Optimized J evaluation scheme for the Fracture Mechanics Assessment of complex piping systems subjected to various loading sets

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ABSTRACT
This paper describes an optimization scheme for the J parameter calculation for cracks postulated in complex geometrical configurations such as elbow entries/exits and/or thickness transitions. The principle of this scheme comes from the RSE-M/5.4 appendix allowing the definition of a specific compendium for specific configurations.

After a detailed presentation of the numerical protocol, an illustration of the required effort and the potential benefits is proposed for an elbow configuration. It is then shown that:
- The effort is significant but can be anticipated and automated;
- The potential benefit in terms of applied be is significant (a ratio of three in the proposed application).

NOMENCLATURE

\begin{align*}
a, c & \quad \text{Crack depth and half-length} \\
E, E^*, \nu & \quad \text{Young modulus and its Plane Strain formulation: } E^* = E/(1-\nu^2), \text{ Poisson coefficient} \\
\varepsilon, \sigma & \quad \text{Strain and stress on the material stress-strain curve} \\
f_{gb}, f_p, f_T & \quad \text{Influence functions for bending moment, internal pressure and torsion} \\
f(L_R) & \quad \text{Plastic correction of the J parameter} \\
\Phi_c & \quad \text{Elbow angle} \\
\gamma & \quad \text{Interaction coefficient of the L_R parameter} \\
J_{el}, J & \quad \text{Elastic and elastic-plastic J} \\
J_{el(i)}, J^{(i)} & \quad \text{Elastic and elastic-plastic J at load level } i \\
K_{I}, K_{II} & \quad \text{Mode I and III Stress Intensity Factor} \\
K_{eq} & \quad \text{Equivalent Stress Intensity Factor} \\
L_R, L_R^{(i)} & \quad \text{Dimensionless loading parameter, same parameter for load level } i \\
L_{R, \text{no}(i)} & \quad \text{Dimensionless loading parameter for loading level } i \text{ without geometrical correction} \\
M_1, M_2 & \quad \text{Torsion and bending moment} \\
m_1, m_2, p & \quad \text{Dimensionless torsion, bending moment and pressure} \\
M'_1 & \quad \text{Moment at the elbow entry (j = 1 to 3)} \\
M''_1 & \quad \text{Moment in the defect axes (j = 1 to 3)} \\
P & \quad \text{Internal pressure} \\
q_m, q_p, q_T & \quad \text{Geometrical corrections for bending moment, torsion and pressure} \\
r_i, r_e, r_m & \quad \text{Internal, external and mean radii of the weld section} \\
\sigma_{gb}, \sigma_p, \sigma_T & \quad \text{Nominal stresses for bending, pressure and torsion loadings} \\
\sigma_y & \quad \text{Conventional yield stress } (\varepsilon_{pl} = 0.2\%) \text{ of the material stress-strain curve} \\
t & \quad \text{Pipe thickness} \\
FEM & \quad \text{Finite Element Modelling} \\
FMA & \quad \text{Fracture Mechanics Assessment} \\
PWR & \quad \text{Pressurized Water Reactor} \\
SIF & \quad \text{Stress Intensity Factor}
\end{align*}
1 INTRODUCTION
Auxiliary piping of PWR reactors constitute a large and complex set of piping systems, connected to large components of primary circuit and submitted to various loadings such as internal pressure, seismic loading, thermal expansion, stratification, thermal shocks… Those piping systems are complex in geometry, including a large number of welds, thickness transitions, elbows and tee junctions. Being class 1 piping, a Fracture Mechanics Assessment (FMA) is required at design level for the welds where manufacturing defects smaller than the Non Destructive Examination capability detection could exist.

Regarding the large number of loading situation to be considered in the assessment of those piping, the conventional approach for FMA relies on the J analytical schemes codified in the 5.4 appendix of RSE-M. This appendix provides envelop solutions for straight pipes, thickness transitions and elbows, but in practice those solutions appear to be overly conservative for some complex geometries such as thickness transitions and elbows. Margins being reduced for some welds, an optimization of the J analytical scheme is required.

In such situations, a direct Finite Element Modelling (FEM) is a solution for optimizing the J parameter calculation. But such modelling has to be repeated for a large number of loading situations and might rapidly become over costly and time consuming. For that reason, an alternative solution is to develop a dedicated Stress Intensity Factor and limit load formulae which allows calculating all the encountered loading situations with the same set of pre-established FEM.

