of T-butt weld.
Comparison of SIFs for different residual stress profiles.

Weld Geometry	T-butt weld	Case Number	2.5	2.17	2.11
Defect Orientation	Longitudinal	Residual Stress Distribution	SINTAP Fig 2d	SINTAP Fig 2d	SINTAP Fig 2d
Defect Type	Short surface	Analysis Method	SAQ AI.3	SAQ AI.3	SAQ AI.3
Initiation Point	A	Aspect Ratio, 2c/a	Infinity	10	3.33

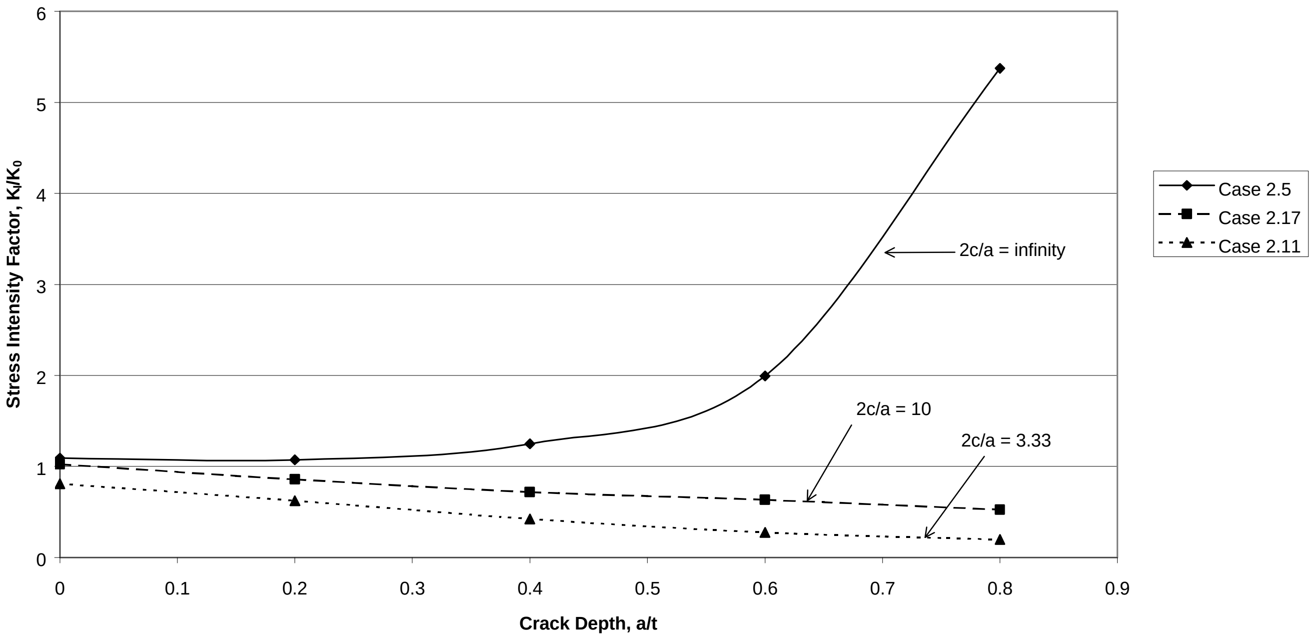

Fig. 16. Normalised SIF at deepest point of short surface crack at toe of T-butt weld.
Effect of aspect ratio.

Weld Geometry	T-butt weld	Case Number	2.18	2.12
Defect Orientation	Longitudinal	Residual Stress Distribution	SINTAP Fig 2d	SINTAP Fig 2d
Defect Type	Short surface	Analysis Method	SAQ AI.3	SAQ AI.3
Initiation Point	B	Aspect Ratio, 2c/a	10	3.33

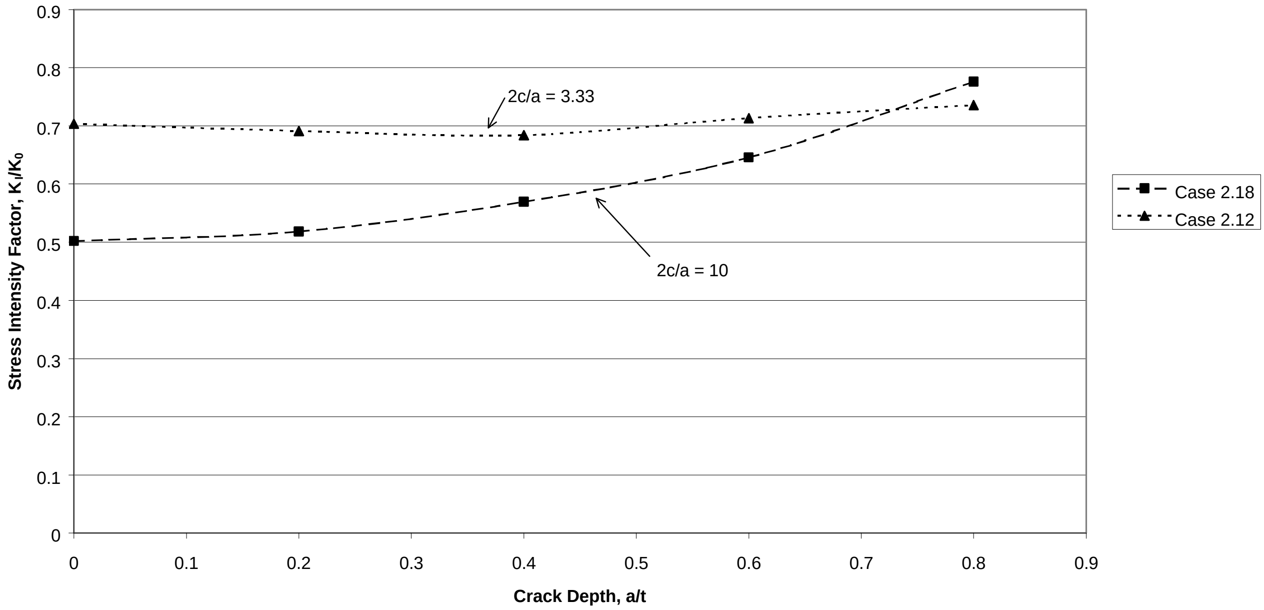

Fig. 17. Normalised SIF at surface intersections of short surface crack at toe of T-butt weld. Effect of aspect ratio.

