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RSE-M/RCC-MRx Analytical scheme for the J parameter calculation on cracked pipes and vessels submitted to through thickness thermal loading

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Abstract

This article deals with the analytical scheme to estimate J for pipes and vessels submitted to through thickness thermal loading, combined or not with mechanical loading, and codified within the RSE-M/RCC-MRx appendixes devoted to Fracture Mechanics Assessment. This scheme basically relies on an elastic J calculation and on a specific plastic correction (named k_{th}) which allows taking into account the stress relaxation observed for such loading situations.

The work specifically dedicated to thermal loading development was performed in parallel by two teams, resulting in two options available for the k_{th} correction coefficient. The purpose of this paper is to present the background of these two options, completed by the associated validation through a comparison with reference F.E. solutions.

Additionally, recent developments performed for weld joints (evaluation of the effect an overmatch weld joint) and for residual stresses consideration are presented. Those developments are resulting from on-going R&D and are candidate for short term integration in the codes.

Notation

E, α	Young modulus, Thermal expansion coefficient
ΔT_1, ΔT_2	Linear and non-linear through thickness thermal gradients
K_I	Stress Intensity Factor
J, J^m, J^{m+th}	Total elastic-plastic J, mechanical contribution, mechanical + thermal contribution
J_{el}, J_{el}^m, J_{el}^{th}	Total elastic J, mechanical contribution, thermal contribution
J_s, J_{FE}	J determined from the analytical scheme, from the F.E. modelling
Lr	Loading parameter for plastic correction of primary loadings ($Lr = \sigma_{ref} / \sigma_y$)
L_{th}	Loading parameter for plastic correction of thermal loading
σ_{ref}, ε_{ref}	Reference stress, associated reference strain on material stress-strain curve
σ^{th}, ε^{th}	Thermal stress, associated strain on material stress-strain curve
σ_{el}^{th}	Elastically determined thermal stress
σ_y	Material yield stress
Ψ	Confined plasticity correction
ASN	Nuclear Safety Authority (*in French*)
BM, WM	Base Metal, Weld Metal
CLC	Corrected Limit Load (‘*Charge Limite Corrigée*’ in French)
CEP	Elastic-Plastic Stress (‘*Contrainte Elastique Plastique’* in French)
FBR	Fast Breeder Reactor
FMA	Fracture Mechanics Assessment
ISI	In Service Inspection
PWR	Pressurized Water Reactor

1. Introduction

A large effort is being performed in France since 20 years in order to develop J analytical schemes in structures. Initially, this effort was performed in support of Fracture Mechanics Assessment (FMA), for defects detected during ISI which requires a short delay of analysis in order to limit the outage. Those developments were thus introduced in RSE-M (code dedicated PWRs maintenance) and RCC-MR (code dedicated to FBRs) which became RCC-MRx further. 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 actors of the nuclear field in France. The developments were then 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 conditions, a major part of the developments are focused on piping systems and vessels with their welds, the associated specific defect configurations and the encountered loading: a particular attention was dedicated to thermal loading transients which constitute an important loading situation for thick nuclear components.

The purpose of this paper is to detail the formulation proposed within the RSE-M [1] and RCC-MR [2] FMA appendixes for the specific case of thermal loading. For that purpose, a presentation of the physical background of the proposed formulation is made. Then, the two different available options and few elements of validation are presented.

2. Description of the problematic

The problematic we are dealing with in this paper is relative to the Fracture Mechanics Assessment in which a structure (containing a postulated conventional crack or a detected crack-like defect) is assessed against a fracture mechanics criterion in order to check the possibility of this defect to propagate or become unstable. In the nuclear field:

- This structure is submitted to primary loading: Pressure at first, but also bending moment and axial loading, torsion… for piping systems,
- and also secondary loading: thermal loading due to fluid temperature evolution with time.

