

Estimation of the Impact of Residual Stress on Parameter J Calculation for a Welded Joint

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1. ABSTRACT

This paper presents recent work to gain a better understanding of the impact of residual stress on structural integrity analysis as per nuclear design codes such as Appendix A16 of the French RCC-MR rules. The main objective of the study was to produce experimental data for evaluating the effect of residual stress on fracture analyses, focusing on the values of Parameters K and J and the associated criteria.

The work involved several different scientific disciplines and the special skills of a number of organizations: the Léon Brillouin Laboratory, Veqter Ltd, the LISN and the French Institute for Nuclear Safety and Radiation Protection (IRSN).

To determine the impact of residual stress on crack propagation, a typical welded joint used in the nuclear industry was studied. A set of special experiments were made. Tests were carried out on brittle fracture under increasing monotonic increasing and under fatigue conditions.

Two different methods of residual stress measurement were used and the results were subjected to the same mechanical analysis to estimate the influence of residual stress on crack growth.

2. INTRODUCTION

The goal of the study was to obtain experimental data making it possible to evaluate the effect of residual stress on fracture mechanics analysis focusing on the values of Parameters K and J and the associated parameters [1].

The main experimental results obtained with the tests carried out on two mock-ups with welded V-joints each with a central external semi-elliptical circumferential crack are given, as well as additional data relating to toughness and tensile strength at -150°C obtained with specimens.

This is followed by a description of how residual stress readings were used to determine the value of the induced stress intensity factor.

3. Fracture tests on welded joints

3.1 MOCK-UP GEOMETRY

The task of making the welded joints was entrusted to the company Essinox. The procedure was in accordance with the RCC-M Level 2 recommendations. They were 37.5° V-joints. Figure 1 shows the overall dimensions of the welds made.

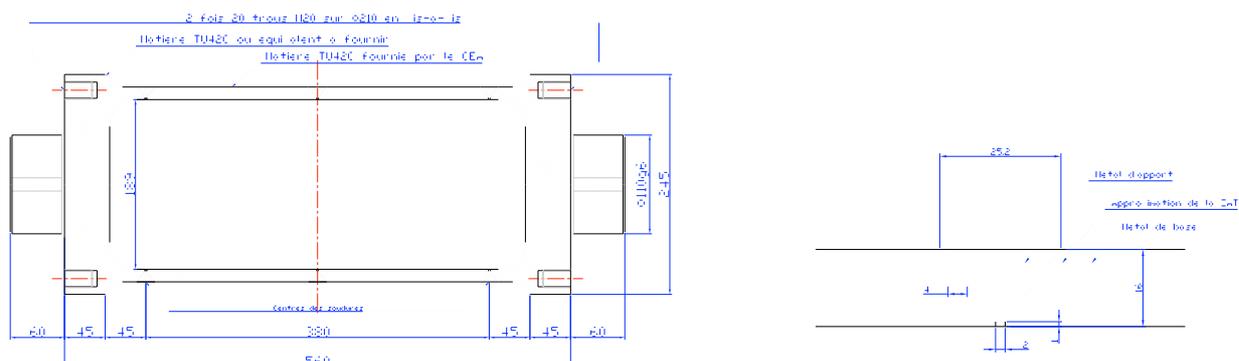


Figure 1 – Welded joint geometry and mock-up design

The test apparatus was a four-point hydraulic bending machine able to apply an overall bending moment of up to 50 tonnes. In view of the direction of the loading, a defect of the circumferential type was decided upon. To be able to monitor the changes, the defects were placed on outer surfaces of the mock-ups. The defects were external semi-elliptical circumferential ones, 3.5 mm deep and 21 mm wide. Figure 2 shows the welded joints, with their initial notches, welded to sleeves used to bolt them onto the arms used to apply the loading.

