FRACTURE MECHANICS TREATMENT OF RESIDUAL STRESSES IN DEFECT ASSESSMENT

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ABSTRACT

Over the last decade, as more in-depth understanding of weld residual stresses is being achieved, particularly of their characteristic distributions in pressure vessel and piping components, the residual stress effects on stress intensities at welds are becoming better understood. In this paper, some of the important residual stress characteristics are first identified in the form of either "bending" dominated or "self-equilibrating" dominated types for girth welds. The applicability in other joint configurations in welded structures is then discussed, with a collection of validated residual stress distributions. The characterization of both "bending" and "self-equilibrating" types in residual stress distributions provides a consistent framework for stress intensity factor considerations in either fracture and fatigue assessment. The contribution of weld residual stresses to stress intensities at welds are shown to be in the form of *K* solutions under displacement controlled conditions. The "bending" type residual stresses provide a longer range of influence than "self-equilibrating" type in *K* solutions. The contribution of "self-equilibrating" type residual stresses to stress intensities is shown to be dominant when crack size is small, while the contribution of the "bending" type dominant for crack size up to a much larger size with respect to wall thickness.

IIW-Thesaurus keywords: *Fracture mechanics; Residual stresses; Stress distribution; Pressure vessels; Pipework; Welded joints; Circumferential welds; Multirun welding; T joints; Finite element analysis; Computation; K1C; Thickness; Reference lists.*

1 INTRODUCTION

Fracture mechanics assessment of welds in pressure vessel and piping components often requires knowledge of weld residual stress distributions [1]. In most of codes and recommended practices, simplified and conservative distributions were often assumed, as discussed in some recent publications [1-3]. For instance, welding-induced residual stresses are often assumed to be tensile, of yield magnitude (or a specified percentage, if post-weld heat treatment applies), and uniform through the thickness. However, over the recent years, there has been a major progress in a better understanding of weld residual stresses, in part, due to the availability of advanced weld residual stress modelling tools [e.g., 4-8]. It has been demonstrated that the current structural integrity assessment procedures can significantly over-estimate the residual stress effects in most cases and under-estimate their effects in others [1-2, 9-12].

It is generally accepted that residual stresses can exhibit various complex features, depending on joint types, materials, and welding procedures. However, a systematic analysis of various residual stress distributions that are well documented in the open literature showed that some important residual stress characteristics can be generalized for fracture mechanics applications. In this paper, two general residual stress categories are discussed, based on a large amount of residual stress results available to date. Their different contributions to the stress intensities at welds are then discussed. A simple and robust finite element procedure based on recent advances in structural stress computation procedures [13] is presented for consistent fracture and fatigue estimation of welded components.

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2 WELD RESIDUAL STRESSES: COMMONALITIES AND DIFFERENCES

Based on a large amount of residual stress information available to date, weld residual stress distributions can exhibit rather complex behaviour at a local level and can be dependent upon, to varying degree, joint geometry, weld and base metal properties, and welding procedures, as summarized by Dong [1, 3, 14] and Bradford [2]. However, some invariant features can be identified for generalizing the residual stress distributions for structural integrity assessment purposes. As shown by Dong [1], two characteristics residual stress types for girth welds are shown in Fig. 1, in the form of "bending" and