Weld Geometry	T-butt weld	Case Number	2.17	2.7
Defect Orientation	Longitudinal	Residual Stress Distribution	SINTAP Fig 2d	SINTAP Fig 2d
Defect Type	Short surface	Analysis Method	SAQ AI.3	Newman and Raju
Initiation Point	A	Aspect Ratio, 2c/a	10	10

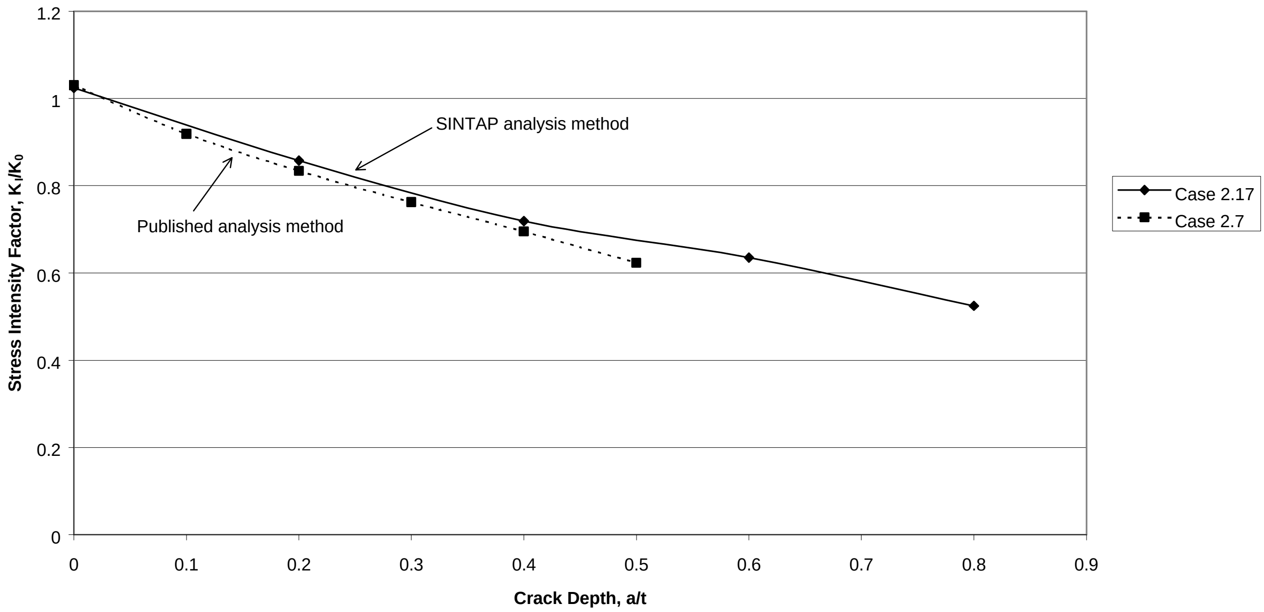

Fig. 18. Normalised SIF at deepest point of short surface crack at toe of T-butt weld. Comparison of SIFs for different analysis methods with aspect ratio = 10.

SAQ AI.3

Weld Geometry	T-butt weld	Case Number	2.18	2.8
Defect Orientation	Longitudinal	Residual Stress Distribution	SINTAP Fig 2d	SINTAP Fig 2d
Defect Type	Short surface	Analysis Method	SAQ AI.3	Newman and Raju
Initiation Point	B	Aspect Ratio, 2c/a	10	10

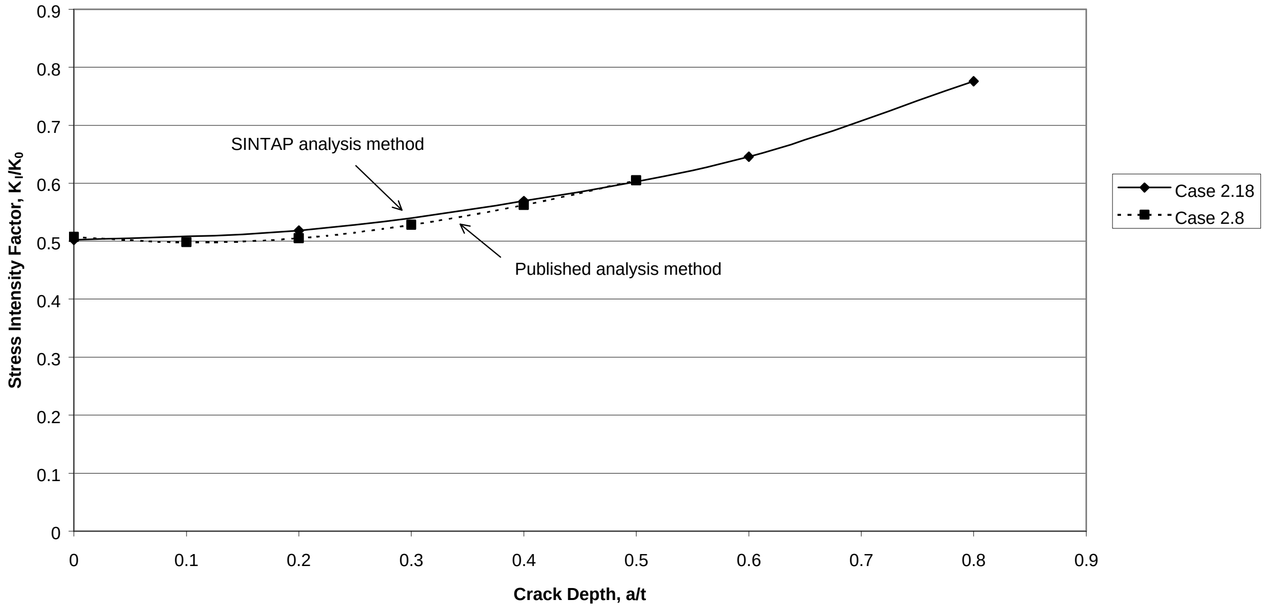

Fig. 19. Normalised SIF at surface intersections of short surface crack at toe of T-butt weld. Comparison of SIFs for different analysis methods with aspect ratio 10.

