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Residual stresses in as-welded joints: finite element modeling and neutron diffraction stress measurements

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Abstract. This paper describes the numerical analysis method used to estimate welding induced residual stresses in K-shape tubular bridge joints. The knowledge of residual stress distribution is required to design the geometry of K-joints loaded under fatigue stresses. Numerical simulations are focused on the arc welding MAG process, generally used to weld joints in bridge construction. Thermo-mechanical analyses are performed in 3D using two finite element codes: ABAQUS® and MORFEO®. ABAQUS has the advantage to offer large analysis capabilities (nonlinear, transient, dynamic, etc.) whereas MORFEO is more dedicated to welding processes and offers the possibility to analyze crack propagation under fatigue loads. Computed residual stresses in the region surrounding the weld are compared with measured residual stresses in order to estimate the ability of the codes to reproduce these stresses. Position, orientation and magnitude of the highest residual stress components are discussed.

Introduction

Residual stresses created by thermal induced deformations during welding are particularly high in the surface surrounding the weld. Combined with applied cyclic loadings, they influence the fatigue crack propagation (onset, rate and shape) [1, 2]. This study evaluates residual stresses in order to control and optimize the design of K-joints geometry.

Finite element simulations made in this paper are focused on the welding process of S355 steel. An uncoupled formulation is used; the transient thermal analysis is followed by an elasto-plastic mechanical analysis. These simulations provide the 3D residual stress distribution along the weld. The calculated residual stresses are compared with previously measured residual stresses in order to evaluate the accuracy of numerical models.

Presentation of the finite element analysis

A three dimensional thermo-mechanical finite element analysis is performed in order to simulate the stress generation during welding. In the case of a mild steel such as the S355 steel, it has been shown by [3] that phase transformations have a small effect on residual stresses generation, therefore phase transformations are not considered in this analysis.

An uncoupled approach is used to solve, first, the 3D transient temperature field and, then, the displacement field using the temperature field as input data.

Thermal analysis. The thermal analysis is based on transient non-linear heat conduction formulation (Eq. 1).

$$\rho\, C_{eq}\, \frac{\partial T}{\partial t} \;=\; \boldsymbol{\nabla}^{T}\, \mathbf{D}\boldsymbol{\nabla} T + s \tag{1}$$

where ρ is the material density [kg/mm^3], C_{eq} is the specific heat C combined with the latent heat L induced by melting [J/(kg.°C)], T is the temperature [°C], t is the time [s], D is the thermal conductivity tensor reduced to one coefficient k for isotropic case [W/(mm.°C))] and s is the volumetric heat source [W/mm^3].

The temperature-dependent thermal properties k, C and ρ are taken from the EN 1993-1-2:2005(E) for mild steel. The conductivity value is increased to three times its value at the solidus temperature [4, 5] to take into account the convection flow in the weld pool and kept constant at $T \geq T_{solidus}$. The latent heat L induced by fusion/solidification between solidus and liquidus temperatures (1465-1544 °C for S355 steel) is considered using a value of 247000 J/(kg.°C) [6]. Heat losses by radiation and convection (boundary conditions) are considered on all surfaces.

The 7-passes welding, generating the K-joint weld, is simulated as a single pass with an equivalent heat source. Each pass is made in four steps (half weld at the right brace toe, half weld at the left brace toe and the two symmetrical half welds). This heat source is composed of a volumetric flux moving along the weld path at a speed of 5.5 mm/s. The characteristics of the heat source are determined so that the computed size of the weld pool matches the one measured on a macrograph. In ABAQUS, the heat source is a sphere with a radius r = 15mm, in MORFEO, this is a truncated circular cone model with a radius r_1= 15 mm for its first base, r_2= 9.3 mm for its second base and a height h= 15 mm. To merge the seven weld passes into one equivalent pass, it is recommended by [7] to keep the total heat input of the seven weld passes, Q = 41500 W. Metal deposition of the MAG arc welding is not considered, the finite elements representing the weld are present in the model from the beginning.

Figure 1 depicts the 53966 nodes and 48549 elements used to model the K-joint composed of two braces (diameter 88.9 mm, thickness 8 mm) welded onto a chord member (diameter 168.3 mm, thickness 20 mm). The heat source traveling around the weld is also shown. 8-node brick linear elements for heat transfer are chosen for the thermal analysis.

Mechanical analysis. The mechanical analysis is based on an elastic-plastic material behaviour with a linear isotropic work hardening ignoring rate-dependent (creep) effects at high temperatures.