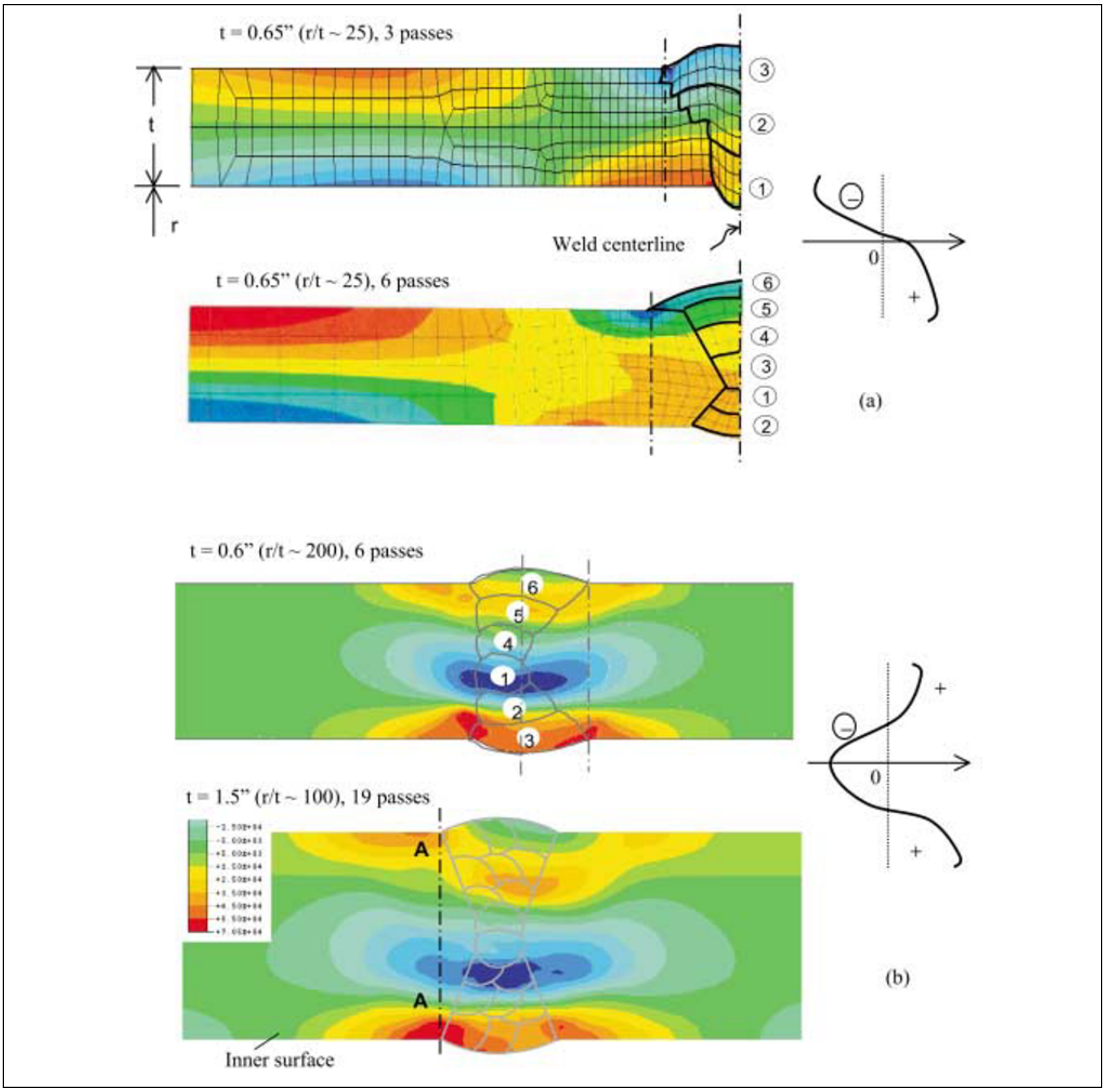

Fig. 1. Two types of through-thickness axial residual stress distributions in multi-pass weld in girth welds.
(a) "bending" type
(b) "self-equilibrating" type

"self-equilibrating" types. Note that the hoop residual stress component parallel to a weld is much easier to characterize than the axial component perpendicular to the weld, as discussed in [1, 14]. As shown in Fig. 1 (a), girth welds with the two drastically different pipe r/t ratio and pass profile still possess essentially the same residual stress distributions, i.e., "bending" type with compressive axial stresses near outer surface and tensile stresses at the inner surface. With the bending type of residual stress distributions, one additional important feature is that a clearly defined counter bending action can be seen a few thicknesses away from the weld, as shown in Fig. 1 (a). The presence of the long-range bending feature away from the weld can be used for experimental residual stress measurement considerations either as additional confirmation to or as an indirect estimation of the residual stresses at welds. In Fig. 1 (b), the self-equilibrating type can be identified for the girth welds with significantly different geometry and weld pass profiles. It can be seen that the axial residual stresses in the self-equilibrating type achieve the equilibrium within the weld area. As a result, the residual stress distributions are essentially confined with the weld itself. Away from the weld, free-stress state is dominant.

Besides an appropriate heat input parameter definition [2], joint restraint conditions (note: heat input can be captured as a part of joint restraint conditions) can be demonstrated to serve a key parameter for the relative bending and self-equilibrating content in the final residual stress distributions, as demonstrated using a T-fillet

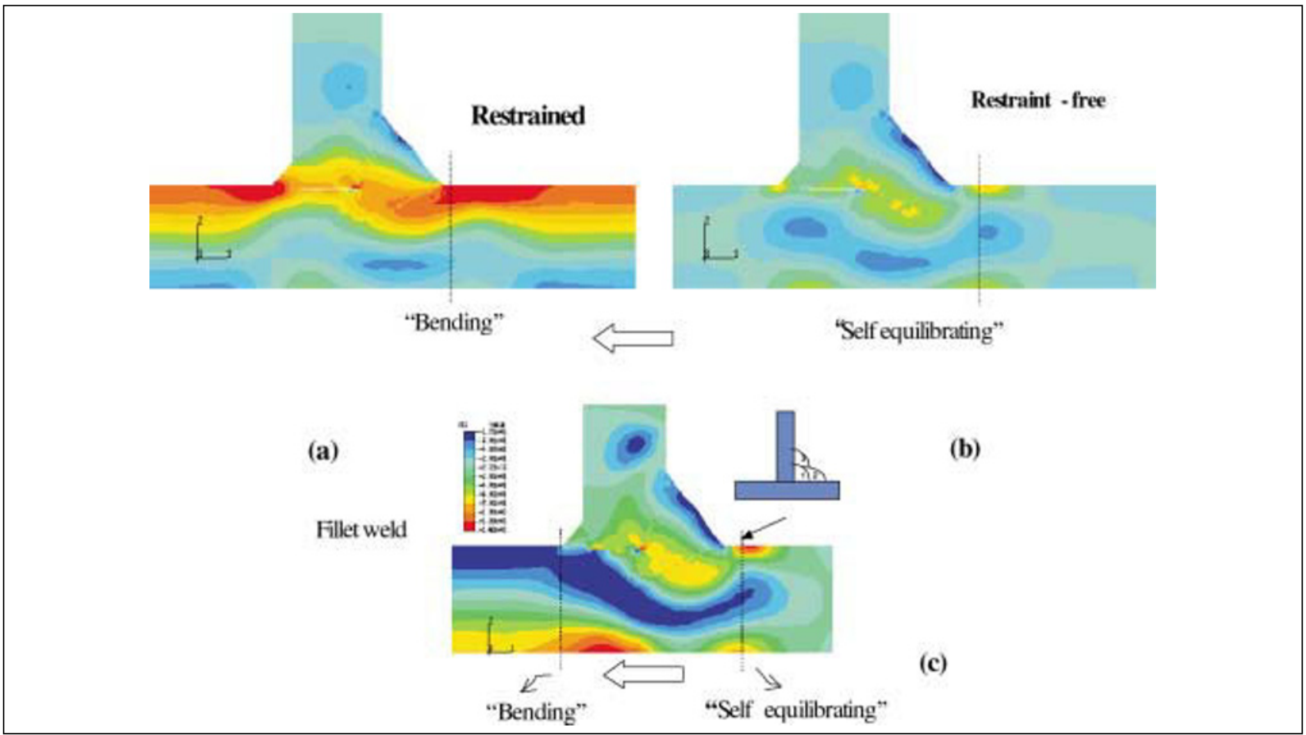

Fig. 2. Joint restraint effects on transition from self-equilibrating to bending types.

joint simulating a corner joint in storage tanks (Fig. 2). The resulting function form can be constructed parametrically from Fig. 3 as follows:

$$f(\zeta) \sim \underbrace{\sin\left[\pi/2\,(\zeta/\zeta_0 - \alpha)\right]}_{\substack{\text{Welding procedures} \\ \text{e.g., heat input parameter}}} + \underbrace{(\Delta\sigma + \Delta\theta \cdot \zeta)}_{\substack{\text{Restraint factors:} \\ K_t \text{ and } K_\theta}} \quad (1)$$

It is worth noting that typical residual stress distributions in other joint types can also be characterised in terms of bending or self-equilibrating types, somewhere in between by Eq. 1, as shown in Figs 4-5. Such characterisations can be readily extended to repair welds, in addition to recognising the invariant features of the 3D residual stress distributions in repair welds, as shown in Fig. 6.