In nuclear applications, due to the strong thicknesses of components and/or the large temperature variations (up to ~300°C), the thermal loading has as a significant importance which cannot be neglected in FMA. For that reason, an important R&D effort was performed in France in order to develop specific formulations for the consideration of this loading. Those developments are covering:

- Stainless steel primary piping and their welds: ~80 mm thick austenitic and austeno-ferritic pipes and elbows submitted to various combinations of internal pressure, bending moments, axial and torsion loads;
- Ferritic steel secondary piping: less thick pipes but with more complex geometry and submitted to the same type of loading;
- Large ferritic components: very thick and large structures (cladded in general case) essentially submitted to internal pressure.

In all those cases, the FMA concentrates on welds, cladded and cast structures, where potential crack like defects may exist: non detected defects during manufacturing or defect appeared during service life. For that reason, the developed analytical scheme had to consider both ferritic and austenitic base metals and associated weld joints configurations, for various size, orientations and locations of the postulated defects.

3. General formulation of the J_s parameter

Formulation for mechanical (primary) loading:

The J_s formulation relies on limit loads analysis initially proposed by Ainsworth [4]. Some considerations were added in order to take into account influencing parameters such as triaxiality, interaction between mechanical loadings, stress redistribution… in the limit load evaluation. Within that frame, the correction due to plasticity for mechanical loading relies on the Lr parameter which allows evaluating the level of plasticity within the section containing the crack via the stress-strain curve of the material. The general formulation is the following:

$$J^m = J_{el}{}^m \cdot \left[\frac{E \cdot \varepsilon_{ref}}{\sigma_{ref}} + \psi_{RSEM} \right] \text{ with: } \psi_{RSEM} = \frac{1}{2} \cdot \frac{Lr^2}{1 + Lr^2} \text{ (\textit{CLC option}) or 0 (\textit{CEP option})}$$

This formulation corresponds to a correction of an elastic J determined through K_I Stress Intensity Factor ($J_{el} = K_I^2/E$) by a correction which depends on the ratio between the reference strain ε_{ref} (strain associated to reference stress $\sigma_{ref} = Lr.\sigma_y$ on the true stress-true strain tensile curve of the material) and the elastic strain σ_{ref}/E.

Except for the Ψ correction corresponding to a confined plasticity correction (limited to 0.5 in practice), this formulation is fully consistent with the R6 option 2 [3] for treatment of primary stresses. At this step, the main difference between the two codes is on the providing of Lr (or σ_{ref}) solutions which is extensively developed for piping systems and vessels in the appendix 5.4 whether R6 rules provide much less solutions: in a general case, the user has to provide his own formulae.

For that mechanical evaluation, two options are available (CLC and CEP options), both of them relying on the same reference stress approach but with a slightly different formulation, the CLC one being strictly equivalent to the R6 formulation.

Within those two options, the weld joints (over-matched weld joints) are treated without considering the deposit material: this provides an overestimation of the plastic correction since the yield stress of the base metal is lower than the one of the weld metal. A development was initiated in order to develop specific corrections for weld joints. However, the phenomena associated to that problem are difficult to generalize in a simple way and is not validated yet by the French safety authority (ASN).

