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STATUS OF THE ON-GOING R&D DEDICATED TO THE RESIDUAL STRESS CONSIDERATION IN FRACTURE MECHANICS ASSESSMENT

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ABSTRACT

An important R&D effort is going on, within the French AREVA/EDF/CEA working group dedicated to the improvement of the 5.4 appendix of the RSE-M, in order to develop and validate specific analytical schemes for the consideration of residual stresses within Fracture Mechanics Assessments. This effort is motivated by the need to consider the residual stresses in the defect tolerance evaluation of welds in the UK-EPR™ project.

The present paper proposes a status of this development phase which is mainly dedicated to two weld joint configurations: the narrow gap stainless-steel weld of the Main Coolant Line and the ferritic weld joint of the main steam line. For those two configurations, main results are highlighted, and a formulation for the consideration of residual stresses in the assessment is proposed. The expected continuation of this program is then provided.

NOMENCLATURE

E, α	Young modulus, Thermal expansion coefficient
ΔT_1, ΔT_2	Linear and non-linear through thickness thermal gradients
J, J^m, J^{res}, J^{th}	Total elastic-plastic J, mechanical contribution, RS contribution, J for thermal loading
J_{el}, J_{el}^{res}, J_{el}^{th}	Total elastic J, RS contribution, thermal contribution
J_{IC}	Material toughness
L_{th}, L_{res}	Loading parameter for plastic correction of thermal loading and RS
k_{th}, k_{res}	Attenuation factors for thermal loading and RS
σ_{res}	Residual Stress
σ_y, σ_{yB}, σ_{yW},	Material yield stress, Yield stress of base metal, of weld metal
M	Weld joint mismatch
ν	Poisson's ratio
FBR	Fast Breeder Reactor
FMA	Fracture Mechanics Assessment
PWR	Pressurized Water Reactor
RS	Residual Stresses
GDA	Generic Design Assessment
HIC	High Integrity Component

1 INTRODUCTION

The Fracture Mechanics Assessment (FMA) is part of the Defence-in-Depth demonstration performed for the integrity justification of components important for the safety (generally classified as class 1). Its aim is to demonstrate that gross failure by propagation of a crack-like defect can be discounted. Three legs are part of this assessment:

- The inspection at manufacturing and during in-service;
- The knowledge of material behaviour during the service life;

- The use of fracture mechanics to determine the critical defect size (in terms of fracture).

The two first points are not detailed in this paper. Concerning the third point, the determination of the critical defect size generally relies on a J based FMA in which the J imposed to the postulated crack via external loading (mechanical and/or thermal shock loading) is compared to an envelope J_{IC} for the material under consideration. In consistency with the R6 rule [1], depending on the difficulty of the problem to consider, three different routes are possible to determine this imposed J: complete analytical determination of the J parameter (also called level 1), a mix of elastic F.E. calculations and analytical elastic-plastic corrections (called level 2) and a complete elastic-plastic F.E. analysis on a cracked model for more complex cases (level 3).

A large effort has been performed in France since 20 years for the development of this level 1 methodology for PWR structures. Initially, this effort was performed in support of FMA for defects detected during In Service Inspection which requires a short time of analysis in order to limit the outage. Those developments were thus introduced in RSE-M [2] (code dedicated PWRs maintenance) and RCC-MR [3] (code dedicated to FBRs) which became RCC-MRx later. But rapidly, those analytical schemes have become the reference for design where a strong increase of justifications (in terms of zones to analyse, loading configurations…) is requested.
Most important part of this effort is performed within a tri-parties working group including EDF, AREVA-NP and CEA, the three main actors of the nuclear field in France. The developments were thus specifically dedicated to nuclear applications, and in practice to PWR structures (the option largely developed in France) with specific complements for high temperature assessment for FBRs. In those nuclear applications, due to the large thickness of components and/or the strong temperature variations (up to ~300°C), the thermal loading has a significant importance which cannot be neglected in FMA. For that reason, an important R&D effort was performed in order to develop specific formulations for the consideration of this type of loading [4-7]. Those developments are covering stainless steel primary piping and their welds (~70 to 80 mm thick austenitic and duplex cast stainless steel pipes and elbows submitted to various combinations of internal pressure, bending moments, axial and torsion loads), ferritic steels of secondary piping (thinner pipes but with more complex geometry and submitted to the same type of loading) and large ferritic components (very thick and large structures, generally cladded, essentially submitted to internal pressure).