It is evident that knowing the residual stress type for a particular application and its parametric descriptions can provide enormous benefits for performing structural integrity assessments. However, although some of the controlling parameters governing each of the two types of residual stress distributions can be qualitatively identified based on some of the existing residual stress results to date, the demarcation line separating the two types of residual stresses in terms of component geometry and welding procedures remain to be established for general applications. Consequently, there exists an urgent need in the pressure vessel and piping commu-

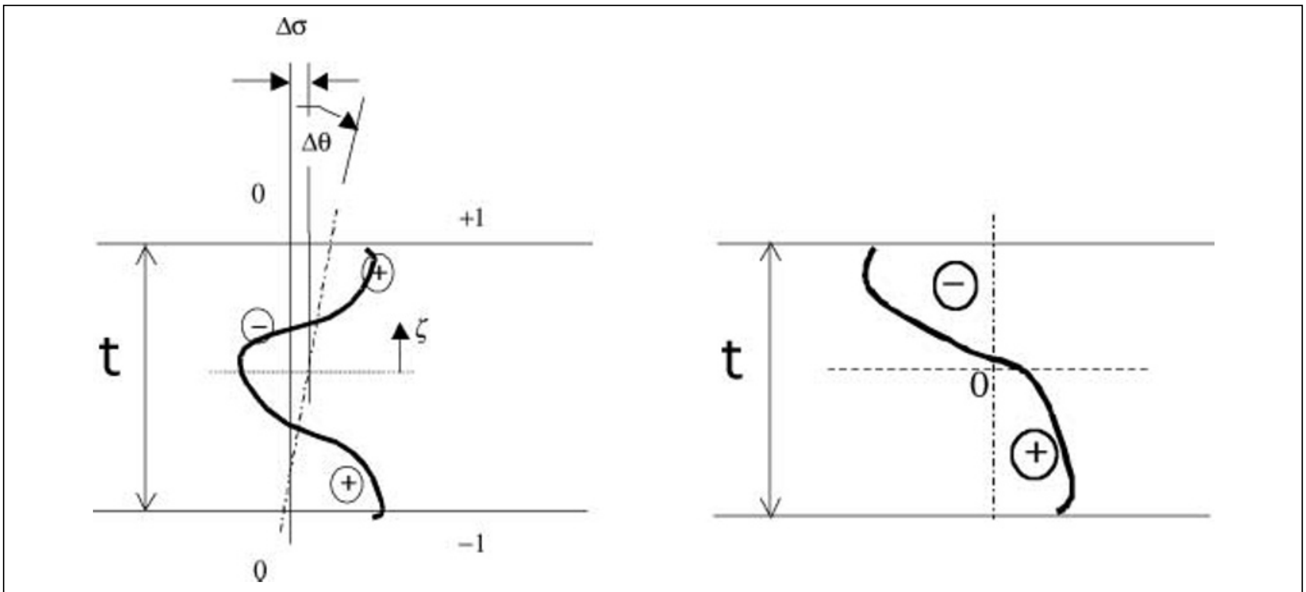

Fig. 3. Parametric descriptions of generalized residual stress distributions between self-equilibrating to bending types.

