Impact of Welding Residual Stresses on the risk of fracture in the brittle to ductile transition of ferritic steels

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ABSTRACT

This paper describes a test campaign initiated by EDF and FRAMATOME on the topic of the Welding Residual Stress consideration within the Fracture Mechanics Assessment of components.
For that purpose, pipes mock-ups with a non-post-weld heat-treated weld at its centre part and containing an initial crack are submitted to 4 points bending load tests at low temperature up to failure.

The paper describes the material used for this campaign, the Welding Residual Stresses characterisation, and the post-test interpretation of the first test achieved today. Despite a non-expected failure during the test, this first test illustrates the large conservatism of the design approach relying on global approach and a consideration of the Welding Residual Stress contribution through an envelope membrane stress through-thickness stress distribution.

INTRODUCTION

The primary and secondary Pressurized Water Reactor (PWR) circuits are a complex set of pressure-welded steel piping and components. As the second barrier to the spread of fissile materials is concerned, demonstrating the integrity of these circuits is a major safety objective. This demonstration must cover all possible loading situations encountered in service (normal operation as well as accidental situations) and all possible failure modes, material functions and associated conditions of use.
For the structures we are talking about, welded joints are most often concerned by the Fracture Mechanics Assessment (FMA): the welds may present defects (ex. lack of fusion) and generally have a lower fracture resistance than the forged base metal. Additionally, they may present some Welding Residual Stresses (WRS) that might be considered in the assessment.

Those WRS are due to the fact that welding process is a process that generates residual stresses due to the high temperature gradients it creates. Their potential impact on the risk of cracking is directly related to material behaviour. In open literature, these WRS have been shown to have an impact on the risk of fast fracture in the brittle domain where the behaviour is quasi-elastic, but this impact appears to be overestimated in the lower shelf. Therefore, the needs of the industry are to put in place criteria adapted to the problem of taking WRS into account in the FMA, and to validate these criteria through experiments at different scales, then define the domain where these stresses must be considered or can be neglected.

The main purpose of work presented here is to perform representative experimental tests to quantify the effect of WRS in the brittle to ductile transition temperature range. For this, four-point bending tests on representative welded pipes with a non-stressed relief weld and including a crack are planned in the brittle to ductile transition domain. The objective is here to measure the fracture resistance in the presence of WRS, then to compare it to the prediction of numerical models with or without considering WRS. Those models are directly transferred from the specimen to the structure using the local approach (through the BEREMIN model).

MATERIAL DESCRIPTION

Base metal (BM)

The material considered in this study is a C-Mn steels pipe (P265GH in French denomination) representative of the auxiliary piping system of French PWR. The initial pipe structure was 7.5 m long, with an external diameter of 406.4mm and a thickness of 23mm.
Tensile properties of this base metal at room temperature and -70°C are provided in table 1.

Temperature (°C)	σ_y (MPa)	σ_u (MPa)	A(%)
20	334	499	33.2
-70	377	584	36.5

Table 1: Base metal material properties

Weld metal (WM)

The weld joint investigated in this test campaign is a manual arc weld representative of the auxiliary piping welds (weld metal denomination: Tenacito-R).
Seven weld joints were prepared by FRAMATOME, one for weld metal mechanical characterisation, six others for pipe testing. For maximizing the possible impact of the WRS on fracture, those welds are not post-weld heat-treated.
The table 2 provides the chemical composition of this weld metal.

C	Mn	Si	P	S	Cu	Cr	Ni	Mo	Sn
0.094	1.090	0.592	0.005	0.0056	0.064	0.319	0.034	0.009	-

Table 2: Chemical composition of the weld metal

Stress-Stain curves of the weld junction

The material behaviour of the welded junction was measured through tensile specimens taken across the welded metal (see fig. 1) then tested with the CEA-IMEC process [1] which allows measuring the material behaviour al along the calibrated part of the specimen. The resultant yield stress and tensile cure obtained at -70°C are shown on figure 2. From those data, three mean behaviours are defined for describing the junction in modelling: the weld metal (with a yield stress σ_y = 530), the Heat Affected Zone (HAZ, σ_y = 450 MPa) and the base metal (σ_y = 377 MPa – this last asymptotic value being determined with specimen taken within the base metal).