For PWRs applications, no particular effort was performed in the past for the consideration of the welding Residual Stresses (RS) within the FMA of weld joints. The main reason for that is the fact that ferritic components are Post-Weld-Heat-Treated (resultant RS are assumed to be low and negligible) and stainless-steel material has a high toughness and a low yield stress: the RS are supposed to vanish when plasticity appears in the structure. In addition, in French regulation for operation (the scope of the RSE-M), a safety factor is applied on the loading, thus amplifying the plasticity and the attenuation of RS.
Nowadays and in particular for UK-EPR™ applications, those welding RS have to be taken into account within the FMA. For that purpose, a dedicated R&D was launched in order to propose a formulation consistent with the three levels of analysis previously listed and which provides an accurate and conservative evaluation of the impact of RS on the J parameter.

The purpose of the present paper is to make a status on this R&D. In a first part, it describes a first methodology which was proposed for the UK-EPR Generic Design Assessment (GDA). Then, in a second part, the following R&D performed in order to improve/consolidate this proposition is presented.
As it is explained in this paper, the R&D is still going on. Some perspectives and orientations are finally given together with the conclusion of this paper.

2 FIRST PROPOSAL FOR THE CONSIDERATION OF RESIDUAL STRESSES

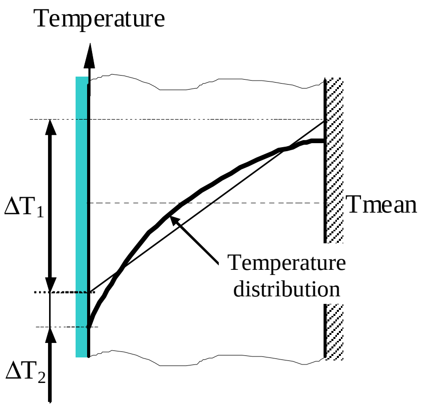
As explained in the introduction, the present paper deals with the problematic of the consideration of RS within the analytical schemes dedicated to the J calculation.
Regarding the fact that RS are associated to imposed strains, it was logically considered in a first approximation that those stresses can be considered the same way as thermal loading.

2.1 Consideration of the through thickness thermal loading

As it is explained in detail in the paper [7], the RSE-M/5.4 and RCC-MRx/A16 appendixes differentiate the thermal loading which can be imposed to the thick PWR structures within four categories:

1. The turbulent mixing of hot water and cold water which may appear in mixing zones. This loading is not significant for FMA;
2. The stratification which corresponds to a temperature gradient through the section of horizontal pipes;
3. The axial variation of temperature which is equivalent to the previous one, but for vertical pipes and in area with strong thickness transitions.
4. The through thickness thermal gradient which corresponds to temperature differences through the thickness of the component. It is generally associated to a temperature variation at the inner skin of the component (thermal shock or smooth temperature variation) and is due to the duration of warming up or cooling down the complete thickness of the component. As it is illustrated on Fig. 1, in PWRs, because of the strong thicknesses and/or high temperature variations, this loading creates stresses significantly higher than the yield stress.

Even if all those loadings correspond to temperature variations, they are strongly different in nature and need different formulations for the definition of plastic correction: stratification and axial temperature variations correspond to an imposed displacement whether through thickness gradient correspond to an imposed strain. We focus here to the one dedicated to through thickness thermal loading (which thus does not apply for imposed displacements – see [8]).



For a stainless steel and ΔT_1 = 300°C

$$\frac{E\cdot\alpha\cdot\Delta T_1}{2\cdot(1-\nu)} \approx 640\text{MPa} \Rightarrow 0 < \frac{E.\alpha.\Delta T_1}{2.(1-\nu).\sigma_y} < 6$$