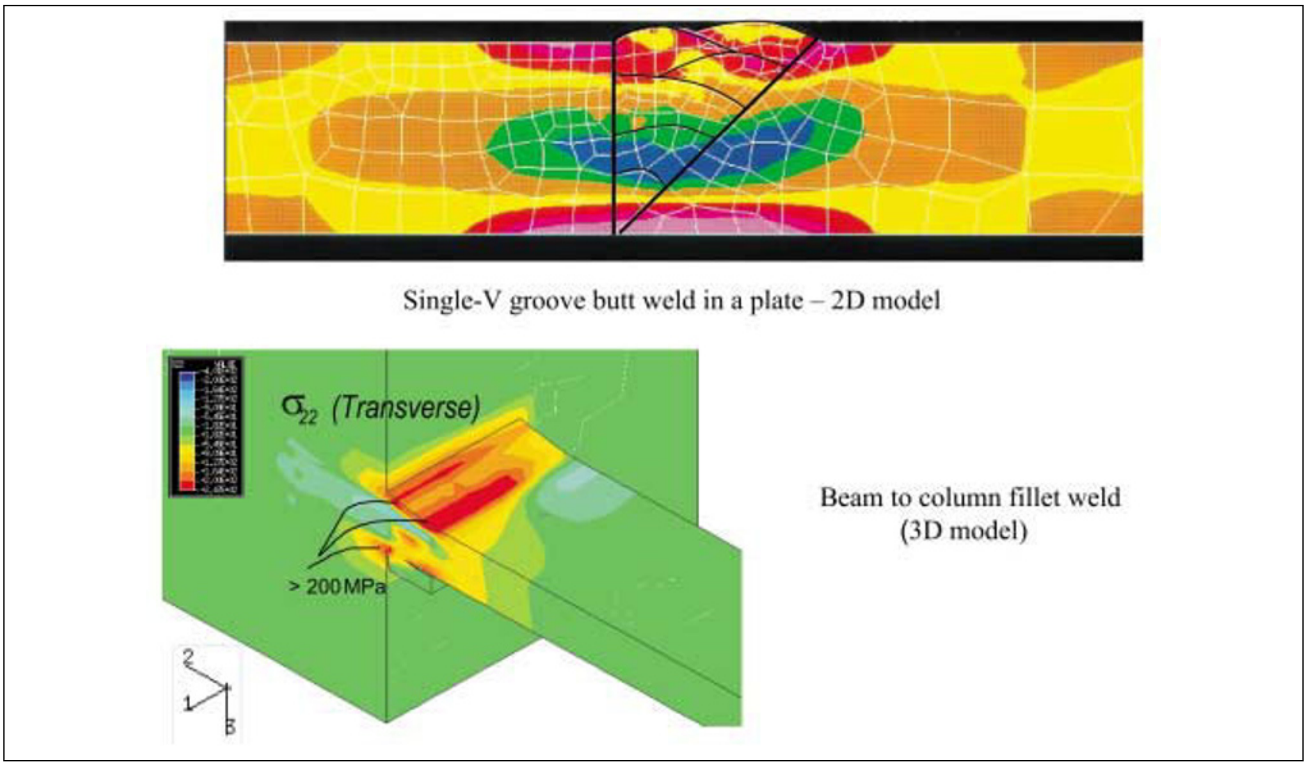

Fig. 4. Self-equilibrating type residual stress distributions in plate structures.

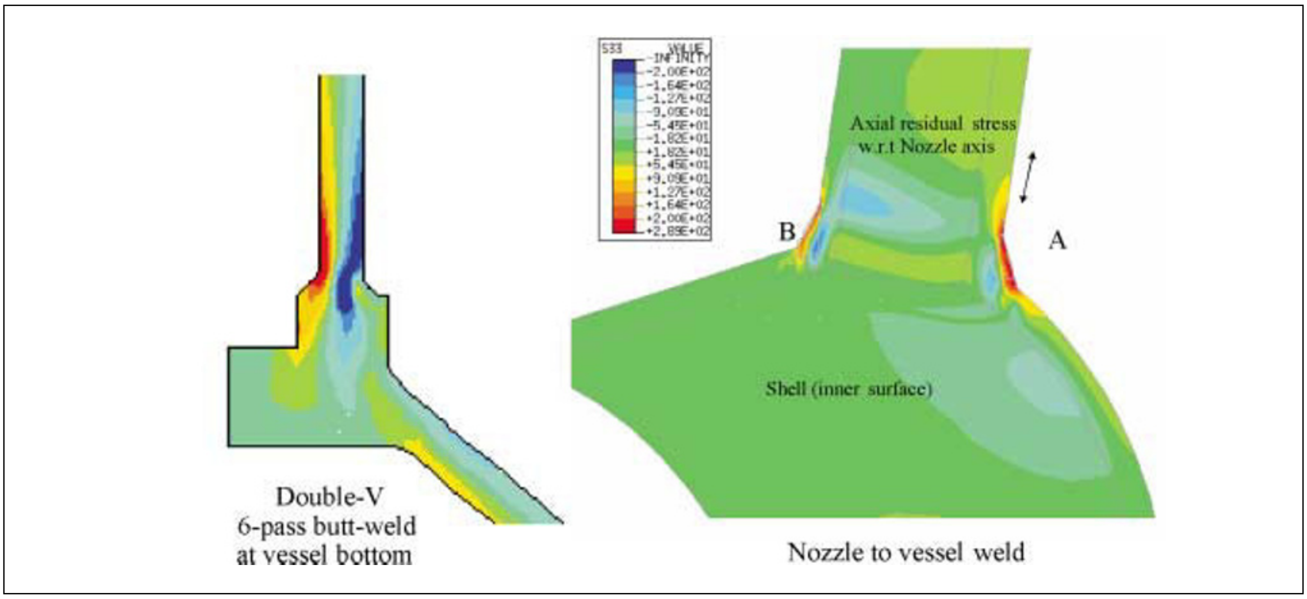

Fig. 5. Bending type of residual stress distributions in vessel and nozzle joints.

nity to develop the required knowledge base for quantitative definition of the residual stress types as well as the corresponding parameterised distributions, as shown in Eq. 1.

Along this line, some of the noted collaborative research efforts are currently under way, for instance, by Pressure Vessel Research Council (PVRC) to conduct comprehensive investigation on residual stress distributions for a wide range of pressure vessel and piping components [15]. Once the results are available, Eq. 1 can be used for providing a simple form of the generalised residual stress distributions for various fracture mechanics applications.

3 CONSISTENT STRESS INTENSITY FACTOR SOLUTIONS

Once a through-thickness residual stress distribution is available and expressed in the form of polynomial function $\sigma^r(x)$ as in Eq. 1, weight function techniques can be conveniently used for performing integration to obtain the stress intensity factor for a given crack size a:

$$K(a) = \int_0^a \sigma^r(x) w(a, x)\, dx \qquad (2)$$

For a given through-thickness residual stress distribution described by $\sigma^r(x)$ either generated from a detailed finite element residual stress model or from a parametric