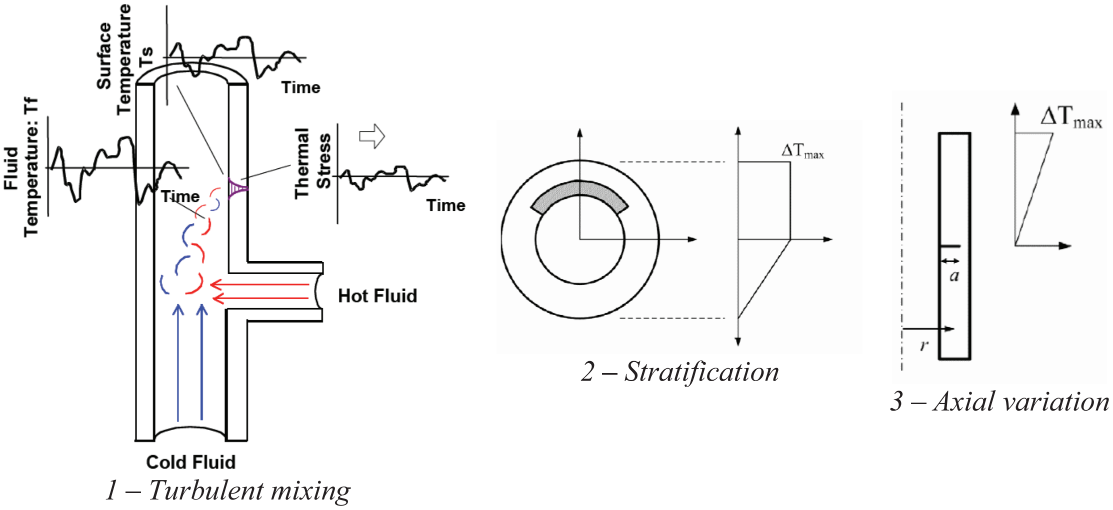
Formulations for thermal (secondary) loading:

The RSE-M/5.4 and RCC-MRx/A16 appendixes differentiate the thermal loading which can be imposed to a structure within the following categories (fig. 1 & 2):

1. *The turbulent mixing:* this type of loading appears in mixing zones where hot water and cold water mix together. If the mixing is turbulent, temperature fluctuation may affect the internal skin of the component. This loading corresponds to a high cycle fatigue loading in the elastic regime which affects essentially the internal skin of the component.
2. *The stratification:* This type of loading corresponds to a temperature gradient through the section of the pipe. This loading may appear in horizontal pipes where the cold water (at the bottom) and a hot water (at the top) do not mix together because of the differences in the density. It corresponds to an

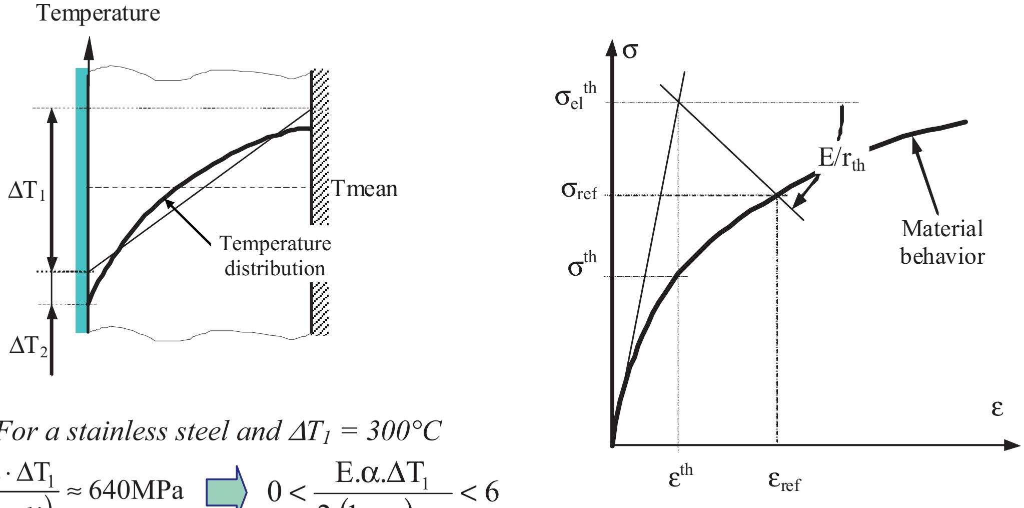
imposed rotation of significant amplitude that may induce plasticity in the pipe and thus that needs to be taken into account in the FMA.

3. *The axial variation of temperature:* This type of loading is equivalent to the previous one, but for vertical pipes with temperature differences along the axis. This loading may also appear in area with thickness transitions (the time to cool-down or warm-up is longer for a thick part than for a thin one). Like previously, the type of loading corresponds to an imposed displacement.
4. *The through thickness thermal gradient:* This type of loading corresponds to temperature differences through the thickness of the component. It is associated to a temperature variation on the internal surface of the component (thermal shock or smooth temperature variation) and is due to the delay to warm-up or cool-down the complete thickness of the component. As it is illustrated on fig. 2, in nuclear field, due to the strong thicknesses and/or high temperature variations, this loading creates stresses significantly higher than the yield stress.