Figure 1: Through-thickness thermal loading

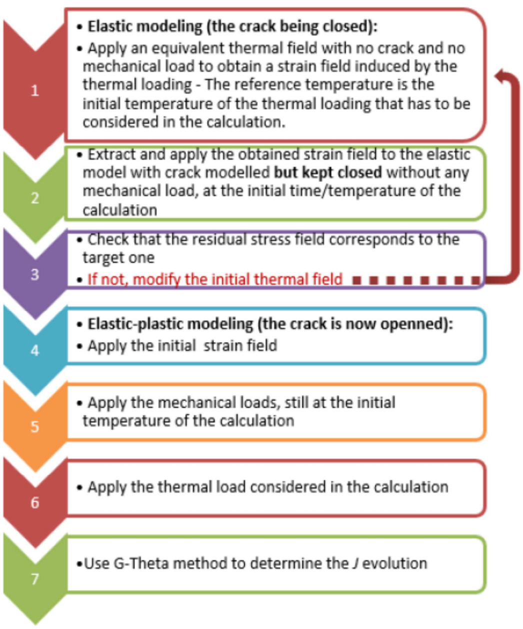


Figure 2: F.E. modelling protocol for RS consideration

For such through thickness temperature gradients, many numerical simulations were done and have shown the possible attenuation of the J parameter (in comparison to elastic J_{el}^{th}) due to plasticity. This phenomenon is related to the attenuation of stresses under imposed strains for elastic-plastic material behaviour and is explained in detail in [5]. As a result, the following general formulation for J calculation under through thickness thermal loading is proposed:

$$J^{th} = J_{el}^{\ th}.k_{th}^{\ 2},$$

where k_{th} is a coefficient which is, in a general case, equal or smaller than 1. The J parameter for an elastic-plastic behaviour is thus lower than the same parameter determined with an elastic model.
Two options are proposed for the determination of this k_{th} coefficient with, in the simplest one, an evaluation scheme which relies on the L_{th} loading parameter directly determined from the through thickness temperature gradient ΔT_1 and ΔT_2 as defined on Fig. 1:

$$L_{th} = \frac{3}{4.S_0}.\frac{E\alpha}{(1-\nu)}\left(\frac{\Delta T_1}{2} + \Delta T_2\right).f\left(\frac{a}{h}\right) \textit{ and then: } k_{th} = \text{Min}\left[\ 1\ ;\ \frac{1+\exp[-0.46(L_{th}-1)]}{2}\ \right]$$

In this simplest option, the geometrical parameter is the f(a/h) coefficient which depends on the crack type and size. The material behaviour is defined through the stress S_0 (stress for which $\varepsilon_{el} = \varepsilon_{pl}$).

2.2 First proposal for the GDA applications

For the UK-EPR™ GDA, some FMA were required for weld joint of High Integrity Components (HIC) including the consideration of possible RS. For that purpose, regarding the fact that the RS under consideration correspond to through thickness imposed strains due to the welding process, in a first approximation, those stresses were considered in the same manner as the through thickness thermal loading, i.e. through the k_{th} coefficient which has become:

$$L_{th} = \frac{3}{4.S_o}\left[\sigma_{res} + \frac{E\alpha}{1-\nu}.\left(\frac{\Delta T_1}{2} + \Delta T_2\right)\right].f\left(\frac{a}{h}\right)$$

The conservatism of this formulation is ensured by two main hypotheses:

1. The through thickness residual stress distribution is considered here as a membrane stress distribution (which corresponds to the first level of assessment of the R6 rule [1]);
2. The material characteristics S_0 is the one corresponding to the weld metal whether recent developments have shown the evaluation should be performed through the base metal characteristics (see [7]).

The main result of those two points (and in particular the second one) is that, in many cases, no attenuation of the residual stress was anticipated ($k_{th} = 1$). This appears to be very conservative, in particular for austenitic stainless streels welds and repairs.

3 FIRST SET OF MODELLING

3.1 Overall modelling strategy

Motivated by the strong need to develop an accurate formulation for the consideration of RS within the analytical J estimation schemes, a R&D program was launched between AREVA, EDF and CEA. For such development, as explained in [9], the general strategy used by the dedicated expert working group relies on the development of a specific reference F.E. results data base and then its use to develop/validate the specific analytical scheme. This database has of course to be focused on representative materials, geometrical configurations and loading situations.

For that preliminary step, a modelling matrix was defined and distributed within the expert group for calculation. As shown in Table 1, this matrix focuses on nuclear applications with narrow-gap weld joints,

repairs in cast components and Dissimilar Metal Welds. The numerical protocol (see Fig. 2) associated to that calculation matrix was shared and validated within the group through comparisons between Cast3M (for CEA), ASTER (for EDF) and SYSTUS (for AREVA) F.E. codes.
Next paragraphs deal with the straight pipe (#1) and repairs (#3) configurations. Next Fig. 3 gives some examples of 3D models used for those modelling.