Figure 1: Tensile specimen for welded joint characterisation.

Brittle to ductile transition

Toughness tests were performed for both the weld metal (tests performed within this study) and the base metal (data provided by CEA which provided a T_0 = -140°C).
The Master-Curve (MC) reference temperature T_0 of the welded joint was determined in two steps through different specimen geometries:

- Three Charpy test were performed for a first rough evaluation of the T_0 reference temperature evaluation. Those tests, associated to larger available data of the same material family provided a TK_5 then T_0 estimates: TK_5 = -83°C, T_0 = -150°C.

- A more accurate T_0 determination was done through CT12.5SG20% specimen following the ASTM-E1921 [2] standard. Eight tests were done for that purpose, between -150°C and -100°C. This second set of tests provided T_0 = -110°C.

The figure 3 compares the toughness data obtained for the two materials. As it is illustrated on that figure, the two materials are exhibiting the same behaviour in the brittle to ductile transition.
From this figure, the pipe tests temperature was decided at -70°C (ie. T – T_0 = 50°C), considering that:

- This temperature is within the highest temperatures of the brittle to ductile transition. At this temperature fracture test results on CT specimen are dominated by ductile initiation.
- This temperature is the one selected by the CEA for base metal testing.
- This temperature is also a reasonable limit for the cooling device designed for the pipe testing.

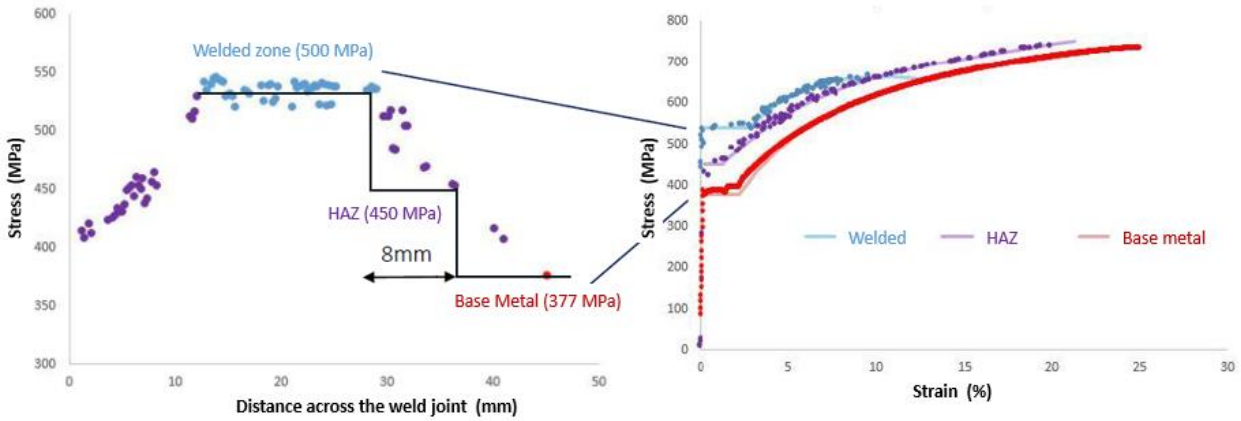

Figure 2: Material behaviour across the welded junction at -70°C

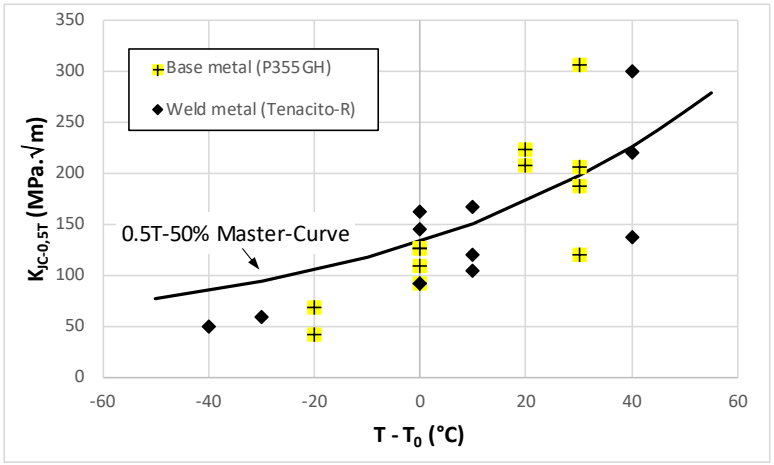

Figure 3: Brittle fracture toughness data on CT12.5SG20% specimen

CHARACTERISATION OF THE WELDING RESIDUAL STRESS FIELD

The as-welded WRS were measured at room temperature by 2 different processes:

- X-ray diffraction measurement which provides information on surfaces. This measurement was performed on both inner and outer surfaces on a half-pipe weld before machining the CT specimen (see fig. 4, left picture).
- Deep-Hole Drilling (DHD) measurement which provides information across the thickness of the weld (see fig. 4, right picture). The DHD measurements were done at two locations: at the middle of the weld

joint (where the initial defect is located for the pipe test) and through the last weld bead on external surface (corresponding to the highest level of WRS).

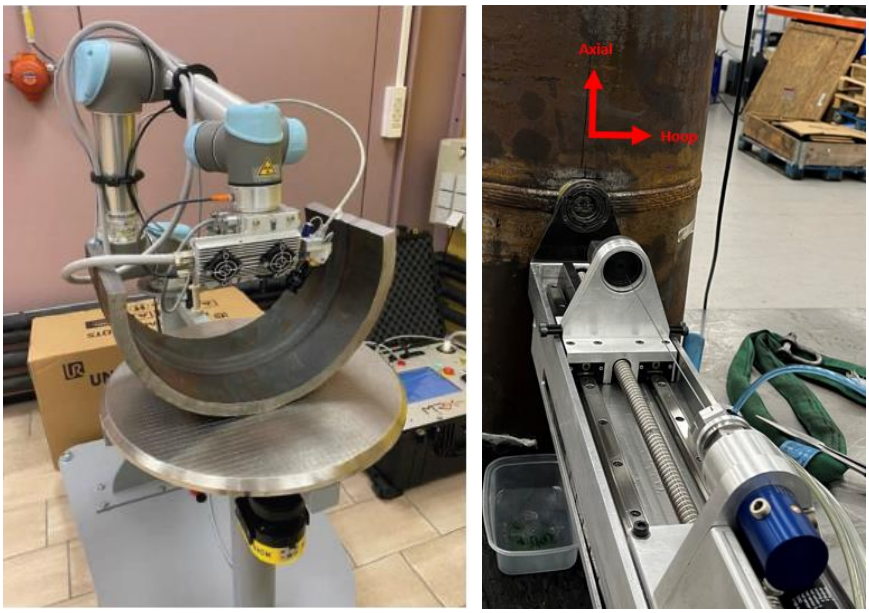

Figure 4: X-ray diffraction measurement (on left) and Deep-Hole Drilling measurement (and right)