1 – Turbulent mixing
2 – Stratification
3 – Axial variation

Figure 1: The different types of thermal loading



For a stainless steel and $\Delta T_1 = 300°C$

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

Figure 2: Through-thickness thermal loading

Even if all those loading are corresponding to temperature variations, they are strongly different in nature and need different formulations for the definition of plastic correction: stratification and axial temperature variations are corresponding to an imposed displacement whether through thickness gradient is corresponding to an imposed strain. For that reason two different formulations are proposed within the FMA appendixes, the one detailed in this paper being associated to through thickness thermal loading (which thus does not apply for imposed displacements).

For such through thickness gradients many numerical simulations were done and have shown the possible attenuation of J parameter (in comparison to elastic J_{el}^{th}) due to plasticity. This phenomenon, linked to the attenuation of stresses under imposed strains for elastic-plastic material behaviour can be summarized as follows (see [5] for more details):

- Through thickness thermal gradient is corresponding to an imposed strain represented by ε^{th} on fig. 2. The elastically determined stress σ_{el}^{th} thus overestimates the real stress σ^{th} imposed to the structure which is reduced by plasticity. Elastic J (J_{el}^{th}), which is proportional to the square of the stress, must be reduced by the term $(\sigma^{th}/\sigma_{el}^{th})^2$.
- On the contrary, plasticity in the cracked section amplifies J_{el}^{th} and a potential elastic follow-up between cracked and un-cracked sections may appear since the cracked section is weaker. The reference stress σ_{ref} is thus higher than the stress σ^{th}.

In the general formulation for J calculation, the analytical J becomes:

$$J^{m} = J_{el}^{th} . \left(\frac{\sigma^{th}}{\sigma_{el}^{th}} \right)^{2} . \left[\frac{E \cdot \varepsilon_{ref}}{\sigma_{ref}} + \psi_{RSEM} \right] = J_{el}^{th} . k_{th}^{2}$$

To provide a reasonable approximation of those two opposite phenomena, a k_{th} coefficient multiplying those two corrections was defined. In a general case, the coefficient k_{th} is equal or smaller than 1 since the stress reduction correction is dominating. The J parameter for an elastic-plastic behaviour is thus lower than the same parameter determined with an elastic model.

Like for mechanical loading, two options are available (options 1 and 2) for the k_{th} coefficient determination. In both cases, the evaluation scheme relies on a loading parameter directly determined from the through thickness temperature gradient ΔT_1 and ΔT_2 defined on fig. 2:

- *In option 1*, there are again two options (*a* and *b*) to define this loading parameter:

  In *option 1a*: $L_{th} = \dfrac{E\alpha\left(\dfrac{\Delta T_1}{2} + \Delta T_2 \right)}{\dfrac{4}{3}(1-\nu).S_o} .f\left(\dfrac{a}{h}\right)$ and in *option 1b*: $\varepsilon^{th} = 0.85 \dfrac{\alpha.\left(\dfrac{\Delta T_1}{2} + \Delta T_2 \right)}{\dfrac{4}{3}(1-\nu)} .f\left(\dfrac{a}{h}\right)$

  The associated k_{th} coefficients are then determined through the following formulae:

  $$k_{th-1a} = \mathrm{Min}\left[1 \ ; \ \frac{1+\exp[-0.46(L_{th}-1)]}{2} \right], \text{ and: } k_{th-1b} = \mathrm{Max}\left[\frac{1}{2} \ ; \ \sqrt{1.28 \frac{\sigma^{th}}{E.\varepsilon^{th}} - 0.28 \left(\frac{\sigma^{th}}{E \cdot \varepsilon^{th}} \right)^{2}} \right]$$

  In this *option 1*, the varying parameter is the f(a/h) coefficient which depends on the crack type and size. In *option 1a* the material behaviour is defined through the stress S_0 (stress on the stress-strain curve where $\varepsilon_{el} = \varepsilon_{pl}$) and in *option 1b* through the complete stress-strain curve of the material (σ^{th} being the stress associated to ε^{th} on the stress-strain curve of the material – see fig. 2).