The purpose of the present paper is to describe this alternative solution. A 3D elbow configuration is chosen to illustrate the modelling effort which has to be developed, then the benefit of the approach illustrated.

2 CONTEXT AND BACKGROUND

2.1 Overall context
For class 1 piping systems, the FMA is a defence in depth approach which aims to demonstrate the robustness of the system by demonstrating its tolerance to large potential manufacturing defects. Those defects are not known ‘a priori’ and are thus postulated in the welds where there’s a risk of having a non-detected manufacturing defect (at the opposite of pipes where manufacturing processes are preventing the pipe from having any defect significant for safety). For conservatism reasons, those defects in welds are envelop in size of the potential manufacturing defects and are considered in worst positions and orientations (inner or outer surface circumferential defects) for all possible load sets imposed to the piping system.

In French codified rules for FMA [1] and for piping with thicknesses less than 40 mm, the defect size is defined as the min value between half thickness and 10 mm, which represents a significant thickness reduction for the weld junction. From this defect size, all potential loading situations have to be assessed with the standard $J_{IC}$ criterion for crack initiation and $J_{R-\Delta a}$ curve for crack propagation. In many cases, those two criteria cannot be satisfied because of the overall conservatism of the schemes used for the calculation of the J parameter. In those cases, an optimization of the J parameter is required.

2.2 Background of the optimisation
The set of loading to be assessed in FMA is generally large for a piping system since it has to cover normal situations (where pressure, thermal transients and thermal expansion loading are dominating) up to accidental situations (generally dominated by seismic loading). This very large scope was one of main motivations for developing the dedicated analytical schemes of the RSE-M/5.4 appendix (see [2] and [3]). However, despite the large effort performed in this field for many years, the codified solutions remain approximate in many complex geometrical configurations such as thickness transitions or elbows.
entries/exits: in practice the number of required geometrical parameters for describing this type of geometry is too large and approximate solutions (i.e. conservative assumptions) had to be defined.

To overcome this difficulty, it was decided to complete the codified solutions by defining specific dedicated solutions for all welds where criteria are not met and where an important conservatism of the codified analytical scheme is expected. Those solutions are defined following the RSE-M/5.4 appendix (§VII.1.2 – [3]) where the possibility to develop specific compendia is offered to the user.

This specific compendia development focusses on primary loading (through thickness thermal loading are not investigated here), that is to say bending moments, torsion and internal pressure which constitutes the most important loading components for elongated piping systems. For those loading components, following the RSE-M/5.4 appendix formulation (which is equivalent to the R6 rule [4] formulation), the \( J \) parameter can be written as follows:

\[
J = \frac{K_{eq}^2}{E^*} f(L_R)
\]

Two main parameters are composing this formulation:
- The Stress Intensity Factor \( K_{eq} \) which can be derived from the crack free stresses thanks to the influence function formulation;
- The plastic correction \( f(L_R) \) which is determined from the \( L_R \) dimensionless loading parameter and the parent true stress-strain curve of the parent material.

For piping systems where the primary loading dominates, the plastic correction generally dominates and thus constitutes the main parameter to optimize. However, since we are looking here to relatively large defects (up to the half thickness of the pipe), in the following we are looking to the both \( K_{eq} \) and \( f(L_R) \) parameters.

Additionally, one should not that we are not considering here the mismatch between weld and parent materials (which is about 2.5 for austenitic piping). Considering this mismatch in the analytical scheme remains too complex and constitutes a conservatism which can only be quantified through direct FEM.

3 DETAILS OF THE APPROACH

3.1 General formulation – geometry description of the problem

The piping systems we are investigating in this paper are composed by elongated pipes and elbows connected all together by circumferential butt-welds. In addition, those piping are generally connected to large components, valves or larger piping systems though reinforced connections (i.e. generally with strong thickness transition). Fig. 1 shows for illustration an example of such piping systems which appears to be very complex in geometry and which illustrates the large number of welds to consider in the assessment.

As already mentioned, defects are postulated in all the welds of the piping systems. For conservatism purpose, those defects are relatively large (up to the mid-thickness) and in the worst configuration in terms of loading and position:
- The defects are circumferential, internal and external surface defects (CDSI and CDSE within the RSE-M/5.4 appendix notations [3]);
- They are postulated in the mid-section of the weld, perpendicular to the outer/inner surface of the pipe.