Weld Geometry	T-butt weld	Case Number	2.11	2.9
Defect Orientation	Longitudinal	Residual Stress Distribution	SINTAP Fig 2d	SINTAP Fig 2d
Defect Type	Short surface	Analysis Method	SAQ AI.3	Newman and Raju
Initiation Point	A	Aspect Ratio, 2c/a	3.33	3.33

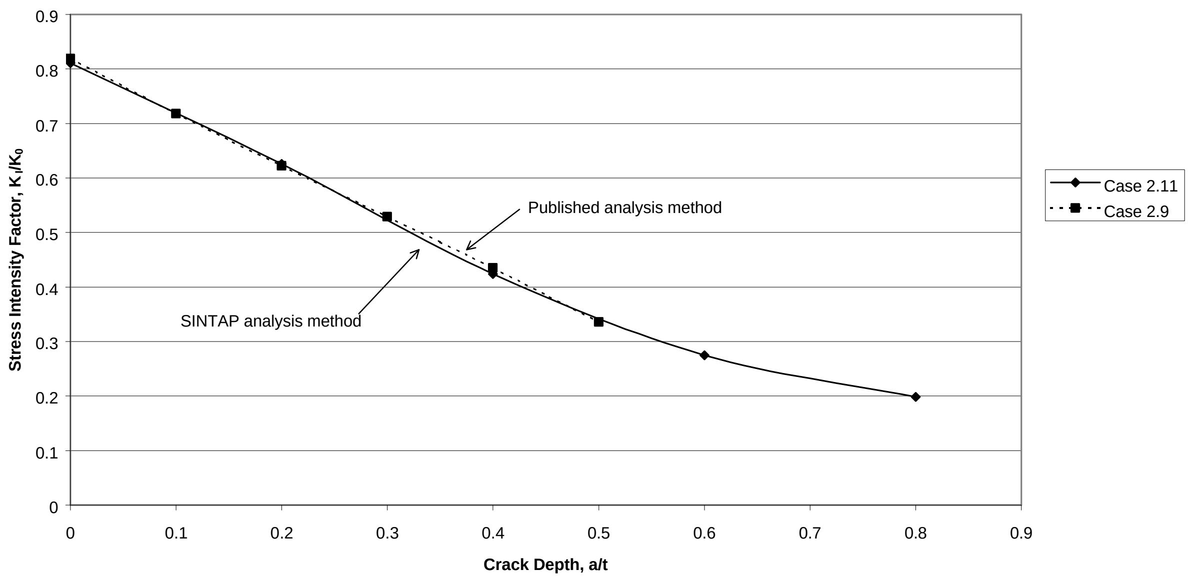

Fig. 20. Normalised SIF at deepest point of short surface crack at toe of T-butt weld. Comparison of SIFs with different analysis methods with aspect ratio 3.33

Weld Geometry	T-butt weld		Case Number	2.12	2.10
Defect Orientation	Longitudinal		Residual Stress Distribution	SINTAP Fig 2d	SINTAP Fig 2d
Defect Type	Short surface		Analysis Method	SAQ AI.3	Newman and Raju
Initiation Point	B		Aspect Ratio, 2c/a	3.33	3.33

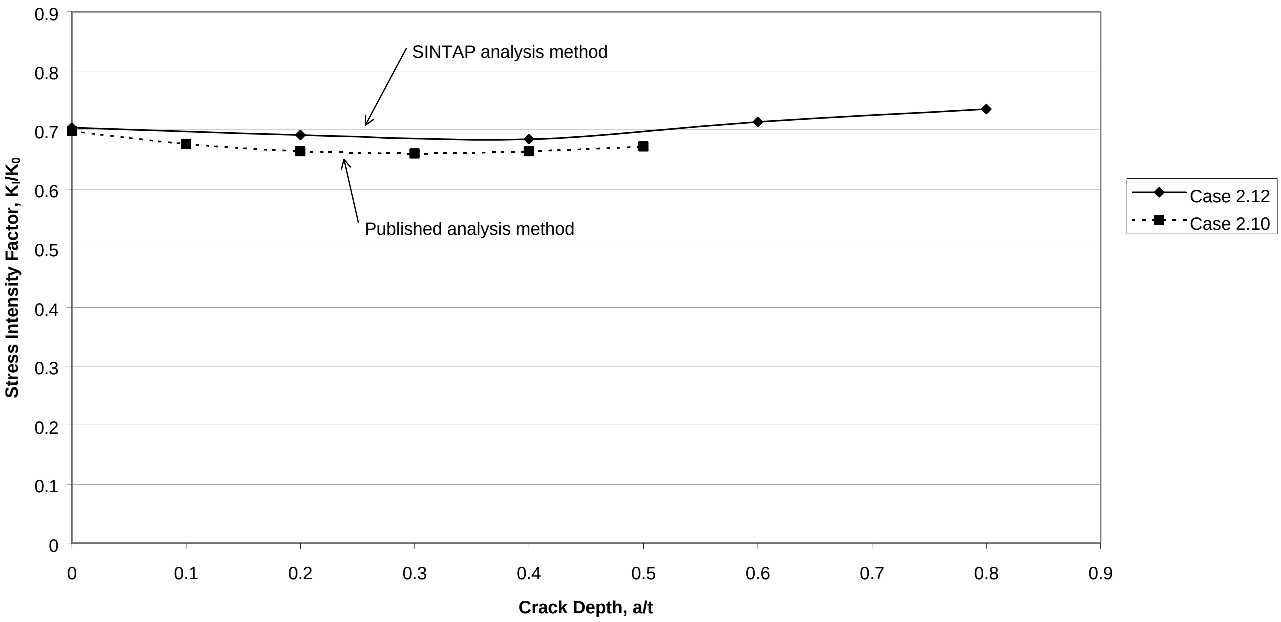

Fig. 21. Normalised SIF at surface intersections of short surface crack at toe of T-butt weld. Comparison of SIFs for different analysis methods with aspect ratio 3.33

