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Stress intensity factor calculation for surface defects in elbows

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Abstract

The number of relevant parameters for the characterisation of the geometry of an elbow with a surface crack is too high to develop a specific compendium of influence function for the stress intensity factor calculation. RSE-M and RCC-MRx codes proposed an alternative solution based on a classical observation that influence functions are little affected by the component geometry for shallow defect (a/t < 0.25). Hence, it is proposed to use influence functions codified for cracked pipes with the same defect and a specific solution to estimate accurately the nominal elastic stresses everywhere in the elbow. This last solution was developed on the basis of 3D F.E. calculation of uncracked elbows for in-plane, out-of-plane and torsion moment. Pressure solution is based on the classical toroidal assumption.

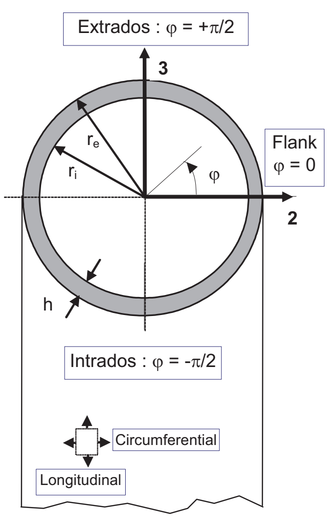
This paper summarises the solution proposed in the French codes and presents a wide validation based on around 300 3D F.E. reference cases.

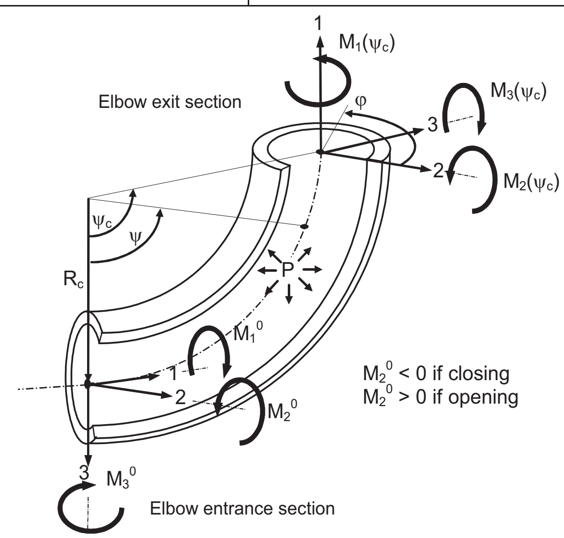
Notation

a	Crack depth (mm)
c	Crack half-length (mm)
E	Young's modulus (MPa)
$\mathbf{i_{0,..,4}}$	Influence function related to the nominal polynomial stresses for K_I calculation
$\mathbf{K_I, K_{II}, K_{III}}$	Mode I, II and III stress intensity factor ($MPa.m^{0.5}$)
P	Internal pressure (MPa)
u	Through-thickness variable (mm)
$\mathbf{u_1}$	Axial displacement (mm)
X	r_m/h
Z	Section modulus
$\boldsymbol{\nu}$	Poisson's ratio
$\sigma_{0,..,4}$	Components of the nominal polynomial through-thickness stress representation
σ_{1b}	Longitudinal shell bending elastic stress (MPa)
σ_{1m}	Longitudinal membrane elastic stress (MPa)
σ_{12b}	Through-thickness linear part of the shear elastic stress (MPa)
σ_{12m}	Constant through-thickness shear elastic stress (MPa)
σ_{2b}	Circumferential shell bending elastic stress (MPa)
σ_{2m}	Circumferential membrane elastic stress (MPa)
σ_{gb}	Global bending elastic stress (MPa)
σ_{no}	Nominal elastic stress (MPa)