As defined by the ZG appendix of the RCC-M [1], those defects are semi-elliptical and defined by an elongation ratio \( c/a = 3 \) (where \( c/a \) is the half-length / depth ratio of the crack). For such postulated defect and investigated primary loadings, the deepest point of the crack is the most loaded point and thus the assessment can concentrate on this point.
3.2 **General formulation – SIF formulation**

For a circumferential weld in a piping system, if we concentrate on bending moment, torsion and internal pressure and the deepest point of the crack front, the SIF can be expressed as follows:

\[
K_I = (\sigma_{gb} \cdot f_{gb} + \sigma_p \cdot f_p) \cdot \sqrt{\pi \cdot a}, \quad K_{III} = \sigma_T \cdot f_T \cdot \sqrt{\pi \cdot a}, \quad \text{then: } K_{eq} = \sqrt{K_I^2 + \frac{K_{III}^2}{1 - v}}
\]

In this formulation:
- \( f_{gb} \), \( f_p \) and \( f_T \) are the influence functions which has to be defined for the specific geometry;
- \( \sigma_{gb} \), \( \sigma_p \) and \( \sigma_T \) are the nominal (crack free) stresses in the ligament supporting the defect and defined on the basis of the imposed load:

\[
\sigma_{gb} = \frac{4 \cdot r_e \cdot M_2}{\pi \cdot (r_e^3 - r_i^3)}, \quad \sigma_T = \frac{2 \cdot r_e \cdot M_1}{\pi \cdot (r_e^4 - r_i^4)}, \quad \sigma_p = \frac{r_e^2 \cdot P}{r_e^2 - r_i^2} \text{ (int. defect)}, \quad \sigma_p = \frac{-r_i^2 \cdot P}{r_e^2 - r_i^2} \text{ (ext. defect)}
\]

\( M_2 \), \( M_1 \) and \( P \) are respectively the imposed bending moment, torsion and internal pressure. The \( \sigma_p \) stress is deferent for internal and external surface defects since it includes for the internal surface defect the pressure on the lips of the crack.

Following this SIF calculation, it simply comes:

\[
J_{el} = \frac{(1 - v^2) \cdot K_{eq}^2}{E}
\]

In practical applications, knowing the imposed loading, \( J_{el} \) relies on only 3 influence functions.

3.3 **General formulation – f(LR) correction**

The determination of the f(LR) correction relies on the same principle consisting in defining specific coefficients for the geometrical configuration under investigation. For that purpose, it is assumed that the
LR formulation provided by the RSE-M/5.4 appendix [3] remains the same. For an elbow, the LR parameter is expressed as follows:

\[ L_R = \sqrt{\left( \gamma^2 \frac{m_2}{q_m \cdot \mu_{em} \cdot \mu_t} \right)^2 + \left( \frac{p}{\mu_{ep}} \right)^2 + \left( \frac{m_1}{q_n \cdot \mu_{em}} \right)^2 + (1 - \gamma^2) \frac{m_2}{q_m \cdot \mu_{em} \cdot \mu_t}} \]

In this formulation:
- \( q \) and \( \mu \) are corrections depending on structural and defect geometry and position.
- \( m_2, m_1 \) and \( p \) are the dimensionless loading defined as a fraction of the associated unitary limit load:
  \[ m_2 = \frac{M_2}{4. \, r_m^2 \cdot t \cdot \sigma_y}, \quad m_1 = \frac{\sqrt{3} \cdot M_1}{2. \, \pi \cdot r_m^2 \cdot t \cdot \sigma_y}, \quad p = \frac{\sqrt{3} \cdot P \cdot r_m}{2. \, t \cdot \sigma_y} \]

In practice, the \( q \) and \( \mu \) corrections could only be developed, optimized and codified for simple situations such as straight pipes and mid-sections of elbows. The main reason is linked to the too large number of parameters to consider in the analysis (geometry/loading/defect position/material…) for covering accurately more complex geometries. Outside this scope, solutions are provided by the code but they are relying on simple and envelop corrections which integrate an important intrinsic conservatism.

