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Numerical and simplified analyses of large scale ductile tearing tests on cracked elbows

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ABSTRACT

EDF and FRAMATOME have undertaken an important effort of research for assessing the integrity of aged duplex cast stainless steel elbows. One part of this program is devoted to the analysis of cracks which represent a much more severe defect than any potential shrinkage cavity. On the one hand, experiments on large scale cracked elbows under in-plane bending with or without pressure were designed and conducted by EDF, and on the other hand FRAMATOME has developed a crack driving force J estimation scheme named KJ95. Detailed finite element analyses have been conducted by EDF and FRAMATOME, allowing to make a link between experimental results an the J values predicted by KJ95. This paper first presents some of these finite element results and in a second part compares the finite element J variations as a function of loading with the KJ95 predictions. Finally, using finite element or KJ95 computed J in combination with a resistance curve obtained from CT specimen, load - crack growth curves are derived for the surface cracked elbows. These curves are compared to the experimental one. It is concluded that the KJ95 estimation scheme allows predicting initiation as well as ductile crack tearing in surface cracked elbows under pressure and bending.

1. INTRODUCTION

EDF and FRAMATOME have conducted an important programme on the fracture behavior of aged duplex cast stainless steel elbows. The bulk of this programme consists in three tests performed by EDF on large diameter cracked elbows ([1] to [3]). The two first tests were conducted on elbows with a single crack under in-plane closure bending at 320°C. The third elbow contained two cracks and was loaded under pressure and in-plane closure bending at 60°C. EDF and FRAMATOME have performed several full 3D finite element elastoplastic analyses of these experiments. Furthermore, FRAMATOME has developed for EDF a scheme, named KJ95, which estimates the crack driving force J in surface cracked elbows under pressure and in-plane bending [4],[5]. This paper presents FRAMATOME's finite element analysis of the third test and compares all KJ95 predictions to finite element J results for all configurations.

2. DESCRIPTION OF THE TESTS

2.1. *Description of the test facility and tested elbows*

The experimental facility used by Electricité de France (EDF) is shown in figure 1. One end of the elbows is fixed to a rigid welded frame, the other end being lengthened by a 6 m long straight pipe used as a moment arm. For the two first tests, two connecting carbon steel pipes are inserted between the elbow and the arm pipe and between the elbow and the flange. The moment loading is generated by pulling on the arm pipe with a ram. For the third test, an internal pressure is applied in addition to the moment loading. Consequently, two flat heads are also inserted: one between the connecting pipe and the arm pipe and the other between the elbow and the flange.

Three 90 degree externally surface cracked elbows were considered in the experiments. The first presented a longitudinal slender semi-elliptical crack on the crown and was subjected to an in-plane closure bending (SEM1 test). The second contained a circumferential semi-elliptical crack between the crown and the intrados and was subjected to the same loading (SEM2 test). The third elbow (SEM3 test) presented two semi-elliptical cracks: a longitudinal one, located on the flank and a circumferential one in between the intrados and the crown . Both cracks were centred in the middle section. The elbow was pressurised and then, under constant pressure, was loaded by an in plane closing moment,. For all tests, notch characteristics are given in Table 1 and shown on Figure 2. They were made by electric discharge machining.

Test	Notch Location	Notch Orientation	Length 2c (mm)	Depth a (mm)	c/a
SEM1	Flank	Longitudinal	210	10.5	10
SEM2	Near the Flank (15° towards extrados)	Circumferential	88	14.7	3
SEM 3	Flank	Longitudinal	210	10.5	10
	Near the Flank (15° towards extrados)	Circumferential	88	14.7	3

<u>Table 1:</u> Characteristics of machined notches

The main dimensions of the three elbows are identical : 580 mm outer diameter, 44 mm thickness, 900 mm bend radius and 90 degree bend angle.

2.2. *Material data*

The elbows are made of Z3 CND 19-10 M duplex stainless steel and have been aged during 3000 hours at 400°C for the two first tests and during 1000 hours at 400°C for the third one. The material characterisation programme included chemical analysis tensile tests and J-resistance curves determined on CT specimens. For the duplex stainless steel elbows, the chemical composition (especially elements contents like Cr, Mo, Ni and δ ferrite) leads to a severe thermal ageing and low toughness values after thermal ageing at 400°C.