Figure 1: Geometry of the elbow

r_i : internal radius **r_e** : external radius **r_m** :average radius $r_m = r_e - \frac{h}{2}$ **R_c** : bend radius	**φ** : azimuth in the section (in radian) **h** :thickness If there is extra thickness on the inside surface ⇨ h(φ): thickness as a function of azimuth $h = \frac{1}{2\pi} \cdot \int_0^{2\pi} h(\varphi) \cdot d\varphi$: average thickness	$Z = \pi . r_m{}^2 . h$ $\quad \lambda = \frac{h \cdot R_c}{r_m^2}$ $X = \frac{r_m}{h}$ $\quad L_a = \sqrt{\frac{r_m^3}{h}}$
ψ_c : elbow bend angle (in radian)	**ψ** : angle in radians between the entrance section and the considered section ψ=0 :elbow entrance section $\psi = \psi_c/2$: elbow median section $\psi = \psi_c$: elbow exit section	**P** :internal pressure
Moments in the entrance section	**Moments in a given section**	**Moments in the mid section**
M_1^o : torsion moment	$M_1 = M_1^o \cdot \cos\psi - M_3^o \cdot \sin\psi$	$M_1\left(\frac{\psi_c}{2}\right) = M_1^o \cdot \cos\left(\frac{\psi_c}{2}\right) - M_3^o \cdot \sin\left(\frac{\psi_c}{2}\right)$
M_2^o : in-plane bending moment	$M_2 = M_2^o$	$M_2\left(\frac{\psi_c}{2}\right) = M_2^o$
M_3^o : out-of-plane bending moment	$M_3 = M_1^o \cdot \sin\psi + M_3^o \cdot \cos\psi$	$M_3\left(\frac{\psi_c}{2}\right) = M_1^o \cdot \sin\left(\frac{\psi_c}{2}\right) + M_3^o \cdot \cos\left(\frac{\psi_c}{2}\right)$





1 Introduction

The stress intensity factor is the main basic element of the analytical methods developed for fracture mechanics analyses.

In the frame of the development of the fracture mechanic appendices of AFCEN codes (RSE-M and RCC-MRx codes [1,2]), a particular attention has been paid to the development of the mode I stress intensity factor for plates [3] and pipes [4,5] in the case of a surface crack. The solution is based on a polynomial representation of the through thickness opening stress distribution (calculated in the un-cracked structure) in the opening direction of the defect, weighted with influence functions which are functions of the geometry and defect sizes. Their determination has been performed from 3D F.E. calculations [3,4,5].

For more complex geometries such as elbows, the development of the details solutions is not realistic due to the large number of parameters to characterize completely the geometry. For example, in the case of an elbow, the geometry is described by the internal radius and the thickness like a straight pipe, but also by the curvature radius, the angle of the elbow and the position of the defect in the elbow. All theses parameters are defined in figure 1.

Of course, some specific solution exist, like the compendium proposed by Kim and al [6] for throughwall defects, but it don't cover the complete problem in term of defect type, size and position : for cast elbows, the defect can be chosen everywhere in the elbow, at the inner or the outer skin.

In the AFCEN codes, an alternative solution is proposed: It is advised to use the pipe's influence functions (up to a limited maximum defect size a/h = 0.25) and analytical solutions for the elastic opening stress distribution: the effort has then been focused on the development of an analytical solution for the calculation of the elastic nominal stresses in elbows for mechanical loads (pressure and moments).

The first part of the paper presents these solutions, with some details on the origin of the equations. The second part focuses on the validation of these solutions from the comparison with F.E. calculations.

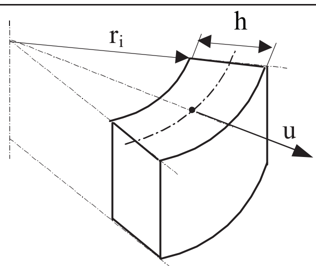
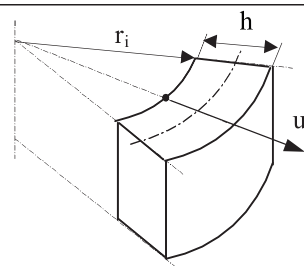
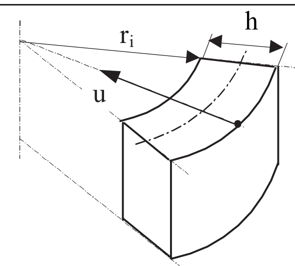
2 RSE-M and RCC-MRx methodology for K_I calculation

