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Finite Element Modelling of Residual Stress - A Powerful Tool in the Aid of Structural Integrity Assessment of Welded Structures

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Abstract
Structural integrity assessment of structures containing welds may require the use of numerical methods for welding residual stress field characterisation. This paper includes a brief description of a welding residual stress assessment methodology based on coupled thermal and mechanical analysis using the finite element method and general purpose computer codes. Two applications are presented. The first one refers to the case of a single short bead weld on a thick steel plate. The components of residual stress field obtained by 3-D modelling are in good agreement with experimentally determined ones by British laboratories. Comparison with provisions of level 1 of residual stress assessment according to British R6 procedure reveals a significant reduction of the assessment conservatism by using the modelling technique. The second application refers to the case of butt-welding of thin plates. In this case, the use of a double elliptic distribution of the heat flux yielded an excellent agreement with experimentally determined weld pool geometry. Computed residual stress distributions reveal the ability of the model to emphasize their self-equilibration characteristic.
Keywords: welding, residual stress, modelling, finite element, structural integrity assessment

1. Introduction

Fusion welding, as a joining or repair process, induces a high residual stress field (as-welded residual stress components may exceed the material yielding stress) which combines with stresses resulting from in-service loads, strongly influencing in-service behaviour of welded components. When combined with stresses due to service loads, tensile residual stress reduces crack initiation life, accelerates growth rates of pre-existing or service-induced defects, and increases the susceptibility of structures to catastrophic failure by fracture.

Knowledge of welding residual stress characteristics is essential for structural integrity assessment of welded joints or weld repaired components and therefore current life assessment procedures (e.g. British R6 [1] or API 579 [2]) include their quantification as a required step when a defect is placed in a welding residual stress field.

Advanced structural integrity assessment of structures containing welds implies the use of numerical methods for welding residual stress assessment and subsequent life assessment analysis. This may be required by the need to reduce the conservatism of residual stress evaluation when using simplified assumptions or bounding profiles or by the lack of provisions of assessment procedures for certain geometries or considered materials.

There is a growing trend towards the use of advanced finite element (FE) systems for modelling the generation of residual stresses and material phenomena during welding. This fact yields also an improvement of structural integrity assessment procedures. For example, improved guidance on residual stress modelling techniques will be incorporated into a future issue of the R6 defect assessment procedure [3].

National and international cooperation in welding residual stress research constitute one of the best ways for pushing toward the knowledge in this field. An example is the NET

Network (European Network on Neutron Techniques Standardization for Structural Integrity) coordinated by European Commission – Joint Research Centre which joins partners from research institutes, academic media and industry within the framework of a sustained research program of experiments and modelling related to welding residual stress assessment.

One of the applications of a numerical welding residual stress assessment methodology first presented in this paper refers to the case of a single short bead weld on a thick steel plate, one of the problems studied in the framework of NET. Another application example refers to the case of butt-welding of thin plates where the modelling was calibrated using experimental results obtained at the Institute of Nuclear Research Pitesti (INR). Simulations were performed using the general purpose finite element computer code ANSYS [4].

2. Modelling methodology

Welding analysis has to consider three main coupled fields, which interact more or less strongly [5]:

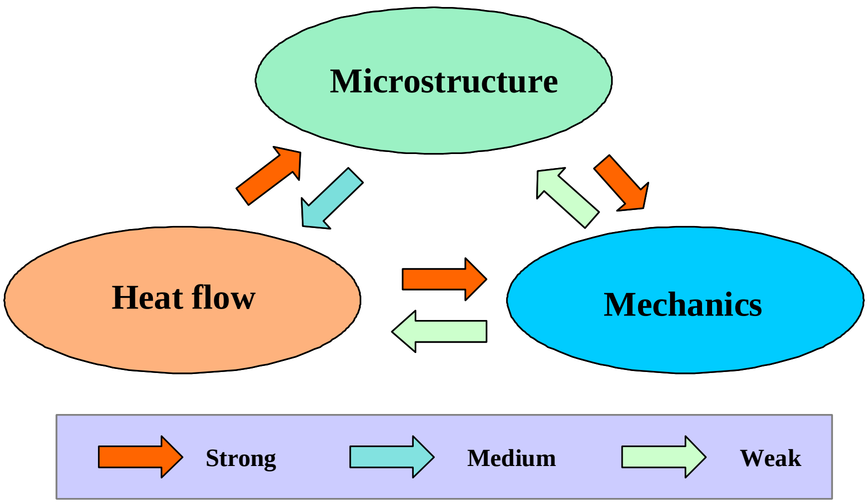

Figure 1. Coupled fields in welding analysis

When the objective of the analysis is to determine the mechanical effects of welding (residual stress and distortions) the simplest approach is to consider the thermal and mechanical coupling only. The field of microstructure can be accounted for by more or less sophisticated techniques for material modelling and so, there is in the analysis an indirect incorporation of micro structural aspects in the material description, exploiting the microstructure dependency on temperature and deformation [5][6].

Nowadays, the finite element method (FEM) is the most used tool for solving this kind of problems.

Because there is a weak coupling from mechanics to heat flow (heat generation by deformation can be neglected), the most used approach is a sequentially coupled thermal and mechanical analysis, unless the structure deformation during welding significantly changes thermal boundary conditions. This approach gives also the possibility for the use of general purpose finite element computer codes.

First, a transient heat transfer analysis is performed, determining the temperature history in all nodes. Then, a static mechanical analysis is performed, having as loading the temperature field previously determined. Each step of the mechanical analysis corresponds to a time step in the thermal analysis. The thermal dilatation, which includes the volume changes due to phase transformations (if any), drives the deformation. Restrained thermal expansion (e.g. in the weld region temperatures are much higher than in the adjacent one that consequently has a higher stiffness) causes plastic strains development. Finally, at the last step, when temperatures attain their initial values, the residual stress field is obtained as result of all intermediary analysis steps.

3. Applications examples

3.1. Short weld bead on a plate

The example presented in the following, refers to the case of a single weld bead of limited length, deposited on a flat plate. This process introduces a strongly varying 3D residual stress field that has similar characteristics to a short repair weld and is a good vehicle to demonstrate the numerical method and validate its predictions against experimental data. The problem constituted the study object of a task group of the NET network and experimental programs as well as round robin simulations activities were carried up by the NET partners.

A single Tungsten Inert Gas (TIG) weld bead was deposited along the centre-line of several AISI 316L austenitic stainless steel plate specimens (figure 2) using an automated procedure and welding parameters were recorded. The heat input was about 630 J/mm and the weld penetration about 1.5 mm.

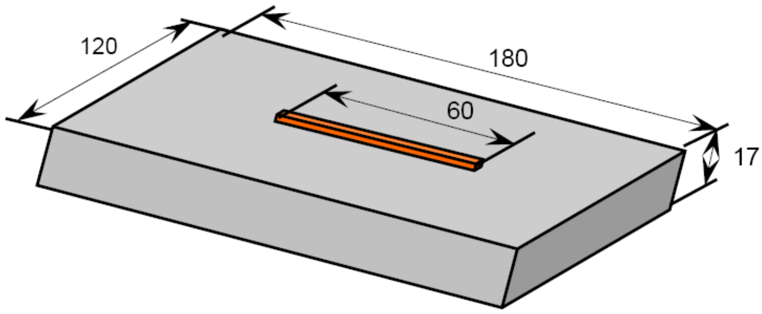

Figure 2. Thick plate geometry

In the FE analysis, thermal and mechanical material properties were defined as temperature dependent over the entire temperature range between the room temperature and the solidus temperature using experimental data [7].

In the thermal analysis, a simple but efficient moving heat source model (uniform heat generation in a single row of elements) was used. Figure 3 presents an example of temperature distribution obtained during welding phase simulation. Due to problem symmetry, only half of the plate was modelled.