It is assumed here that the main conservatism of the LR formulation relies on those \( q \) and \( \mu \) coefficients. For a given complex geometry and for optimization purpose, the idea is then simply to develop specific dedicated solutions. Only \( q \) coefficients are defined and then \( L_R \) becomes:

\[ L_R = \sqrt{\left( \gamma^2 \frac{m_2}{q_m} \right)^2 + \left( \frac{p}{q_p} \right)^2 + \left( \frac{m_1}{q_T} \right)^2 + (1 - \gamma^2) \frac{m_2}{q_m}} \]

Where \( q_m, q_P, q_T \) and \( \gamma \) are the new optimized coefficients. At the end, with those geometrical corrections, 7 coefficients are required for a complete elastic plastic evaluation.

### 3.4 Numerical determination of the coefficients and adaptation to an elbow configuration

#### Determination of the geometrical coefficients:

As it was illustrated in previous paragraphs, the J evaluation scheme relies on 7 coefficients. Those coefficients can be separated in three families:
- \( f_{gb}, f_p \) and \( f_T \) are corresponding to influence function which have to be determined through an elastic modeling. This determination is relatively simple with a direct determination of the J parameter through a cracked model (and the G(\( \theta \)) approach) for each elementary loading then, knowing the imposed load, determination of the ad-hoc influence function. As an example, the \( f_{gb} \) influence function is simply:

\[ f_{gb} = \frac{\sqrt{J_{eb}^{(M)} \cdot E^*}}{\sigma_{gb} \cdot \sqrt{\pi \cdot a}} \]

where \( J_{eb}^{(M)} \) is the elastically determined J for the bending moment \( M \).
- \( q_m, q_p \) and \( q_T \) which are corresponding to the geometrical corrections of the LR parameter for each elementary loading. The way to determine those coefficient remains the same with an elastic-plastic determination of the J parameter then, knowing imposed load, a determination of the ad-hoc influence function. However, this determination is a little more complex since it has to integrate the elastic-plastic behavior of the material. As an example, the protocol for determining the \( q_m \) coefficient is the following:
  - A set of \( J^{(i)} \) parameter is determined for an increasing bending moment \( M^{(i)} \);
  - Knowing \( J^{(i)} \) and the associated elastic J (through the influence functions previously determined), the effective plastic correction can be determine through the relation:
In the problem, the material behaviour is known and a plastic correction \( f(L_R) \) can be defined for each point of the stress-strain curve. We can easily defined a \( f(L_R) \) bijective function by:

\[
f(L_R) = \frac{J^{(i)}}{J^{el}}
\]

where \( \varepsilon \) is the total strain associated to the stress \( \sigma \) on the true stress-strain curve of the material. Based on this \( f(L_R) \) definition, a \( L_R \) value (noted \( L_R^{(i)} \)) can be defined for each time step (i) of the modelling. A curve \( L_R^{(i)} \) vs. \( L_{R-no}^{(i)} \) can then be build (\( L_{R-no}^{(i)} = M^{(i)}/4.r_m^2.t.\sigma_y \) in that example). In theory, those two values are proportional and the slope between the two terms is relative to the geometrical correction \( 1/q_m \).

As it is shown on fig 2, when the loading is high enough the two parameters \( L_R^{(i)} \) and \( L_{R-no}^{(i)} \) are quasi proportional which means that a geometrical \( q_m \) correction can accurately be determined.

The \( \gamma \) coefficient relative to the possible interaction between the bending moment \( M_2 \) and the torsion \( M_1 \). For the determination of this parameter, the same process is applied for a combined bending plus torsion loading. Again a \( L_R^{(i)} \) coefficient is determined then, knowing the correction \( q_m \) and \( q_T \) for each unitary loading, the \( \gamma \) coefficient can be determined through the fit \( L_R^{(i)} \) vs. \( L_{R-no}^{(i)} \) curve.

This protocol is theoretically not depending on the material stress-strain curve. However, for precision purpose, the application is performed for the two materials constituting the auxiliary and secondary piping: 304L stainless steel and P355GH carbon-Manganese steel.

As it is illustrated here, 7 FEM are required for each geometrical configuration, three of them are linear elastic (and thus very fast), and the four remaining ones elastic-plastic (thus requiring the largest part of the modelling time).

\[
\begin{align*}
\text{Figure 2: Illustration of the proportionality between the imposed loading (} L_{R-no} \text{) and the stress associated to the effective plastic correction (} L_R^{(i)} \text{).}
\end{align*}
\]

**Application to an elbow configuration:**

For a straight pipe or a thickness transition configuration, the modelling effort can be limited to 7 calculations. However, this is no more the case for an elbow since in that case the geometrical coefficients are depending on the defect position within the weld circumference.
An example of such configuration is presented in fig. 3 where a weld connecting an elbow to a large component is investigated. On this figure, the defect position in the circumferential direction of the weld is defined by the angle $\theta$, $\theta = 0$ corresponding to the elbow extrados and $\theta = 0$ at the intrados.

