NEW WELDING RESIDUAL STRESSES COMPENDIUM INCOPORATED INTO THE SINTAP STRUCTURAL INTEGRITY ASSESSMENT PROCEDURE

A Stacey*, J.Y. Barthelemy†

Residual stresses are an important consideration in the fracture assessment of welded joints and reliable predictions of structural integrity require that the residual stress distribution is adequately accounted for. Residual stress distributions can vary widely with weld geometry and, in the absence of comprehensive information on distributions in welded joints, it is usually necessary to make conservative assumptions. This can result in unrealistic predictions and further information on the nature and behaviour of residual stress distributions in welded structures is required.

The significance of residual stresses has been recognised in the EC funded project Structural Integrity Assessment Procedures for European industry, SINTAP, and the development of a methodology for the assessment of residual stress effects is a principal task. The task involves a review of residual stress distributions in a range of welded joint geometries, numerical predictions of welding residual stresses, prediction of their behaviour with crack growth and applied loading and the formulation of recommendations. This paper gives an overview of the programme and the current status of the work on residual stresses.

INTRODUCTION

Residual stresses can have a detrimental effect on structural integrity and are an important consideration in the defect assessment of welded structures. They are introduced during fabrication by various processes and are particularly relevant to welded structures where tensile residual stresses of up to the material yield strength can occur.

* Offshore Safety Division, Health & Safety Executive, London, United Kingdom
† Institut de Soudure, Ennery, France

The combination of high welding stresses with the high operating stresses to which engineering structures and components are subjected can promote failure by fatigue and fracture. The risk of failure can be reduced by the application of stress relieving processes, e.g. post-weld heat treatment (PWHT). Alternatively, defect assessment procedures can be used to determine fitness-for-purpose and this approach is being used increasingly. The most widely used defect assessment procedures, BS PD 6493 [1] and Nuclear Electric R6 [2], enable the contribution of the residual stress on the prediction of fracture to be quantified.

Failure predictions can be very sensitive to the residual stress distribution used in the defect assessment and there is a need for more realistic estimates of residual stresses. This was identified by the BSI WEE/37 panel responsible for the revision of the BS PD 6493:1991 procedure, now designated BS 7910:1997 [3], and the new document includes recommendations on residual stress distributions in welded joints based on reviews [4, 5] of the recommendations in R6 Rev. 3 [2].

The treatment of residual stresses in defect assessment is being investigated in the EC funded SINTAP (Structural Integrity Assessment Procedures for European Industry) project [6] whose aim is to develop a unified procedure for the structural integrity assessment of welded joints. Seventeen organisations from eight EC countries are participating in SINTAP which is being part-funded by the Fourth Framework BRITE-EURAM programme.

THE SINTAP PROGRAMME

The overall aim of the SINTAP task on residual stresses is to determine and validate the most appropriate methods of accounting for residual stresses in as-welded, weld repaired and post-weld heat treated welded joints for use in structural integrity assessment.
The work performed for BS 7910:1997 and R6 Rev.3 was used as the starting point and the work has entailed the updating of the reviews of residual stresses [4, 5] to include additional data that has become available since the completion of the work for BS 7910:1997. In addition, numerical predictions of the development of welding residual stresses and the effects of applied load are being performed.
The SINTAP task on residual stresses comprises a number of sub-tasks:

Satus Review

Existing information on the treatment of residual stresses in fracture prediction is being reviewed and includes code-defined secondary stress profiles.

Collation of residual stress profiles

Existing experimental and numerically predicted residual stress profiles are being collated and compared with those recommended in codes, particularly BS 7910:1997.

Experimental and Numerical Studies

Experimental and numerical investigations of residual stress distributions in welded joints are being performed in this sub-task. The numerical analysis work addresses the need for PWHT, the determination of its effectiveness and the derivation of criteria for PWHT of as-welded and repair-welded structures. Studies of through-wall defects are being performed with reference to available experimental data and will include further experimental work on thick, welded A533B steel plates.

In addition, a study is being performed of the estimation of J-integral when dominant residual stresses are present using centre-cracked panels, thus providing an insight into the influence of residual stresses on the fracture behaviour.

Standardised Residual Stress Profiles

The information from the above sub-tasks will be used to derive standardised residual stress profiles for welded joints. A framework for incorporation of residual stresses into fracture assessment procedures based on the Failure Assessment Diagram (FAD) will be defined.

Procedure Development & Validation

Guidelines for the assessment of residual stress effects will be developed, validated and subsequently incorporated into the the SINTAP procedure.

TREATMENT OF RESIDUAL STRESSES IN DEFECT ASSESSMENT PROCEDURES

The BS 7910:1997 procedure [3] is the most recently developed defect assessment procedure and provides the basic elements of the method for the assessment of residual stresses in SINTAP. An outline of the BS 7910:1997 procedure, highlighting the aspects relevant to the assessment of residual stress effects, is presented below, thus placing the residual stress study in the proper context.

The fracture assessment procedure is based on the use of the failure assessment diagram (FAD) which combines considerations of fracture with plastic collapse.