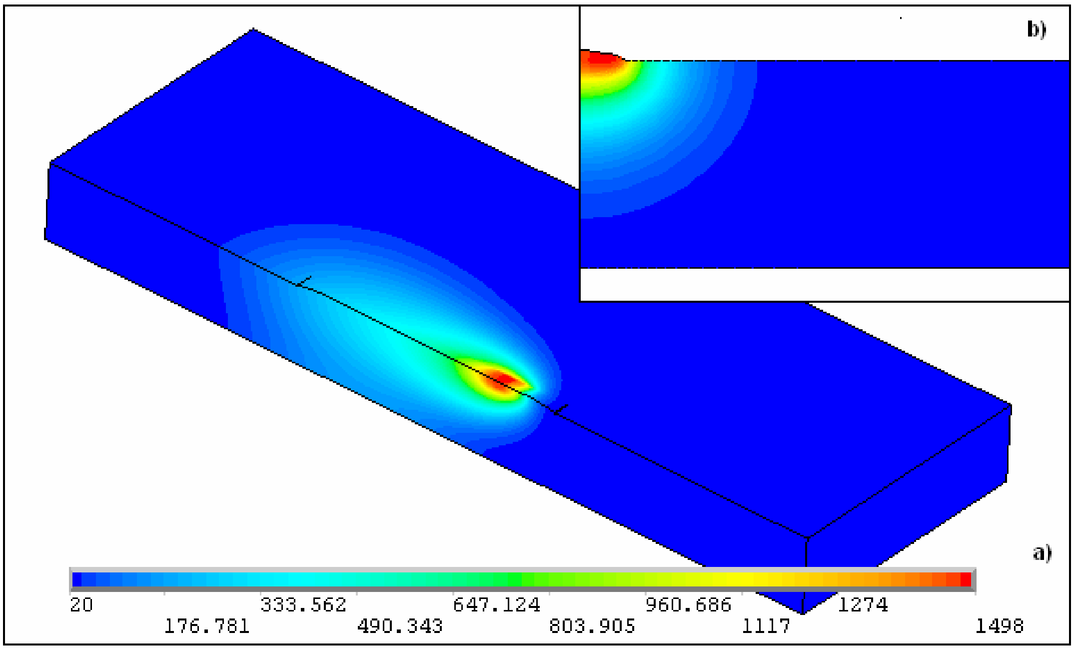

Figure 3. Predicted temperature distribution during welding
a) General view b) Cross-section transverse to the weld

During the welding process and the cooling phase the material undergoes complex mechanical cycles, therefore the accuracy of the predicted residual stresses depends not only on reliable stress-strain data under monotonic loading, but on an adequate model for the material behaviour under cyclic loading. For this problem, it was found that a nonlinear kinematic hardening (Chaboche) model is the most appropriate [8].

Figure 4 presents the residual stress distributions obtained by FEM modelling. It can be observed the residual stress characteristic related to their self-equilibration over the plate structure. Tensile residual stresses in certain regions are counterbalanced by compressive stresses in other regions. Through-thickness residual stresses are significant at weld bed ends corresponding regions only but they are considerable less than transverse and longitudinal stresses. Due to 3-D effects, the peak values of transverse and longitudinal residual stress field components exceed the material yield stress.

Figure 5 presents the variation of transverse stress on a through-thickness line at plate mid. There is a good agreement between prediction and measurements carried up by using two techniques, at the Open University (UK) [9].

Figure 6 presents a comparison between predicted longitudinal residual stress and experimentally determined ones [10]. It refers to the longitudinal residual stress variation along the through thickness direction at plate mid length, in the longitudinal symmetry plane. There is a good agreement between measurements and predictions.

Figure 7 presents a comparison of predicted transverse residual stress at plate mid, 3 mm from weld center-line (i.e. required for the assessment of a longitudinal crack in weld) and the residual stress according to assessment level 1 of the R6 Procedure (through-thickness constant stress). This would be the only possible approach in an R6 assessment, as there aren't any other provisions (level 2 bounding profiles) regarding through-thickness residual stress distributions for repair welds in austenitic steels. The modelling procedure would significantly reduce the assessment conservatism.