2.1 K_I calculation

For surface cracks, the through-thickness nominal stress description used for the K_I calculation is based on a polynomial fit : the origin of the coordinate system depends on the defect type (Figure 2):

- for through-wall defects, the origin of the coordinate system is located at the middle of the thickness,
- for other surface cracks, the origin of the coordinate system is located at the side where the defect appears.

Figure 2: Definition of the origin of the coordinate system for the calculation of the mode I stress intensity factor K_I

Origin in the middle of wall	Origin on the surface	
	Internal defect	External defect
		

For through-wall defects, the coefficient of the polynomial for the nominal stress is characterized by the membrane stress σ_m and the shell bending stress σ_b. Global bending is treated independently and is related to a global bending stress σ_{gb}. These stresses are given for each geometry of component and defect in [7,8,9]. The corresponding influence functions are F_m , F_b and F_{gb}. The stress intensity factor is then calculated using:

$$K_I = \left[\sigma_m.F_m + \sigma_b.F_b + \sigma_{gb}.F_{gb}\right]\sqrt{\pi.c} \tag{1}$$

where c represents the half-length of the defect.

For surface defects, the nominal opening stress is fitted using the following equation:

$$\sigma\left(\frac{u}{L}\right) = \sigma_o + \sigma_1 \cdot \left(\frac{u}{L}\right) + \sigma_2 \cdot \left(\frac{u}{L}\right)^2 + \sigma_3 \cdot \left(\frac{u}{L}\right)^3 + \sigma_4 \cdot \left(\frac{u}{L}\right)^4 \tag{2}$$

with $a \leq L \leq h$ and the variable u defined on the domain $0 \leq u \leq L$. The influence functions i_o, i_1, i_2, i_3, i_4 are provided for the deepest and the surface points of the defect. To this stress description, the global bending stress σ_{gb} should be added, with the corresponding influence functions F_{gb}. The stress intensity factor is then calculated from:

$$K_I = \left[\sigma_0.i_0 + \sigma_1.i_1.\left(\frac{a}{L}\right) + \sigma_2.i_2.\left(\frac{a}{L}\right)^2 + \sigma_3.i_3.\left(\frac{a}{L}\right)^3 + \sigma_4.i_4.\left(\frac{a}{L}\right)^4 + F_{gb}.\sigma_{gb}\right].\sqrt{\pi.a} \tag{3}$$

For the components considered in the RSE-M code [1] and in appendix A16 of the RCC-MRx code [2], each term $\sigma_{i=0,..,4}$ of the nominal stress fit is given as a function of the component and defect geometries and of the loading conditions. Also, the influence functions depend on the component and defect geometries.

2.2 K_{II} and K_{III} for pipes and elbows

According to the defect orientation, some loading components, such as a torsion moment, can create a mode II or mode III input. For each component and defect, the situations where one of these two modes has to be taken into account are listed [1,2]. In theses cases, the stress intensity factor expression is similar to the mode I equation and the influence functions are those for the mode I, which is supposed to be pessimistic. Only nominal stresses are different and these are provided when necessary.

2.3 Keq

In general, criteria use an equivalent stress intensity factor to take into account the contribution of all modes. This equivalent stress intensity factor is also used to calculate the parameters J and C*. This parameter is determined from the following equation, based on the link between the Griffith's energy release rate G and the stress intensity factors:

$$K_{eq} = \sqrt{\left[\max(K_I,0)\right]^2 + K_{II}^2 + \frac{1}{1-\nu} \cdot K_{III}^2} \tag{4}$$

3. Elastic nominal stresses in an uncracked elbow

The AFCEN codes provide detailed solutions to calculate the nominal elastic stresses in an uncracked elbow for mechanical loads (pressure and moments).

