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Overview and background of the RSE-M/RCC-MRx appendixes devoted to Fracture Mechanics Assessment at both design and operation level

Stéphane Chapuliot[1], Stéphane Marie[1], Yann Kayser[2], and Patrick Le Delliou[3]

[1] AREVA-NP, France
[2] CEA, DEN, DM2S, SEMT, LISN, 91191 Gif-sur-Yvette, France
[3] EDF Research & Development, Moret sur Loing, France

Abstract

A large effort was initiated in France 20 years ago in order to develop, validate and then codify analytical schemes for Fracture Mechanics Assessment (FMA) of nuclear components and piping systems. At the origin, this work was pushed by the need to define specific analyses rules, material behaviour, acceptance criteria… more generally all the necessary information needed for the assessment of defects detected during In-Service-Inspection or periodic safety re-evaluation. The target (analytical tool development) is a direct consequence of the need to perform quick and accurate evaluations for defects detected in service. But regarding the problematic of design with a large number of loading situations and the large number of potential defects to consider in the Defence-In-Depth demonstration, those appendixes have rapidly become the reference solution for FMA of PWR, at both design and operation level.

This article gives an overview of those appendixes devoted to FMA, with a particular focus on the analytical J formulation (called J_s) for which a huge compendium of formulae specifically devoted to K and J fracture mechanics parameters calculation is provided. Within that frame, an overview of the formulations developed and their background (including the validation and codification strategy) is proposed. Finally a highlight of the on-going R&D devoted to EPR^{TM} needs is presented.

Notation

E	Young modulus
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 ($Lr = \sigma_{ref} / \sigma_y$)
σ_{ref}, ε_{ref}	Reference stress, associated reference strain on material stress-strain curve
σ_y	Material yield stress
Ψ	Confined plasticity correction
ASN	Nuclear Safety Authority (*in French*)
CLC	Corrected Limit Load ('*Charge Limite Corrigée*' in French – 1st option for J analytical scheme in RSE-M ap 5.4)
CEP	Elastic-Plastic Stress ('*Contrainte Elastique Plastique'* in French – 2nd option for J analytical scheme in RSE-M ap 5.4)
FBR	Fast Breeder Reactor
FMA	Fracture Mechanics Assessment
ISI	In Service Inspection
PWR	Pressurized Water Reactor

1. Introduction

The Fracture Mechanics Assessment (FMA) is part of the Defence-in-Depth demonstration performed for the 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 criteria justification).

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. Depending on the difficulty of the problem to consider, three different routes are possible to determine this J imposed to the postulated crack:

- First one is a complete analytical determination of the J parameter. This route is possible for the simplest geometrical configurations (i.e. where an analytical determination of elastic stresses is possible) and is a very convenient one since it allows very fast evaluations;
- Second one is a mix of F.E. calculations and analytical plastic corrections. This applies for more complex cases, for example in case where elastic stresses has to be determined by F.E. calculation on non-cracked model, or for configurations not covered by the code;
- Third one is a complete elastic-plastic F.E. analysis on a cracked model for the more complex cases. This constitutes the most accurate but also the most expensive justification in terms of time and money.

For the two first levels relying on analytical development for stress determination and/or plasticity corrections, analytical solutions were developed in France and introduced in the RSE-M 5.4 appendix [1] and in RCC-MRx A16 appendix [2]. The solutions provided by those two appendixes are reference solutions in France in the nuclear domain and are widely used for PWRs (RSE-M) and FBRs (RCC-MRx) defect assessments, but are not widely used outside France. Thus the objective of this paper is to present the background and the validation support of the proposed formulae described in those appendixes for low temperature assessment. This presentation is performed in comparison to the R6 rules [3] which constitute a reference for FMA in Europe (in both nuclear and non-nuclear fields).

We concentrate here on the analytical J formulation (called J_s) with a particular focus on the mechanical loading evaluation, the evaluation of through thickness thermal loading and the validation strategy. The provided solutions are relying on a huge compendium of formulae specifically devoted to FMA through K_I and J fracture mechanics parameters. It results from an important R&D work initiated in 1995 between the three major nuclear actors in France (EDF, AREVA and CEA) with the objective to define accurate analytical tools for FMA for defects detected in service where a fast analysis process is required to limit the outage. But regarding the problematic of design with a large number of loading situations and the large number of potential defects to consider in the Defence-In-Depth demonstration, the appendix 5.4 has rapidly become the reference solution for FMA of PWRs at both design and operation.