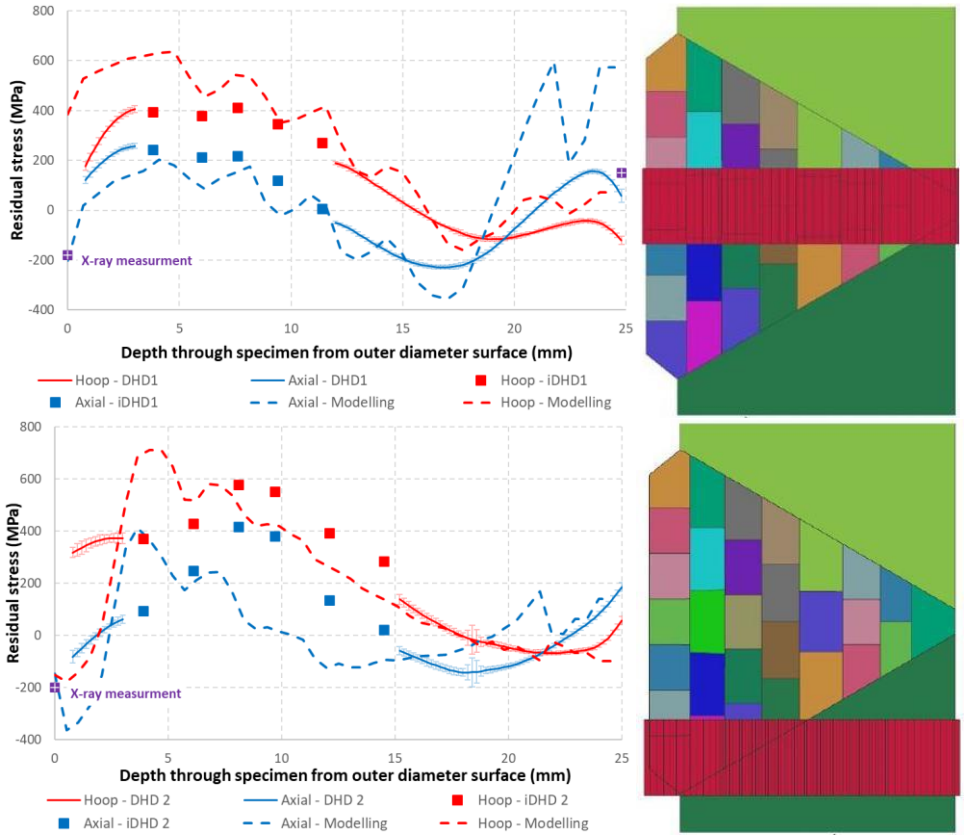

Figure 5: Comparison of the different WRS results: at the middle of the weld joint (on top) and across the weld bead (bottom)

Those measurements were completed by a Numerical Welding Simulation (NWS) of the welding process. This NWS was performed with the 2D model represented on figure 5. For comparison to the DHD measurements, the stresses determined through the NWS are corresponding to a mean value on the red width represented on figure 5. As shown on this comparison, the accordance between the three information is relatively good.

Regarding the possible impact of the WRS on fracture:
- The defect of interest is the circumferential surface defect corresponding to the postulated flaws in FMA performed at design level.
- For machining and measurements feasibility reasons, the tested initial defect for the pipe test is located on the external surface, at the middle of the weld joint.
- For this location, the WRS of interest are the axial stresses (stresses in blue on fig. 5). Those stresses are negative at the near outer surface of the weld, but rapidly become positive 3 mm bellow this surface.

As a synthesis, from all those measurements and modelling and considering a surface defect ~10 mm deep at the external surface, a positive SIF associated to the WRS is expected for defect position.

Depth a	**Half length c**	**$K_{res}(\sigma_{max})$**	**$K_{res}(\sigma_{mes})$**	**$Kres(\sigma_{max})/K_{JC}$**	**$Kres(\sigma_{mes})/K_{JC}$**
(mm)	(mm)	(MPa.√m)	(MPa.√m)		
10	50	67	28	0.88	0.27

Table 3: Contributions of the WRS to the Stress Intensity Factor

The table 3 Provides an evaluation of the contribution of the WRS to the Stress Intensity Factor (SIF). Within this table:
- Kres is the determine contribution on the basis of the maximum residual stress (σ_{max}) or on the basis of the measured axial stress distribution (σ_{mes}). The first value corresponds to a common design approach which consider the WRS distribution through the thickness as a membrane stress distribution at the maximum level of the stress field.
- K_{JC} corresponds to the 1% fracture toughness of the Master-Curve for T – T_0 40°C.

FIRST PIPE TEST

Pre-sizing – definition of the test temperature

The figure 6 gives a scheme of the tested pipe and a picture of the 4 points bending loading device:
- Two ferritic arms are welded to the central part mock-up containing the tested weld joint. The total pipe length is about 5 m. For the mock-up, the external diameter is Φ_{ext} = 406 mm and the thickness t = 22 mm.
- The cooled area is between the two central loading points. This cooling is obtained by a liquid nitrogen circulation on the external surface (fig. 7). Thanks to the good thermal conduction of the ferritic steel, the temperature difference within the central mock-up is less than 4°C (less than 0.3°C at the defect location).

The mock-up and the test temperature being defined, the target of the test pre-sizing is to define the crack size for which the ductile crack initiation can be reached before the plastic collapse of the pipe and maximizing the possible impact of WRS. For that purpose, two indicators are defined:

$$r_1 = \frac{K_{res}(\sigma_{mes})}{K_{JC}} \quad , \qquad and: \; r_2 = \frac{M(J = J_{0.2})}{M_L} \quad , \qquad with: M_L = 4.r_m^2.t.\sigma_y(BM\ at - 70°C)$$

In those formulae:

- K_{JC} is the toughness associated to the 1% MC failure probability (K_{JC} = 75 MPa.√m)
- $J_{0.2}$ is the measured WM toughness on CT12.5SG20% at -70°C ($J_{0.2}$ = 505 kJ/m²).
- M_L corresponds to the limit load bending moment of the base metal part of the pipe.
- M(J = $J_{0.2}$) corresponds to the bending moment at ductile crack initiation (without considering WRS).