For pressure, the solution is based on the classical analytical solution of a torus submitted to internal pressure.

For bending and torsion moments, a first solution was produced in [10] for in-plane bending moment. This solution was built from a fit of F.E. calculations. A normalization of the results of these calculations allows the development of a general solution, covering a wide range of elbow geometries. The equations provided stresses solution in the mid section and the entrance section of the elbow. An interpolation methodology allows the calculation of the nominal elastic stresses in the other sections of the elbow.

Based on the same strategy, a new set of equations was produced to cover in-plane bending, out-of-plane bending and torsion [11,12].

The following paragraph presents an overview of the final solutions.

3.1. Internal pressure P

For internal pressure, nominal elastic stresses are:

- longitudinal membrane stress: $\frac{P \cdot r_i}{2 \cdot h(\varphi)}$ (5)
- circumferential membrane stress: $\frac{P \cdot r_i}{h(\varphi)} \cdot \left[\frac{2 \cdot R_c + r_i \cdot \sin\varphi}{2 \cdot (R_c + r_m \cdot \sin\varphi)}\right]$ (6)

3.2. In-plane and out-of-plane bending and torsion moments M_2, M_3 and M_1.

For an in-plane bending moment M_2, out-of-plane bending moment M_3 and torsion moment M_1, elastic nominal stresses are a function of the elbow angle ψ_c and of the considered section. The moment values to be considered are the values calculated in the considered section.

- **For elbows of 45°, 90° and 180° ($\psi_c = \pi/4, \pi/2, \pi$),** in the entrance section ($\psi = 0$) and the mid section (ψ□= $\psi_c/2$), the elastic nominal stresses are given by trigonometric series functions of the defect azimuth φ:

For the longitudinal and circumferential stresses (σ_{no1b}, σ_{no2b}; σ_{no1m}, σ_{no2m}):

In-plane bending: $$\sigma_{no} = -\frac{M_2}{Z} \cdot [s_1 \cdot \sin(\varphi) + s_3 \cdot \sin(3\varphi) + s_5 \cdot \sin(5\varphi) + c_o + c_2 \cdot \cos(2\varphi) + c_4 \cdot \cos(4\varphi)] \quad (7)$$

Out-of-plane bending: $$\sigma_{no} = \frac{M_3}{Z} \cdot [c_1 \cdot \cos(\varphi) + c_3 \cdot \cos(3\varphi) + c_5 \cdot \cos(5\varphi) + s_2 \cdot \sin(2\varphi) + s_4 \cdot \sin(4\varphi) + s_6 \cdot \sin(6\varphi)] \quad (8)$$

Torsion: $$\sigma_{no} = \frac{M_1}{Z} \cdot [c_1 \cdot \cos(\varphi) + c_3 \cdot \cos(3\varphi) + c_5 \cdot \cos(5\varphi) + s_2 \cdot \sin(2\varphi) + s_4 \cdot \sin(4\varphi) + s_6 \cdot \sin(6\varphi)] \quad (9)$$

For the shear stresses (σ_{no12b} and σ_{no12m}):

In-plane bending: $$\sigma_{no} = \frac{M_2}{Z} \cdot [c_1 \cdot \cos(\varphi) + c_3 \cdot \cos(3\varphi) + c_5 \cdot \cos(5\varphi) + s_2 \cdot \sin(2\varphi) + s_4 \cdot \sin(4\varphi) + s_6 \cdot \sin(6\varphi)] \quad (10)$$

Out-of-plane bending: $$\sigma_{no} = \frac{M_3}{Z} \cdot [s_1 \cdot \sin(\varphi) + s_3 \cdot \sin(3\varphi) + s_5 \cdot \sin(5\varphi) + c_o + c_2 \cdot \cos(2\varphi) + c_4 \cdot \cos(4\varphi)] \quad (11)$$