TABLE 1 – Numerical matrix dedicated to residual stress consideration

#	Geometrical configuration	Parent materials	Loading situations	Residual stress field
#1	Straight pipes with narrow gap welds	C-Mn ferritic steel 304 Stainless steel	Pressure, bending moments & thermal shocks	Simplified and measured (ferritic conf.)
#2	Vessels with narrow gap welds	Low alloy steel	Pressure & thermal shocks	Simplified
#3	Repairs in cast components	Cast stainless steel & cast ferritic steel	Pressure & thermal shocks	Simplified and measured (stainless steel)
#4	Dissimilar Metal Weld	Primary circuit DMW	Pressure, bending moments & thermal shocks	Simplified and measured

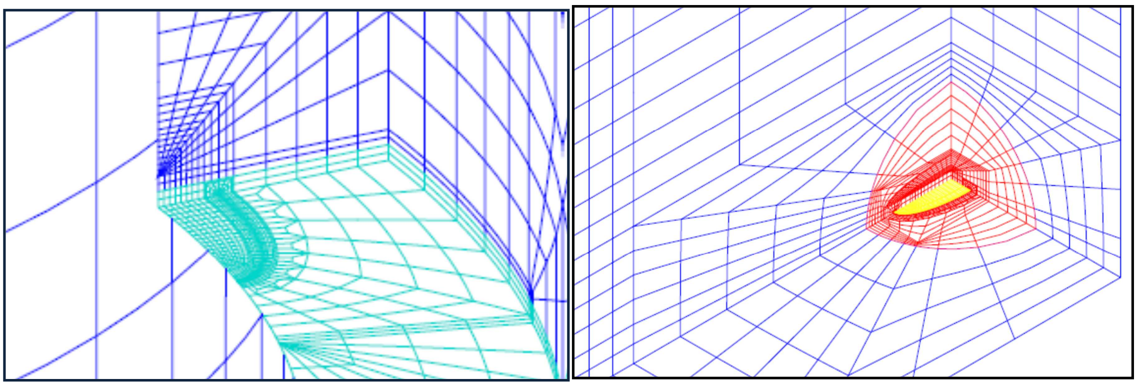


Figure 3: Examples of 3D model
On left: narrow gap TIG stainless steel weld – on right: repair in a thick cast stainless steel component

3.2 Main results obtained with that first set of modelling

Residual stresses acting alone

A first result obtained during that set of modelling is that, especially for complex configurations as the one of repairs, the first modelling steps dedicated to the introduction of the RS in the non-cracked model (steps 1 to 3 on Fig. 2) are not easy tasks since there is no explicit link between initial strain or temperature gradients through the thickness and the effective elastic stresses imposed to the weld metal: an iterative process has to be adopted in order to reach the target value of RS.
The RS field is not unique and thus, from that observation and for each geometrical configuration, different RS fields (with the same max level in the mid-section of the weld joint or the repair) were adopted.
Fig. 4 illustrates some results obtained for the RS acting alone. On this figure, two coefficients are introduced:

- L_{res} coefficient, equivalent to L_{th} and defining a normalized RS level;
- k_{res} coefficient, equivalent to k_{th} and defining the attenuation of the RS contribution to the J parameter.

Those two coefficients are defined by:

$$L_{th} = \frac{\sigma_{res}}{(1-\nu).\sigma_y} \text{ for 3D stress field, } L_{th} = \frac{\sigma_{res}}{\sigma_y} \text{ for 1D, } k_{res} = \sqrt{\frac{J^{res}}{J_{el}^{res}}}$$

As it is shown on this Fig. 4, an attenuation of the J^{res} compared to J_{el}^{res} is usually observed (k_{res} coefficient is lower than 1). This is due to the fact that, the level of RS field being equal to the material yield stress, some plasticity appears at the crack tip and thus reduces the stress level.
In addition, for the majority of the investigated RS fields, the k_{res} coefficient follows a trend similar to the one of through thickness thermal loading. The two series of points below this trend correspond to the repair configuration, with a high stress level within the base metal in the non-repaired part of the ligament (the repair under consideration covers half of the thickness of the component).
At this step, it appears that considering the RS as a through thickness thermal loading is appropriate.