- <u>*In option 2,*</u>the loading parameter is defined through the following formulae:

$$\sigma_{el}{}^{th} = 0.585 \frac{E.\alpha.\Delta T_1}{2.(1-\nu)} \cdot \left[1 + \frac{\Delta T_2}{\Delta T_1} \cdot \left(\frac{2.86}{n} - \frac{0.86}{n^2} \right) \right] .f_{th}$$

From that elastically determined stress, the stresses σ^{th} and the reference stresses σ_{ref} are defined following the scheme represented on fig 2. In this formulation, the crack is taken into account through the f_{th} and r_{th} coefficients. The coefficient n is the exponent of the power law fitting the material stress-strain curve for large strains (~6 for the stainless steel).

The coefficients f(a/h), f_{th} and r_{th} are defined in the appendix A16 of the RCC-MRx for each defect position and orientation. It is then possible to apply *options 1 & 2* with this appendix. Today, the appendix 5.4 of the RSE-M contains only the k_{th1} option, but a proposal is under evaluation in order to include the *option 2* (which has a slightly larger field of application).

<u>Interaction between mechanical (Primary) and thermal (Secondary) loadings:</u>

Regarding the interaction with mechanical loading, it has been shown that the most appropriate general formulation for combined thermal and mechanical loading is the following:

$$J^{m+th} = \left[\sqrt{J^m} + k_{th}^* \cdot \sqrt{J_{el}^{th}} \right]^2 ,$$

where J^m is the contribution due to mechanical loading and $J_{el}{}^{th}$ the contribution due to thermal loading determined for an elastic behaviour. In this formulation, $k_{th}{}^*$ is a coefficient derived from k_{th} depending on the mechanical loading level and nature (within k_{th} option 1 and 2 formulation).

The interaction between mechanical and thermal loading taken into account here is called ‘weak interaction’ since the plasticity amplification applied to the mechanical term (within J^m parameter through Lr or σ_{ref}) does not apply the thermal term $J_{el}{}^{th}$. This constitutes a major difference with the R6 rule (option 2) in which the plastic correction is imposed to both mechanical and thermal contributions (‘strong interaction’): in the R6 formalism, the total J or K_J under combined mechanical + thermal loading is:

$$J^{m+th} = \frac{1-\nu^2}{E} . \left[\frac{K_I{}^m + V.K_I{}^{th}}{f(Lr)} \right]^2 ,$$

where f(Lr) is the plastic amplification of mechanical loading:

$$\frac{1}{f(Lr)} = \sqrt{\frac{E.\varepsilon_{ref}}{\sigma_{ref}} + \Psi_{R6}}$$

The 1/f(Lr) correction can be very important when the mechanical loading is significant (Lr equal or larger than 1), resulting in an important amplification of the thermal contribution. For low level of primary loading, the 1/f(Lr) is close to 1 but the V parameter is higher or equal to 1, which also contributes to the amplification of the elastic contribution due to thermal loading.

This explains why the R6 formulation was not adopted and a completely new k_{th} formulation was developed specifically for through thickness thermal loading for integration within the RSE-M and RCC-MRx Fracture Mechanics appendixes.

4. Consideration of weld joints

Figure 3 gives an example of a J calculation performed through F.E. modelling for a linear through-thickness thermal transient imposed to a weld joint (austenitic piping of 65.5 thickness containing an internal semi-elliptical surface crack with a crack depth a = 20 mm & a half-crack length c = 60 mm). In this modelling, 4 different material modelling are adopted:

- A purely elastic model;
- An elastic-plastic model corresponding to the base metal (BM) material behaviour;
- An elastic- plastic model corresponding to the weld metal (WM) material behaviour;
- A bi-material model combining BM and WM material.