Torsion: $$\sigma_{no} = \frac{M_1}{Z} \cdot [s_1 \cdot \sin(\varphi) + s_3 \cdot \sin(3\varphi) + s_5 \cdot \sin(5\varphi) + c_o + c_2 \cdot \cos(2\varphi) + c_4 \cdot \cos(4\varphi)] \quad (12)$$

The coefficients $s_{1,..,6}$ and $c_{o,..,5}$ for each stress component are functions of the moment type and of the elbow parameters λ and $X = r_m/h$:

$$s_i \text{ or } c_i = a + \left[b \cdot \lambda^2 + c \cdot \lambda + d + e \cdot X + \frac{f}{X}\right] \cdot \lambda^{(p \cdot X^2 + q \cdot X + r)} \quad (13)$$

where the coefficient (a, b, c, d, e, f) and (p, q, r) are given in Tables detailed in [9,11].

- **For other elbow angles ψ_c between $\pi/6$ and π,** in the entrance section ($\psi = 0$) and the mid section (ψ = $\psi_c/2$), the elastic nominal stresses are obtained from the solutions for elbow angles $\psi_c = 45°$, 90° and 180 as follows:

when $\pi/6 \le \psi_c \le \pi/2$: $$\sigma_{no}(\psi_c) = \sigma_{no}(\frac{\pi}{2}) + \frac{4}{\pi} \cdot \left(\frac{\pi}{2} - \psi_c\right) \cdot \left[\sigma_{no}(\frac{\pi}{4}) - \sigma_{no}(\frac{\pi}{2})\right] \quad (14)$$

when $\pi/2 \le \psi_c \le \pi$: $$\sigma_{no}(\psi_c) = \sigma_{no}(\pi) + \frac{2}{\pi} \cdot (\pi - \psi_c) \cdot \left[\sigma_{no}(\frac{\pi}{2}) - \sigma_{no}(\pi)\right] \quad (15)$$

- **In a given section** represented by its angle ψ ($0 \le \psi \le \psi_c$), the nominal stresses are obtained from the stresses calculated in the two main sections (entrance and mid sections):

$$\sigma_{no}(\psi) = \sigma_{no}(0) + \left[\sigma_{no}(\frac{\psi_c}{2}) - \sigma_{no}(0)\right] \cdot \sin\left(\pi . \frac{\psi}{\psi_c}\right) \quad (16)$$

Shear stresses are deduced from the stresses at the entrance section ($\psi = 0$):

$$\sigma_{no}(\psi) = \frac{1}{2}\sigma_{no}(0)\left[\cos\left(\pi\frac{\psi}{\psi_c}\right) + \left(1 - \frac{2\psi}{\psi_c}\right)\right] \quad (17)$$

- **The domain of validity** of these equations is:

$$3 \le r_m/h \le 20 \qquad 0.1 \le \lambda \le 1 \qquad \pi/6 \le \psi_c \le \pi \quad (18)$$

3.3 K_I - Circumferential defect

For a circumferential part throughwall defect, the value of K_I is given by the formula:

$$K_I = \left[\sigma_0.i_0 + \sigma_1.i_1.\left(\frac{a}{h}\right) + \sigma_2.i_2.\left(\frac{a}{h}\right)^2 + \sigma_3.i_3.\left(\frac{a}{h}\right)^3 + \sigma_4.i_4.\left(\frac{a}{h}\right)^4\right].\sqrt{\pi.a} \quad (19)$$

The values of the influence functions i_o, ..., i_4 and F_{gb} are the influence functions of the pipe with the same defect and geometry size (r_i, h) [8]. The values of $\sigma_{o,..,4}$ can be estimated from F.E. analysis or from the linearised solutions given in table 1:

Table 1: Elbows – elastic nominal stresses for K_I calculation for circumferential defects

	σ_0	σ_1
Defect at the internal surface	$\sigma_{no1m} - \sigma_{no1b} + P$	$+2.\sigma_{no1b}$
Defect at the external surface	$\sigma_{no1m} + \sigma_{no1b}$	$-2.\sigma_{no1b}$

For a linear variation of the temperature through the thickness, the stress solution proposed for pipes can be used [8], considering the same geometry dimensions and the same defect.