Weld Geometry	T-butt weld		Case Number	2.11	2.13
Defect Orientation	Longitudinal		Residual Stress Distribution	SINTAP Fig 2d	SINTAP Fig 4d
Defect Type	Short surface		Analysis Method	SAQ AI.3	SAQ AI.3
Initiation Point	A		Aspect Ratio, 2c/a	3.33	3.33

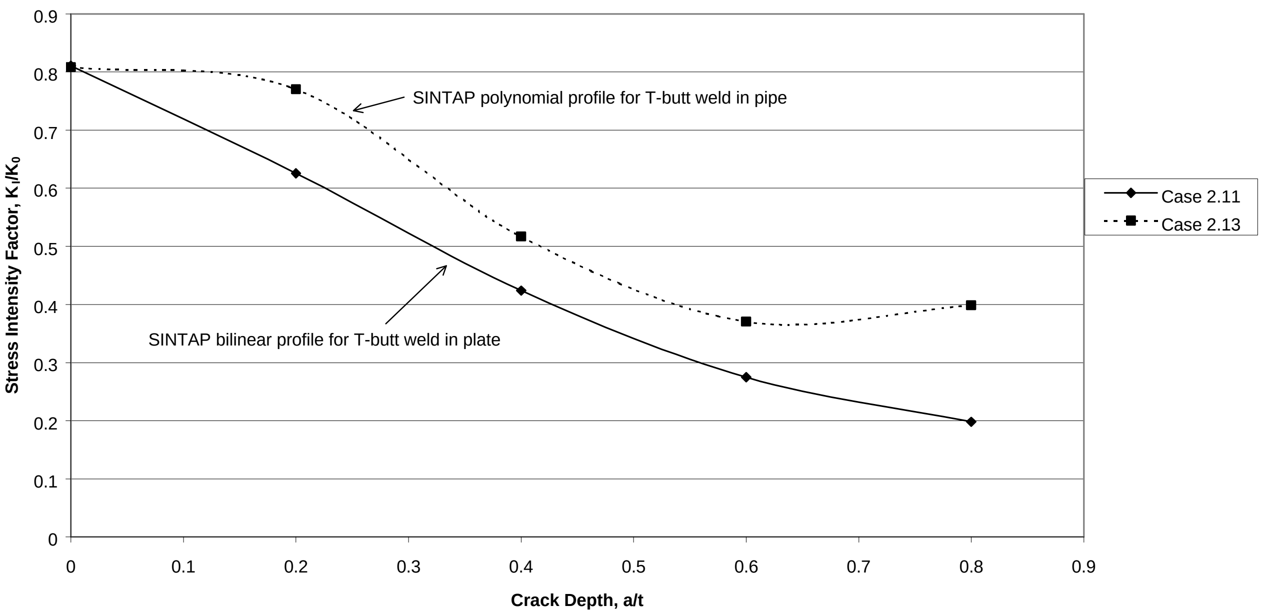

Fig. 22. Normalised SIF at deepest point of short surface crack at toe of T-butt weld. Comparison of SIFs for SINTAP profiles for T-butt welds in plate and pipe.

Weld Geometry	T-butt weld	Case Number	2.12	2.14
Defect Orientation	Longitudinal	Residual Stress Distribution	SINTAP Fig 2d	SINTAP Fig 4d
Defect Type	Short surface	Analysis Method	SAQ AI.3	SAQ AI.3
Initiation Point	B	Aspect Ratio, 2c/a	3.33	3.33

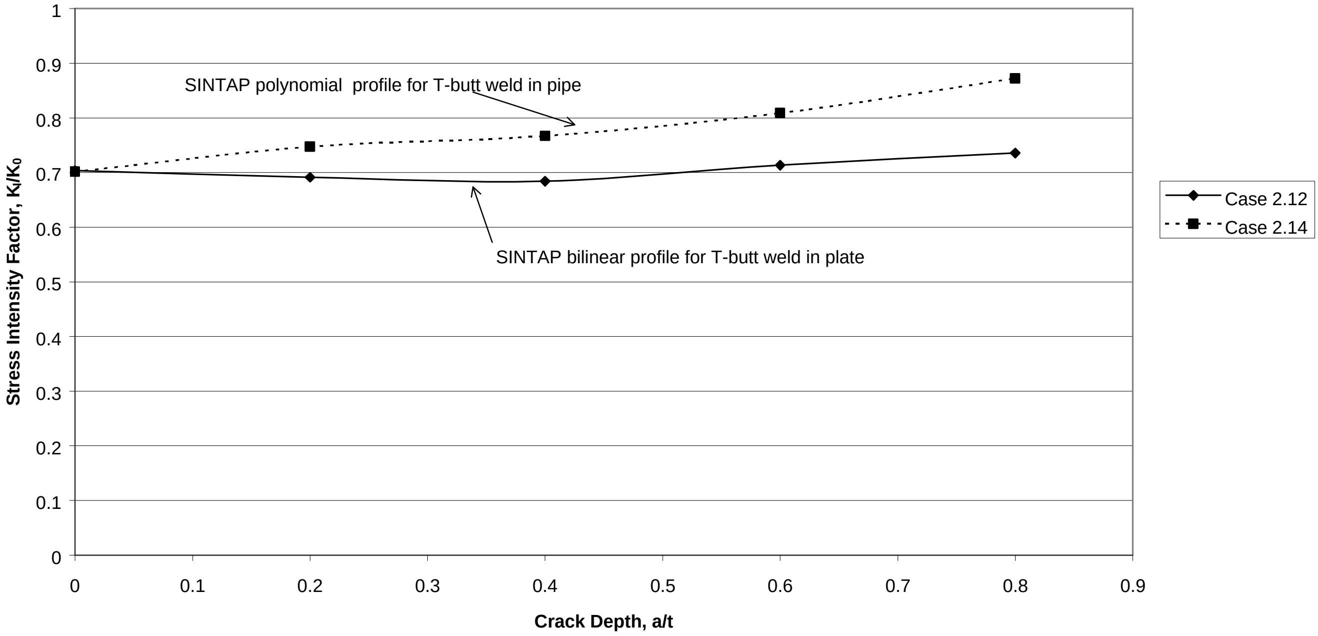

Fig. 23. Normalised SIF at surface intersections of short surface crack at toe of T-butt weld. Comparison of SIFs for SINTAP profiles for T-butt welds in plate and pipe.

