FRACTURE ASSESSMENT OF SURFACE CRACKS IN PRESSURE VESSELS AND PIPINGS BY 3D FEM COMPUTATIONS

dr. L. Pesti jr.*

Crack parameters are evaluated along postulated axial and circumferential belt-line flaws in pressure vessels and along crown side axial cracks in pipings. Stress intensity factors, crack opening displacements and energy quantities were evaluated along surface crack fronts. Estimated safety factors against brittle fracture were calculated as a function of time of the transient. The results obtained have shown that different crack sizes and locations may be critical as a function of time and boundary conditions.

INTRODUCTION

The component integrity assessment in case of pipings and pressure vessels is an important part of an failure prevention, residual life and life extension evaluation system. To assess the conditions which could cause failure in the presence of cracks under operating and transient conditions of power plants has led to the development of CRACK.3D FEM computer code (1,2). The applications - for 3D case studies - included elastic plastic material behavior (3), mechanical and thermal loading for surface cracks in arbitrary structural components (4-7) in order to assess the significant parameters that may influence the safety factors of cracks under all loading conditions. Usually it must be assessed that what flaw size can be tolerated without initiation or what changes should be introduced to keep the propagation of a crack in hand thus assuring the continued safe and reliable operation of power plants of all ages.

The results obtained when evaluating either postulated or detected cracks can easily be utilized in a monitoring and diagnostic system for power plant component aging (8).Recent work gives a brief summary of the results obtained by the CRACK.3D FEM program during the past few years when evaluating the crack parameters along postulated and detected semi-elliptical like surface flaws in the belt-line region of a WWER-440 type pressurized water reactor pressure vessel and pipe-bends of heat power plants.

* Previously at the Inst. for El. Power Res., Budapest (H)
Recently at CISE SpA, Milano (I)

POSTULATED CRACKS IN PRESSURE VESSELS

In the course of investigations the main goal was to get to know the variations of the stress intensity factor (K1) under the effect of normal and various upset transient operating conditions.

First a comparison is made between a FEM result -for an internal pressure type normal and overload - published by deLorenzi (9) and ours. The geometry and loading of the cracked vessel was that of deLorenzi. The type of the crack was the so-called maximum postulated flaw of ASME Code III.App.G.($2c=6a=1.5t$) in the belt-line region. In other words an axial semi-elliptical inner surface crack was evaluated in a long cylinder. The finite element mesh used (169 hexahedron elements with 1041 nodal points) and the results obtained for internal pressure with axial tension and with/without crack surface pressure are plotted on Fig.1. It can be seen that the crack surface pressure has resulted in a 10% increase of the values of the K1.

When evaluating the overloading ($p=31$ MPa) the nonlinear parameters such as crack opening displacement (COD) or the J-integral must be calculated. The so- called dog-bone (now for a semi-elliptical surface crack) and the COD vs. crack front are shown on Fig.2.

Second we compared the FEM and analytical results of a belt-line crack in a WWER-440 PWR type pressure vessel. The calculations according to ASME gave higher values for the K1 as compared to FEM results, while the INTERATOMENERGO approach ($2c=3a=3/4t$) gave closer agreement. The effect of crack depth to wall thickness ratio has also been studied.

Third field of investigation was the effect of temperature change across wall thickness on the crack parameters of a WWER-440 PWR RPV postulated belt-line crack. Among the pressurized thermal shock type transients special attention is focused on the stuck open relief valve on pressurizer (SORVP) and the steam generator tube rupture (SGTR) events. The evaluation of these transients required a detailed parameter study including material characteristics, flaw distribution, stress-strain behavior and thermal hydraulics. The crack configuration is shown on Fig.3. The loading was static internal pressure and temperature change across the wall thickness due to overcooling transients. The material model was linear and isotropic, the strains were supposed to be small. In case of thermal transient the temperature of the coolant must be known as a function of time and wall thickness (Fig.4.). The different coefficients of thermal expansion and conduction of the cladding and the base material were taken into account (LA(cl) = 15.2 W/mC; LA(bs) = 41.2 W/mC; BET(cl) = 1.681*10-5 /C; BET(bs) = 1.15*10-5 /C). The stress intensity factor (K1) vs crack front length of the semi-elliptical inner surface axial crack is shown on Fig.5.