The material characteristics are detailed in [2] and [3]. SEM1 and SEM2 elbows have almost the same tensile properties ($\sigma_y \cong 260$ MPa). The stress-strain curves are compared on Figure 3. For SEM3, which is more closely analysed in this paper, tensile and toughness properties are the following :

$\sigma_y \cong 260$ MPa

$J_{mat} = 84.13(\Delta a)^{0.2698}$ (Δa in mm and J in kJ/m^2) (1)

3. FINITE ELEMENT ANALYSES

During the tests, the moment arm and flanges remain elastic. In the elastoplastic computations the non-linear behaviour of all other parts is taken into account. In all simulations, symmetry of the configuration has been assumed, since it has been proven by comparison to tests results, that the effect of surface cracks on the global behaviour of the structure is negligible [2].

For the SEM1 test, both Framatome and EDF have obtained very close results to all experimental measurements (Rotation, ovalisation, strains, Crack Opening Displacements), using updated Lagrangian formulation [2]. In the SEM3 tests, small and large displacement computation, as well as test measurements give almost the same results. This may be explained by a compensation of two opposite effects on the moment-rotation curve : the pressure opens the elbow and increases its strength, although the closing in plane bending flattens the cross section and therefore decreases the moment value. FRAMATOME has analysed the cracked structure with the finite element code CASTEM 2000 [6]. One half of the structure is meshed as shown in Figure 4, using 15 and 20 node isoparametric elements. The computation has been performed under the small displacement hypothesis and J is derived via the G-θ domain integral method [7].Figure 5 presents the computed and measured load -displacement curves: EDF and FRAMATOME results are on top of each other and the difference with the experimental curve is quite small although the geometry changes have been neglected in the computations. The same degree of accuracy has been obtained on other measured quantities as in the SEM1 test.

4. CRACK DRIVING FORCE PREDICTIONS USING THE KJ95 J-ESTIMATION SCHEME

The theoretical foundations as well as the formulae of the KJ95 J-estimation scheme for surface cracked cylinders and elbows, have been presented in [4] and [5]. As the R6 rule [8], KJ95 is based on the reference stress concept. The reference stress, which measures the yield level in the cracked section, is derived in R6 from a limit load interaction condition. KJ95 generalises this approach to elbows containing mode 1 cracks at any location in the structure even for defects lying outside of the most loaded areas. Hardening and contained yielding effects are also taken into account in KJ95. As in the R6 rule, the derivation of J for a cracked component exhibiting a non-linear behavior, requires the determination of the linear solution J^e, which may be obtained by the influence function technique. In the present applications, J^e values come from the

EDF finite element results and only the non linear behaviour of the elbow has been considered, assuming the whole mock-up remains elastic.

KJ95 has been developed under the small displacement assumption. Therefore, the validation of this scheme must be based on the comparison with Finite Element results derived under the same hypothesis. Figures 6 to 9 show a good agreement between predicted and FE computed J values. For circumferentially cracked elbows under bending, KJ95 uses a reference load which is proportional to the limit load and corrected by a factor accounting for the relative ovalisation of the section but is independent of the crack location in the section. For circumferential cracks located at the intrados, the scheme gives good results [5] but appears to be slightly non conservative for the worst location selected in the SEM2 test (Figure 7). Under constant pressure plus bending (Figs 8 & 9) the scheme overestimates J. This may be explained by two effects not considered in KJ95 : the flat heads increase the elbow stiffness as well as the effect of pressure on bending moment [9]. These two phenomena are independent of the material behavior and are not large displacement effects.

The large displacement J values reveal the weakening effects of the closing mode in elbows subjected to in plane bending. However, for practical applications to primary pipings, high level of bending moment are always associated to pressure. And, as mentioned above, large displacements effects may be neglected in pressurised elbows under closing in-plane bending.

For elbows loaded under pressure and opening bending, the pressure opens the elbows and therefore tends to increase J, but large displacement effects strengthen the elbow and reduce J. It has been shown that KJ95 give good results for such type of loading also, slightly non conservative for cracks at the worst location [5].