Figure 6: Test pipe and four points bending loading device


Figure 7: Cooling device

This last crack initiation bending moment is determined through FEM using a three materials model as defined in figure 2 (see fig. 7). This model provides the elastic-plastic J at the deepest point of the crack.

As illustrated in figure 8, a parametric study was performed for different crack sizes. The final choice for the crack size was a crack depth a = 10 mm and a crack length 2.c = 100 mm, which provides r_1 = 27 % and r_2 ~ 1.

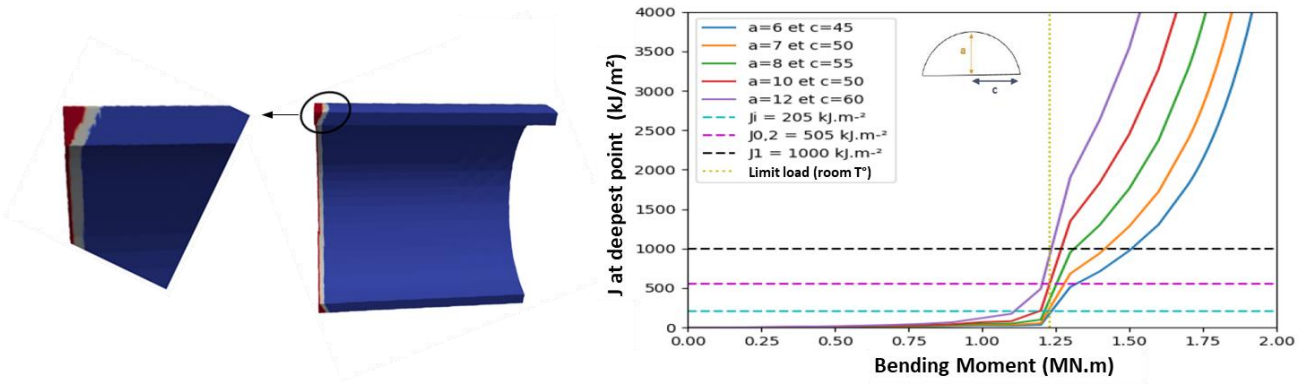

Figure 8: FEM for pipe test pre-sizing

Crack machining and instrumentation

Crack is obtained by first machining an EDM notch and then a fatigue propagation to reach the expected size. Because of presence of residual stress, fatigue propagation is performed with compression loading.

An extensive instrumentation of mock-up (see figure 9) allows us to follow, during tests:

- Load and ram displacement,
- Temperature on mock-up (external and internal surface of the central section),
- Crack opening displacement at three locations along the crack edge,
- Electric potential drop measurements at different locations along the initial notch,
- Rotation of sections of the pipe at roller and weld locations using inclinometers,
- Vertical displacement of the pipe and roller using wire displacement transducers or laser sensor.