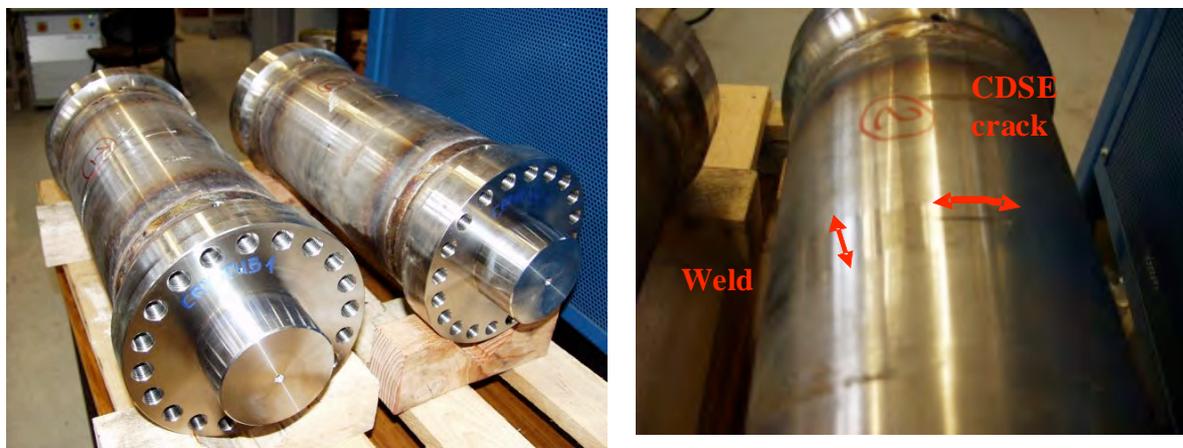


Figure 2 – The TUBRES 1 and 2 mock-ups

The dimensions of the defects were checked by moulding, and the welds (both the central joints and the joints with the sleeves) were checked by X-ray radiography.

1.2 THE MAIN EXPERIMENTAL OBSERVATIONS

The TUBRES 1 fatigue test

The TUBRES 1 test consisted of subjecting the mock-up to cyclic fatigue loading (load factor $R=0.1$) for some 78,000 cycles. This resulted in the crack growing considerably on the outer surface in the circumferential direction and penetrating all the way through the thickness of the mock-up. Figure 3 shows the crack on the outer surface as it appeared before removal of the mock-up from the machine. It was found that the propagation of the crack deviated slightly from a strictly circumferential direction, while remaining in the filler metal.



Figure 3 – Crack propagation on the outside surface

The mock-up instrumentation (cut-wire gauge and potential difference sensor) showed that through-wall penetration did not occur while propagation on the outside surface was still limited (total straightening of the defect before growing circumferentially, see Figure 4).

After the test, the TUBRES 1 mock-up was post-cracked by brittle fracture, and the fracture face obtained can be seen in Figure 4.

On the inside surface, the full length of the final defect was estimated at around 95 cm whereas it was estimated at 125 mm on the outside surface. It was observed that the crack trajectories did not run completely straight through

the thickness, being at an angle (in terms of the width divided by the inner or outer radius) of between 35° at the outer surface and 29° at the inner surface.

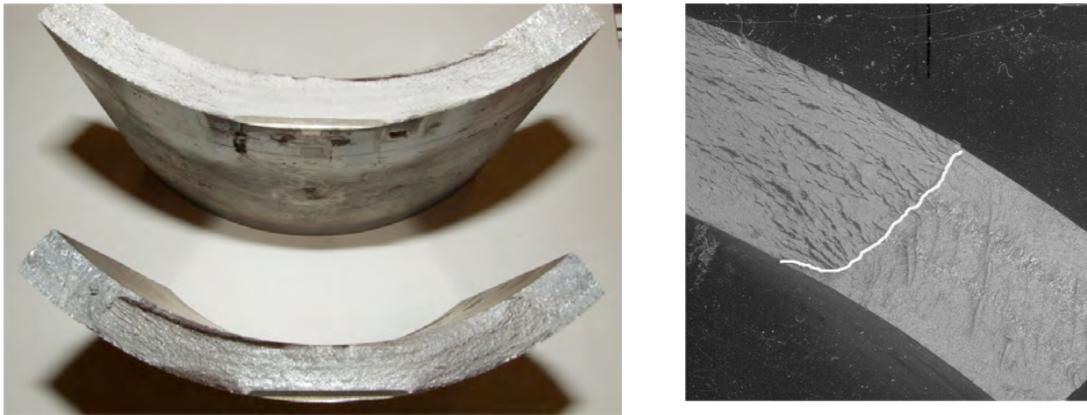


Figure 4 – Fracture face and closeup of final front

The TUBRES 2 brittle fracture test

The TUBRES 2 mock-up was first pre-cracked by fatigue to obtain a real crack rather than a machined notch. The pre-cracking needed, however, to be limited as it was expected that the deeper the initial crack was the less the influence of the residual stress would be, as the latter is highest at the surface.

After 48,000 fatigue cycles to obtain pre-cracking (which resulted in propagation of slightly less than 1 mm, see Figure 6), the brittle fracture test was carried out at -150°C. This temperature was adopted for the following reasons:

- the data currently available at the LISN on welded material indicate that there is a non-negligible risk of mixed ductile and brittle fracture failure at temperatures of around -50°C; to make sure that fracture was purely brittle, it was necessary to keep the temperature at a completely different level,
- a dry run without mechanical loading showed that it was possible to maintain such a temperature sufficiently constant despite the substantial volume of material.

Complete fracture of the mock-up is shown in Figure 5.