Finite element computations and KJ95 estimates have been used to predict crack propagation in the SEM3 test. In both cases, the J-Resistance curve is given by equation (1) which has been fitted on several resistance curves measured on CT specimens. For three different crack sizes (initial, 13.5 and 16.5 mm depth), EDF has computed the J versus ram force using a finite element model under the small displacement hypothesis. For the same cracks, we have computed the J-force relationship with KJ95, the moment at the crack location being linearly related to the arm force. In both approaches, all loadings (pressure, dead weight and moment) are taken into account. The comparison of the resistance curve to the applied J values gives the force versus crack growth curve for the elbow. During the test, crack growth has been measured by the electric potential drop technique. The amount of crack extension at the deepest point is assumed to be proportional to the variations of potential. The results , presented in Table 2, show that both finite element and KJ95 give good and safe predictions.

	Initiation	$\Delta a = 3$ mm	$\Delta a = 6$ mm
Measurement	392	528	550.5
Finite Element computation	400	486	492
KJ95 prediction	362	439	442

Table 2: Measured and predicted ram force (kN) versus crack growth curves.

These results prove that, for the present material and configuration, the J approach may be used to predict crack growth up to 6 mm. The KJ95 scheme gives smaller loads than finite element computations, but the difference appears to be constant for the three crack sizes. This shows that the conservatism of the J estimation by KJ95 is due to structural effects on the reference stress independent of the crack size (strengthening of flat heads and coupling between pressure and bending). For the considered case, the effects of bending and crack size seem to be correctly taken into account in KJ95.

5. CONCLUSIONS

For all SEM tests on cracked elbows, EDF and FRAMATOME have conducted finite element simulations giving excellent results compared to experimental global as well as local values.

For longitudinal or circumferential cracks in elbows under closing in-plane bending or pressure plus closing in-plane bending, the KJ95 J-estimation scheme provides good predictions when compared to finite element computations conducted under the small displacement hypothesis. The large displacement effects, not accounted for in the KJ95 approach, rise the J value under pure closing bending and lead to unconservative J predictions. In practical cases, however the elbows are pressurised, and large displacement effects may be neglected under pressure and closing bending.

Even though the accuracy of the KJ95 J-estimation scheme could still be improved, the present formulation is able to safely predict the ductile tearing of surface cracks in elbows under pressure and in-plane closing bending, using a resistance curve extrapolated from fracture tests on small specimens.

6. REFERENCES

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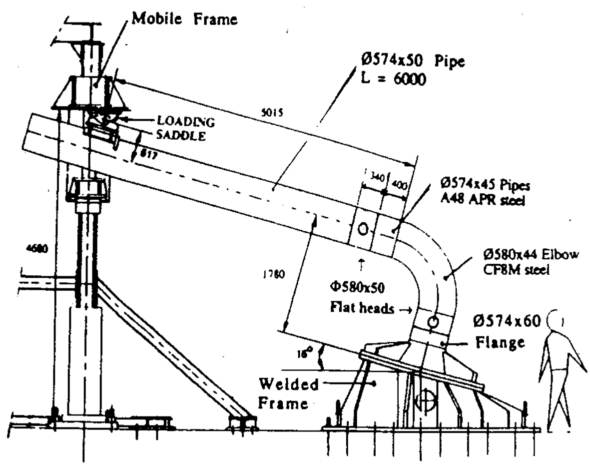

FIGURE 1 Schematic view of the SEM test device (SEM3 configuration [3])