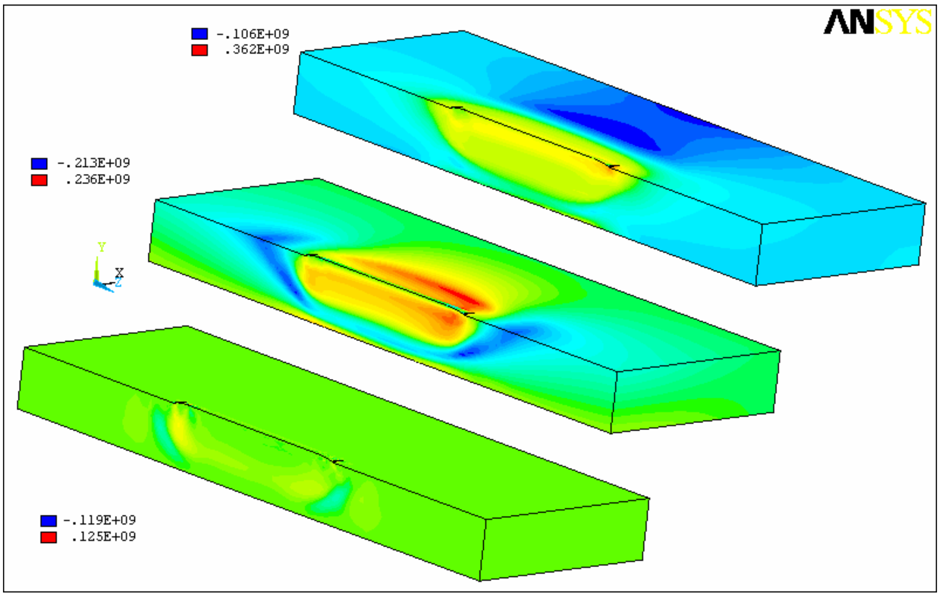

Figure 4. Residual stress distributions (Pa)
a) Longitudinal stress b) Transverse stress c) Through-thickness stress

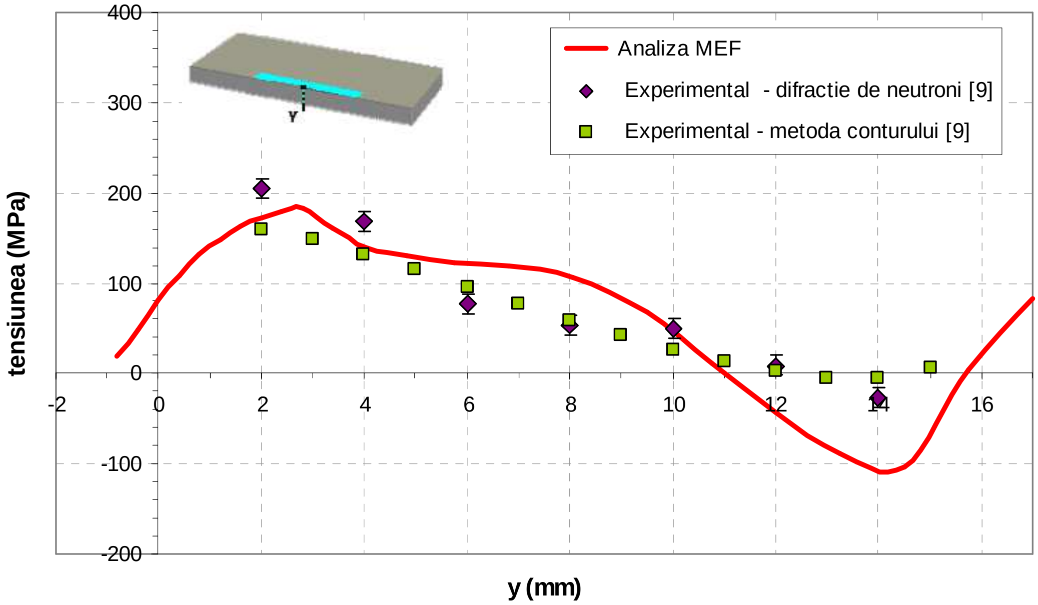

Figure 5. Comparison of predicted and experimentally determined [9] transverse residual stress variation at plate mid, in through-thickness direction