3.4 K_I - longitudinal defect

For a longitudinal part throughwall defect, the value of K_I is given by the formula:

$$K_I = \left[\sigma_0.i_0 + \sigma_1.i_1.\left(\frac{a}{h}\right) + \sigma_2.i_2.\left(\frac{a}{h}\right)^2 + \sigma_3.i_3.\left(\frac{a}{h}\right)^3 + \sigma_4.i_4.\left(\frac{a}{h}\right)^4\right].\sqrt{\pi.a} \quad (20)$$

The values of the influence functions i_o, ..., i_4 and F_{gb} are the influence functions of the pipe with the same defect and geometry size (r_i, h) [8]. The values of $\sigma_{o,..,4}$ can be estimate from F.E. analysis or from the linearised solutions proposed previously:

Table 2: Elbows – elastic nominal stresses for K_I calculation for longitudinal defects

	σ_0	σ_1
Defect at the internal surface	$\sigma_{no2m} - \sigma_{no2b} + P$	$+2.\sigma_{no2b}$

Defect at the external surface	$\sigma_{no2m} + \sigma_{no2b}$	$-2.\sigma_{no2b}$

As in-plane bending moment leads to strong through-thickness bending stresses, it can lead to the closure of the defect in some azimuth. In this case, the effect of the bending moment M_2 has to be removed. Table 3 summarises all these situations.

For a linear variation of the temperature through the thickness, the stress solution proposed for pipes can be used [8], considering the same geometry dimensions and the same defect.

Table 3: Elbow with a longitudinal defect: effective in-plane bending moment for K_I

		Intrados	**Extrados**	**FlanK**
Defect at the internal surface	Closure (M_2^o<0)	$M_2 = M_2^o$	$M_2 = M_2^o$	$M_2 = 0$
	Opening (M_2^o>0)	$M_2 = 0$	$M_2 = 0$	$M_2 = M_2^o$
Defect at the external surface	Closure (M_2^o<0)	$M_2 = 0$	$M_2 = 0$	$M_2 = M_2^o$
	Opening (M_2^o>0)	$M_2 = M_2^o$	$M_2 = M_2^o$	$M_2 = 0$

3.5 Calculation *of K_{II} and K_{III}*

Torsion moment M_1 and bending moments M_2 and M_3 lead to:

- a mode II stress intensity factor at the surface point of semi-elliptical defects, which can be calculated from:

$$K_{II} = \left[\tau_0.i_0 + \tau_1.i_1 \cdot \frac{a}{t}\right].\sqrt{\pi a} \tag{21}$$

- a mode III stress intensity factor at the deepest point of part through wall defects, which can be calculated from:

$$K_{III} = \left[\tau_0.i_0 + \tau_1.i_1 \cdot \frac{a}{t}\right].\sqrt{\pi a} \tag{22}$$

The values of the influence functions i_o and i_1 are the influence functions of the pipe with the same defect and geometry size (r_i, h) [8]. τ_0 and τ_1 can be deduced from Table 4.

Table 4: Elbows – elastic nominal shear stresses for K_{II} and K_{III} calculation

	τ_0	τ_1
Defect at the internal surface	$\sigma_{no12m} - \sigma_{no12b}$	$+2.\sigma_{no12b}$
Defect at the external surface	$\sigma_{no12m} + \sigma_{no12b}$	$-2.\sigma_{no12b}$

4. F.E. data base

The analytical method for the J calculation have been developed using a large number of 2D and 3D F.E. calculations. These calculations were performed by CEA, EDF and AREVA-ANP [13].

The development of the data base was performed in the frame of an expert working group following 4 main steps:

- calculations on pipes and cylindrical shells with a circumferential defect,
- calculations on pipes and cylindrical shells with a longitudinal defect ,
- calculation on elbows with a longitudinal defect,
- calculation on elbows with a circumferential defect.