Weld Geometry	T-butt weld	Case Number	2.9	2.15
Defect Orientation	Longitudinal	Residual Stress Distribution	SINTAP Fig 2d	$\sigma_R^T = \sigma_Y^*$
Defect Type	Short surface	Analysis Method	Newman and Raju	Newman and Raju
Initiation Point	A	Aspect Ratio, 2c/a	3.33	3.33

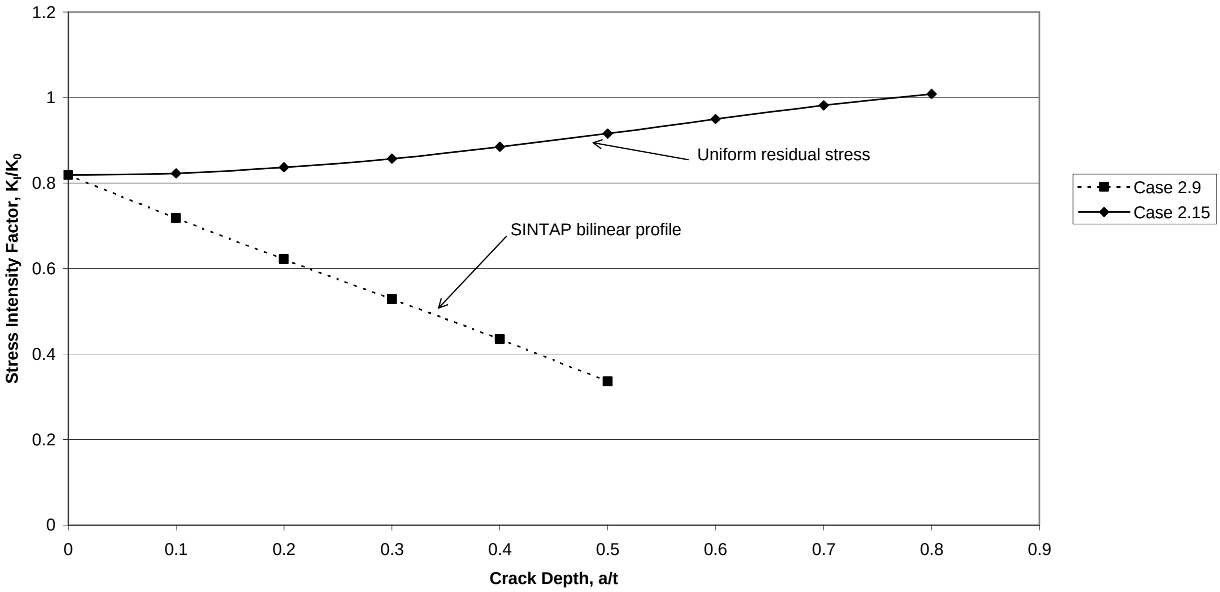

Fig. 24. Normalised SIF at deepest point of short surface crack at toe of T-butt weld. Comparison of SIFs for different residual stress profiles.

Weld Geometry	T-butt weld	Case Number	2.10	2.16
Defect Orientation	Longitudinal	Residual Stress Distribution	SINTAP Fig 2d	$\sigma_R^T = \sigma_Y^*$
Defect Type	Short surface	Analysis Method	Newman and Raju	Newman and Raju
Initiation Point	B	Aspect Ratio, 2c/a	3.33	3.33

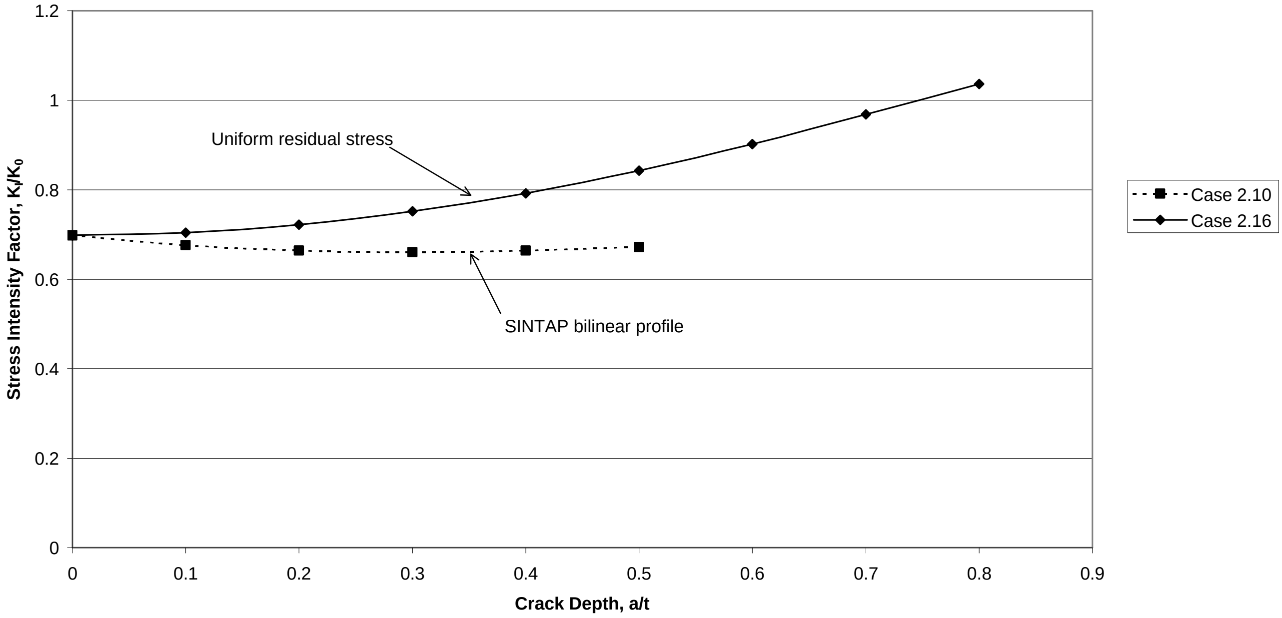

Fig. 25. Normalised SIF at surface intersections of short surface crack at toe of T-butt weld Comparison of SIFs for different residual stress profiles.