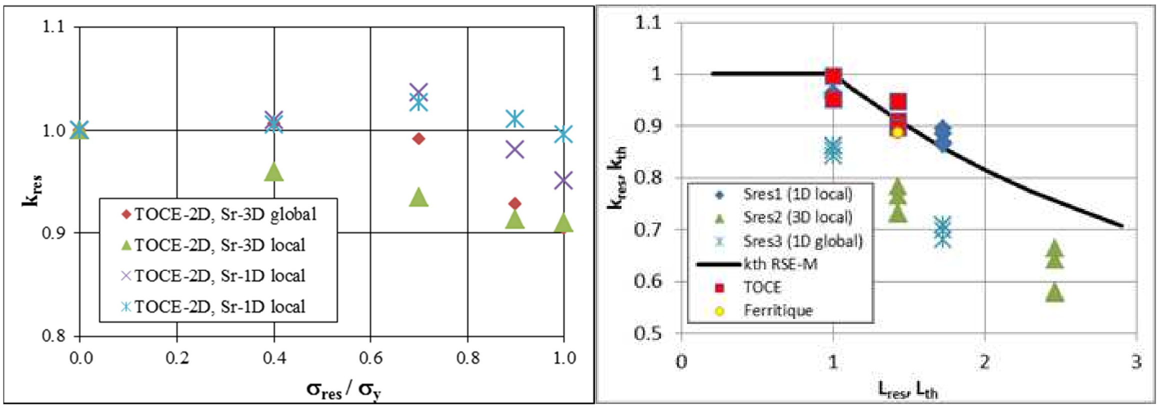


Figure 4: Examples of the RS relaxation when acting alone
TOCE & Ferritic refer to the Narrow-Gap austenitic stainless steel-weld & C-Mn welds (#1 of Table 1), 3D/1D, global or local refer to the type of residual stress field (tri or mono direction, overall or local), Sres1 to 3 refer to different residual stress fields imposed to the austenitic steel repair (#3 of Table 1)

<u>Interaction between residual stresses and applied mechanical loading</u>

Fig. 5 gives few examples regarding the interaction between RS and mechanical loading. Those two graphs present results obtained on straight pipe geometry (#1) made of austenitic stainless steel (left side) and C-Mn ferritic steel (right side).
On Fig. 5, the k_{res} coefficient still represents the correction due to plasticity of the RS contribution in the J parameter. It is defined here by:

$$k_{res} = \frac{\sqrt{J} - \sqrt{J^m}}{\sqrt{J_{el}^{res}}}$$

Where J is associated to the complete loading set (RS + mechanical loading), and J^m to the mechanical loading only. This definition means that two elastic-plastic modelling are required for the definition of k_{res}: one with the complete loading and another without RS.

From Fig. 5, one can see two very different behaviours:

- For the austenitic stainless steel configuration, different sets of loading combining bending moments and internal pressure are imposed. In every case, the relaxation initiated with RS acting alone is amplified by the mechanical loading. For L_R-nominal close to 1, the reduction of the contribution of

RS is important with a k_{res} coefficient between 0.5 and 0.6. From this graph, a reasonable bi-linear envelop curve can be defined.

- For the ferritic C-Mn steel, the evolution of the k_{res} coefficient is different: for every loading set and the two levels of RS investigated, an enhancement of the RS contribution within J parameter is observed for L_R-nominal close to 0.8. For the lowest level of RS this enhancement is quite high, with a k_{res} coefficient close to 1.2.

At this step, the strong difference between the narrow gap austenitic weld joint and the C-Mn ferritic steel was not understood. For that reason, a second step of parametric modelling focused on the interaction between RS and mechanical loading was launched for understanding purpose.