Our preliminary calculations have shown that for the circumferential cracks the temperature distribution due to several downcomers may result in extremely high axial stresses. The finite element mapping was more complicated (see Fig.3.d.) with 838 elements and 4380 nodal points ($a/c=2/3$; $a/t=1/4$; $a=35$; $Ri/t=11.8$; $t=147$; $Ri=1771$; $E=198.5$ GPa; $nu=0.3$). The K1 vs crack front for the SORVP type and the SGTR type transients are shown on Fig.6. Lots of transients were analyzed. As one can see on the previous figures, as well the location and the maximum value of K1 highly depend on the temperature and pressure distribution at the vicinity of the crack, namely the thermal and mechanical boundary conditions. The maximum value may occur either at the free surface point, or at the deepest point of the crack depending on the geometry and boundary conditions.

The effect of several circumferential temperature distributions due overcooling with different downcomer configurations were evaluated in (6). The K1 and a safety factor (SF = K1c/K1) for the SORVP transient is shown on Fig.7a-b. Based on these calculations in different operational years it can be estimated that which cracks may initiate or propagate and so which cracks (Fig.7c-d.) must be monitored with sophisticated tools.

Fourth a postulated inlet nozzle crack in a WWER-440 PWR reactor pressure vessel was studied (see Fig.8.a.). The variation of K1 along the front can be seen on Fig.8.b. The goal of this investigation was the assessment of flaw behavior under the integrity pressure test of the vessel at different operating years which meant different irradiation embrittlement.

SURFACE CRACKS IN PIPE-BENDS

Semi-elliptical surface cracks often occur at the inner part of the so-called crown side of pipe-bends at power plants. The results of the bending process are the regular or irregular ovality and the wall thickness change.

First a downtube type pipe-bend with irregular cross sections and changing wall thickness was investigated. The finite element mesh was mapped from the original tube by slicing it into small parts and measuring the necessary data (see Fig.9.). An inner semi-elliptical surface crack was postulated at the upper crown side. In practice such type of cracks were detected and so it was necessary to assess the model. The K1 along the crack front is shown on Fig.9., as well. The change of the stress distribution was effected by the rather irregular cross section and it was growing high when approaching the bend zone as compared to the straight part. The fracture mechanical analysis gave a useful contribution to the evaluation of the detected cracks and gave reasons to cracking in practice.

Second, the next case was that of a cracked main steam line bend. A postulated semi-elliptical inner surface crack was postulated and mapped with a special technique onto the crown side at straight pipe/bend intersection (see Fig.10.). The task was the investigation of the K1 of different crack depth to wall thickness ratios with different but regular ovality along the bend. For a cross section of 8% of ovality with different a/t ratios the K1 vs crack front change is shown on Fig.10., as well. When performing linear elastic analysis it can be seen that with growing crack depth the greater K1 values occur closer to the bend part reflecting the effect of geometry.

CONCLUSIONS

The effect of orientation of postulated semi- elliptical inner surface cracks and the boundary conditions is not unique as for the stress intensity factor, etc.

distributions and maximum values. The most dangerous crack can not be found easily. Each possible transient, load configuration, boundary condition must be evaluated. As for the belt-line crack of a PWR increasing the temperature of the coolant the value of the safety factor against brittle fracture has also increased but strongly depending on the characteristics of the overcooling transient. And sometimes the costs of the coolant warm-up are much higher as compared to the in-service examinations. For the axial crack the steam generator tube rupture type transient resulted in the smallest safety factor, while for the circumferential crack the stuck open relief valve on pressurizer transient resulted in the smallest value.

For all structural members under investigation it was observed that at different operational years various cracks may initiate or propagate depending on the geometry, loading and boundary conditions.