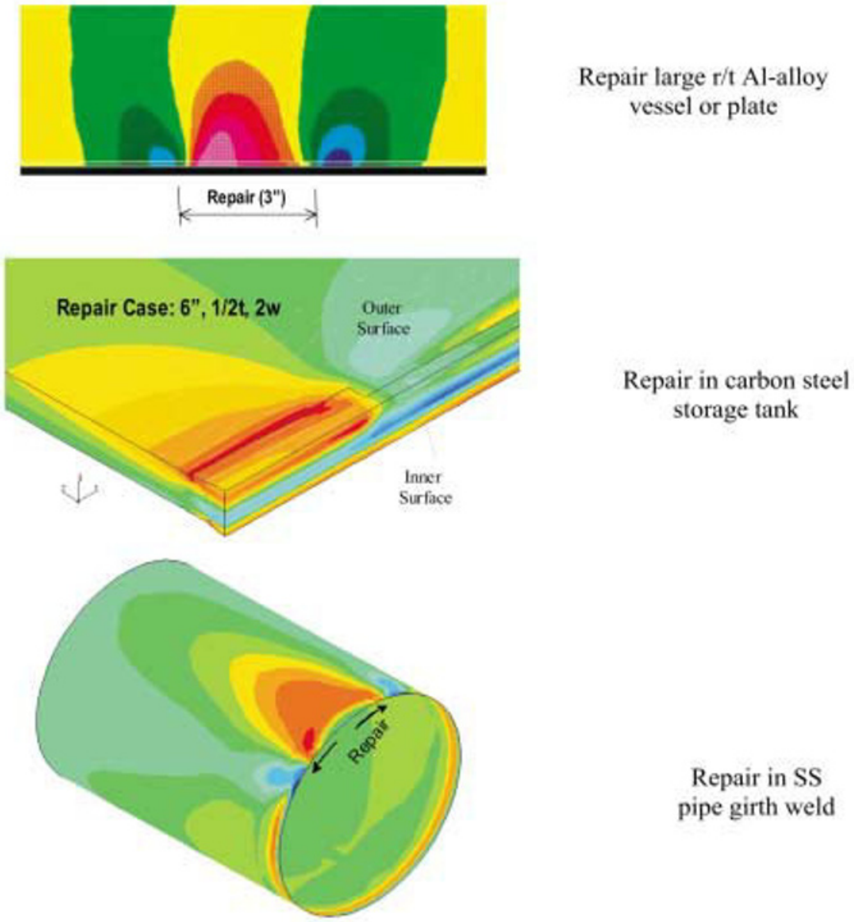

Fig. 6. Invariant 3D transverse residual stress features in repair welds.

model such as the one shown in Eq. 1, it can be decomposed into three parts: (a) membrane, (b) bending, and (c) self-equilibrating components for easy treatment in calculating K solutions. This is illustrated in Fig. 7 by the following calculations:

$$\sigma^r_m = \frac{1}{t} \cdot \int_0^t \sigma^r(x)\, dx$$

$$\sigma^r_b = \frac{6}{t} \int_0^t \sigma^r(x) \left(\frac{t}{2} - x\right) dx \qquad (3)$$

$$\sigma^r_{s.e.} = \sigma^r(x) - \sigma^r_m - \sigma^r_b \left(1 - \frac{2x}{t}\right)$$

Similar decomposition techniques in a mesh-insensitive manner were discussed in [13] for loading-induced stress distribution at a weld for both characterising stress concentration effects and K solutions [16]. With the residual stress components being obtained through Eq. 3, the K solution in Eq. 2 can be written with respect to the well-established weight function $w_p(a,x)$ for a simple straight plate as follows:

$$K(a) = \int_0^a (\sigma^r_m + \sigma^r_b (1 - 2x/t) = \sigma^r_{s.e.}(x)) \cdot w_p(a, x)\, dx \qquad (4)$$

or

$$K(a) = K_m\,(a/t) + K_b\,(a/t) = K_{s.e.}\,(a/t) \qquad (5)$$

The significance of Eq. 3 lies in the fact that the three components of a general residual stress distribution in Eq. 3 fully contains the geometry effects of the weld residual stresses for a given weld geometry and that the K solution can be performed using the same weight function $w_p(a,x)$ for a simple straight plate specimen. Similarly, K_m, K_b, and $K_{s.e}$ in Eq. 5 for a simple plate specimen can be found in handbooks. Displacement controlled conditions with respect to a region in which the residual stresses achieve full equilibriums should be considered in the K solution. The self-equilibrating part $K_{s.e}$ may only be available for one or two simplified stress distributions in the literature. Weight function method can always be used for general self-equilibrating type of distributions.

In most of applications, the component $\sigma_m{}^r$ is negligible unless there exist severe restraint conditions during welding, which may occur in a final assembly weld under poor fit-up conditions. Recalling the two dominant types of residual stress distributions (Fig. 1) discussed earlier, the bending type distribution, by definition, will be dominated by $\sigma_b{}^r$, while self-equilibrating type dominated by $\sigma^r_{s.e.}$ after the decomposition through Eq. 2. Only one of the three components may possibly reach to yield magnitude in an actual weldment.

To demonstrate the relative contributions of residual stresses to stress intensity factor solutions, in Fig. 7, a simple pure bending type ($\sigma_b{}^r = 30Ksi$) residual stress distribution is assumed. The stress intensity factor solutions using three methods are compared in the same figure. If weight function for an edge crack specimen or a handbook K solution for the same specimen is used, the K solution behaves as load-controlled, rapidly increasing for a/t larger than 0.2. In such a solution, the stress state is assumed to be constant with respect to crack size. However, the bending type residual stress state can be simulated in 3D finite element alternating model (FEAM), in which re-distribution of the residual stresses as the crack advances is properly accounted for, the stress intensity factor peaks about $a/t = 0.2$ and decreases after that (Fig. 8). The use of a weight function simulating displacement controlled conditions generates essentially the same results as those by FEAM [11]. The effects of bending type and self-equilibrating type residual stress distributions on K are shown in Fig. 9 by assuming two hypothetical simple residual stress distributions. The peak residual stress values for both types are same, i.e., 30 Ksi. As expected, the bending component has a much stronger contribution to K than self-equilibrating component. The contribution from the self-equilibrating type to K is only noticeable within a/t less than about 0.3.