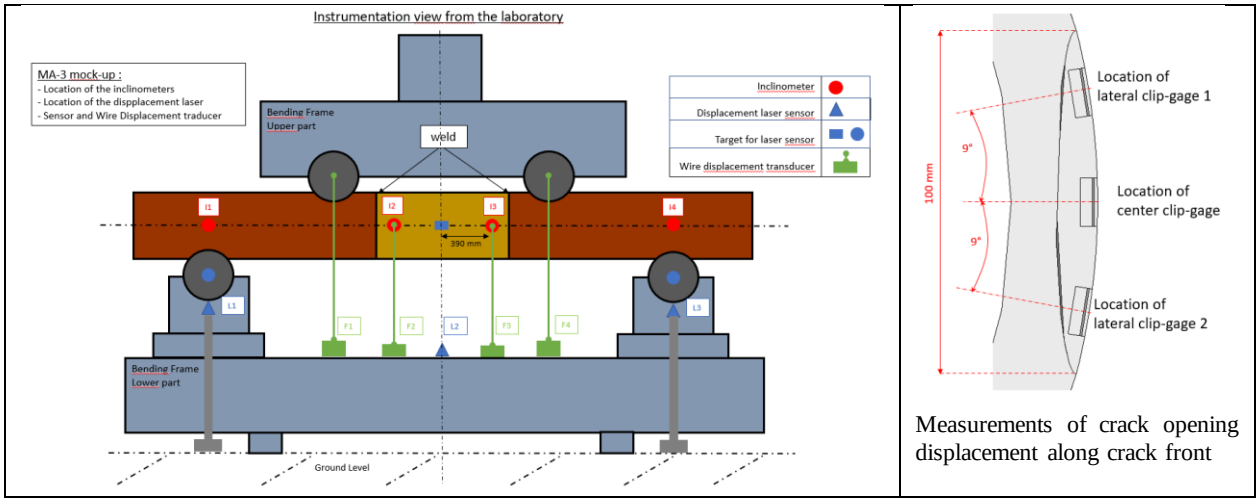

Figure 9: test instrumentation

First phase of post-test interpretation

During the test, the displacement of the jack (upper part of the bending frame) is controlled with a speed equal to 0.5mm/min. When load reached 1533 kN (which corresponding to a moment of 0,99 MN.m) an unexpected fracture occurred in one of the welds between central part and a bending arm. This event did not allow us to achieve the expected loading level in the central weld.

For evaluating the SIF along the crack front at this maximum loading, FEM were performed with the effective crack shape at the end of the pre-fatigue loading. For that purpose, the crack shape was extracted

from the mock-up after breaking by bending load at very low temperature. Figure 10 shows the shape of the crack front and a view of the mesh used for the computations.

A 3D-FEM using the three-materials model given in figure 2 was performed without considering the WRS. This model provides the elastic-plastic J along the crack front at the end of the test (see figure 11). The simple evaluation of the SIF reached at the end of the test can be determined for the following equation:

$$K_{J-max} = \sqrt{\frac{J_{max} \cdot E}{1 - \nu^2}} + K_{res}$$

Where J_{max} is the elastic-plastic J at the deepest point of the crack front at the end of the test, and K_{res} is the elastically determined contribution of the WRS.

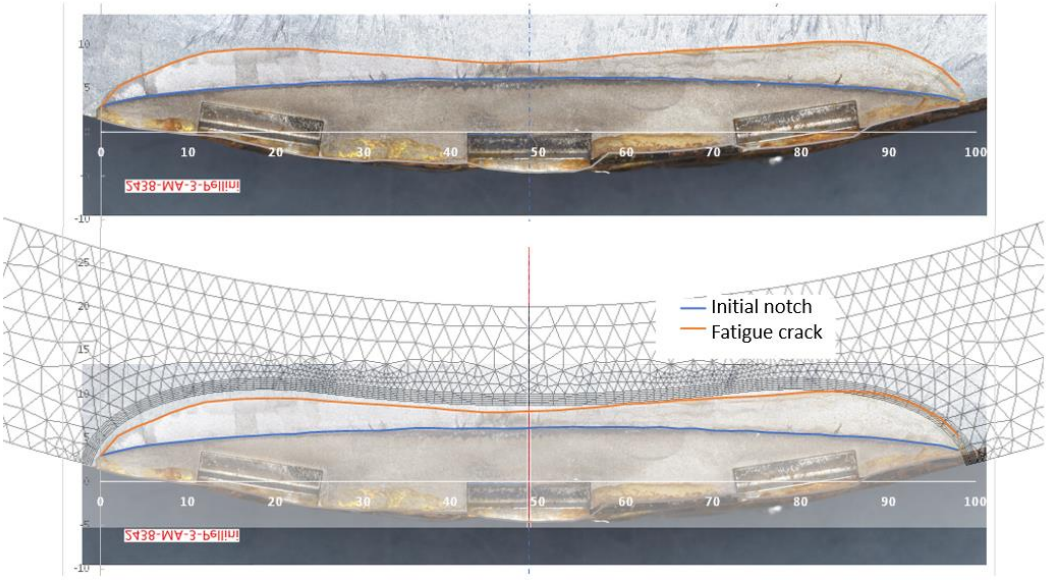

Figure 10: Comparison between crack effective shape and mesh

Three K_{res} evaluations are proposed in table 4:
- Two values derived from the K_{res} contributions provided in table 2.
- One value without considering the WRS.