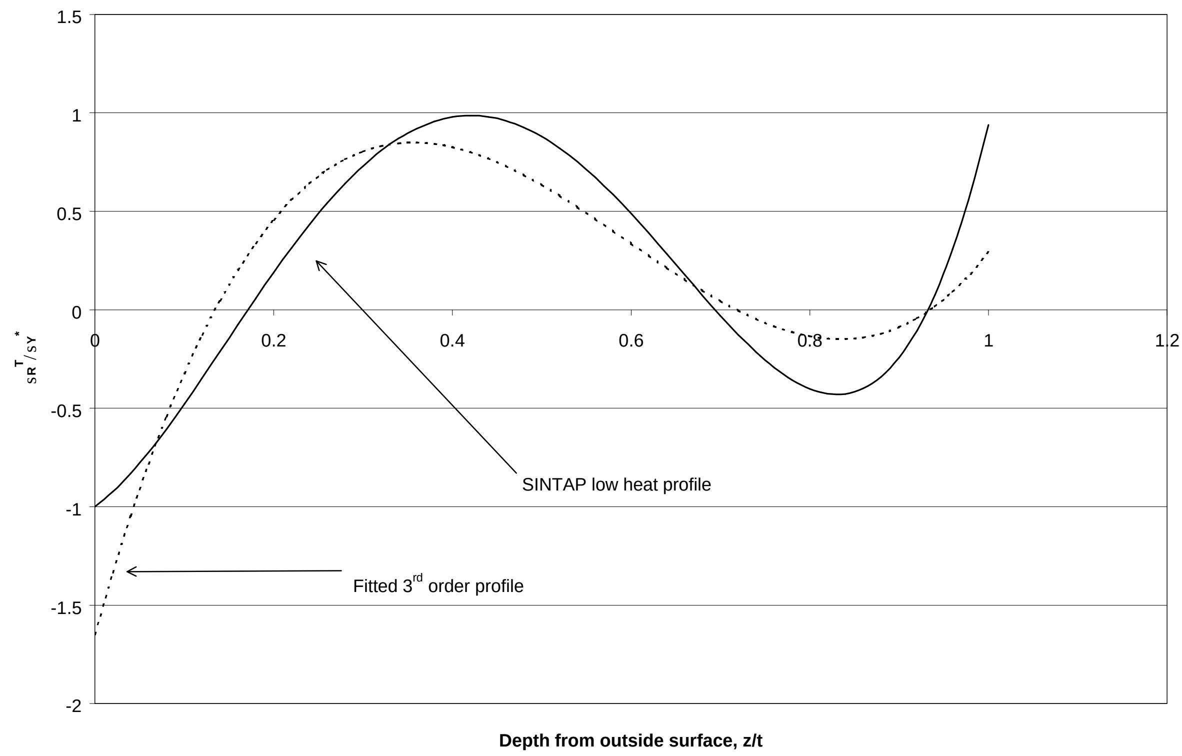

Fig. 26. Through thickness profile of transverse residual stress at low heat input pipe butt weld. Comparison of SINTAP profile and fitted 3rd order profile.

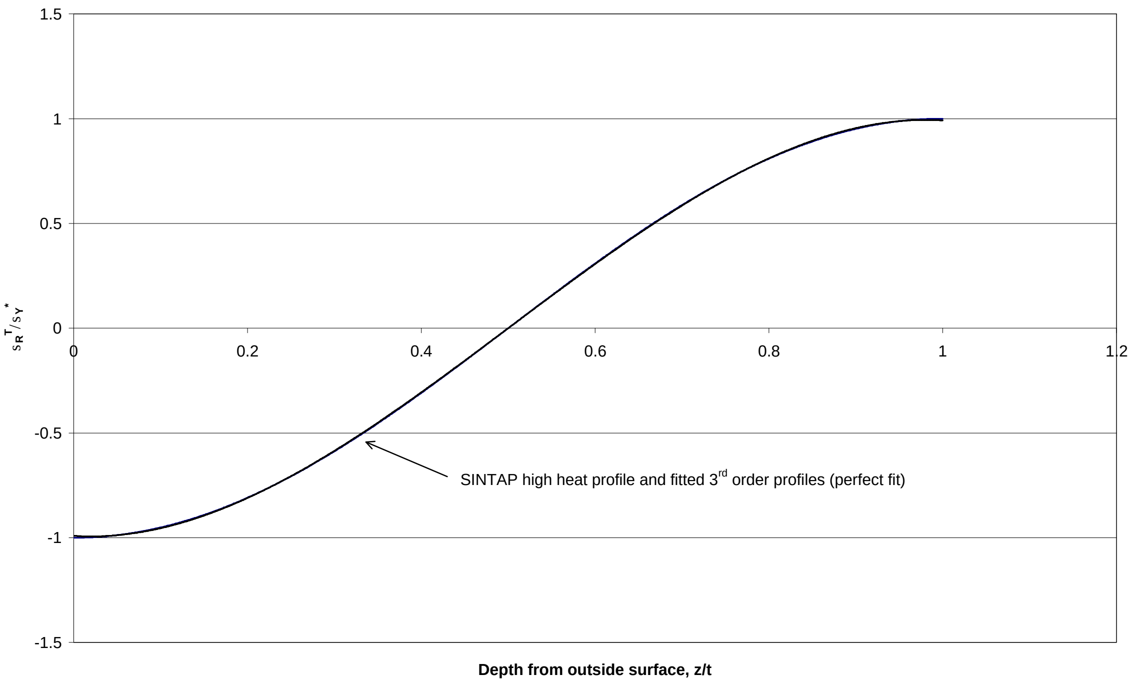

Fig. 27. Through-thickness profile of transverse residual stresses at high heat input pipe butt weld. Comparison of SINTAP profile and fitted 3rd order profile.