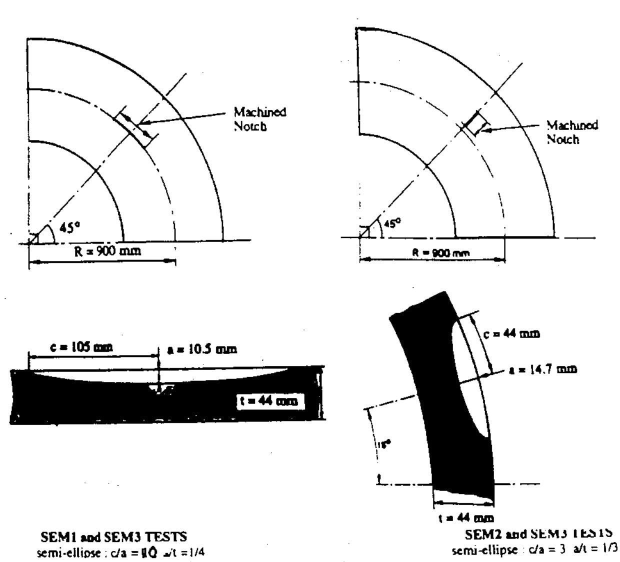

FIGURE 2 Location and Shape of the defects (from [3])

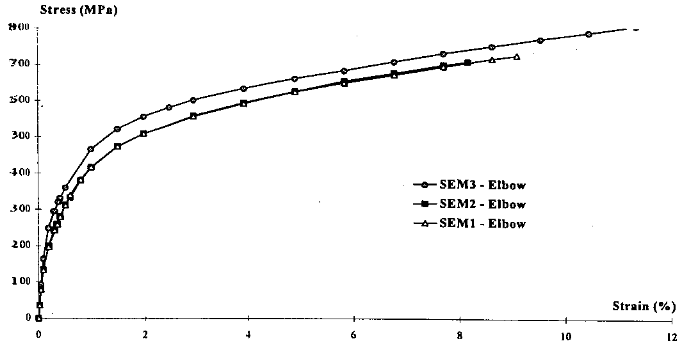

FIGURE 3 True stress-strain curves for the three elbows

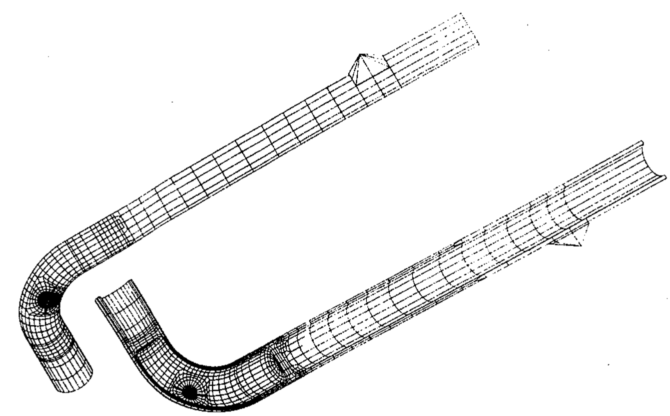

FIGURE 4 Finite Element model of the SEM3 test (16820 nodes)

SEM3 TEST - CRACKED ELBOW UNDER BENDING AND INTERNAL PRESSURE

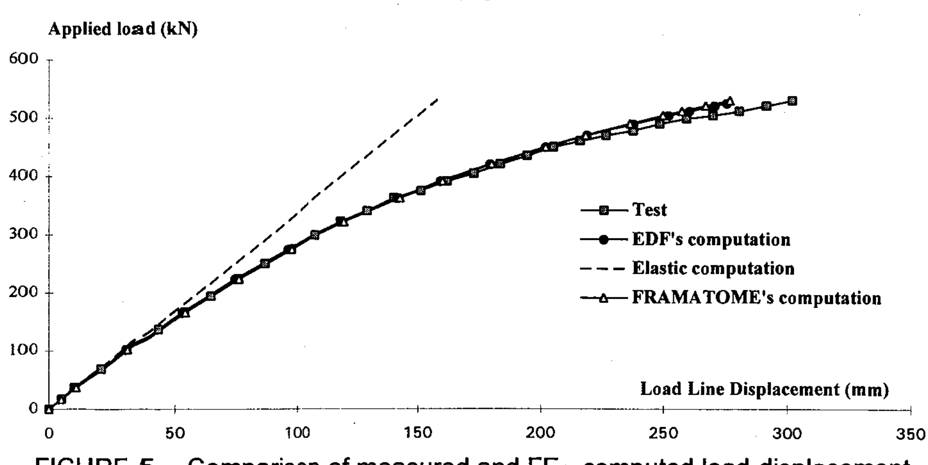

FIGURE 5 Comparison of measured and FE - computed load-displacement curves (SEM3 test)