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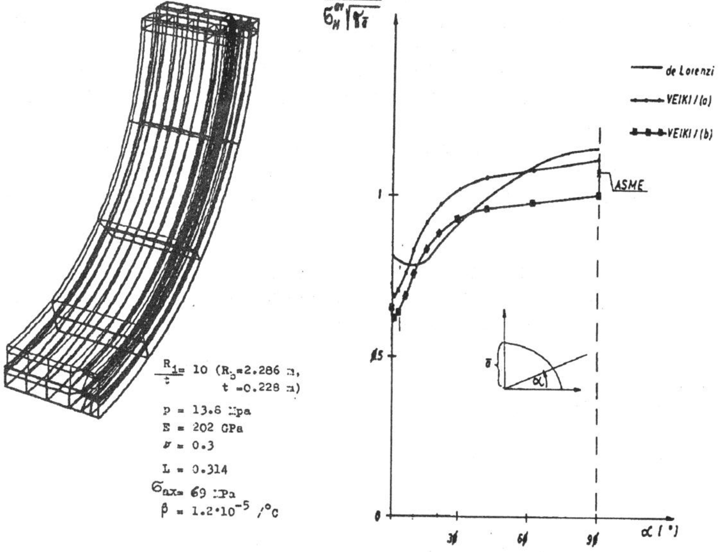

Figure 1 The mesh of the vessel and the stress intensity factor (K1) vs. crack angle (ALFA)

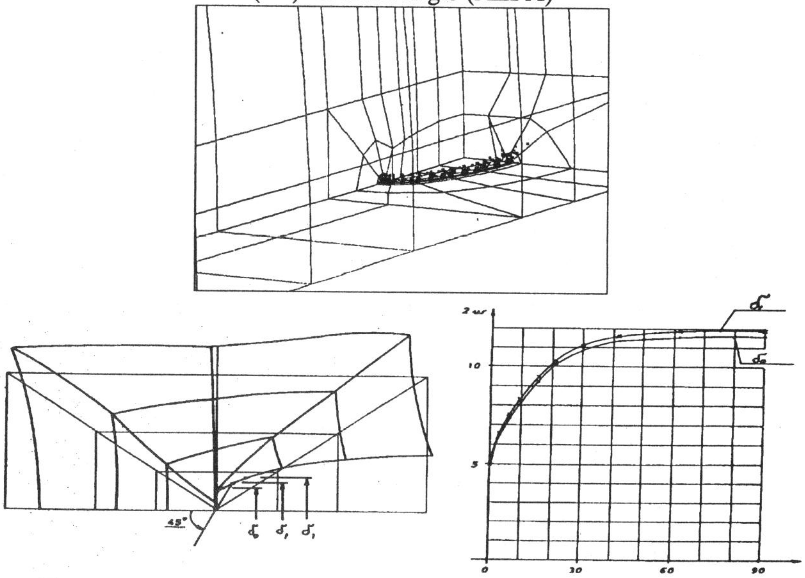

Figure 2 The "dog-bone" for the surface crack and the crack opening displacement (COD) vs. ALFA