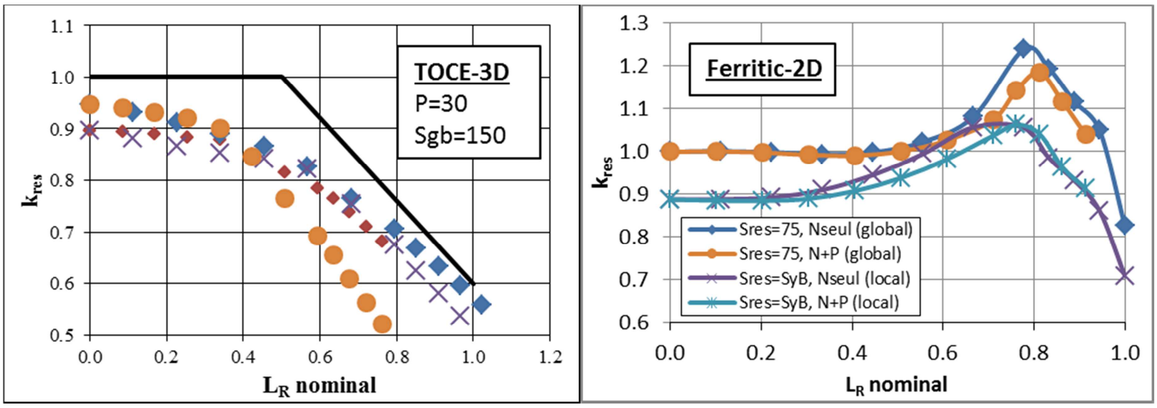


Figure 5: Examples of interaction between RS and mechanical loading,
P=30 (internal pressure) & Sgb=150 (global bending stress) refer to the applied mechanical loading
N refer to axial tension and N+P to axial tension combined with pressure,
Sres=75 or SyB refer to the level of RS (75 MPa or Base Metal yield stress),
L_R-nominal is the L_R loading parameter determine without considering the defect (as defined in [2])

4 SECOND SET OF PARAMETRIC MODELLING

4.1 Overall modelling strategy and scope

For this second step of modelling, the straight pipe configuration was investigated more in depth with the objective to determine what are the parameters governing the RS contribution enhancement. Within those parametric numerical analyses, the following configurations were adopted:

- Two weld joint geometries are represented: the thick (t = 76 mm) narrow gap austenitic stainless steel weld joint and the V shape C-Mn ferritic steel (t = 38.7 mm) weld joint. Both 3D and 2D modelling were considered. In every case, the defect is on the inner surface;
- Different crack depths were adopted: from a/t = 0.13 to 0.5. For the 3D modelling, the defect is semi-elliptical with a crack depth ratio c/a = 3;
- Different RS profiles through the thickness were defined by a second order polynomial distribution, the mean level of stress on the crack surface being kept constant in order to ensure a quasi-constant elastic J associated to RS (J_{el}^{res} ~ Cte).
- Two families of simplified bi-linear material behaviours were used (see fig. 6):
    - o The first one corresponds to a strong elastic-plastic hardening modulus (25 GPa) and a strong mismatch ($M = \sigma_{yW}/\sigma_{yB}$ = 1, 2 or 3). This family represents an austenitic type of stress-strain curves. In that case, σ_{yB} = 143 MPa;

- o The second one corresponds to a low hardening modulus (1 and 15 GPa respectively for base and weld metal) and a smaller mismatch ($M = \sigma_{yW}/\sigma_{yB}$ = 1.2, 1.6 or 2). This family represents a C-Mn ferritic type of stress-strain curves. In that case, σ_{yB} = 241 MPa;

In both material families, the mismatch was calculated for 0.2% plastic strain. Fig. 5 gives a representation of those simplified stress-strain curves. The Young modulus is E = 176.5 GPa.

- Different types of mechanical loading are imposed: internal pressure, axial tension (for 2D models) and global bending (for 3D models).

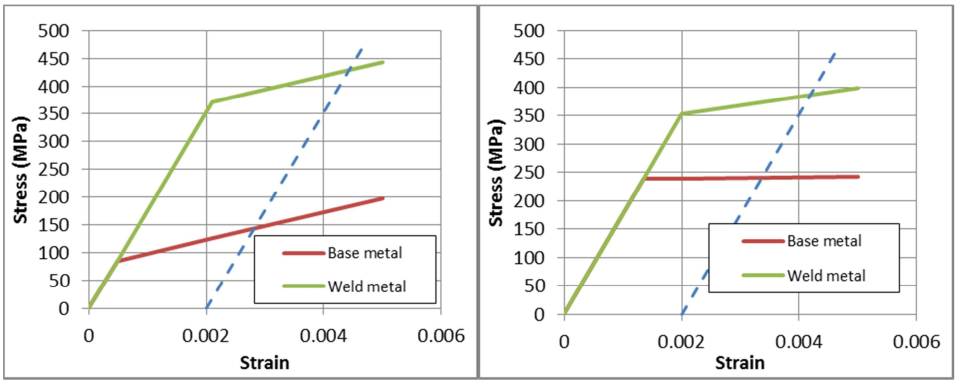


Figure 6: Simplified bi-linear stress-strain curves
on left 'austenitic' type of stress strain curve, on right 'ferritique' type of stress strain curve

4.2 Main results

Figures 7 and 8 represent some examples of $k_{res}/k_{res}(0)$ evolutions (k_{res} normalized by its value before imposing the mechanical loading) for different geometries, different mechanical loadings and the two types of material. Nine different curves are represented corresponding to three values of mismatch and three different RS distributions.