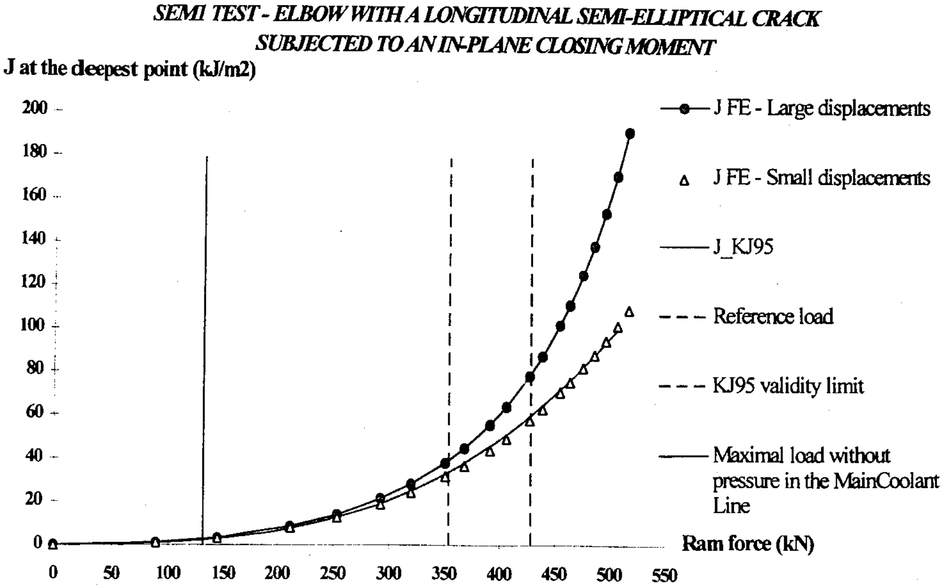

FIGURE 6 Comparison of Finite Element J results and KJ95 predictions for the SEM1 test (Longitudinal crack, pure bending)

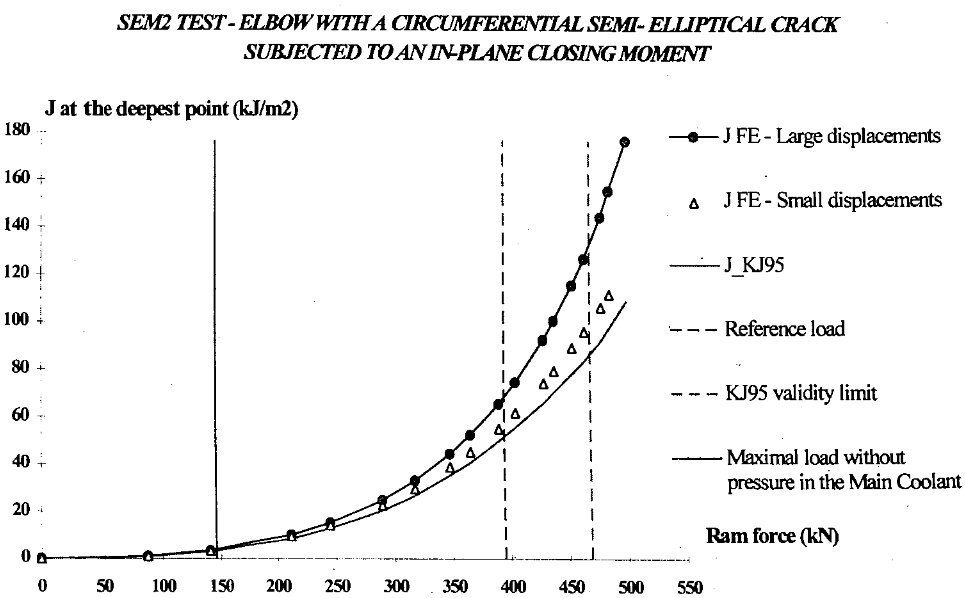

FIGURE 7 Comparison of Finite Element J results and KJ95 predictions for the SEM2 test (Circumferential crack, pure bending)