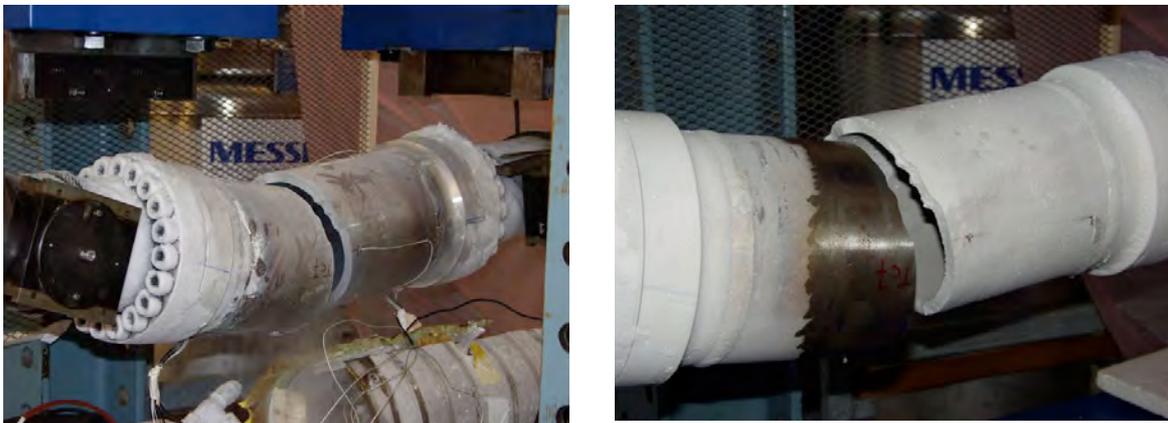


Figure 5 – The TUBRES 2 mock-up after testing

The fracture moment was around 1.05×10^8 N.mm at an actuator travel of 16 mm and slight opening of around 0.04 mm.

Figure 6 shows the fracture face after testing, the front corresponding to the initial cut notch is in blue and the front corresponding to pre-cracking is in red.

As in the TUBRES 1 test, the crack did not stay in the circumferential plane of the initial crack.

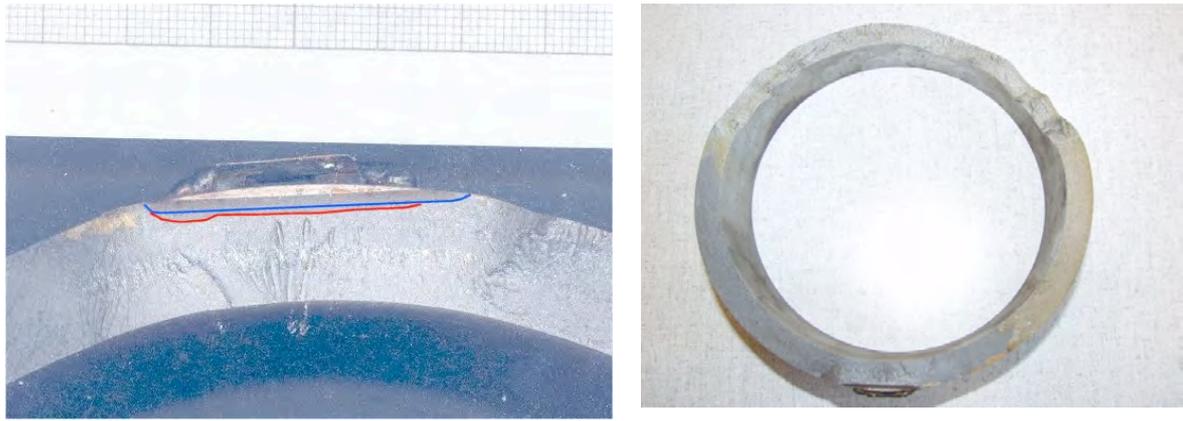


Figure 6 – Photos of the mock-up after testing

2 Measurement of residual stress in the welded joint

2.1 MEASUREMENT OF RESIDUAL STRESS IN THE WELDED JOINT BY NEUTRON DIFFRACTION

2.1.1 Measurement method

The principle of the method resides in measuring the lattice spacing of a crystal and using it as a strain gauge. Neutrons allow far greater penetration of most materials and require a volume of at least 1 mm³. In comparison, the volume used by X-rays is around 10⁻⁶ to 10⁻⁵ mm³.

When a neutron beam impinges on polycrystalline material, it is diffracted in accordance with Bragg's law:

$$n\lambda = 2d_{hkl} \sin\theta_{hkl}$$

where (hkl) represents the Miller factors of a diffraction plane, d_{hkl} being the lattice spacing of a plane (hkl), observed at an angle of $2\theta_{hkl}$ while λ is the wavelength of the neutrons and n is the order of reflection, which was considered to be equal to 1 in the measurements. If stress is then applied to the material, and hence to the crystal planes, the lattice spacing will be changed. It then behaves as a strain gauge, with:

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_0}{d_0}$$

where ε_{hkl} is the strain normal to the planes (hkl) and d_0 is the reference lattice spacing of the planes (hkl). Term d_0 represents the reference lattice spacing, a value generally hard to assess as it corresponds to the value for a material free of any stress.