Pr	$K_{JC}(Pr)$	$K_{J\text{-}max}(\sigma_{max})/K_{JC}$	$K_{J\text{-}max}(\sigma_{mes})/K_{JC}$	$K_{J\text{-}max}(0)/K_{JC}$
1%	76	**2.75**	2.24	1.87
50%	180	1.16	0.94	0.79

Table 4: $K_{J\text{-}max}$ evaluations compared to the Master-Curve toughness.

As it can be seen in this table, the test result is significantly higher than the codified toughness (which corresponds to $K_{JC}(1\%)$. For this test, the design approach assuming a membrane WRS distribution (red value in table 4) appears very conservative (for a test where no fracture occurred!).

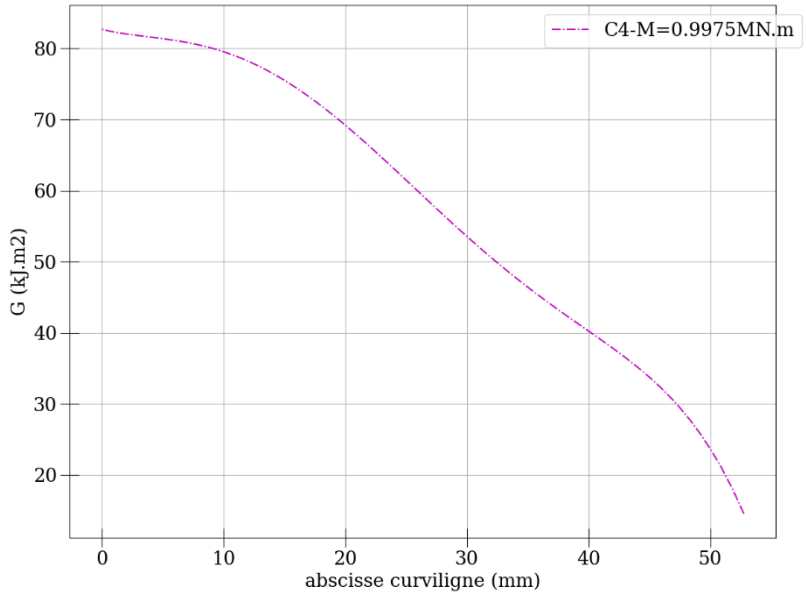

Figure 11: elastic-plastic J along the crack front at the end of the test

Second phase of post-test interpretation

A second interpretation phase is under preparation in parallel of the preparation of the second pipe test. The objective of this modelling is to determine accurately the contribution of the WRS on the crack loading:

- By introducing the WRS in the model.
- By determining their contribution through the J parameter and through a BEREMIN model similar to the one used in [4] for parametric studies.

SYNTHESIS AND CONCLUSION

This paper provides the first results obtained in a test campaign developed by EDF and FRAMATOME on the topic of Welding Residual Stress consideration within the Fracture Mechanics Assessment of components.

For that purpose, pipes mock-ups with a non-post-weld heat-treated weld at its centre part are submitted to a large bending load at low temperature:

- The selected materials for those pipe testing are C-Mn base and weld metals representative of the materials encountered in the French PWR secondary and auxiliary piping systems.
- The selected test temperature corresponds to a temperature close to the upper shelf of the weld metal within its brittle to ductile transition: T = -70°C corresponding to $T - T_0 = 40°C$.
- An external surface defect is machined then pre-cracked at the middle of the weld joint.
- A detailed Weld Residual Stress characterisation by measurement and Numerical Welding Simulation was achieved for estimating their contribution on the fracture process.

The first test was performed but the expected loading couldn't be reached since an unexpected failure occurred in a weld linking the mock-up to the loading arms. Nevertheless, for the maximum loading level reached during the test, the first post-test interpretation phase achieved today illustrates the strong conservatism of the design approach relying on an envelop membrane residual stress distribution.

The work of this test campaign is continuing with the preparation of other pipe tests (4 new tests are planed) and the development of more accurate models integrating the Welding Residual Stresses (both local and global approaches models).

ACKNOWLEDGMENT

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