The fracture parameter, which is represented by Kr or $\sqrt{\delta r}$, is expressed in terms of the plastic collapse parameter, Sr or Lr, i.e.

$$Kr = f(Sr, Lr) \qquad (1)$$

Three assessment levels are given. These are, in order of increasing complexity and decreasing conservatism :

- Level 1 - a preliminary screening procedure. The level 1 method entails making very conservative assumptions about the treatment of the applied and residual stress field in the wall thickness.

- Level 2 - the usual assessment method for structural applications and that generally used for offshore structures. The Level 2 method yields realistic predictions for situations where ductile tearing is limited.
- Level 3 - this procedure is appropriate to ductile materials which exhibit stable tearing. The Level 3 method is rarely applied to offshore structures. Three options are available at this level , i.e. Option 1 to 3 in order of decreasing conservatism, depending on the accuracy required and the information available.

REVIEW OF RESIDUAL STRESS DISTRIBUTIONS IN WELDED JOINTS

A review was performed of transverse and longitudinal through thickness residual stress distributions in a range of geometries of welded joints manufactured from ferritic and austenitic steels:

(a) plate butt welds
(b) T-butt and fillet welded joints
(c) pipe butt welds
(d) pipe seam welds
(e) pipe to plate joints
(f) tubular joints
(g) repair welds

The review included consideration of the effects of a number of key parameters on the residual stress distribution:

- joint geometry
- plate thickness
- heat input
- post-weld heat treatment

CONTINUING WORK

Current work in the task on residual stresses is described below.

Residual Stress Profiles

The numerical analysis work being performed in the SINTAP residual stress investigation is generating additional information on distributions in plate and pipe butt welded joints.

The profiles for plate and pipe butt welds will be reviewed further and revised to incorporate additional data from the numerical analysis work being performed, as appropriate. In addition, the tubular, pipe to plate and plate T-butt joint distributions will be reviewed to determine whether they can be amalgamated.

Other aspects of the work on residual stress profiles are as follows:

- an assessment to determine whether distributions for set-through and set-in nozzles can be developed.
- a review of the recommendations for transverse residual stresses in PWHT ferritic steel joints and for dissimilar metal welds using the results from numerical analysis.
- the derivation of formulae for surface transverse and longitudinal residual stress

distributions followed by experimental validation.

Numerical Study of Residual Stress Redistribution

The application of external load may cause redistribution of the residual stress distribution in welded joints due to plasticity caused by the interaction of applied and residual stresses. The redistribution of the residual stress distribution under the action of the external loading may be significant and requires careful consideration. This is particularly relevant to T-butt, pipe-to-plate and tubular welded joints because of the high stress concentration at the weld toe.

The interaction of residual stresses with applied stresses is being investigated numerically in the SINTAP project with a view to providing recommendations on the treatment of weld residual stresses in fracture assessment. The contribution of thermal and weld-induced residual stresses in a welded pipe to the total CTOD and J-integral has been evaluated. The results suggest that residual stress effects decrease rapidly at high Lr but that the contribution is not negligible at high loads. The results also demonstrate that J and CTOD can be used to quantify weld residual stresses in fracture assessments and that the R6 procedure is conservative.

Numerical analyses will be performed to predict longitudinal and transverse residual stresses in circumferential and longitudinal welds in carbon manganese steel pipes manufactured by submerged arc welding. A welding repair procedure will then be simulated for the circumferential weld. The redistribution of the residual stress field after proof loading will also be simulated.

Finally, numerical pedictions will be made of the residual stress field in symmetrical fillet welded assemblies of carbon manganese steel manufactured by single and multi-pass welding procedures.

Experimental Work

Residual stress measurements on both an as-welded and a PWHT A533B welded plate specimen with a surface defect in a self-balancing residual stress field are being performed and the specimens subsequently fracture tested to validate the R6 procedure. The experiments are being carried out in the low Lr regime.

Development of Recommendations

The residual stress profiles and the results of the numerical and experimental investigations will be used to develop and validate recommendations on the treatment of residual stresses which will be incorporated into the SINTAP defect assessment procedure.

CONCLUSIONS

Information on the nature of residual stresses in welded joints and on the treatment of residual stresses in defect assessment procedures has been presented. Overall, it has been shown that residual stress distributions are highly variable and despite the progress made in recent years, there is a need for further information on distributions in welded joints, the interaction of applied and residual stresses, and the development and validation of revised recommendations if more realistic predictions are to be made.

The SINTAP project is making a particularly significant contribution on the assessment of residual stresses and this paper has summarised the scope of work, progress to date and the studies currently being performed, i.e :

- through-thickness residual stress profiles for a range of welded joints fabricated from both ferritic and austenitic steels have been reviewed and the latest recommendations have been presented. These will be revised as further data from the numerical studies being undertaken become available.
- numerical studies have provided information on the behaviour of residual stresses under applied load and on the contribution of residual stresses to the prediction of fracture.
- experimental validation of fracture predictions for welded structures is currently underway and improved recommendations for the treatment of residual stresses will be formulated shortly.

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