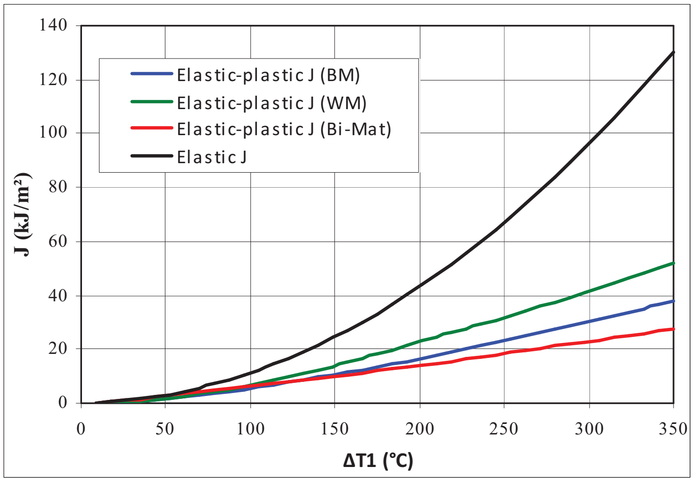


Figure 3: J calculation for a weld joint

One can see on that figure that, as expected by the analytical scheme, the elastic plastic J is in every case lower than the elastic one: the stress relaxation due to plasticity is dominating. The attenuation for a WM behaviour is lower than for the BM: this is again an expected situation since the WM material behaviour is higher than the BM one. As a consequence, the stress attenuation is reduced.

But what is more surprising is that the curve for the modelling corresponding to the bi-material behaviour is lower than the one corresponding to the BM behaviour. This can be explained by the following considerations:

- The $(\sigma^{th}/\sigma_{el}^{th})^2$ correction corresponds to the far-field attenuation due to plasticity. It has then to be relied to the BM material behaviour. As a consequence, the stress relaxation for Bi-material configuration is equivalent to the one of the BM configuration.
- At the opposite, the J amplification through the reference stress is local and is then governed by the WM (where the crack is located). Due to the fact that the WM behaviour is higher than the BM one, the amplification is reduced.

As it is done for mechanical loading, this benefit is not taken into account within those two options since it is difficult to generalize: the weld joints are treated without considering the WM. This applies only for over-matched weld-joints.

5. Consideration of residual stresses

For PWRs applications, no particular effort was performed in the past for the consideration of the residual stresses within the FMA of weld joints. The main reason for that is the fact that ferritic components are Post-Weld-Heat-Treated (resultant residual stresses are assumed to be negligible) and stainless-steel material has a high toughness and a low yield stress: the residual stresses 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 the residual stress effect.

Nowadays and in particular for EPR-UK applications, those residual stresses had to be taken into account within the FMA. For that purpose, regarding the fact that the stresses under consideration are corresponding to through thickness imposed strains due to the welding process and in a first approximation, those stresses were considered in the same manner than the through thickness thermal loading, i.e. through the k_{th} coefficient. In k_{th} *option 1* the loading parameters become:

$$L_{th} = \frac{3}{4.S_o}\left[\sigma_{res} + \frac{E\alpha}{1-\nu}.\left(\frac{\Delta T_1}{2} + \Delta T_2\right)\right].f\left(\frac{a}{h}\right) \text{ and: } \varepsilon^{th} = 0.6375\left[\sigma_{res} + \frac{\alpha.}{1-\nu}\left(\frac{\Delta T_1}{2} + \Delta T_2\right)\right].f\left(\frac{a}{h}\right)$$

No formulation has been defined for k_{th} option 2 at the moment. However, a specific R&D effort has been launched on that topic in order to improve and validate that evaluation scheme [6]. Within that frame, the *option 2* will be completed in the coming years.