For most of them, the RS distributions and the mismatch levels have an effect on the k_{th} evolution, the impact of the RS distribution being globally more important. This is due to the fact that those RS distributions through the thickness are significantly different (mean stress over the crack depth is equivalent but on the remaining ligament the stresses are different). However, despite the dispersion between the curves, it is important to notice that for both graphs, the curves trends are similar for a given configuration, which confirms that the mechanical loading is the parameter governing the attenuation (or enhancement) of the RS contribution. This effect of RS is not discussed further since it needs more investigations to explain those different trends.

For the 'austenitic' type of material (Fig. 7 and 8), a global attenuation of k_{res} is observed when increasing the mechanical loading. Some enhancement is observed for smaller cracks, but it remains moderated (almost 10%). This tendency is obtained whatever the type of mechanical loading, the geometry of the weld joint (narrow gap or V shape), and the crack depth.

For the 'ferritic' material (Fig. 9), the trend is different with a strong enhancement (sometimes up to 2) of the k_{res} coefficient, and again, for all geometrical configurations and types of mechanical loading. Thus, from those examples, it is clear that the material behaviour is the major parameter governing the relaxation or enhancement of the RS contribution to the J parameter. All other parameters such as weld joint geometry, crack depth, or type of mechanical loading are of second order.

One can notice on Fig. 9 that, for the same crack depth, weld joint geometry and loading nature, the enhancement for the semi-elliptical defect is smaller than for the axisymetrical defect. Additionally, for the 'ferritic' material, what is important to notice is the very low hardening module for the base metal leading to the conclusion that this enhancement is mainly due to a loss of rigidity in the base metal when it enters in the elastic-plastic domain. In such condition, the defect can open more easily, thus increasing the contribution of RS to the J parameter.

For the ‘austenitic’ material, the elastic-plastic hardening module of the base metal is significantly higher and a relaxation of the RS contribution similar to the one observed for through thickness thermal loading is observed.