For such geometry, the weld is directly at the exit of the elbow and thus strongly influenced by the stress distribution in the elbow which is a complex combination of membrane and through-thickness bending stresses for opening/closing bending moments, out-of-plane bending moments and torsional bending moment. As a consequence J parameter and the q corrections are necessarily depending on the defect ($\theta$ angle).

![Figure 3: Example of an elbow connection to a large component – the postulated defect is here an external surface defect (CDSE in RSE-M/5.4 [3] notations)](image)

For this kind of elbow entry/exit, a strong assumption is made in order to limit the numerical scope: for a given in-plane and out-of-plane bending combination, the most severe position for the defect (the $\theta$ angle) corresponds to the plane were the bending stress are maximum.

A first corollary of that assumption is that the defect position is directly defined by the $M_3$ (out-of-plane) vs. $M_2$ (in-plane) bending moments ratio.

A second corollary is that, for a given defect position, the geometrical coefficients $f$, $q_m$ and $\gamma$ have to be determined for a $M_2/M_3$ combinations which procures a maximum bending stress at the $\theta$ angle: if $M_1$ and $M_2$ are the expected bending moments in the crack axes (X, Y, Z), the bending set to be imposed at the entry of the elbow is simply in axes (X’, Y”, Z’), (see fig. 3 for axes definition):

\[
\begin{align*}
M'_1 &= M_1 \cdot \cos(\Phi_c) - M_2 \cdot \sin(\Phi_c) \cdot \sin(\theta) \\
M'_2 &= M_2 \cdot \cos(\theta) \\
M'_3 &= M_1 \cdot \sin(\Phi_c) - M_2 \cdot \cos(\Phi_c) \cdot \sin(\theta)
\end{align*}
\]

where $\Phi_c$ is the elbow angle.

Based on that assumption, the set of geometrical correction can simply be define through a choice of angle positions, then determining the corrections through FEM as explain previously for each angle $\theta$. 
For the compendium development, 13 angle positions were chosen (θ = 0 to 180°) for the influence function definition (f coefficients) and 5 angle positions for the geometrical corrections of the L_R function (q and γ corrections). This means that 40 elastic-plastic FEM (2 positions x 5 angles θ x 4 unitary and combined loadings) are required for a given elbow correction. The number of elastic FEM is larger but the modelling is faster and thus does not represent the bounding modelling time. The number of required elastic-plastic FEM appears relatively high. However, for all configurations to be investigated, the set of modelling is always the same and can run automatically (both modelling and post-treatment of the results). Another important fact is that this modelling can be anticipated without knowing the load sets to investigate in the FMA: once the set of coefficient is defined, it covers all the possible loading sets of the FMA.

Validation and Verification (V&V) of the results
Regarding the large number of FEM required for many different geometrical configurations, V&V is an important step for this work. Meshing and post-treatment procedures being previously validated (those are the ones used for the RSE-M/5.4 [3] SIF and reference stress compendia development), V&V has to concentrate on the coherence of the data, the entry data (crack size, loadings…) the material behaviour… To do so, 4 different indicators were defined, applying on both elastic and elastic-plastic results. Those indicators are the following:

- For a given geometry, defect position and imposed loading, the direct calculation of the SIF is compared to an application of the RSE-M/5.4 SIF compendia dedicated to pipes with circumferential surface defects. This means that, in addition to the elastic and elastic-plastic FEM with a crack model, an elastic modelling with a crack free model is required. For determining the stress through the thickness of the weld and at the ligament supporting the crack. This indicator is relatively sensible to any defect position, mistake in load application… and is thus a major one;

- A fit of each influence function as a function of the angle θ is made in order to simplify the application. Then the maximum error between the fit and the direct result is determined. This indicator was defined since it is able to detect the effect of a coarse mesh in the elbow description;

- For elastic-plastic modelling, the proportionality between the L_R parameter determined through the ratio J/J_{el} and the imposed loading (through L_{R-no}) is evaluated. This indicator aims to show that the load imposed in the elastic-plastic FEM is high enough to capture the limit load of the investigated configuration and also that the material stress-strain curve used for the post-treatment is the same than the one used for the FEM;

- A comparison of all coefficients (for all investigated geometrical configuration) is also performed in order to check the coherence of the different results. This indicator is qualitative but can highlight some surprising non-coherent results between two similar geometries.