As strain is measured by this method, the stresses can be determined using elasticity theory equations.

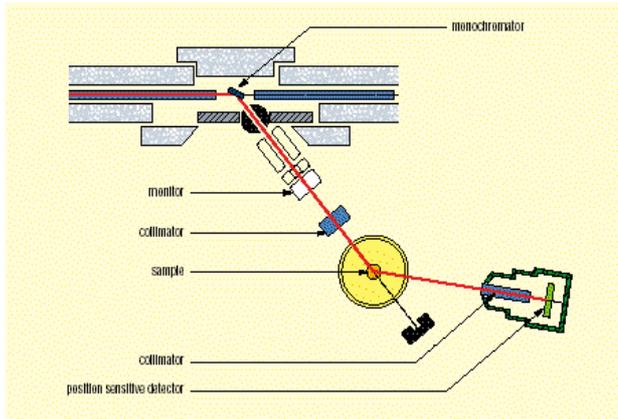
2.1.2 Instrumentation

The measurements were made in the Leon Brillouin Laboratory (LLB), using the Orphée research reactor. This pool-type reactor has a thermal power rating of 14 MW and is designed to provide an intense source of thermal neutrons (at around 70 MeV). It is used by researchers in a number of fields (chemistry, metallurgy, physics etc.).

The neutrons produced are fed to different experiment zones via guides (G1 to G6) consisting of rectangular-section glass tube of which the walls are made reflective to neutrons with a layer of nickel. A vacuum is maintained in the guides and, by total internal reflection, neutrons can be channelled through them from the research reactor over distances of up to fifty metres with very little loss.

Diffractometer G5-2 is installed in one of the cold neutron guides. This diffractometer is of the two-axis type and is mainly intended for stress evaluation. The two main features of the instrument are the presence of a system of slots for the incident and reflected beams to enable precise determination of the volume to be analysed with the neutrons.

Also, the specimen is mounted on a Euler cradle or a three-axis adjustable mounting with powered movement along the x and y axes.



General layout of the diffractometer G 5-2.



Figure 7 – The G5.2 diffractometer in the LLB Laboratory in Saclay

2.2 MEASUREMENT OF RESIDUAL STRESS IN THE WELDED JOINT

The measurements were made in the Leon Brillouin Laboratory by V. Klosek. The measured volume was 1 mm^3 . The measurements were made at four depths (2, 6, 10 and 14 mm) at lateral distances of up to 17 mm from the centreline of the weld. A set of measurements were made on either side of the weld to correct for possible misalignment of the centreline.

The reference lattice spacing was determined on the basis of null radial stress.