6. Validation against F.E. reference data

General strategy

The validation phase is an important one in terms of presentation and acceptability of the analytical schemes by the ASN. Approaches become more and more sophisticated and an illustration of their conservatism through comparison to reference cases is needed. For that purpose, the expert working group devoted to the J analytical schemes has developed a specific reference F.E. modelling database in order to provide reference solutions for the J parameter. A maximum of loading configurations, structural and defect geometries, materials… are investigated in that frame. For some difficult geometry (e.g. for elbows), this validation could also be separated in 2 parts: K_I validation and reference stress validation. This work is performed within the working group. Reference [7] and [8] give more detail on the background and example of results obtained during this work.

With such reference results database, the validation of the analytical scheme becomes a simple comparison of the J value determined through the analytical scheme and the reference F.E. solution for the same loading case. This comparison is made systematically for all the available reference cases then registered in a specific set of ‘validation reports’. This set of ‘validation reports’ is re-edited regularly, including new reference data, new developments or methodologies, corrections…: the last one for mechanical loading was issued in 2006 then re-edited in 2012 in the frame of EPR-UK, the last one for thermal loading in 2011.

Synthetic presentations of the results (internal cracks in pipes and vessels)

The fig. 4 and 5 give some example of direct comparisons between reference F.E. solutions and the J determined the evaluation schemes. Two configurations are presented:

- The 2D axi-symmetrical configuration of a pipe with an internal crack surface crack;

- The 3D configuration of a pipe containing an internal, longitudinal semi-elliptical surface crack. In that case, the J values are those corresponding to the deepest point of the crack.

On those two figures, each point is corresponding to a F.E. reference solution for various loading amplitude, thermal shock severity, defect sizes, combinations with mechanical loading… The applied analytical schemes and the associated options are the following:

- The RSE-M/RCC-MRx formulations, option CLC (*option 1b*) and CEP (*option 2*);
- The R6 [3] formulation based on option ρ (for a $J_{mat} = 50$ kJ/m²) and option V.

On this graphs, the black line is corresponding to the bisector line whether the red line corresponds to a ratio of 5 between the reference solution and the analytical scheme. With a perfect evaluation scheme, all the points should rely on or close to the bisector line.

- As it is shown on fig. 4 and 5, the points corresponding RSE-M/RCC-MRx applications are close or above the bisector line. As it is explains in [7] this corresponds to a target of the working group to provide as best as possible but conservative analytical schemes;
- At the opposite, the R6 applications are much more conservative, sometimes with a ratio larger than 5 with the reference solution. The highest points of those graphs are corresponding to combined mechanical + thermal loading. This means that the principal reason for that over-conservatism is due to the consideration of a ‘strong interaction’ (see §3) between the two types of loadings.

7. Synthesis and conclusions

This article gives a presentation of the background and the analytical formulations, proposed within the RSE-M and RCC-MRx appendixes dedicated to FMA, for evaluation of pipes and vessels containing a surface crack and submitted to through thickness thermal loadings (thermal shocks). Those formulations are compared to the R6 [3] formulation showing two major differences:

- For thermal loading alone, a k_{th} coefficient generally lower than 1, is introduced allowing reproducing with the analytical scheme the stress relaxation due to plasticity observed for thermal loading. At the opposite, R6 options 2 is relying on ρ and V coefficients which are equal or larger than 1.
- For combined mechanical + thermal loading, a ‘weak interaction’ is considered: the plastic amplification due to the mechanical loading (through Lr parameter) is not imposed to the thermal contribution. At the opposite, R6 option 2 imposes the amplification to the thermal loading.

As it is illustrated in two examples, this second point creates strong over-conservatisms of the R6 formulation in comparison to reference F.E. solutions, whether the RSE-M/RCC-MRx appendixes formulations are providing reasonably conservative solutions.