For High temperature reactors (FBRs), the equivalent appendix dedicated to FMA is the A16 appendix of the RCC-MRx [2]. It was developed at the same time than the RSE-M FMA appendixes (within the same working group) and thus proposes the same basic tools for low temperature assessments, completed by specific tools and formulae for high temperature assessments (for significant creep regime).

Regarding the initial objectives of those appendixes devoted to FMA, it is important to notice that they focus on nuclear components and type of materials with the objective to prescribe all the basic tools, formulae and material data within the scope under consideration. This constitutes an important difference with other rules like R6 which allow using formulae from the open literature and thus does not guaranty a homogeneous validity between the different basic tools.

2. General strategy for the analytical J calculation

Expert working group and associated R&D

In France, the analytical formula development for the ductile range started in the 90s, first by individual work in the different organisms involved in the nuclear field, but rapidly through cooperative work including the three major actors.

In 1995, a group was formed to merge the resources between RCC-MR (with the A16 fracture mechanics appendix under the responsibility of CEA and devoted to Fast Breeder Reactors) and RSE-M (with the 5.4 appendix under the responsibility of EDF/AREVA and devoted to Pressure Water Reactors). This working group was composed of teams of experts from CEA (governmental research organisation with a division specifically devoted to the support of nuclear energy), EDF and AREVA. The financial support of this working group came from the R&D budgets of the three partners (CEA, EDF and AREVA) and from the IRSN (technical support of the French Nuclear Safety Authority) which has also an interest in the understanding and the validation of the analytical approaches.

This working group is still active today and continues to develop and validate the tools for FMA. Some of the actual developments are focused on specific needs for EPR-UK, the RSE-M appendix 5.4 being the reference solution for fast-fracture analysis of class 1 components (see §7 devoted to on-going R&D).

Scope and process

Since the beginning of the working group, a step by step approach was followed in order to cover a maximum of geometry and loading configurations encountered in nuclear vessels and piping systems. Today, the formulae and methodologies presented in the appendix 5.4 are covering:

- Pipes and cylindrical shells containing circumferential or longitudinal, internal or external surface defects;
- Cladded vessels;
- Elbows with defects in mid or inlet/outlet sections, containing circumferential or longitudinal, internal or external surface defects;
- Tapered transitions with circumferential surface defects.

For all these structures, a large scope of potential loading was investigated: mechanical loading, through thickness thermal loading (temperature gradient or thermal shock) or combined mechanical plus thermal loading. Again, the objective of this work is to cover a maximum of industrial configurations in support of defect assessment demonstrations.

In every case, the process to develop new formulae is constituted by four major steps:

- First step is devoted to the constitution of a reference F.E. database;

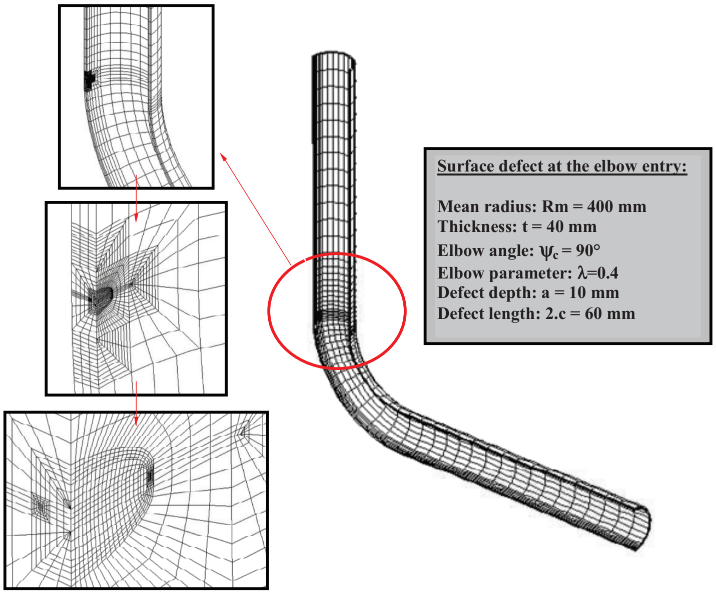
- Second step is devoted to the methodology development of a new formula itself (basically influence for K_I and reference stress for plastic corrections) with possibly complementary F.E. developments;
- Third step devoted to the final validation against the overall reference cases database;
- Fourth and final step devoted to pre-codification and presentation to the French Nuclear Safety Authority.