4 ILLUSTRATION THROUGH AN EXAMPLE
The complete protocol previously presented is applied to the weld junction represented on fig. 3. As it is shown on that figure, the weld configuration is cumulating the influence of an elbow exit and the presence of a thickness transition. This weld configuration is defined by r_i = 225 mm and t = 28.47 mm. For this thickness, the conventional defect depth is a = 10 mm at both inner and outer surfaces.

4.1 Determination of the geometrical coefficients
Next fig. 4 and 5 give examples of influence function evolutions with the defect position θ. As it can be seen on those figures, the defect position has a strong influence on the bending influence function f_{gb}. At the opposite, the effect of the defect position is limited for pressure (term f_p).

The application of RSE-M/5.4 formula based on a calculation of the nominal stresses is also represented on those figures. It is then shown that the f_{gb} and f_p evolutions are similar but slightly higher. This result is considered as normal since the defect size is here close to the mid-thickness defect: for such relative thickness, the influence functions are depending on the surrounding geometry.
Figure 4: influence function for the internal surface defect

Figure 5: influence function for the external surface defect

The Figure 6 gives a representation of the $q_m$ to $q_T$ corrections evolution with $\theta$. Similarly than for the influence functions $f$, the angle $\theta$ has a strong influence on the global bending term $q_m$ and a limited one on the other corrections ($q_x$ & $q_T$).

This $q_m$ correction is very low for $\theta = 0$ (defect at the elbow extrados) which means that the plastic correction through $L_x$ is very important at this defect position. At the opposite, a high value of $q_m$ is obtained for the defect at the intrados: this is due to the fact that this position encounters a stress redistribution when global plasticity appears in the elbow. This defect position is not pertinent for FMA. The $\gamma$ coefficient is not represented here but equals to 1 in all defects locations, except for $\theta = 180^\circ$ (which is a non-pertinent position as explained previously).

Figure 6: Geometrical corrections for internal and external defects

4.2 Comparison to a direct calculation of $J$

In this section, the application of the protocol is compared to a direct calculation of the $J$ parameter for a loading set cumulating pressure, bending moments and torsion. The geometrical configuration is the one presented in fig. 3 and the load set is defined by:

$\{P, M_1, M_2, M_3\} = \{12.3 \text{ MPa, } 987 \text{ kN.m, } -754 \text{ kN.m, } -481 \text{ kN.m}\}$

For this loading set, the defect angle is directly defined by the maximum opening bending moment in the cracked section, that is to say for an angle position $\theta = 32.5$ deg. The comparison is made here for an inner surface defect which constitutes the most severe position.
The comparison between a direct modelling (red curve) and an application of the semi-analytical scheme (black points) is provided on fig. 7. As it is shown on that figure, the proposed protocol provides a very accurate value of both elastic and elastic-plastic J.

Within this protocol application, the $f(L_R)$ correction determined through the optimized scheme is $f(L_R) = 4.7$, whereas the RSE-M/5.4 application gives $f(L_R)=15.6$ (and thus a total $J \sim 320 \text{ kJ/m}^2$ approximately 3 times larger). Based on that result, one can easily understand the interest of developing accurate dedicated solutions for geometrical configurations submitted to the highest loading sets.

5 CONCLUSIONS AND PERSPECTIVES

This paper presents a protocol for optimizing the J parameter calculation in complex configurations such as elbows entries/exits and thickness transitions. The developed idea is that, for each of those complex geometry, a specific compendia for SIF and elastic-plastic J can be developed through dedicated FEM.

After describing the protocol, the paper illustrates its application to a complex elbow configuration. It is then shown that, for such configuration, the number of required elastic-plastic modelling is significant (40 elastic-plastic modelling required) but can be anticipated and easily automated for both calculation and the coefficient determination. Once the coefficients are defined, the FMA is immediate for any loading set imposed to the investigated weld.

The comparison of the protocol to a direct determination of J for a given loading set shows that it provides very accurate results and a substantial benefit in comparison to the codified analytical solution: J is divided by three in the example.

6 REFERENCES


[3] 5.4 appendix of the RSE-M, RSE-M, Rules for In-Service Inspection of Nuclear Plant Components, AFCEN, Paris