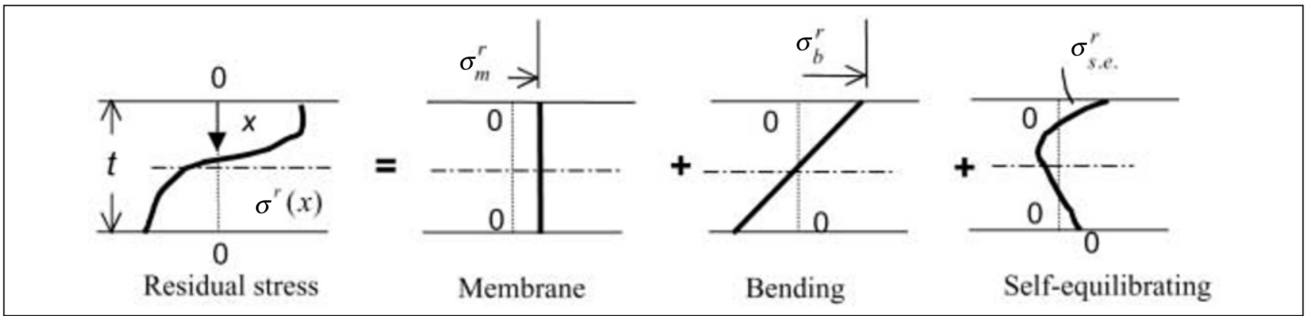

Fig. 7. Residual stress decomposition into 3 simple stress states.

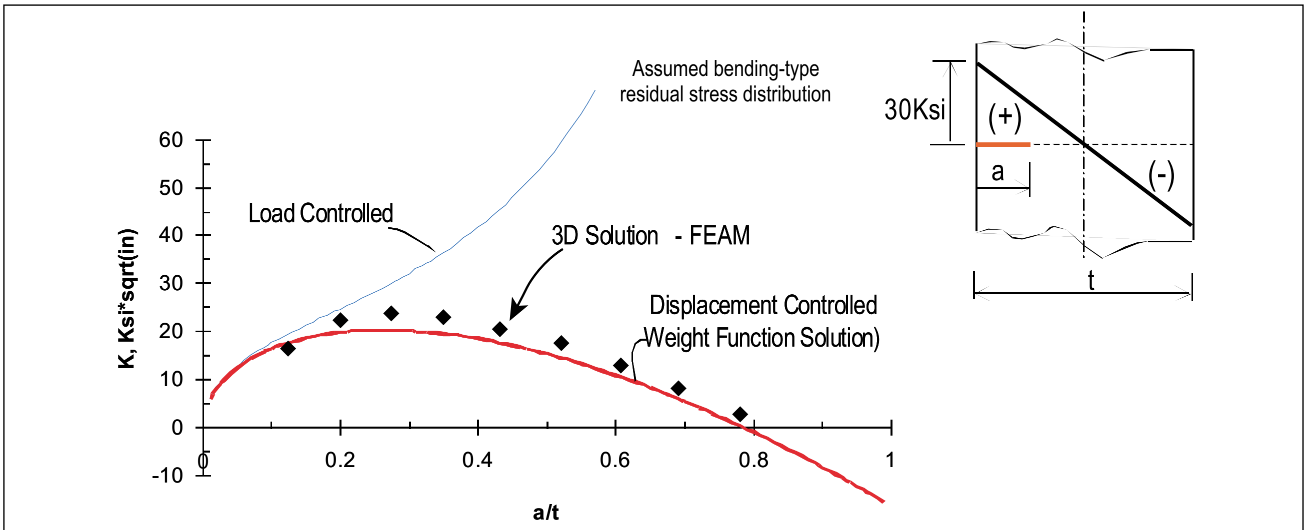

Fig. 8. Stress intensity factor solution for an edge crack.

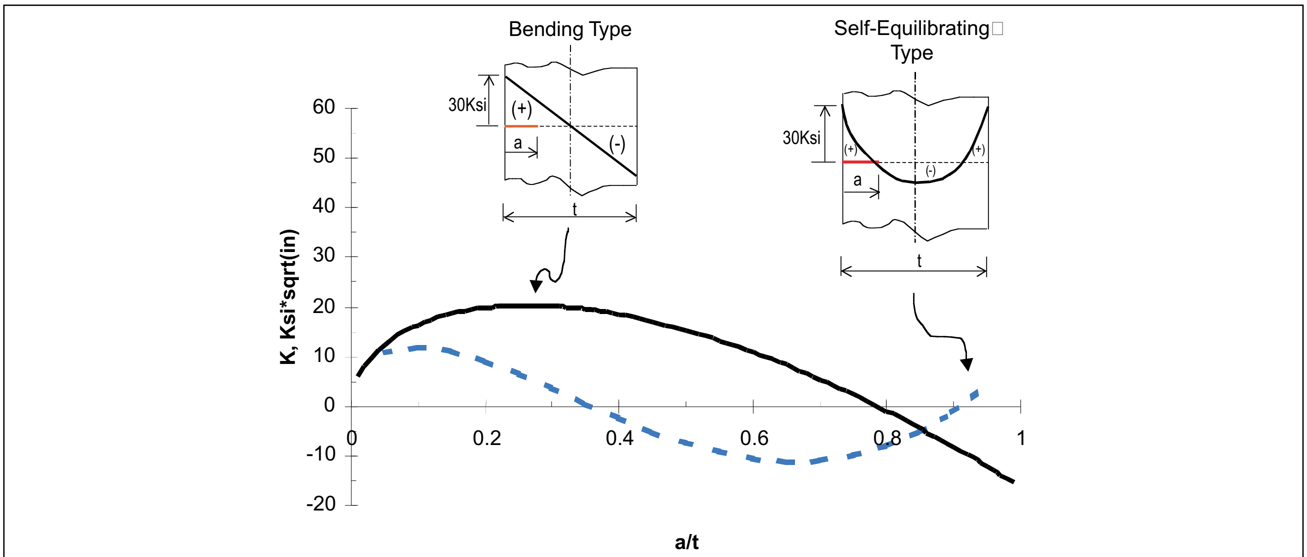

Fig. 9. Comparison of stress intensity factor solutions between the two types of residual stress distributions (bending versus self-equilibrating) under displacement controlled conditions.