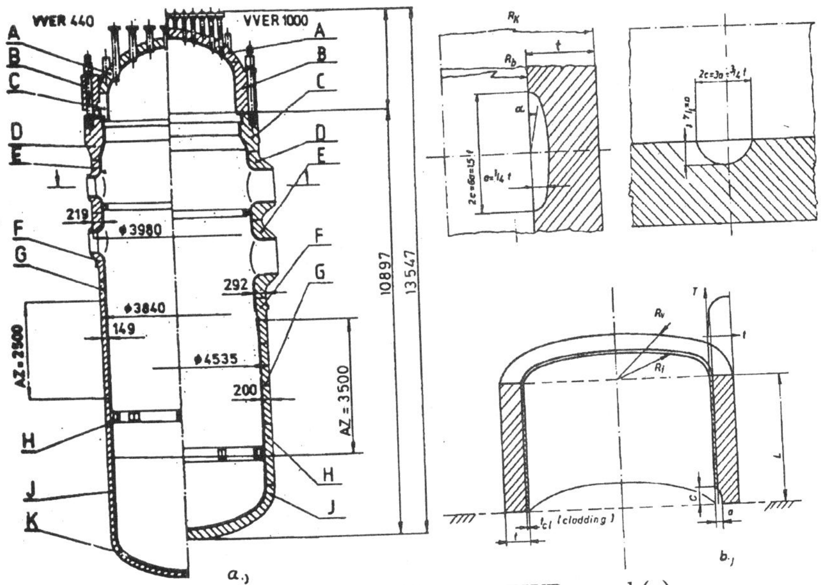

Figure 3a-b The WWER-440 PWR vessel (a) and the postulated cracks (b)

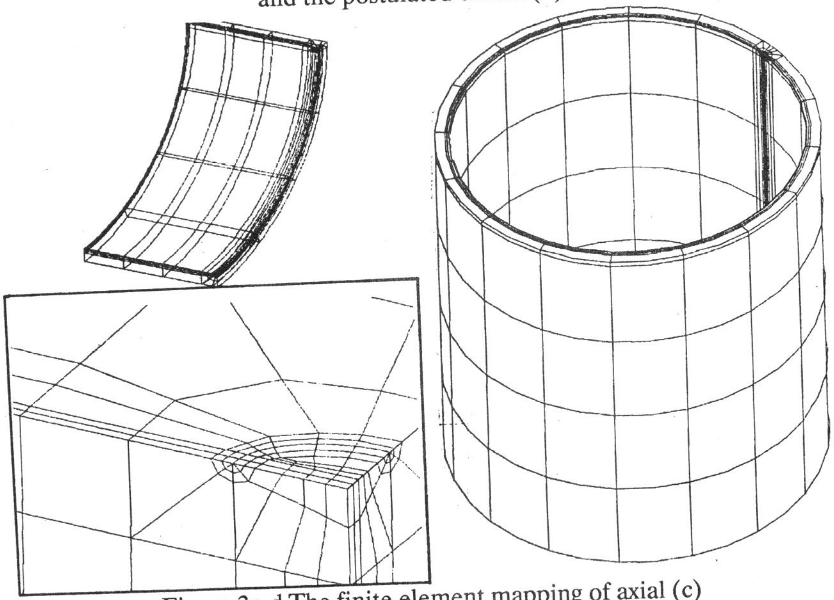

Figure 3c-d The finite element mapping of axial (c) and circumferential (d) surface cracks

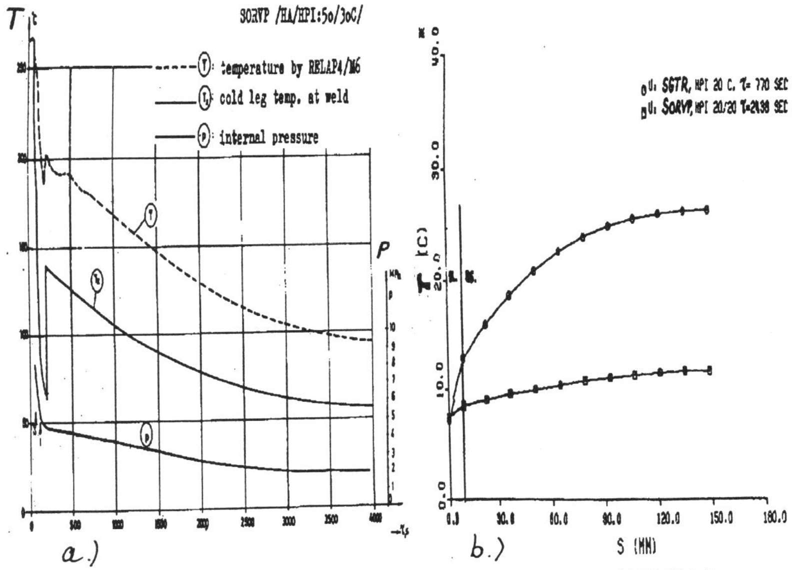

Figure 4 Coolant temperature vs. timeduringSORVP(a), temp. vs. wall thickness (b) for SGTR & SORVP