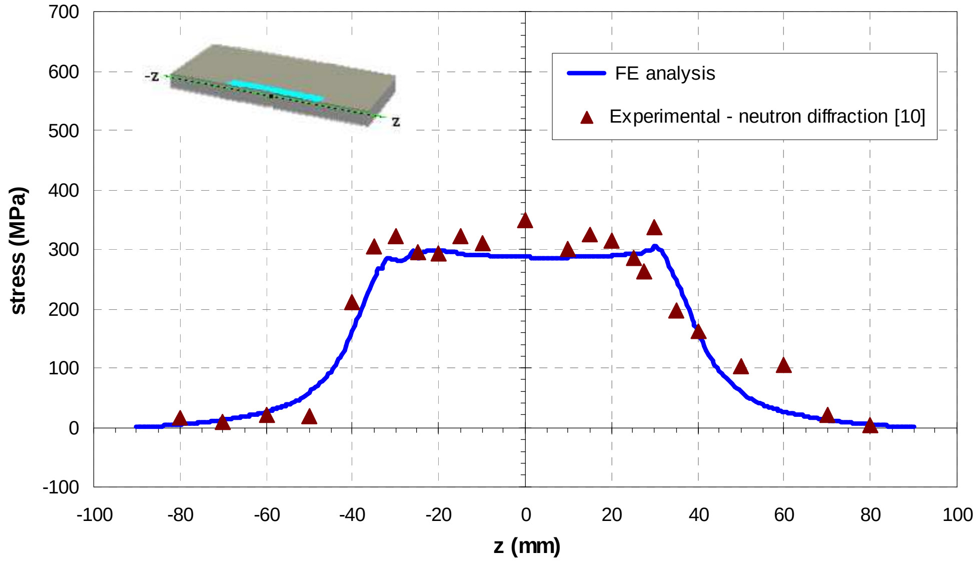

Figure 6. Comparison of predicted and experimentally determined [10] longitudinal stress variation along a longitudinal line, 2 mm beneath the plate top surface

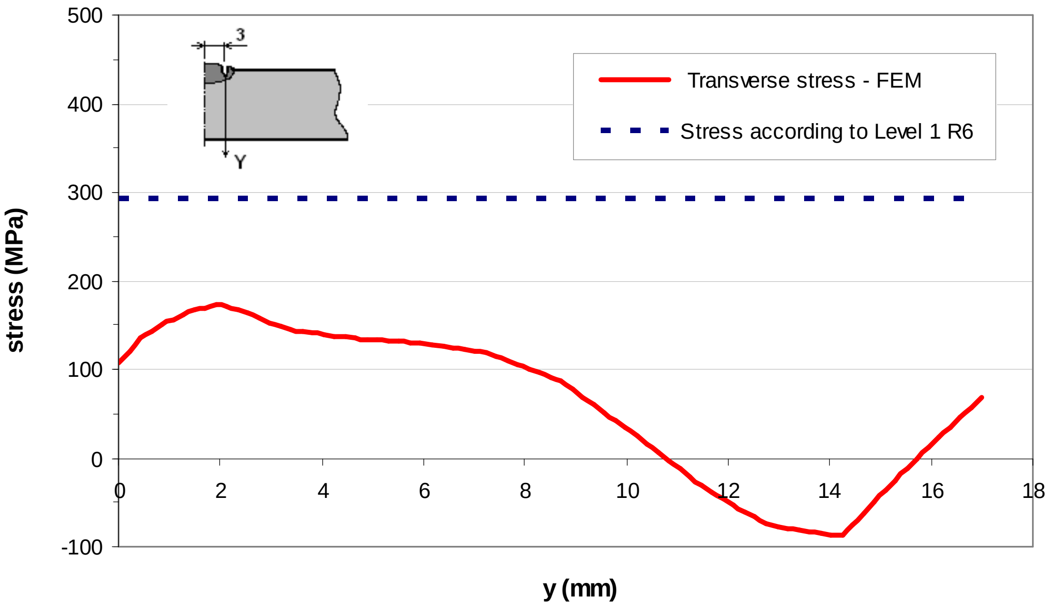

Figure 7. Comparison of predicted residual stress and residual stress quantification according to level 1 of R6 Procedure