Weld Geometry	Circ. butt weld in pipe	Case Number	3.1	3.2	3.3
Defect Orientation	Circumferential	Residual Stress Distribution	SINTAP Fig 3d Low heat	SINTAP Fig 3d High heat	$\sigma_R^T = \sigma_Y^*$
Defect Type	Long, outside surface	Analysis Method	SAQ A1.38	SAQ A1.38	SAQ A1.38
Initiation Point	n/a	Aspect Ratio, 2c/a	n/a	n/a	n/a

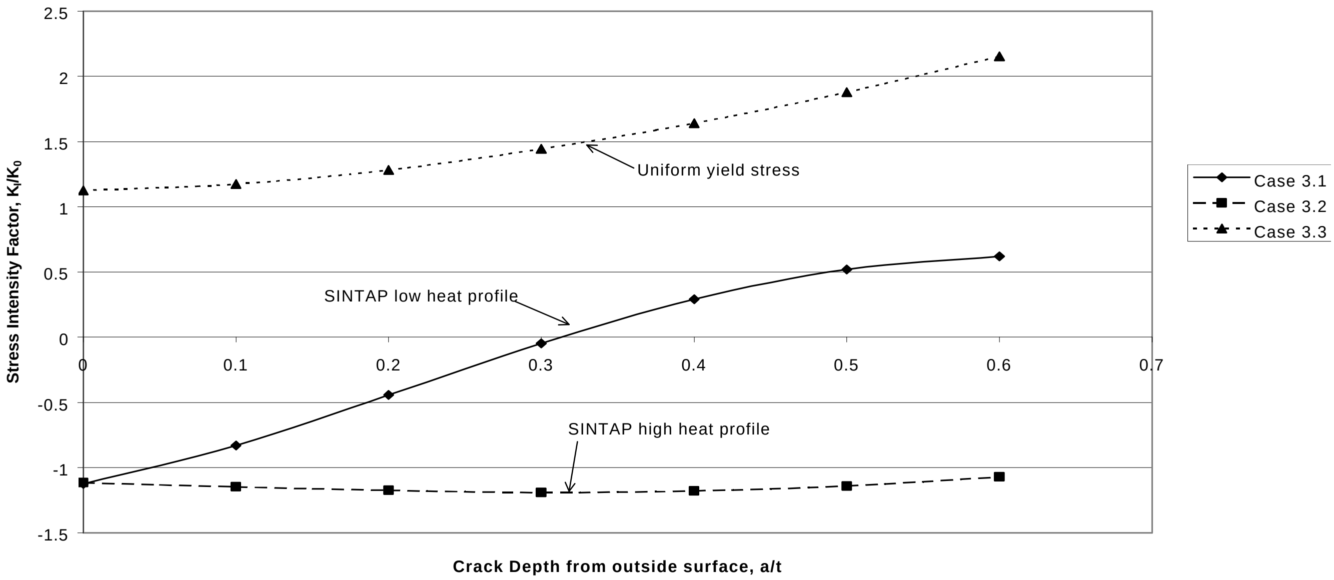

Fig. 28. Normalised SIF at fully circumferential crack at outside surface of pipe. Comparison of SIFs for different residual stress profiles.

Weld Geometry	Circ. butt weld in pipe	Case Number	3.4	3.5	3.6
Defect Orientation	Circumferential	Residual Stress Distribution	SINTAP Fig 3d Low heat	SINTAP Fig 3d High heat	$\sigma_R^T = \sigma_Y^*$
Defect Type	Long, inside surface	Analysis Method	SAQ A1.30	SAQ A1.30	SAQ A1.30
Initiation Point	n/a	Aspect Ratio, 2c/a	n/a	n/a	n/a

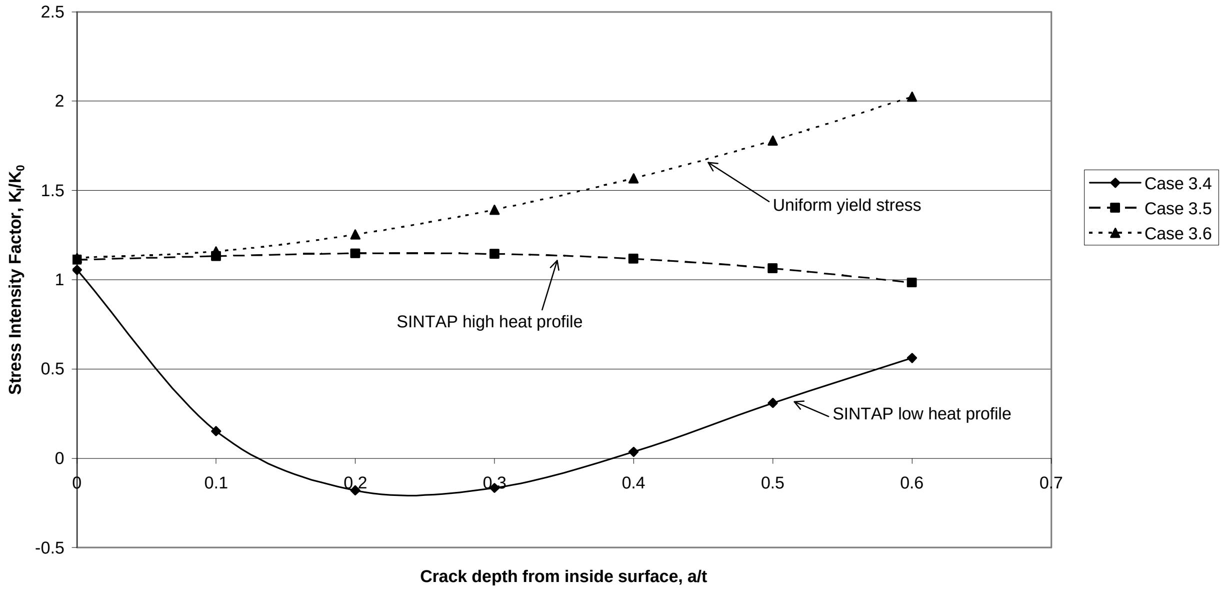

Fig. 29. Normalised SIF at fully circumferential crack at inside surface of pipe. Comparison of SIFs for different residual stress profiles.