At the beginning of each step, the first phase was a benchmark of F.E. reference solutions: the fracture mechanics experts of the three organizations performed the analysis of the same cases with their own F.E. software and the comparison of the results allowed qualification of the calculation procedures. CEA used CAST3M F.E. software [14], EDF used ASTER [15] and AREVA-ANP used SYSTUS [16]. This benchmark phase allowed the definition of 'good practices' of F.E. performance to ensure a correct result. This concerns the mesh construction, the definition of boundary conditions, the loading modeling and the range of load levels for which the calculation has to be performed.

Table 5 gives an overview of the contents of the data base for elbows submitted to mechanical loadings. The data base contains more than 300 3D calculations covering the complete domain of definition of the AFCEN codes methodology. This data base will be used to evaluate the accuracy of the methodology for the KI calculation.

Table 5: Details of the data base for mechanical loadings: number of cases for each geometry and each loading type - Loadings: P: pressure; M_2: bending moment (in plane moment for elbows); N_1: traction load; M_1: torsion moment; M_3: out-of-plane bending moment for elbows.

ELBOWS Number of cases		P	M_2	$P+M_2$	M_2+M_3	$P+M_2+M_3$	M1	$M_1+M_2+M_3$	M_1+M_3	M_3	$P+M_1+M_2+M_3$	$P+M_1+M_3$	$P+M_3$
circumferential defect													
110	COU-CDSI	22	25	28			3	8	8	6	2	4	4
67	COU-CDSE	9	21	13			2	5	9	3	5		
12	COU-CDAI	2	2	4			1		2	1			
longitudinal defect													
117	COU-LDSI	25	25	63	1	3							
19	COU-LDSE	4	7	8									
8	COU-LDII	2	2	4									

5. Solution validation

The solution validation is simply based on the comparison of the K_I estimation provided by the analytical solution and the F.E. results. To simplify the presentation, this paragraph will focus only on some relevant points of the F.E. results: for each case of the data base, the comparison is made for 3 values of the elastic-plastic of J, relevant of real situations: 50 kJ/m², 100kJ/m² and 200 kJ/m².

To illustrate the comparison between the method based on the influence function of cracked pipes and the F.E results, this comparison is presented in term Kr:

$$Kr = \left(\frac{J_{el}}{J} \right)^{0.5} \qquad (23)$$

The comparison is provided in figure 3, confirming the relevance of the analytical solution for both influence function and analytical stress definitions.