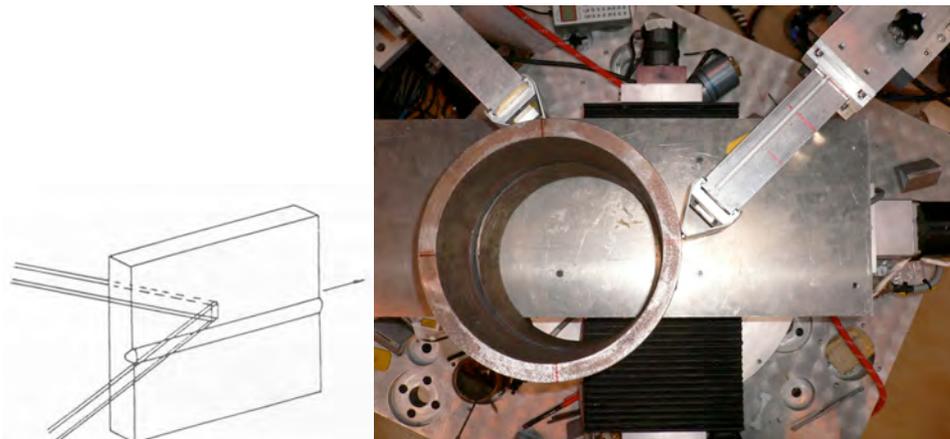


Figure 8 – Measurement of tangential stress

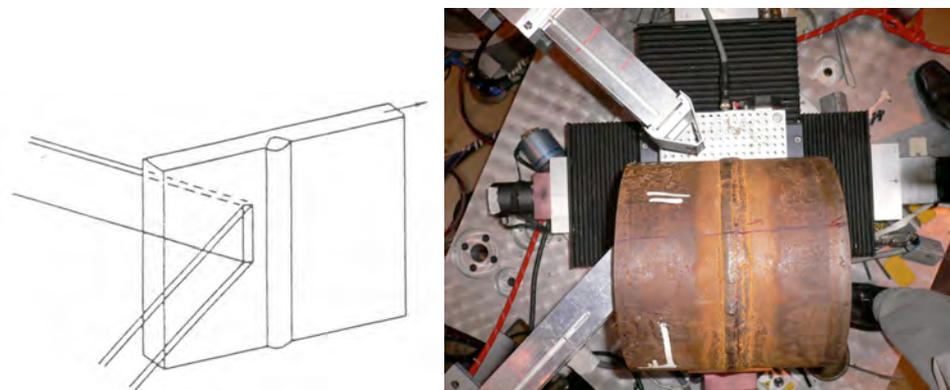


Figure 9 – Measurement of axial stress

2.3 MEASUREMENT OF RESIDUAL STRESS IN THE WELDED JOINT BY THE DEEP HOLE DRILLING METHOD

2.3.1 Principle of the method [3]

The deep hole drilling method for residual stress measurement developed by Vecqter Ltd. is a semi-invasive technique. It is based on measurement of the strain induced by stress relief in a tube is cut from material under residual stress. The measurement procedure is shown in the following illustrations.

The deep hole drilling method consists of the following five steps:

1. Reference blocks are placed on the specimen, on either side of the measuring position.
2. A 1.5 mm hole is drilled through the blocks and the specimen.
3. The hole diameter is measured and constitutes reference diameter \varnothing_0 . The measurement is made along the entire length of the hole in the specimen at 0.2 mm intervals at angular offsets of 22.5°.
4. A cylinder of the material containing the initial hole is removed by electro-erosion cutting. This cylinder has an outside diameter of 5 mm (and an inside diameter of 1.5 mm).
5. The diameter of the hole is measured again along its entire length, in the cylinder and in the reference blocks. The measurements are made at exactly the same points as in Stage 3.

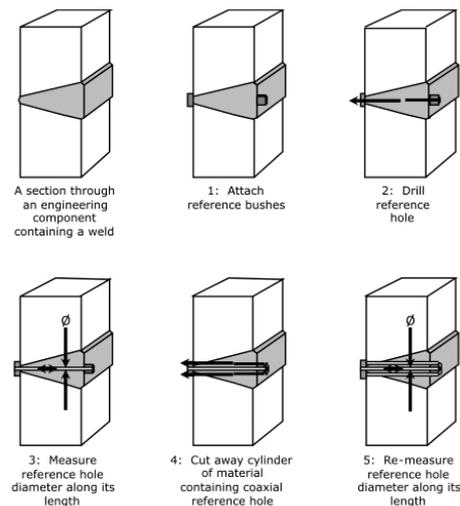


Figure 10 – The deep hole drilling method

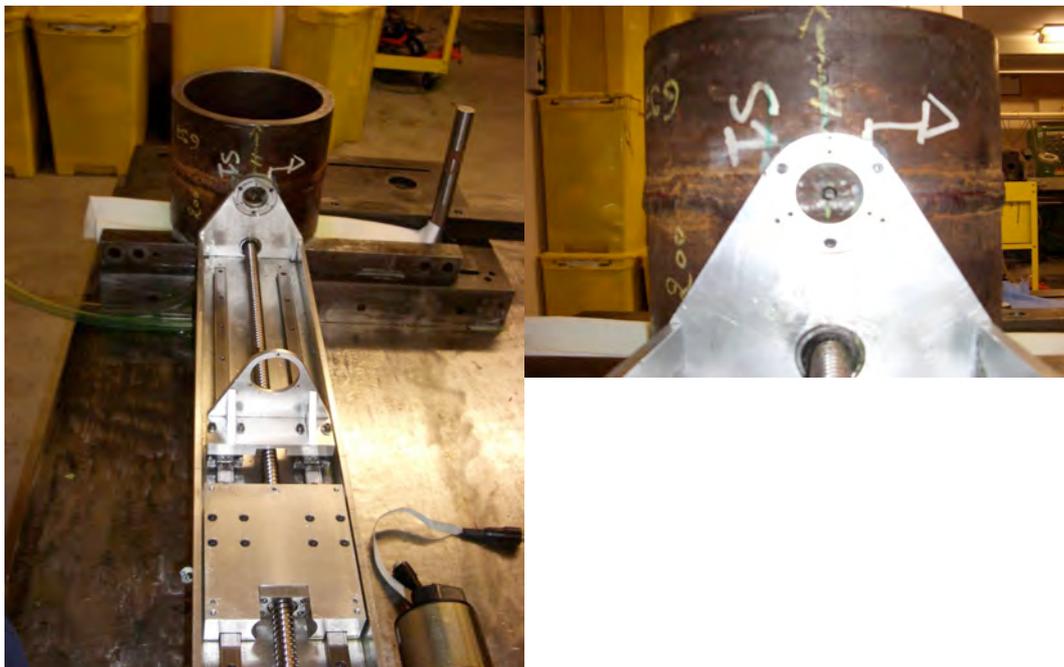


Figure 11 – Measurement setup for the Vecqter Ltd. deep hole drilling residual stress determination method

Diameter \varnothing_0 measured in Stage 3 corresponds to the diameter in the presence of residual stress. The removal of the cylinder of material containing the hole in Stage 4 relaxes the residual stress and the subsequent hole diameter

measurements correspond to the absence of residual stress. The differences between the measurements made in Stages 3 and 5 enable the residual stress initially present in the component to be estimated.