3.2. Butt welded thin plates

The modelling presented in the following, bases on a TIG welding process of thin austenitic steel plates (AISI 304L), used at INR Pitesti for manufacturing recipients for heawy heavy water storage and low level radioactive waste storage. In welding experiments that were carried up by using a manual TIG procedure, the heat input was about 320 J/mm. Plates of 150 mm length, 50 mm width and 1.5 mm thickness were considered for modelling purpose.

The finite element models were built using thermal shells and respectively 2-D structural solids with plane stress option. Thermal and mechanical material properties were defined as temperature dependent over the entire temperature range between the room temperature and the solidus temperature (1400 ºC) using the data from Brickstad [11]. A bi-linear kinematic hardening material model was assumed in the mechanical analysis.

The heat source thermal flux was defined as having a Gaussian, double elliptic distribution adapted from the model proposed by Goldak et al. [12]. This formulation for the moving heat source allowed a good calibration of the predicted fusion boundary (figure 8) using data from experiments. Due to problem symmetry, only half of the structure was modelled and graphic results were completed by symmetry.

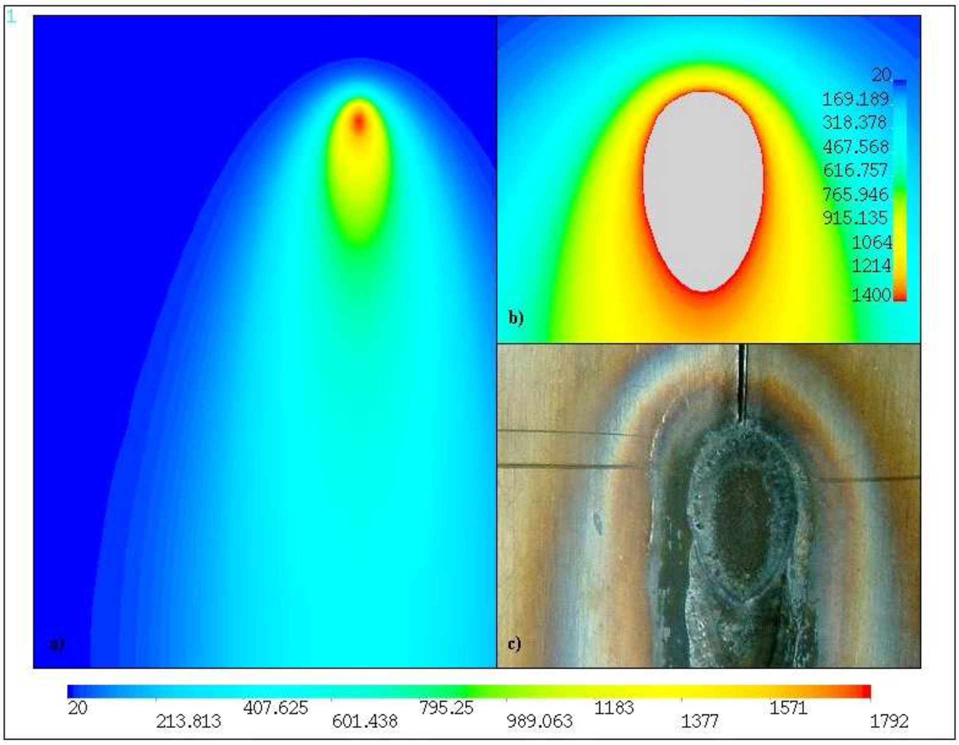

Figure 8. Predicted temperature distribution during thin plates welding
a) General view b) Detail of modelled fusion boundary c) Detail of fusion boundary from experiment

Computed residual stress distributions are presented in Figure 9. In order to emphasize the modelled shrinkage of the structure after welding, distortions are multiplied by a factor of 10. Figure 10 presents modelled residual stress distributions along a line transverse to the weld at plate mid-length (a- longitudinal stress) and respectively along the longitudinal symmetry axis (b- transverse stress). Stress distributions are typical for this kind of geometry and plate material. The computed maximum longitudinal stress was in tension, close to the material yield stress, while maximum tensile transverse stress was about 2.5 times lower. Significant transverse stress concentrations (compressive stress) appear at weld ends, the maximum peak exceeding the material yield stress. Both figures emphasize the ability of the model to characterize the residual stress self-equilibration feature over the plate geometry.