A variation of temperature, obtained as the thermal analysis output, implies thermal strain. In a thermo-elastic-plastic analysis, the generalised Hooke's law is expressed as follows (Eq. 2):

$$\boldsymbol{\sigma} = \mathbf{C}\boldsymbol{\epsilon}^{el} = \mathbf{C}(\boldsymbol{\epsilon} - \boldsymbol{\epsilon}^{pl} - \boldsymbol{\epsilon}^{th}) \tag{2}$$

where C is the elasticity tensor. The temperature-dependent mechanical properties required to solve the previous equation are the Young's modulus E [MPa] and the Poisson's ratio ν for the elastic part, the yield stress f_y [MPa] and the stress evolution as a function of the accumulated plastic strain $f_y + Hp$ (linear isotropic hardening assumption) for the plastic part and the thermal expansion coefficient α [/°C] for the thermal part.

The Young's modulus E is defined according to the EN 1993-1-2:2005(E) and the Poisson's ratio ν, the thermal expansion coefficient α and the yield stress f_y according to [8].

The mesh is identical to the one used for thermal analysis, but reduced integration is used for the mechanical part in the ABAQUS model. Concerning boundary conditions, displacements are set to zero at the chord right extremity, no traction or compression is applied.

Results and discussion

Residual strain measurements were conducted at the Institute Laue-Langevin (ILL) on a K-joint sample with a chord wall of 20 mm thick. This method enables to measure triaxial residual stresses non-destructively deep inside the sample. The residual stresses calculated from these measurements are

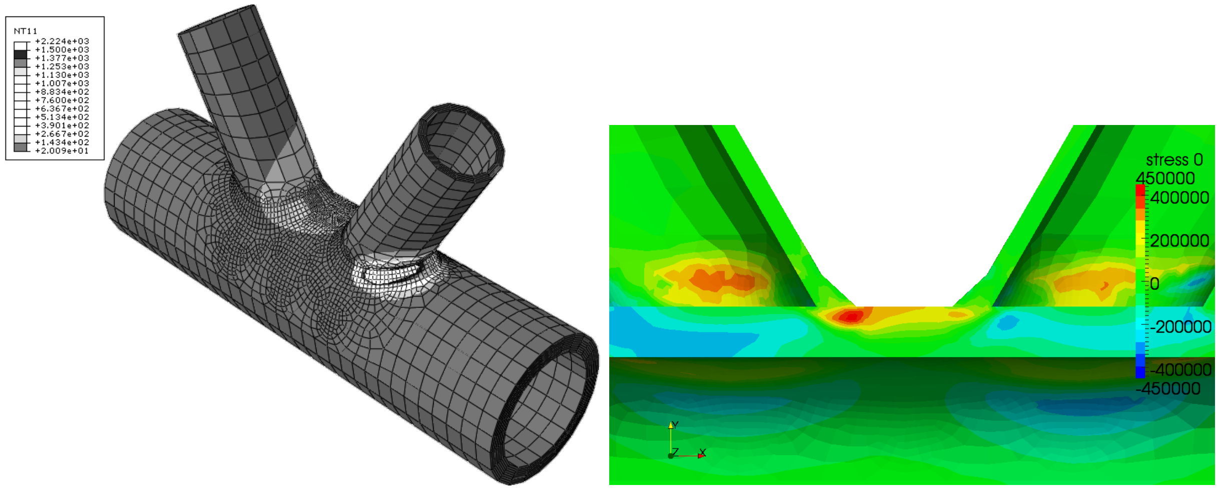

Fig. 1: On the left, temperature field from ABAQUS model during the movement of the torch. On the right, cut view of transversal residual stresses from MORFEO showing a restraining effect in the gap area between the braces (stress values in kPa).

compared in Fig. 2 with residual stresses resulting from numerical models. Stress distributions, along a vertical line passing through the 20 mm chord wall thickness underneath the weld toe, are given in the transverse direction (perpendicular to the weld), the longitudinal direction (parallel to the weld) and the radial direction (in the radial direction of the tube). The same simulation was performed with ABAQUS® [9] and MORFEO® [10] from Cenaero research center.