Reference F.E. database for the J parameter calculation

The strategy adopted for the analytical schemes development and validation is based on the interpretation of reference F.E. results then comparison between the analytical J and the same reference F.E. solutions. The constitution of reference F.E. modelling (through cracked elastic-plastic models) is thus a key point within that development scheme.

For that purpose, a F.E. results database was constituted in the frame of the cooperative CEA/EDF/AREVA R&D. F.E. models used for this database constitution are both 2D and 3D, depending on the problem treated. It was constituted step by step, starting from simple problems such as axi-symmetrical defects in pipes, up to complex cases like semi-elliptical defects in elbows. Figure 1 gives an example of such complex F.E. models developed for elbows. Additional reference F.E. modelling performed in the frame of the CEA/IRSN actions were also developed for methodology development or complementary validations, in particular for thermal loading. At this step, it has to be mentioned that those F.E. modelling were in a major part performed by the experts involved within the working group, which guarantee a good confidence on the results.

For the database constitution and for each geometrical configuration (component and defect geometry), the first step of the F.E. analysis is the validation of the F.E. models by a comparison of elastic-plastic J calculation results on common cases calculated by the three partners using their own F.E. code: Code_Aster (EDF software – [9]), Cast3M (CEA software – [8]) and SYSTUS (AREVA software). Aster and Cast3M softwares are in house F.E. codes, developed and validated internally for internal needs for more than 20 years, whereas SYSTUS is developed and maintained by ESI Group then qualified by AREVA for design applications.



Surface defect at the elbow entry:

Mean radius: Rm = 400 mm
Thickness: t = 40 mm
Elbow angle: $\psi_c = 90°$
Elbow parameter: $\lambda=0.4$
Defect depth: a = 10 mm
Defect length: 2.c = 60 mm

Figure 1: Example of F.E. model for elbows

This step, where accordance between the three different codes is required before the database makeup, constitutes the best validation process and allows the definition of best practice for meshes, loading applications, post-treatment… The model being validated, parametric models are then used in order to multiply in a short time the F.E. results then complete the F.E. database

All the numerical analyses are then reported in documents and the results included in the F.E. database in an imposed format in order to allow simple extraction of the results at the validation step. CEA is in charge of the maintenance of this database which contains today approximately 2000 different elastic-plastic solutions of pipes, vessels and elbows, in both 2D and 3D configurations.

3. General formulation of the J_s parameter

For mechanical 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 a 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:

$$J^m = J_{el}{}^m \cdot \left[\frac{E \cdot \varepsilon_{ref}}{\sigma_{ref}} + \psi_{RSEM} \right] \text{ with: } \psi_{RSEM} = \frac{1}{2} \cdot \frac{Lr^2}{1 + Lr^2}$$

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 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 (CLC and CEP options) are available in appendixes 5.4 and A16, 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.

For thermal loading, the developments relying on k_{th} coefficient are focusing on through thickness temperature gradients. The overall temperature gradients such as stratification or global thermal expansion are not treated within that frame but with another specific approach devoted to 'imposed displacement'.

For such through thickness gradients (the industrial need regarding thermal shock evaluations) many numerical simulations were done and have shown the possible attenuation of J parameter due to plasticity. This phenomenon, linked to the attenuation of stresses under imposed strains for elastic-plastic material behaviour, is explained in [5] and can be summarized as follows:

- Thermal transient, and in particular through thickness thermal gradient, corresponds to an imposed strain. In that case, elastically determined stresses overestimate the real stresses which are reduced by plasticity. Elastic J must be reduced in order to take into account this effect of plasticity on stresses.
- On the contrary, plasticity in the cracked section and potential elastic follow-up between cracked and un-cracked sections can amplify the elastic J, as it is the case for mechanical loading.

To provide a reasonable approximation of those two opposite phenomena, a k_{th} coefficient multiplying those two corrections and eventually an interaction with mechanical loading (through the k_{th}^* coefficient) 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. Again, two options are proposed for the calculation of the coefficient k_{th}.