8. References

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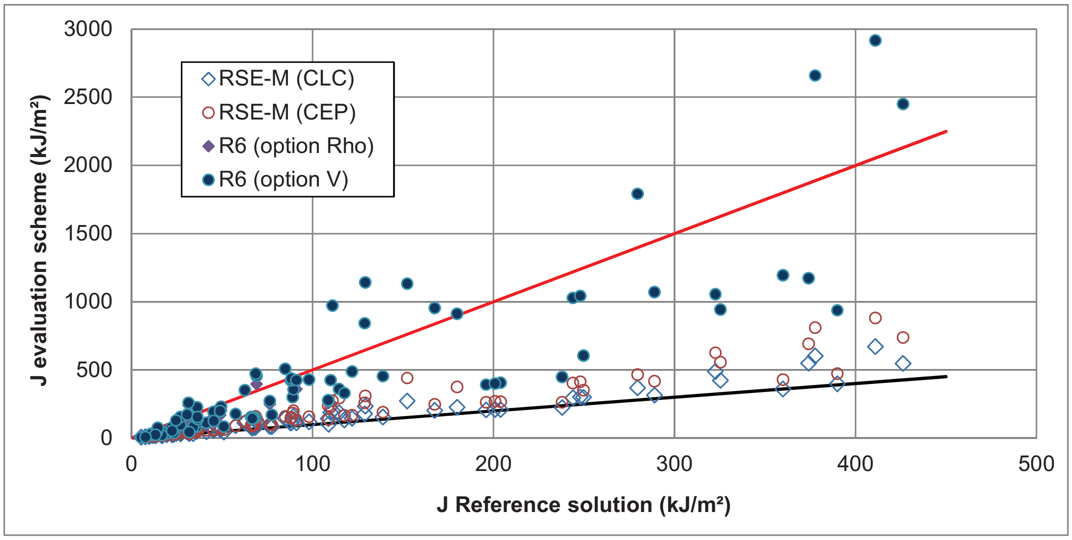

Figure 4: Comparison between F.E. reference solution and J analytical scheme ***(Circumferential axi-symmetrical internal surface defect)***

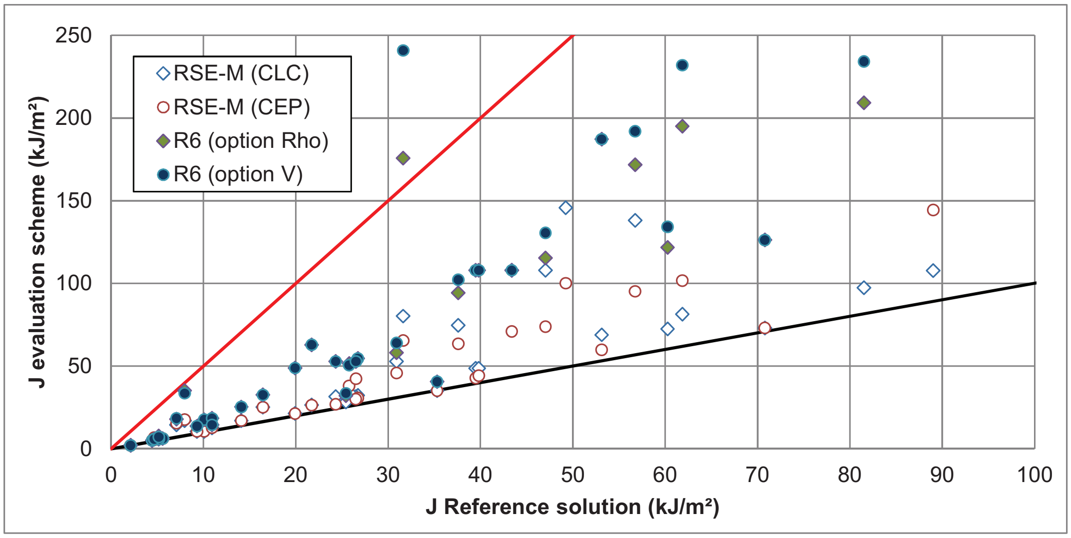

Figure 5: Comparison between F.E. reference solution and J analytical scheme ***(Longitudinal semi-elliptical internal surface defect)***