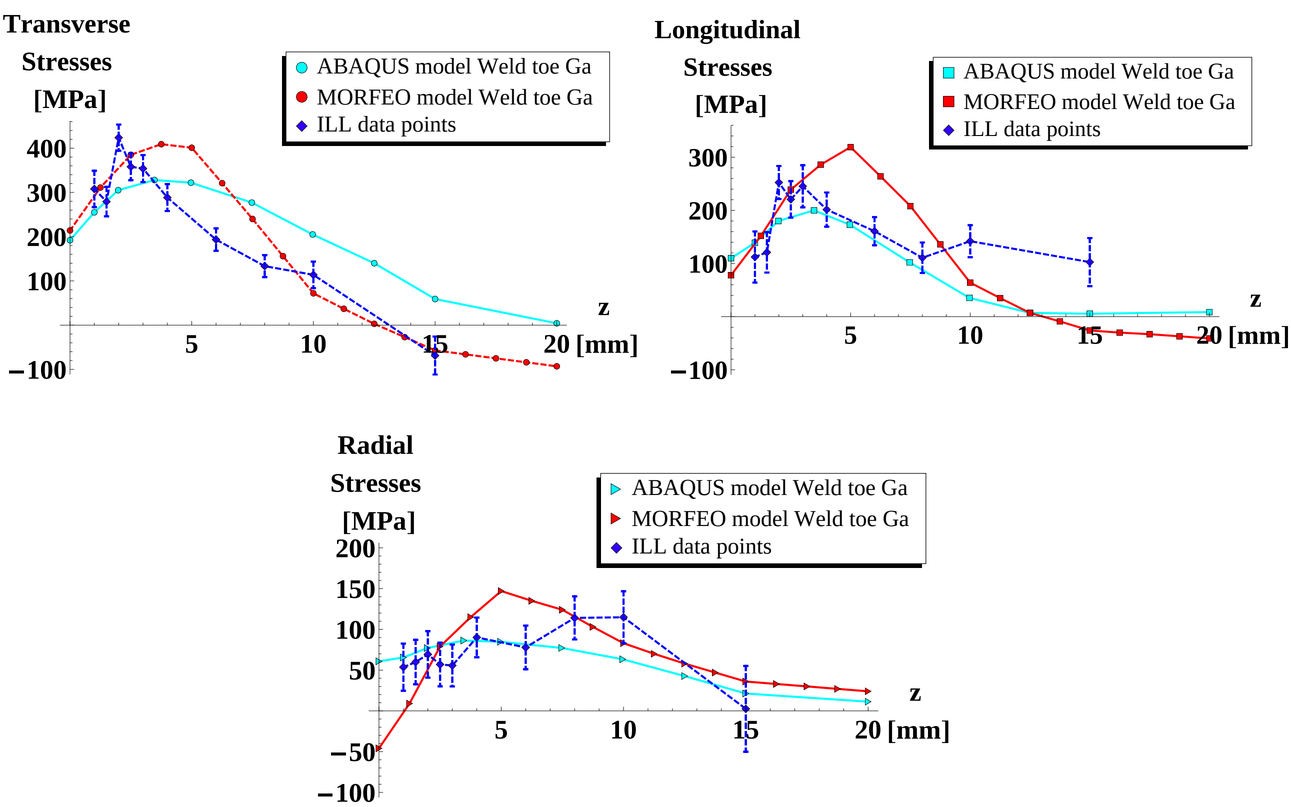

Fig. 2: Comparison of transverse, longitudinal and radial residual stress distributions (ABAQUS, MORFEO and experimental data) at the weld toe though the 20 mm chord wall thickness.

In Fig. 2, the results obtained numerically confirmed that transverse residual stresses are greater than longitudinal ones, which are greater than radial ones. Figure 1b also gives the proof that a strong restraining effect occurs between the braces keeping transversal residual stresses at a high value.

Figure 2 shows that the numerical distributions give the global magnitude of experimental residual stresses and that the maximum values they reach are quite close to the experimental ones. However, the transverse residual stress distribution obtained with ABAQUS is shifted to the right compared with the experimental distribution. It means that transverse residual stresses should be compressive at 13 mm depth but the models present tensile residual stresses through all the depth. MORFEO results predict more accurately the transverse residual stress distributions whereas ABAQUS results fit better the longitudinal stress distribution. The difference between both codes might be attributed to the different heat source models.

Globally, numerical results are in an acceptable agreement with experimental results.

Conclusion

The numerical results, obtained using the ABAQUS and MORFEO codes, have shown to be globally in good agreement with the experimental results obtained from neutron diffraction measurements. Our simplified model proved its ability to reproduce the residual stress distribution in the region surrounding the welds even though the peak values are not always well captured and the distribution is sometimes shifted.

Numerical simulations have clearly confirmed the importance of transverse residual stresses and the restraining effect occurring in the gap area. Transverse residual stresses are detrimental because they will superimpose with applied fatigue stresses which are also predominantly transversally oriented.

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