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. 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: in the R6 formalism, the total J or K_J under combined mechanical + thermal loading is:

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

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 than 1, which also contributes to the amplification of the elastic contribution due to thermal loading.

As a consequence of those two amplifications, the elastic-plastic J evaluated through the R6 analytical scheme is systematically higher than the elastic one, and thus over conservative in comparison to the F.E. reference results showing the inverse trends.

4. Basic formula development

The general formulation of the J analytical scheme being defined, the development work consists in determining the basic formula for all geometries and each loading situations targeted (the objective of the code being to provide all the formula needed for the FMA). Two major steps constitute this development work:

- The influence function development (devoted to K_I and J_{el} calculation);
- The reference stress formulation development (i.e. Lr) for plastic corrections (both mechanical and thermal corrections).

On first point, a huge calculation effort was performed in order to propose a coherent solution of influence functions for surface defects [6]. This work was achieved by systematic F.E. calculations for a wide range of pipes thickness ($1 > t/r_i > 1/80$) and defect size ($0 < a/t < 0.8$ and $1 > a/c > 1/16$). All these solutions are validated by a systematic comparison with existing solutions. For elbows, a numerical analysis was performed and has shown that, for small surface defects, the influence functions developed for the pipes can be used to estimate K_I in the structure [11].

This set of influence function solutions was completed further by solutions for cladded components (under-clad and through-clad defects) and embedded defects. At the end, such coefficients compendia constitute an important part of the FMA appendixes and make it possible to calculate K_I for a large panel of simple structures.

The reference stress formulae (second point) were developed in the same manner through the post-analysis of F.E. modelling for the same panel of structures and defect shapes. The proposed reference stress formulas are then functions of the imposed load and the crack shape. For a given geometry (basically a structure with a given surface defect), the development of the analytical formulation for the global J parameter has been made in two phases:

- Analysis of the individual loadings (pressure, bending moments, thermal shocks…) and issuance of formulations for those individual loadings (basically the Lr and/or σ_{ref} formulations);
- Then determination of the interactions between mechanical loadings and finally between mechanical loading and thermal loading. The final formulation of Lr for mechanical loadings and k_{th} for thermal loading is then defined.

At this step, one should note that in order to avoid any error compensation, the elastic J coming from the F.E. model is used in the determination of plastic corrections in order to be sure that all the differences obtained during the second step are only due to the reference stress or k_{th} proposed solutions.

5. Validation against F.E. reference data – Presentation to the ASN

General strategy

The validation phase is an important one in terms of presentation and acceptability of the analytical schemes by the Safety Authority. Approaches become more and more sophisticated and an illustration of their conservatism through comparison to reference cases is needed.

At the opposite of R6 strategy, the expert working group choice was to develop a specific ‘validation set of reports’ which are note included in the code: due to the large number of validation cases, this set would have been too large. 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.

CEA is in charge of this qualification phase which is performed systematically for all the F.E. reference cases available in the database. To do so, a specifically developed software (called MJSAM [10]) implementing the two options is used. This software is developed with CEA’s internal budget and with the financial support of IRSN in order to secure the application of the analytical scheme and thus the validation.

Another major difference with R6 rule is the validation strategy of the J analytical schemes which is performed against F.E. results and not tests. From the beginning, the working group considered the validation against experimental data as non appropriate for the validation of J analytical scheme for the following main reasons:

- The direct comparison to tests globally includes a lot of uncertainties (loading knowledge, criteria validity and transferability, material data, measurement…) and do not allow the identification of their influence separately. Everything is mix together so that it is very difficult to detect any under or over-conservatisms in the J evaluation scheme.
- This aspect is particularly true in a κ_r-Lr representation where a subjective choice has to be made for the definition of the loading point positions within the diagram:
  - Which formula to define Lr? What is the reference yield stress for this Lr definition? There may be here large uncertainty, in particular for weld joints where the limit load definition is a difficulty by itself;
  - Which value of K_{IC} for κ_r determination (mean or minimum value)? This constitutes a fundamental choice for brittle fracture, but also for ductile fracture;
  - What about the transferability of criteria? Brittle fracture criteria are known to be sensitive to constraint and J_R-Δa curve is known as very conservative when fitted on small size specimen then applied to structures. This over-conservatism could hide an important under-conservatism in J evaluation scheme;
  - For thermal loading, the J_s formulation has a direct impact on the κ_r definition within the R6 formulation (see previous chapter). What about the reality on structures?