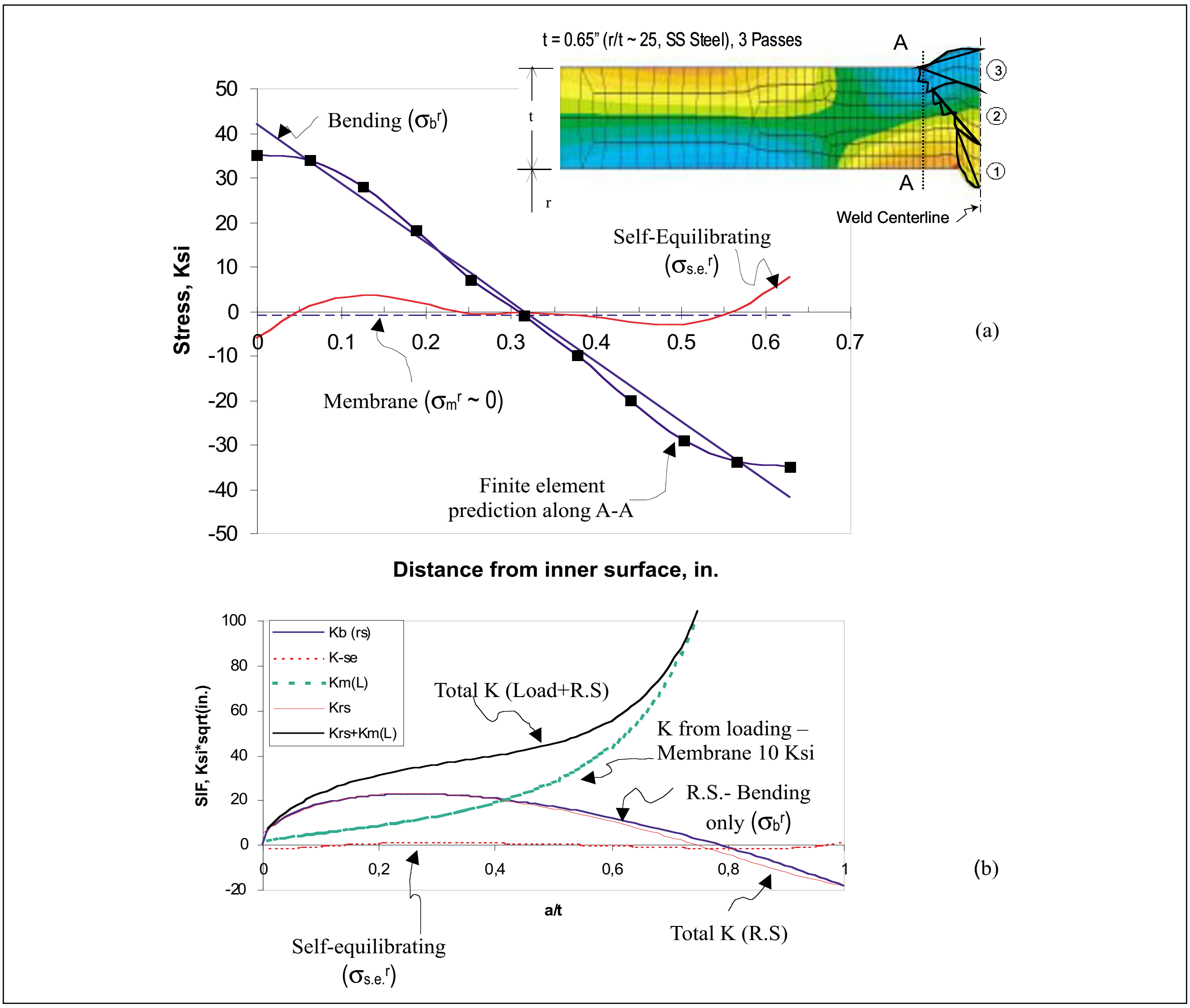

Fig. 10. Residual stress decomposition for a stainless steel girth weld [Fig. 1(a)] and contributions to K solution.
(a) Residual stress components after decomposition
(b) Comparison to K due to residual stress components and a remote membrane loading of 10 Ksi

If realistic residual stress distributions such as those in Fig. 10 are considered, the detailed residual stress contributions to *K* can be quantified and the requirements for residual stress estimate requirements can be demonstrated in terms of *K* solutions. By following the decomposition procedures described in Eq. 3, the membrane, bending, and self-equilibrating parts of the residual stress distribution along line A-A are plotted in Fig. 10 (a). The membrane component σ_m^r is negligible and therefore, its contribution to *K* is not considered further in Fig. 10 (b). The bending component σ_b^r is dominant, with the maximum stress above the base material yield strength (37 Ksi), occurring at the outer surface. The self-equilibrating part $\sigma_{s.e.}^r$ is rather small with peak stresses less than 5 Ksi. The resulting *K* as a function of *a/t* from both bending and self-equilibrating parts of the residual stresses (based on Eq. 4) is shown in Fig. 10 (b), in which the *K* contribution from the self-equilibrating component is nearly not noticeable. As expected, the bending component dominates the residual stress contribution to *K*. To demonstrate the interactions between service loading and residuals stresses, a uniform membrane loading of 10 Ksi is assumed along the pipe axial direction. The corresponding *K* for the 10 Ksi membrane loading is shown in Fig. 10 (b). The difference between the total *K* (due to both loading and residual stresses) and the *K* due to loading only signifies the contribution of the residual stresses for the full range of crack depth (*a/t*).

It is important to note that in this instance the self-equilibrating part of the residual stresses can be ignored in the *K* calculations without introducing any noticeable error [Fig. 10 (b)] after the residual stress decomposition through Eq. 3 for the bending-dominated type residuals stress distribution. As discussed earlier, for welds involving many passes and other subtle residual stress changes due to localised microstructure changes, a high order of residual stress variation is often seen as shown in Fig. 11 (a) [17]. However, such localized variations only contribute the higher order effects of self-equilibrating part of the overall residual stress distribution.