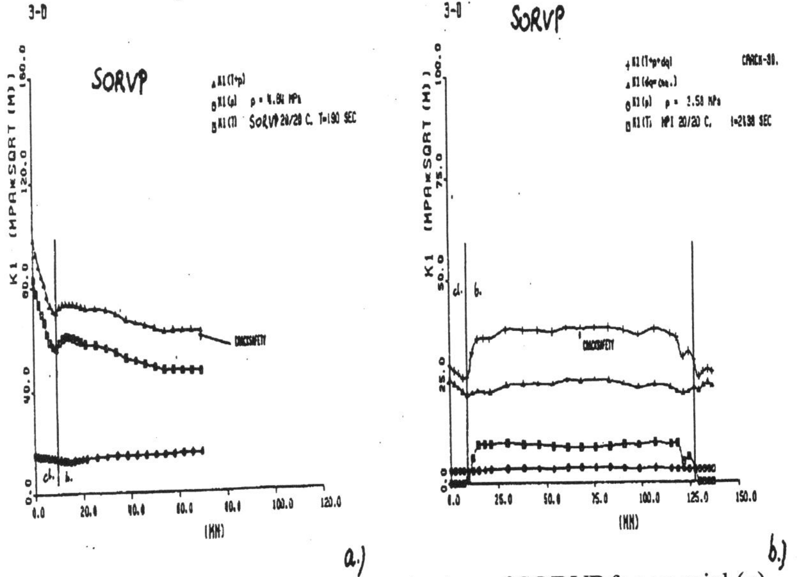

Figure 5 K1 vs. crack front at certain time of SORVP for an axial (a) and a circumferential crack (b).

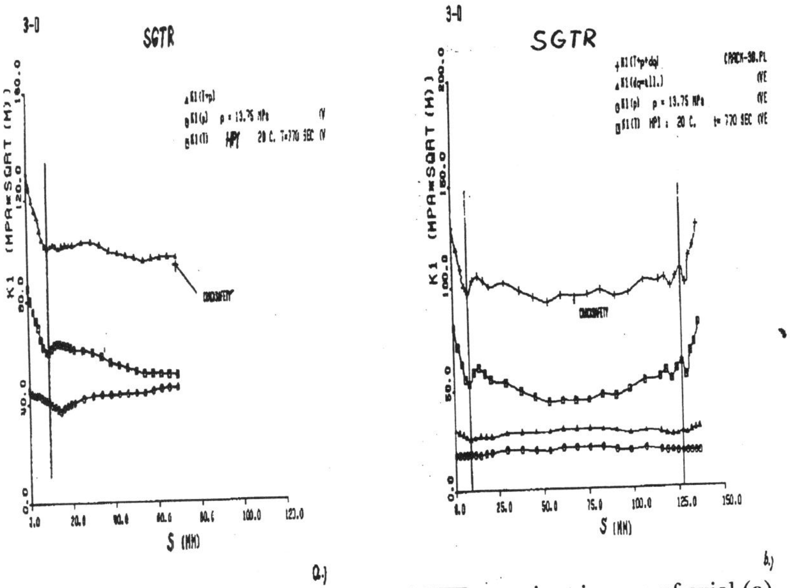

Figure 6 K1 vs. crack front for an SGTR transient in case of axial (a) and circumferent. crack (b)