On the contrary, the strategy defined for the fracture mechanics appendixes of RSE-M and RCC-MRx codes was to separate the overall criteria in two sub-problems: the loading term determination and the criteria itself. In other words, for a criterion expressed as follows:

$$J_s(\text{Load, Geometry, Material}) = J_{IC}(\text{Material}),$$

two separate validations sets are developed:

- On one hand, the analytical J_s formulation is to be validated against reference numerical data. A maximum of loading configurations, structural and defect geometries, materials… are investigated in that frame. For some difficult geometry, this validation could also be separated in 2 parts: K_I and reference stress validation. This work is performed within the working group.
- On the other hand, the criterion validity is checked against experimental data, in particular via tests on specimen and structures, with the objective to evaluate the possibility to predict fracture on the structure based on data fitted on specimen. In major cases, within this criterion validation, J values which are imposed to the specimen or the structure are determined via F.E. modelling, itself validated against experimental data via comparison to measurable data. The F.E. modelling is of course performed in order to avoid a potential lack of precision of an analytical J. This work is performed through separate cooperative actions or through European projects.

Targets imposed by the ASN

The target imposed by the regulator is of course to define a conservative evaluation of the J parameter through the analytical scheme. But in practice, this is not enough since, at the opposite, a too much conservative evaluation is not adequate (e.g. for selection of the worst loading situation purpose) or because it is representative of a physics which is not capture by the model. For that reason, local and global quality indicators were defined and proposed to the French regulator. Those two different type of indicators are relying on a direct comparison of J values which constitutes a very sensitive quality evaluation since J becomes strongly non-linear when Lr becomes larger than 1. For local indicators, two differences are defined:

$$a^{+} = 100 \cdot \max_{0<J<500kJ/m^2}\left[\max\left(0, \frac{J_{EF} - J_S}{J_{EF}}\right)\right],\ a^{-} = 100 \cdot \min_{0<J<500kJ/m^2}\left[\min\left(0, \frac{J_{EF} - J_S}{J_{EF}}\right)\right],$$

whether for global indicators two integrals (see figure 2) are calculated all along the loading path in order to evaluate the global accuracy of the analytical scheme:

$$A^{+} = \int_0^{Lr} a^{+}.dLr\,,\ A^{-} = \int_0^{Lr} a^{-}.dLr$$

In a general case, no under-evaluation is accepted. However, little non-conservatism (above 20%) can be tolerated if they are analyzed and explained and if it is demonstrated that they don't have any impact in the practical demonstrations. In practice, during the development phase, all negative results are analyzed one by one, possibly corrected in order to improve the formulation and at minimum explained in the synthesis report. At the end, after little iteration, the criteria are matched.

Synthetic presentations of the results (example for pipes and elbows)

As explain previously, the comparison between analytical scheme and the F.E. reference solutions is performed systematically, for all cases available within the database. Then synthesis graphs merging the different defect geometries/positions and loading situations are edited for analysis. An example of such synthesis is presented on figure 4 for pipes (TUB) and elbows (COU). This graph represents for all defect positions and loading type, the mean global error obtained by application of the analytical scheme. It thus illustrates the bias between the analytical scheme and the F.E. modelling. One can see on that figure:

- The J estimation scheme is globally conservative, depending on the configuration, the CLC or the CEP option being more conservative;
- Very few under-conservatisms, but very limited and non significantly regarding the type of defect;

For elbows, the conservatism can reach 70 to 80% in some cases. However, regarding the complexity of the problem and the need in terms of precision, an additional effort can be performed or not depending on the industrial need: the effort to improve the analytical scheme can be very heavy in terms of new F.E. calculations and time.

Validation of the criteria against experimental data

In parallel to the analytical J calculation, an effort is performed for the criteria validation. Main purpose of that validation is the transferability of the fracture mechanics data from small specimen (devoted to material characterization) to large structure (where those criteria are applied). This effort relies mainly on test campaigns ideally merging small specimen and large scale tests. In support of those tests, an important numerical effort is performed through F.E. modelling in order to determine as accurately as possible the fracture mechanics parameters.

Figure 4 are summarizing an example of such test campaign presented in [7] and devoted to the validation of J_{IC} criterion for Inconel Dissimilar Metal Welds (three point bending test performed on a pipe containing a through wall crack within the Dissimilar Metal Weld).