The boiler shell repair weld shown in Fig. 11 (a) reported in [17] is used to elaborate such effects. The through-

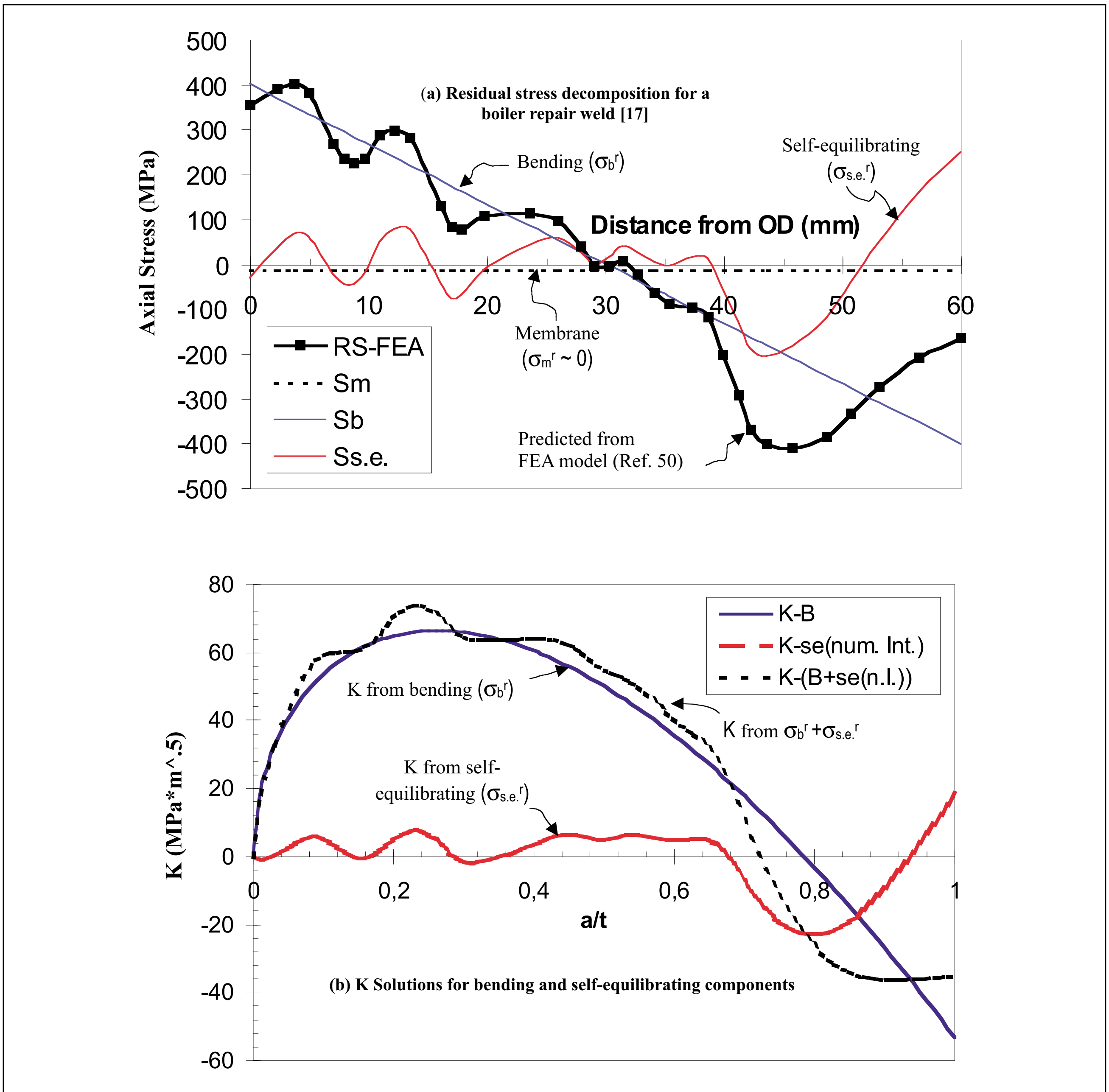

Fig. 11. Residual stress decomposition for boiler vessel repair weld [17] and contribution to K solution.
(a) Residual stress components after decomposition
(b) Comparison of K solutions

thickness axial residual stress distribution predicted from the finite element model and validated using experimental data is re-plotted in Fig. 11 (a). The distribution clearly shows a strong bending mode superimposed with higher order local variations in a rather complex manner. Again, by using Eq. 3, the decomposed residual stress components are also shown in Fig. 11 (a). The membrane component is negligible. The bending component is the dominant one. The self-equilibrating component exhibits more cycles of variations than the one in Fig. 10 (a) due to a lot of more passes involved in the boiler shell repair weld. The corresponding K solutions are summarised in Fig. 11 (b). Again, after a proper separation of the bending component, the self-equilibrating part of the residual stresses only contributes slightly to K at rather localised level.

4 SUMMARY

In this paper, typical residual stress states in various welded joints are assessed in terms of their commonalities and differences in overall distributions. Although detailed residual stress distributions are dependent upon weld joint types, materials, welding procedures, etc., it appears that two characteristic distributions can be generalised. One is the self-equilibrating type and the other is the bending type. Among some important parameters, joint restrain conditions seem to be a key parameter that determines both the transition between the two types and relative composition of the membrane and bending content in a residual stress distribution. By introducing the residual stress decomposition method and displacement controlled based K solutions, the membrane and bending part of the residual stress distributions can be consistently incorporated with remote loading effects. In this manner, the contributions of the individual residual stress components to stress intensities at welds can be clearly established, particularly in terms of crack sizes to be assessed. The contribution of the self-equilibrating type residual stresses to K is typically confined within small cracks (e.g., $a/t < 0.2$), while the contribution of bending type residual stresses to K is rather long range, i.e., for crack size up to about half wall thickness.

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