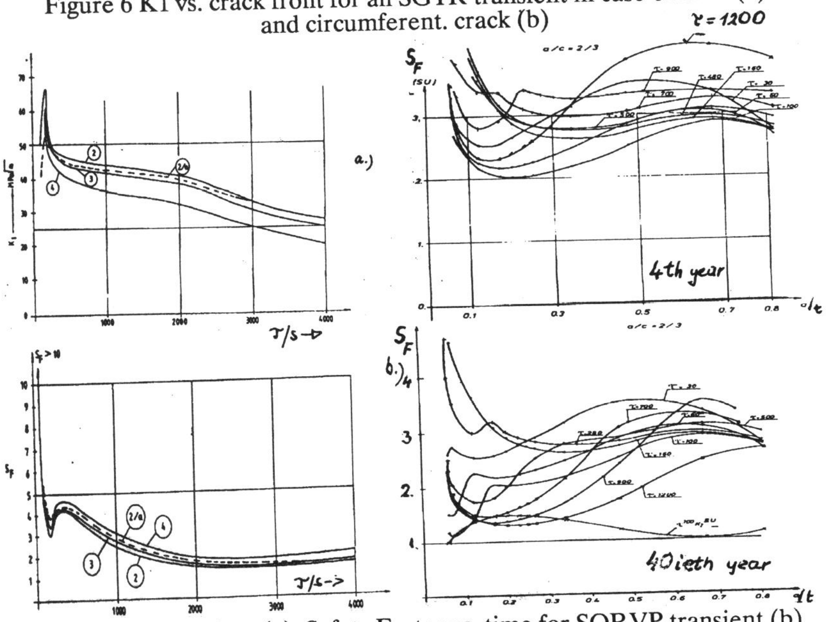

Figure 7 K1 vs. time (a), Safety Factor vs. time for SORVP transient (b) and SF vs. a/t (c)

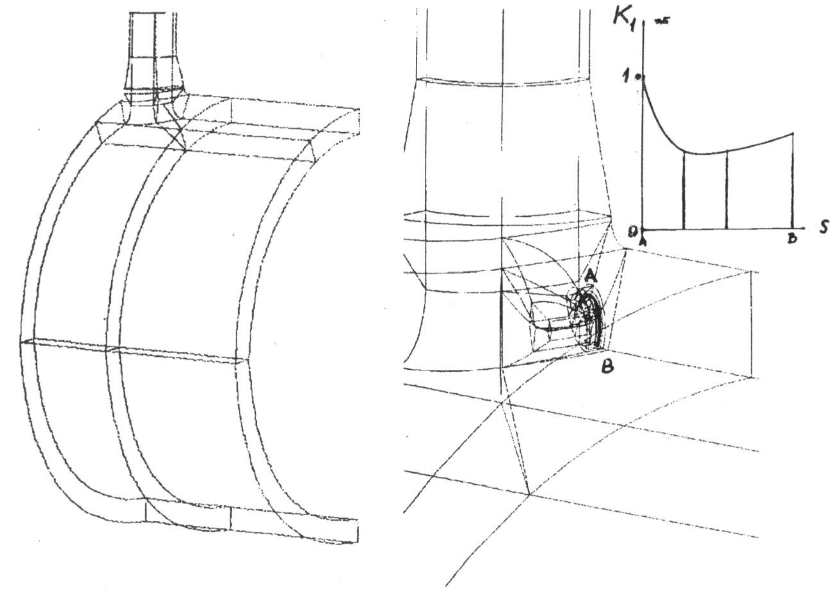

Figure 8 A WWER-440 PWR nozzle mapping (a) with inner surface crack (b) and the K1 distribution