3 Comparison of residual stress measurements

The following figure shows a comparison between the residual stress measurements obtained with two different methods (deep hole drilling and neutron diffraction). The axis representing thickness is orientated as follows: Value 0 corresponds to the inside end of the tube and Value 18 corresponds to the outside one. The crack is accordingly situated on the right hand side of the graph. For clarity, the same colours are used for the components of the stress.

For each component of the measured residual stress, the two methods indicate the same changes along the thickness of the component. To wit:

- As regards tangential stress, there was a zone under tension (with high levels of between 235 and 350 MPa) followed by a drop and a reversal to compression.
- As regards axial stress, there was initially slight compression then tension (500 MPa) followed by compression and finally tension again.
- As regards radial stress, the levels were low.

Maximum levels were reached at the same depths, although this was less true of tangential stress. It is to be noted that neutron diffraction gives the residual stress in a very limited area (corresponding to the size of the neutron beam) while the deep hole drilling method gives an estimate of the residual stress in a wide area, corresponding to the average residual stress within it. This may go some way to explaining the observed differences in tangential stress at a depth of 14 mm.

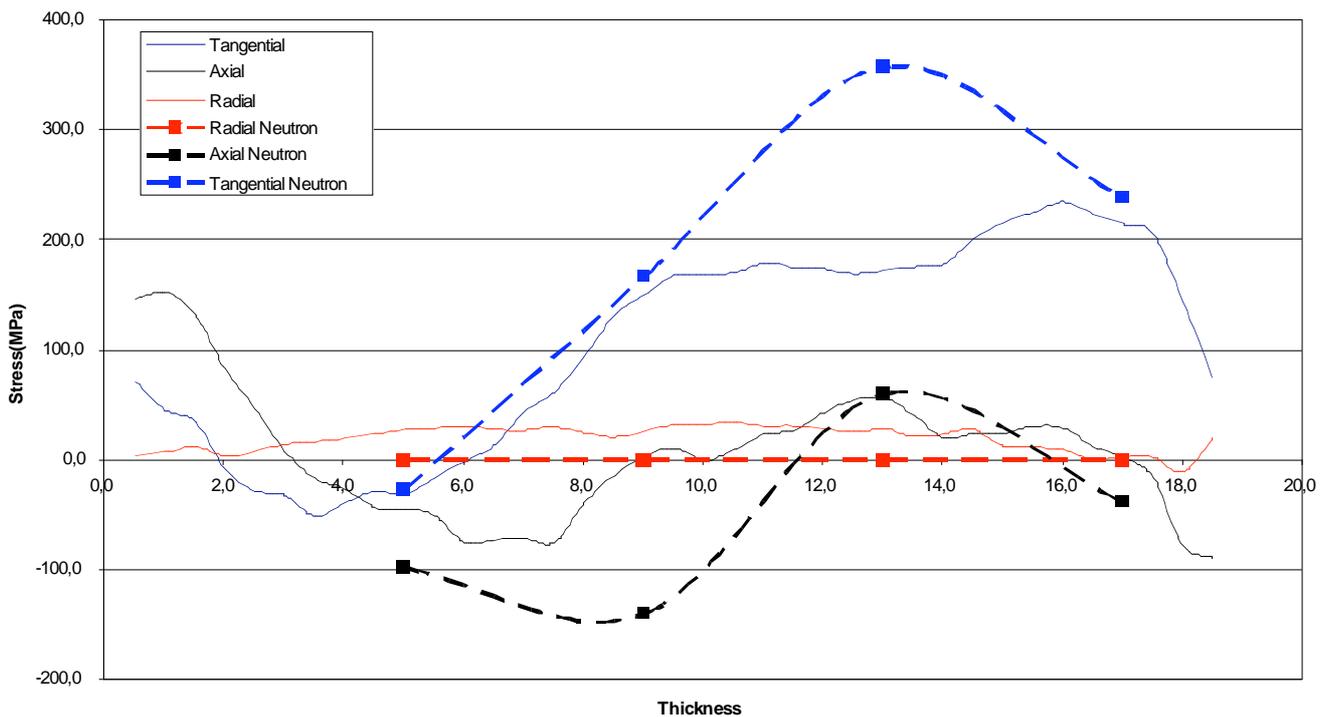


Figure 12 - Comparison of residual stress measurements

The deep hole drilling method offers a precision of 30 MPa. The joint configuration prevented properly estimating the residual stress near the edges, as the depth at which measurement is unaffected by edge-effect is 0.4 mm.