- The validation of the F.E. model is illustrated through a comparison between measurable data (in that case the Crack Mouth Opening Displacement – CMOD) and the equivalent data derived from the F.E. model. The F.E. model relying on a precise representation of the mock-up and defect

geometry associated to a dedicated material characterization, a good correlation between tests and measures is obtained.
- When a good confidence on the model is obtained, the criteria validity can be checked. In that case this is performed through a direct comparison between the J_{IC} measured on CT specimen and the J at crack initiation determined on the pipe mock-up.

Publication strategy

In French codes, the background and the validation of the different formulations and criteria are not included in the code itself but in complementary dedicated documents (which are remaining internal document within AFCEN) and publications.

This is obviously the case for the J analytical schemes where a large number of internal documents exists but remains internal to the working group. However, in the particular case of FMA appendixes, a large number of publications are available, covering both the analytical scheme development/validation and the validation of the fracture mechanics criteria though tests on mock-ups.

6. On-going R&D

The working group dedicated to the J analytical scheme development is still active with the same original objective to extend the scope and the validity domain covered by the codified solutions. An important part of today's developments is focusing on welds with a general target to improve the solutions with the consideration of the mismatch between base and weld metals and the consideration of residual stresses in the FMA.

As usual, those on-going developments are relying on the development of a specific reference F.E. data base in order to develop then validate the proposed analytical schemes. However, in that case, a particular effort is being performed in order to develop then validate a specific protocol for the residual stresses consideration within the F.E. modelling.

In parallel to the effort performed on welds, a work is initiated for defects in nozzles. Regarding the difficulty in that case for both K_I and J calculation, the mid-term objective to provide recommendations then solutions to asses those geometrical configurations under combined mechanical plus thermal loading is under investigation.

7. Synthesis and conclusions

This report is presenting the background and the validation process of the J analytical schemes provided in the RSE-M and RCC-MRx appendixes devoted to Fracture Mechanics Assessment.

Within the RSE-M/RCC-MRx codes, the J analytical schemes are provided in the 5.4 and A16 appendixes. The associated developments were performed through a dedicated expert working group launched in 1995 with the industrial objective to provide fast and accurate J solutions for the assessment of defects detected during in-service inspections. But regarding the design context with a large number of FMA (for different defect positions and loading situations), those solutions have rapidly becomes reference solutions for both design and operation.

For that purpose, the developed basic tools and data are focusing on the industrial need, that is to say the nuclear components and structures where the approaches are applied. An additional objective is to prescribe all the data needed for the analysis. This provides homogeneity in the quality of the evaluations. At the opposite, the R6 rule is more general and do not provide systematically the basic tools for analysis.

For those proposed analytical schemes and for mechanical loading consideration, the approach based on the reference stress concept initially developed by Ainsworth for R6 rules [4] was adopted in RSE-M/RCC-MRx appendixes. Two options were defined for that purpose with a CLC option which is strictly identical to the R6 option 2 formulation.

The main difference between RSE-M/RCC-MRx and R6 rules concerns the thermal loading evaluation: the French methodologies are focusing on through thickness temperature gradients and are relying on F.E. modelling. Those modelling show that, in that case, the elastic-plastic J is generally lower than the elastic one. The RSE-M/RCC-MRx allows taking into account this reduction due to plasticity, which is not the case for the R6 formulation which thus becomes over-conservative.

The validation strategy developed for the RSE-M/RCC-MRx appendixes is also significantly different with a decomposition of the validation in two separate checks: one dedicated to the J analytical scheme (validated through comparison to reference F.E. solutions) and one dedicated to the criteria transferability (validated through tests campaign on small specimen and mock-ups). Additionally those validations are note included in the code but in dedicated documents and external publications. Those two points constitute a significant difference with the R6 rule validation where the validation is performed globally through comparison to tests and integrated in the code.

On that methodology development, the working group is still active today, with actions devoted to weld joints (including the consideration of residual stresses in the assessment) and the consideration of nozzles corners.