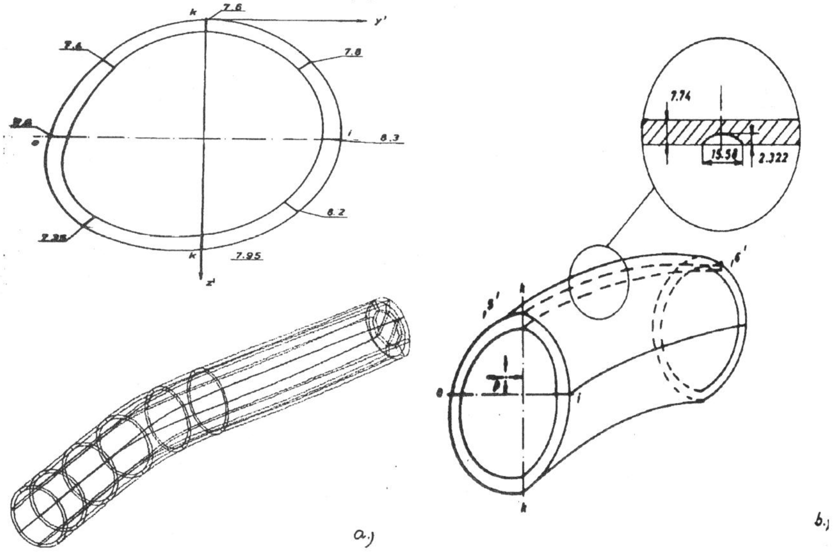

Figure 9a-b A downtube crack: the mapping and an oval cross section (a) and the crack data (b)

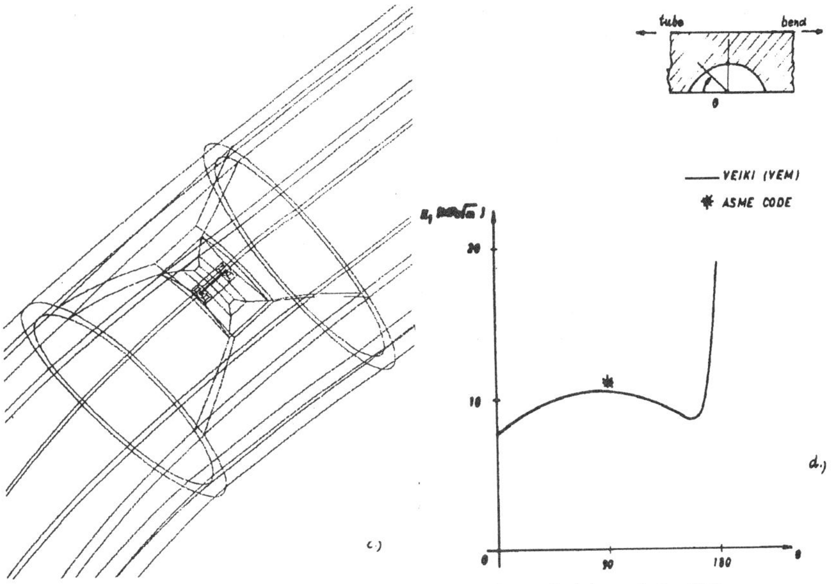

Figure 9c-d The vicinity of the mapped crack (c) and the K1 vs. crack front (d) /straight-bend/

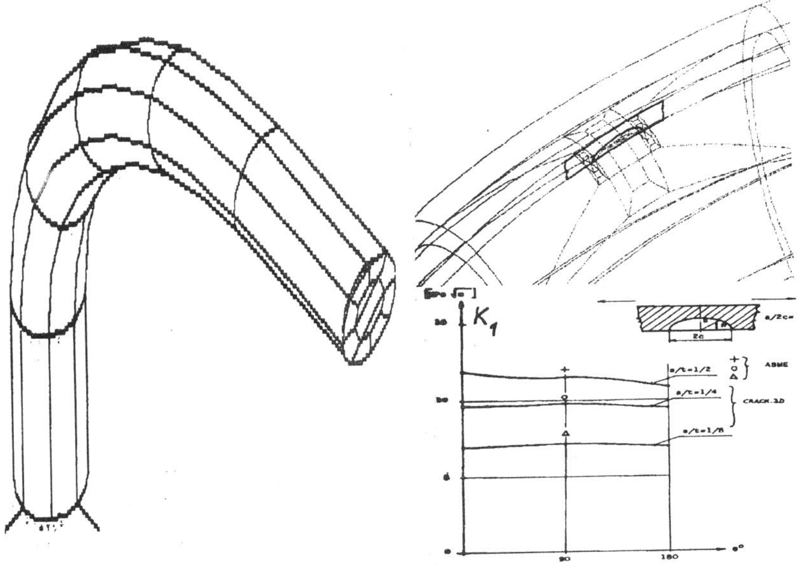

Figure 10 A main steam line crack with the mapping(a), the crack vicinity (b) and the K1s vs front.