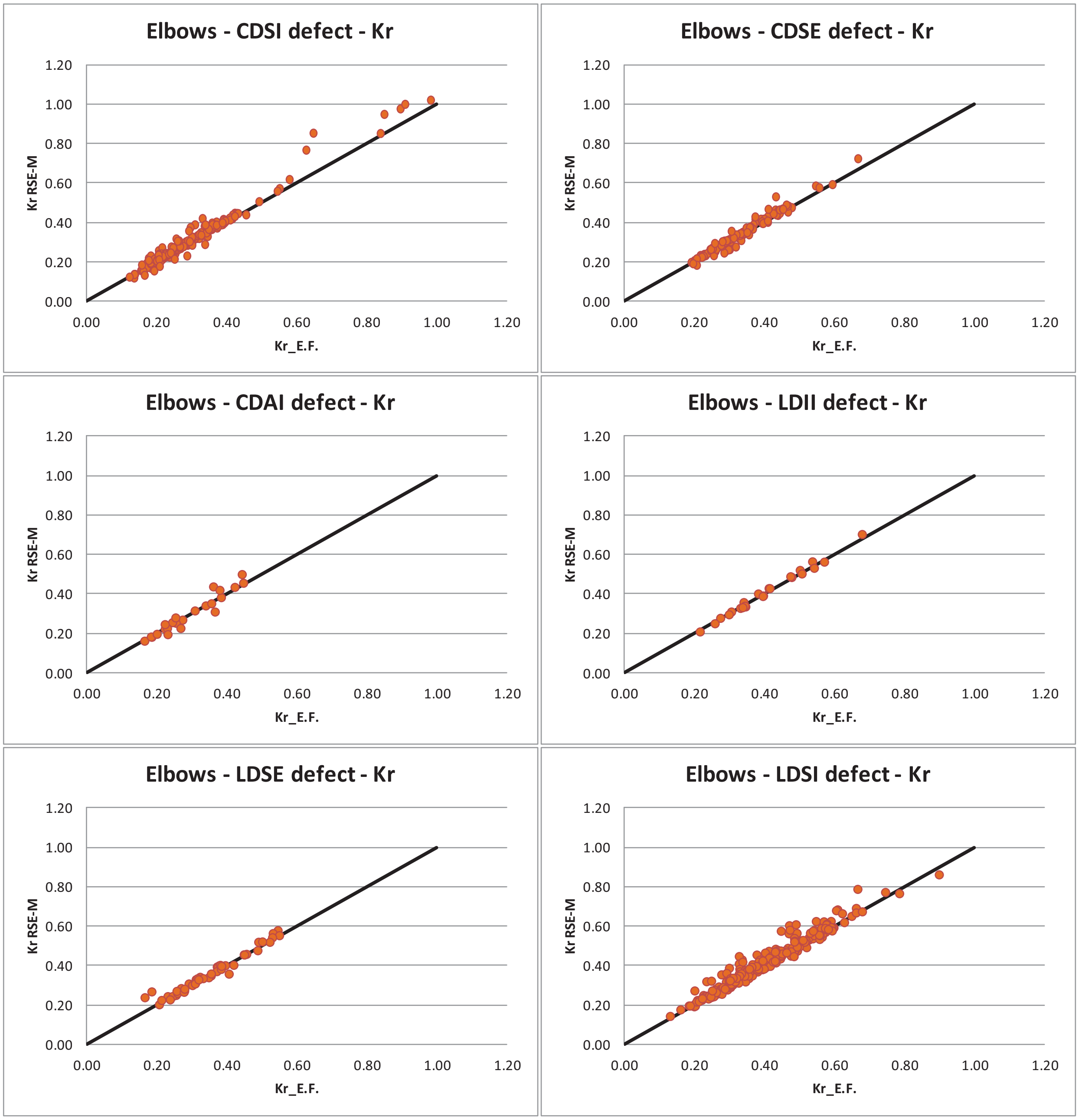


Figure 3 : Comparison between the analytical solution and the F.E. data base.

CDSI / CDSE defect: Circumferential internal/external semi-elliptical surface defect
CDAI defect: Circumferential internal axisymmetrical surface defect
LDSI defect: Longitudinal internal infinite surface defect
LDSI/LDSE defect: Longitudinal internal/external semi-elliptical surface defect

6 Conclusions

The number of relevant parameters for the characterisation of the geometry of an elbow with a surface crack is too high to develop a specific compendium of influence functions for the stress intensity factor calculation.

This paper presented an alternative solution - provided in the RSE-M and RCC-MRx codes - based on a classical observation that influence functions are little affected by the component geometry for shallow defect (a/h < 0.25). It is then proposed to use influence functions codified for cracked pipes with the same defect and a specific solution to estimate accurately the nominal elastic stresses everywhere in the elbow. This last solution was developed on the bases of 3D F.E. calculation of uncracked elbows for in-plane, out-of-plane and torsion moments. Pressure solution is based on the classical toroidal assumption.

The last part of this paper presents the validation of this analytical solution, compared to F.E. calculation data base. This data base was built by AREVA, CEA and EDF for the development of a complete set of compendia for the elastic-plastic J calculation, based on the reference stress concept. This data base includes more than 300 3D F.E. calculations for cracked elbows submitted to mechanical loadings.

The comparison between this data base and the analytical solution illustrates the good accuracy of the analytical solution proposed by the AFCEN codes for the stress intensity factor calculation in cracked elbows.

7 References

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