8. References

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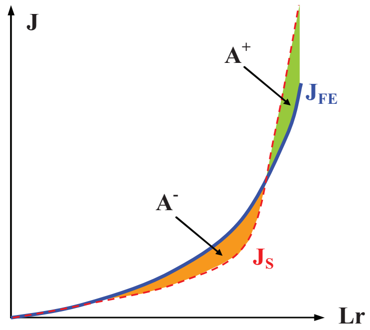

Figure 2: Global assessment indicators for the analytical scheme evaluation

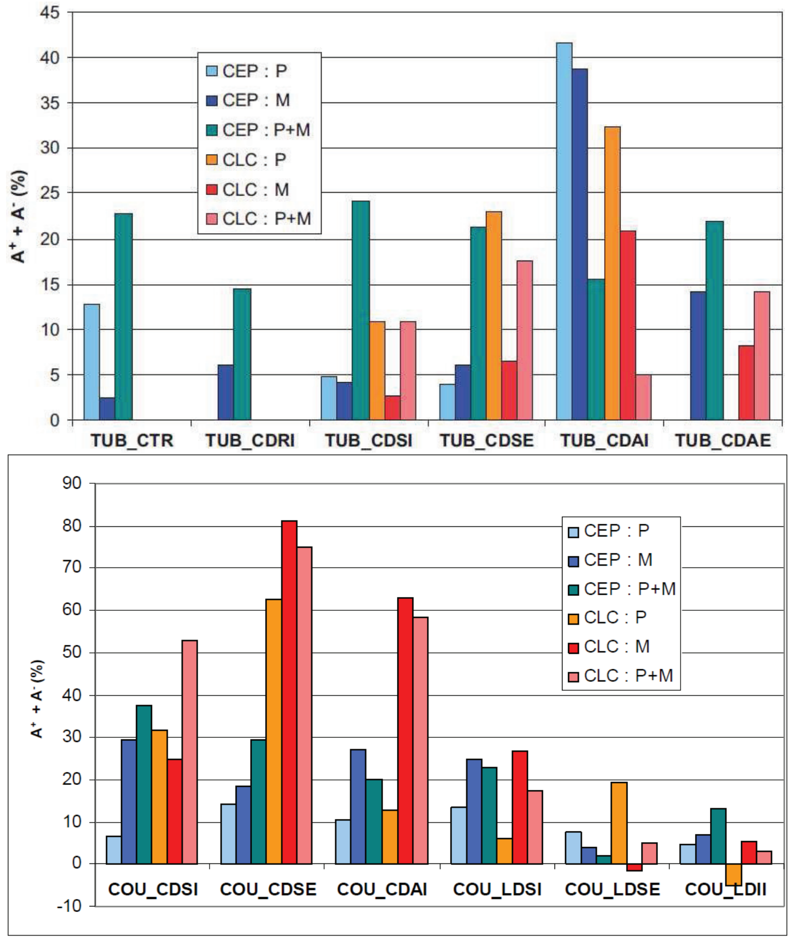

Figure 3: example of synthesis graph for pipes and elbows submitted to mechanical loading

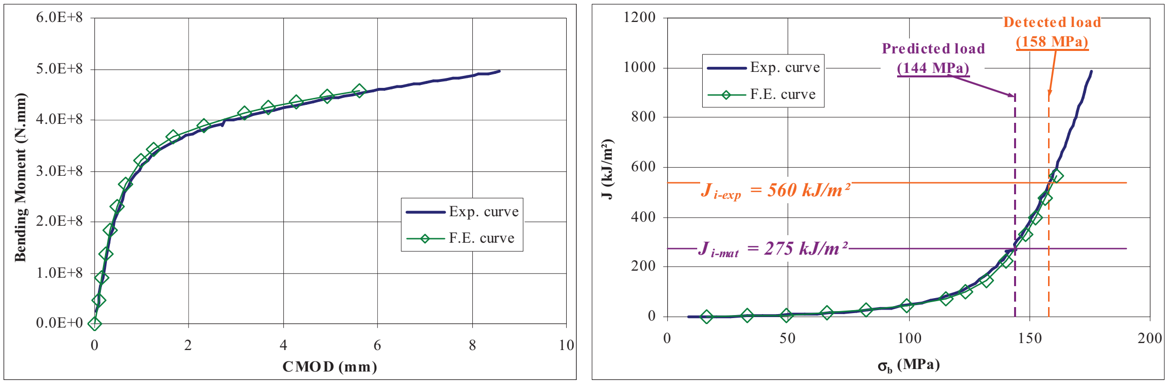

Figure 4: Validation of the F.E. model through comparison to tests