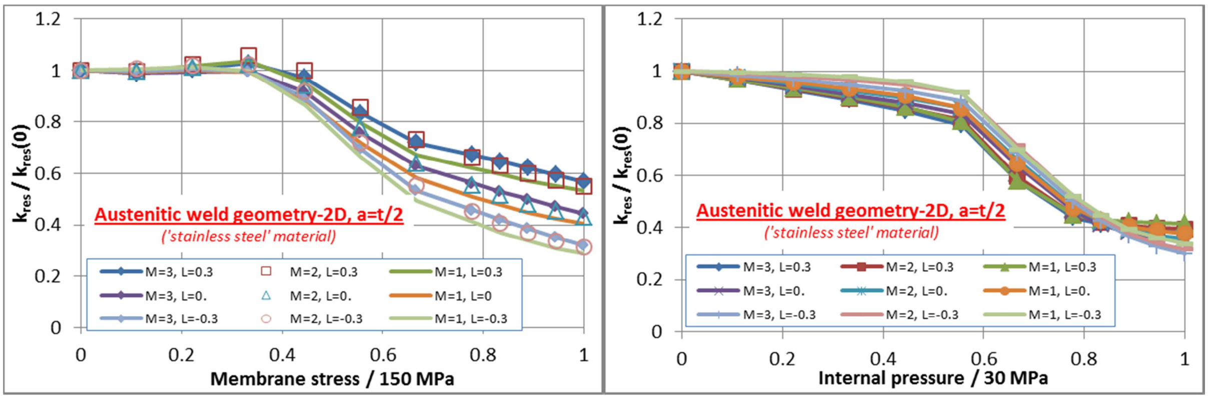


Figure 7: k_{res} evolution for different types of loading

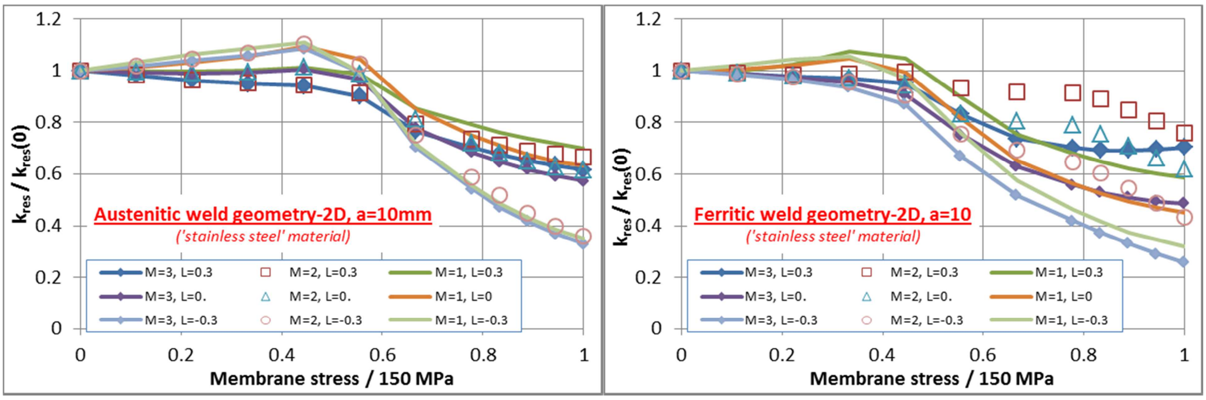


Figure 8: k_{res} evolution for different types of defect and weld joint geometries

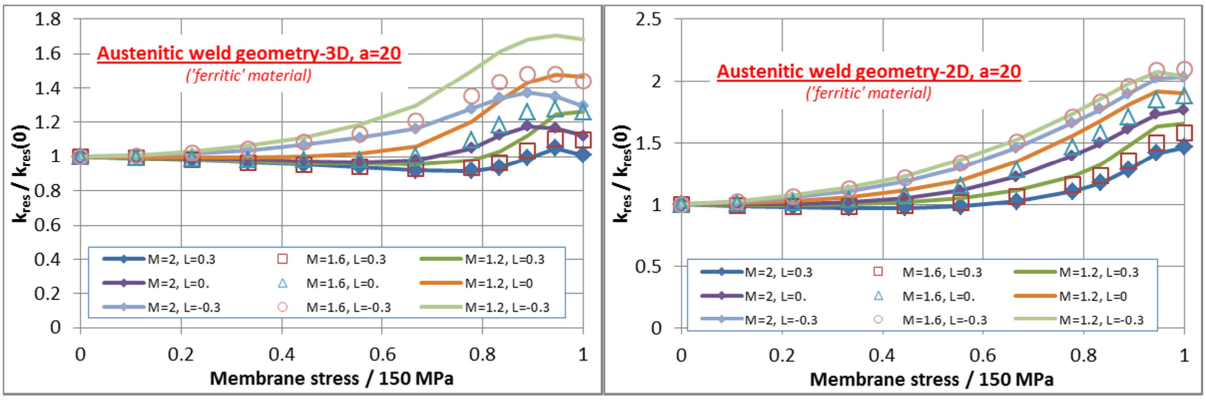


Figure 9: k_{res} evolutions for the ‘ferritic’ material

5 SYNTHESIS

From the numerical parametric study performed here, it is clear that the material behaviour has a strong influence on the interaction between the RS and the mechanical loading. The parameter suspected to be

the most influencing one is the elastic-plastic hardening module of the material which is very small for the ferritic material.
Given that observation, it also appears that the easiest way to provide a simple and accurate analytical formulation for our industrial applications is to provide two separate formulations for austenitic and ferritic materials. This is important to avoid significant over-conservatism in stainless steel applications where the magnitude of RS is the highest (ferritic welds of HIC are post weld heat treated).

For that purpose, two main tasks will be performed for the continuation of this work:
- The complement of those F.E. reference results for codified material behaviours, pertinent RS distributions (RS distributions considered in the FMA) and weld joint geometries. Both internal and external defects will have to be investigated;
- From those results, definition of envelop attenuation coefficients for both families of materials.

6 CONCLUSIONS

This paper deals with the actual R&D performed within AREVA-NP, EDF and CEA for the development of an analytical scheme for the consideration of residual stress fields within the fracture mechanics assessment of High Integrity Components of UK-EPR™ project.
In a first step, a proposition consistent with the one for through thickness thermal loading was made. However, the R&D developments have shown that this proposition is pertinent for austenitic stainless steel configurations, but not for the ferritic one. The expected main reason for that is the low elastic-plastic hardening modulus of ferritic base metal which allows an enhancement of the crack opening and thus the residual stress contribution.
From that observation, the developments are continuing with a strategy based on two separate formulations: one dedicated to the austenitic stainless steel configuration and the other for ferritic steels.

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