3.1 ADDITIONAL PROPERTIES OF THE MATERIAL AT -150°C

To supplement the information on the weld metal, particularly at -150°C, tensile strength specimens and CT12 compact tensile strength testing specimens (maximum possible thickness 13 mm with a tube 16 mm thick) were taken from a welded joint made with the same procedure as the mock-ups tested. Conventional and rational tensile

strength curves for the filler metal at -150°C were thus obtained. Young's modulus at this temperature was estimated at 210 GPa, and the elastic limit at 550 MPa.

CT12 specimens were subjected to brittle fracture testing (monotonic loading and increasing actuator displacement) on a 100 kN hydraulic machine to determine the toughness of the material at -150°C. The fracture faces of the two specimens used are shown in Figure 13, the crack front corresponding to the initial pre-crack made by fatigue being represented with a continuous line. Slight fluctuations in the geometry of the crack fronts are visible.

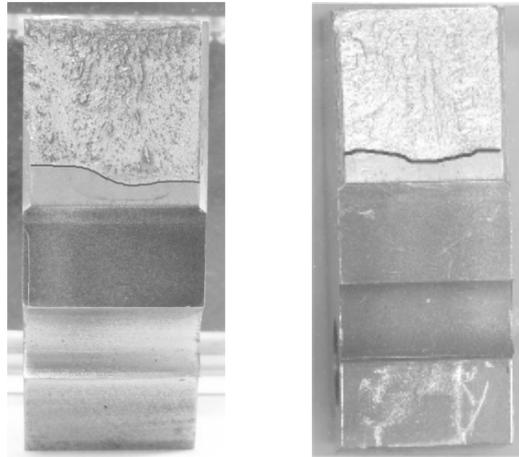


Figure 13 – CT12 specimen fracture faces

To evaluate the value of K_I at the breaking point, the test results were collated by straightforward application of Appendix A16 of the 2007 issue of the RCC-MR rule [1] and it was assumed that the crack front in the specimen was straight. As a check, an elastic finite element calculation was made to assess the possible impact of postulating that the crack front was straight in the light of its actual geometry. Table 1 summarises the results obtained.

	F/ouv	F rupture	a0 estimé (mm)	KI (Cast3M)	KI (A16)
6972 FB	44,62	4,96	13,66	35,12	34,54
6972FC	50,72	4,97	13,03	31,47	31,53

Table 1 – Values of K_I at breaking point (A16 and CAST3M)

It can be seen that there is almost no difference between the values obtained by applying Appendix A16 and by finite element calculation with CAST3M. We therefore adopted an average value for K_{IC} of around $33 \text{ MPa}\cdot\sqrt{\text{m}}$.

These values can be compared to those obtained for the TUBRES 2 mock-up by elastic finite element calculation (behaviour of the filler metal at -150°C) with a crack of a length initially between 4 and 4.5 mm.

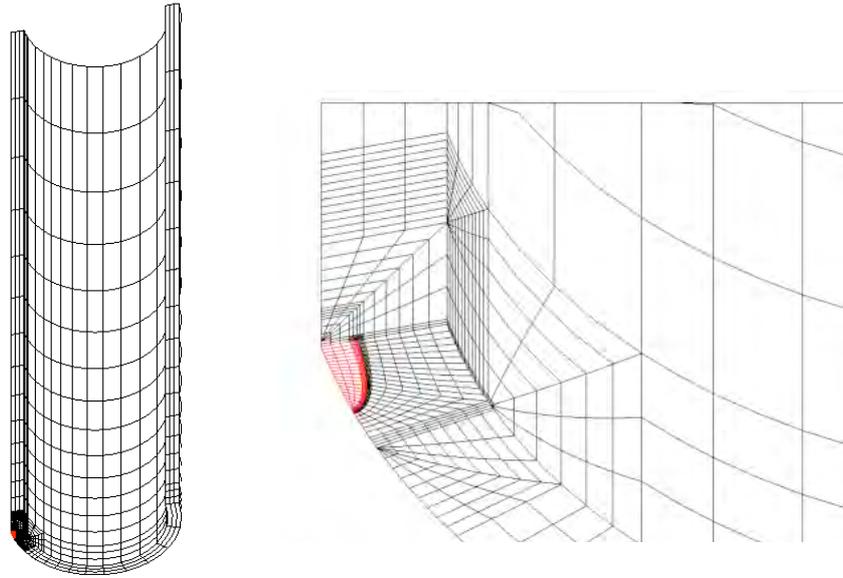


Figure 14 – CAST3M mesh of TUBRES 2 mock-up

For the experimentally determined moment of fracture, the values of K_I were found to be 29 and 30 $MPa\cdot\sqrt{m}$ with a pre-cracks of 4 and 4.5 mm respectively. Values very close to those obtained with CT12 specimens were thus obtained.