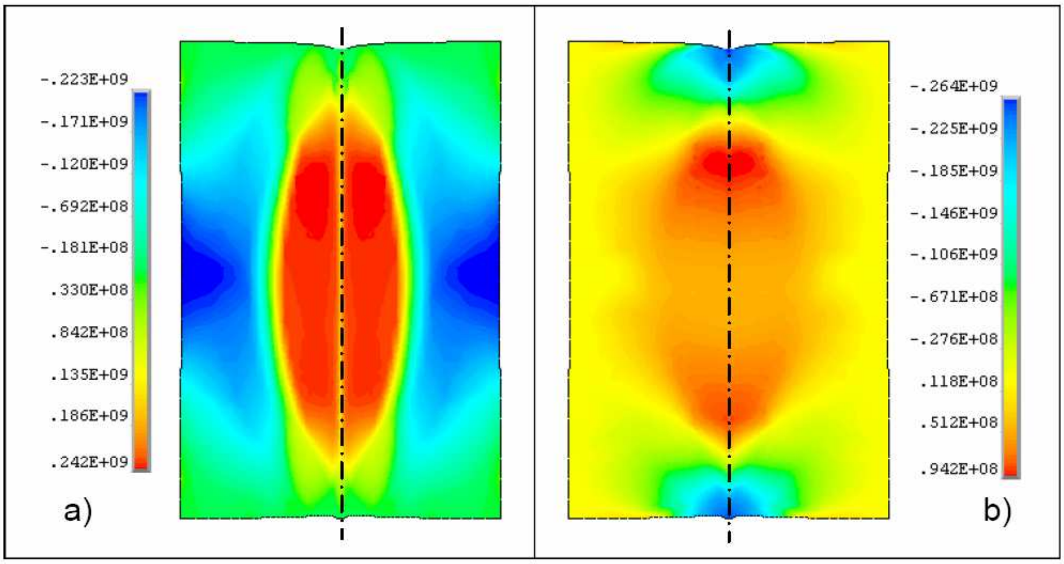

Figure 9. Residual stress distributions (Pa) – Thin plates
a) Longitudinal stress b) Transverse stress