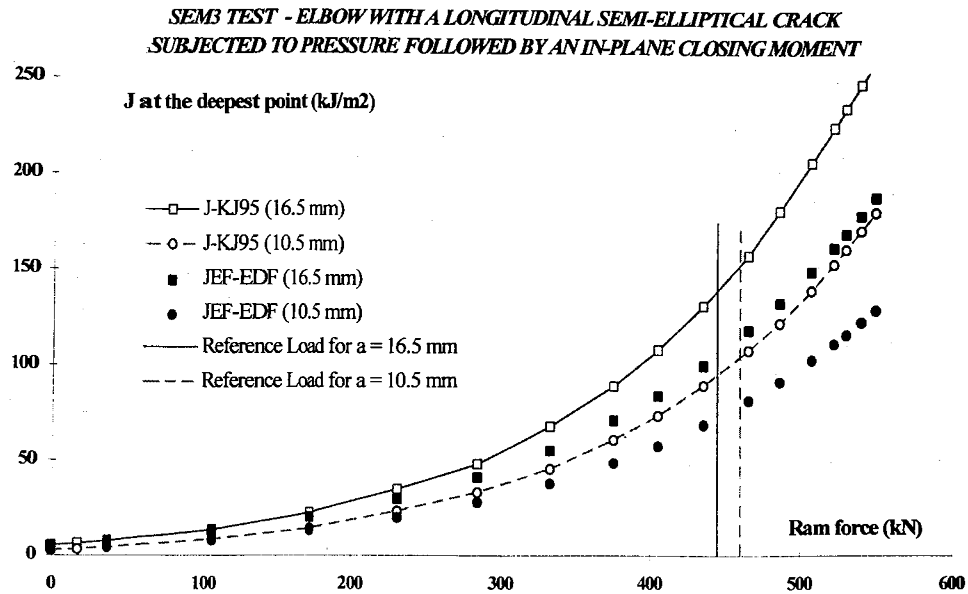

FIGURE 8 Comparison of Finite Element J results and KJ95 predictions for the SEM3 test (Longitudinal crack, pressure then bending)

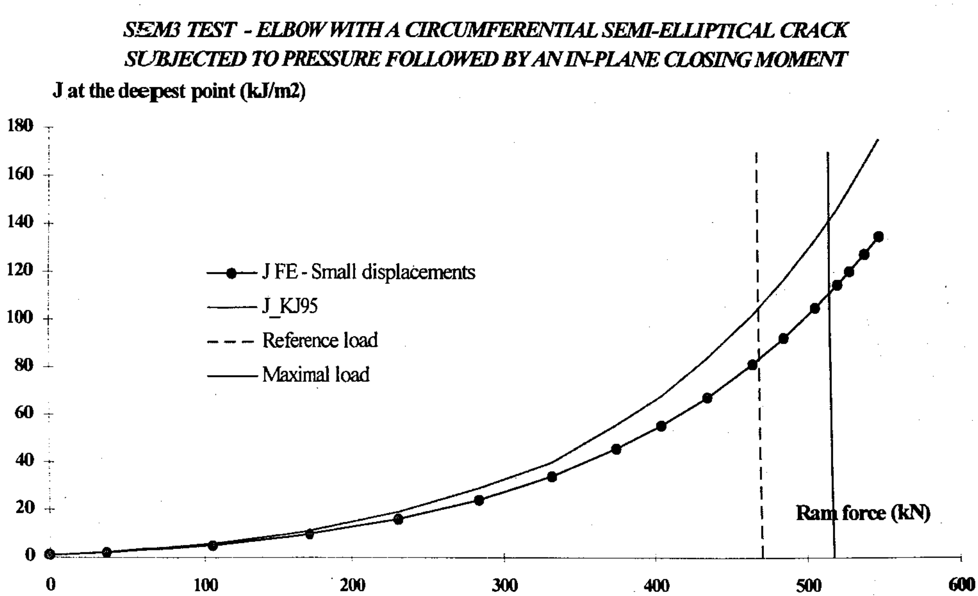

FIGURE 9 Comparison of Finite Element J results and KJ95 predictions for the SEM3 test (Circumferential crack, pressure then bending)