Weld Geometry	Circ. butt weld in pipe	Case Number	3.7	3.8	3.9
Defect Orientation	Circumferential	Residual Stress Distribution	SINTAP Fig 3d Low heat	SINTAP Fig 3d High heat	$\sigma_R^T = \sigma_Y^*$
Defect Type	Short, outside surface	Analysis Method	SAQ A1.32	SAQ A1.32	SAQ A1.32
Initiation Point	Deepest point	Aspect Ratio, 2c/a	4	4	4

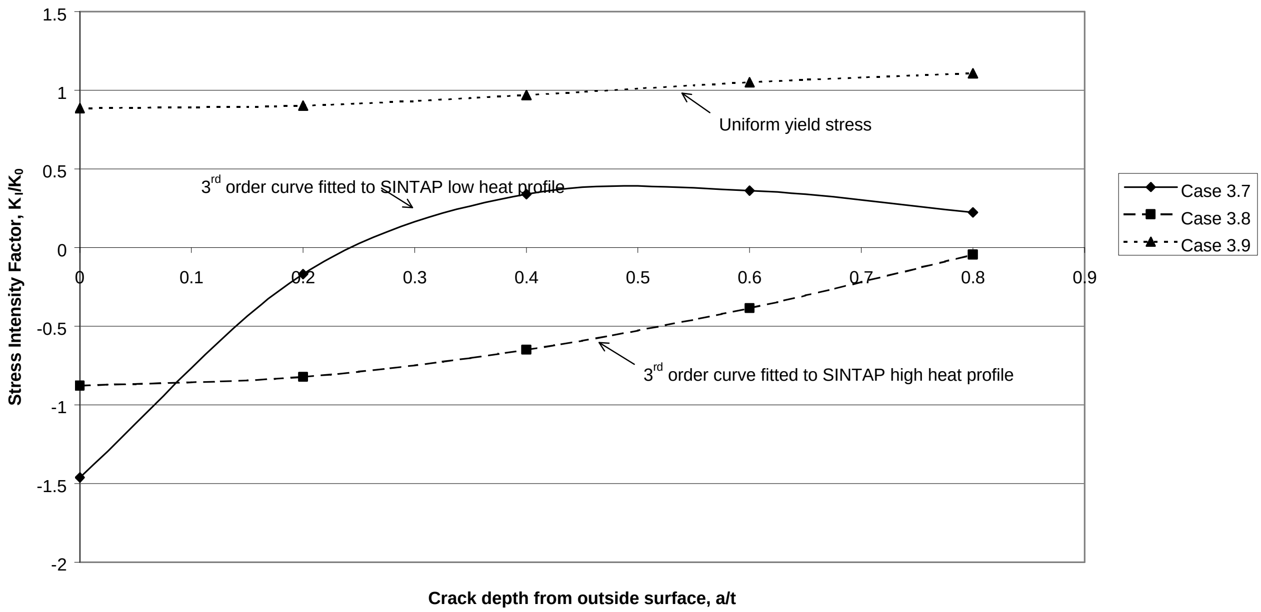

Fig. 30. Normalised SIF at part circumferential crack at outside surface of pipe. Comparison of SIFs for different residual stress profiles.

Weld Geometry	Circ. butt weld in pipe	Case Number	3.10	3.11	3.12
Defect Orientation	Circumferential	Residual Stress Distribution	SINTAP Fig 3d Low heat	SINTAP Fig 3d High heat	$\sigma_R^T = \sigma_Y^*$
Defect Type	Short, outside surface	Analysis Method	SAQ A1.25	SAQ A1.25	SAQ A1.25
Initiation Point	Deepest point	Aspect Ratio, 2c/a	4	4	4

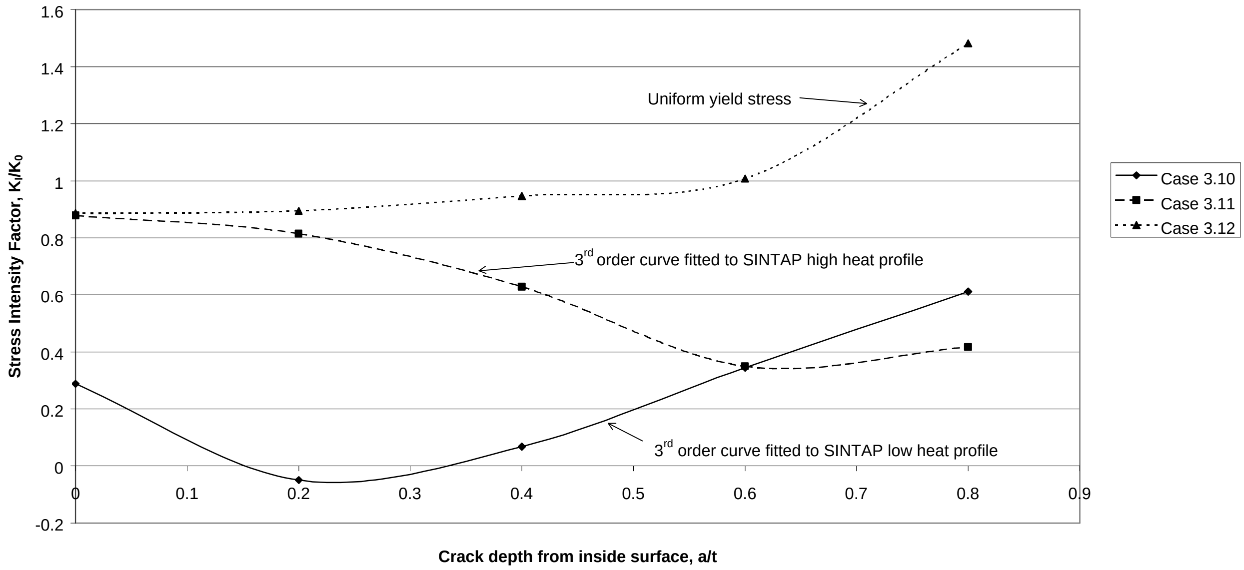

Fig. 31. Normalised SIF at part circumferential crack at inside surface of pipe. Comparison of SIFs for different residual stress profiles.

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