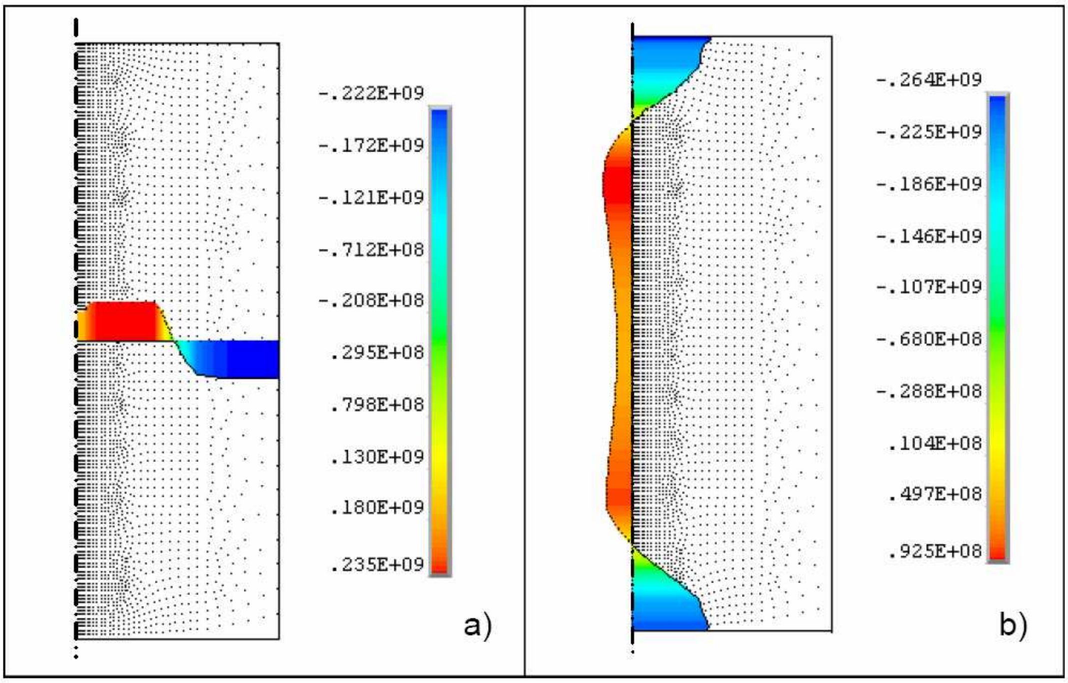

Figure 10. Residual stress (Pa) variation along different lines - Thin plates
a) Longitudinal stress transverse to the weld at the plate mid-length
b) Transverse stress along longitudinal simmetry axis

4. Conclusions

A welding residual stress assessment methodology based on a thermo-elastic-plastic FE analysis was outlined and application examples using the ANSYS computer code were presented. The results emphasize the ability of this method to produce quality results, in agreement with experimental data and to offer the possibility to a better understanding of residual stress field characteristics as well as to reduce the conservatism its components quantification according to the current integrity assessment procedures.

Despite the shortcomings related to the need for information related to the welding process and for complex material data, numerical modelling remains practically the only method able to fully characterise the residual stress field over the whole structure without any limitations related to his geometry or size. Once having residual stress distributions, subsequent simulations of stress relief by mechanical loading or by post weld heat treatments can be performed.

Validated by experiments, FE modelling techniques can constitute an effective support for integrity assessments of structures containing welds.

References

1. "Assessment of the Integrity of Structures Containing Defects", Procedure R6-Revision 4, British Energy, 2003
2. "Fitness-For-Service", API Recommended Practice 579, First Edition, American Petroleum Institute, Washington, D.C., 2000
3. Bates S., "UK Research Programme on Residual Stresses – Review of Progress", Transaction of SMiRT 19, Toronto, August 2007
4. ANSYS 7.1, ANSYS Inc., Canonsburg, PA, 2003
5. Lindgren L-E., "Finite Element Modeling and Simulation of Welding. Part 1: Increased Compexity", Journal of Thermal Stresses, 24: 141-192, 2001
6. Lindgren L-E., "Finite Element Modeling and Simulation of Welding. Part 2: Improved Material Modeling", Journal of Thermal Stresses, 24: 195-231, 2001
7. Smith M.C., Smith A.C., NeT Task Group 1 - Single bead on plate: "Review of phase 1 weld simulation round robin", British Energy report E/REP/0089/GEN/05, 2005
8. Turski M., Edwards L., Pratihar S. and Zhang Y., **"**Residual Stress Measurement Using Neutron Diffraction and the Contour Method"**,** 1st NET Workshop, Petten, The Netherlands, 2004
9. Turski M. et al., **"**The Effect of Plastic Anisotropy on the Residual Stress within a 316L Stainless Steel Bead-on-Plate Specimen"**,** Materials Science Forum Vols. 524-525 pp. 679-684, 2006
10. Deaconu V., "3D Coupled Thermal and Mechanical Analysis for Welding Residual Stress Assessment", ANSYS & Fluent Romanian Conference, Sinaia, 26-27 April, 2007
11. Brickstad B., and Josefson B.L., "A Parametric Study of Residual Stresses in Multi-pass Butt-welded Stainless Steel Pipes", International Journal of Pressure Vessels and Piping, Vol.75, pp.11-25, 1998
12. Goldak, J., Chakravarti, A. and Bibby M, "A New Finite Element Model for Welding Heat Sources", Metallurgical Transactions, Volume 15B, pp. 299-305, 1984