3.2 DETERMINATION OF THE STRESS INTENSITY FACTOR DUE TO RESIDUAL STRESS

The created defect was a semi-elliptical notch on the outside surface of the tube. The defect was orientated circumferentially.

For reference, the initial dimensions of the defect were:

- a (defect depth) = 3.5 mm
- 2c (defect length) = 21 mm

From the axial stress profile, the best interpolation of the stress along the normalised thickness was determined. Axial stress was used as it governs opening (residual tensile stress) or closing (residual compressive stress) of the created defect. The results of the interpolation are shown in the following figure. Then, using the influence coefficients (i_0 , i_1 , i_2 and i_3) defined in Appendix A16 of the RCC-MR rules and taking a thickness to inside radius ratio of 1:20 and an a/c form factor of 0.25, the variation of the stress intensity factor (at the crack root and at the surface) was determined as a function of crack advance. This is shown in the following figure.

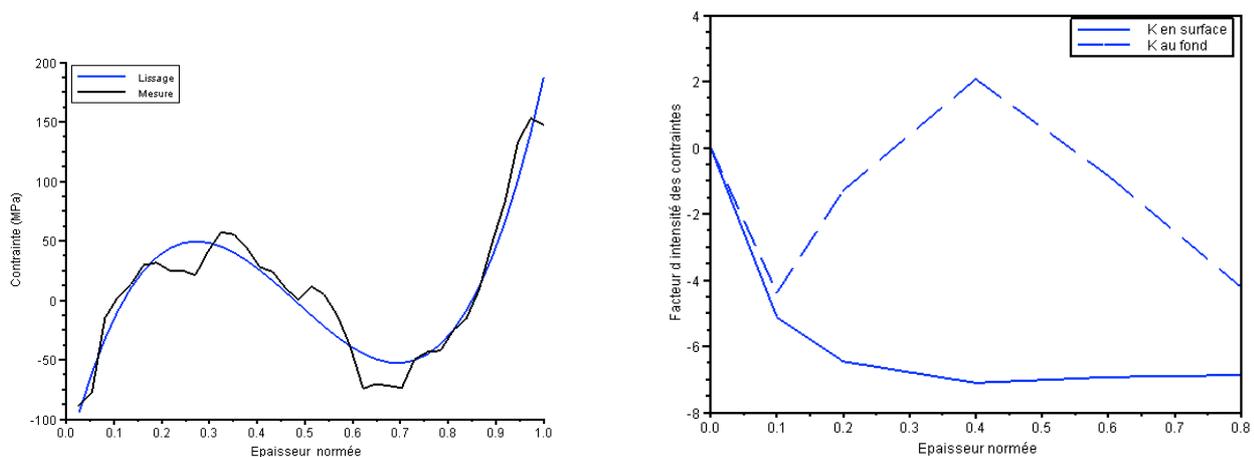


Figure 15 – Interpolation of axial stress and stress intensity factor (at crack root and at the surface) for a circumferential outside semi-elliptical defect

4 General conclusions

The work carried out related to estimating the impact of residual stress on conducting tests on tubes with welded joints. Mock-ups with welded V-joints were made by the company ESSINOX as per RCC-M Level 2 recommendations.

The tests performed on tubes comprised:

- a brittle fracture test at -150°C ,
- a fatigue test under four-point bending cyclic mechanical loading at room temperature,

In the case of the fatigue test, it was observed that crack propagation deviated from the plane of the initial crack, eventually leaving the welded joint. This propagation deviation recurred in the brittle fracture test.

For the experimentally determined moment of fracture, the values of K_I were found to be 29 and 30 $\text{MPa}\cdot\sqrt{\text{m}}$ with a pre-cracks of 4 and 4.5 mm respectively. Additional tests on CT12 compact tensile strength test specimens were carried out to determine K_r at the breaking point. Interpretation of the results of the tests gave an average value of K_{IC} of around $\text{MPa}\cdot\sqrt{\text{m}}$. Values very close to those obtained with tests on tubes were thus obtained.

Also, residual stress was measured using two different methods. The first method involved neutron diffraction in the Orphée research reactor. The second was the deep hole drilling method, conducted by the company Veqter Ltd. The two methods indicated the same variations of residual stress with depth and the similar levels of stress. Residual stress measurements obtained with the two methods were similar and can be considered to be acceptable.

Using the results, an estimate was made of the stress intensity factor due the presence of residual stress. It showed that the level of factor K induced by the residual stress was relatively low and slightly negative (being around $-6 \text{MPa}\cdot\sqrt{\text{m}}$).

This result was consistent with the experimental findings, which showed no major impact of residual stress on the resistance of the welded joint studied.

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- [3] L.O. Chidwick, "Deep-hole drilling stress measurement on a ferritic steel girth-welded pipe section", report, Veqter Ltd, 2008.