Elastic Plastic Analyses of a Cracked Piping System

H. Grebner, A. Höfler, O. Haber
Gesellschaft für Reaktorsicherheit (GRS) mbH, Köln, FRG

ABSTRACT

The paper presents post-calculations of GRS to an experiment performed in the frame of the HDR-(overheated steam reactor) Safety-Program, Phase 2. In the experiment the failure of a large scale piping system (inner diameter 400 mm) loaded by steady internal pressure (10.5 MPa) and an increasing opening inplane bending moment, under conditions similar to those of a nuclear pressurized water reactor, was studied. The piping system failed with leakage through a 400 mm long crack in the crown of a 90 degree pipe elbow.

The finite element program ADINA is used for the nonlinear calculation, including fracture mechanical suboutines for the evaluation of J-integral-values.
Besides structure mechanics results and J-integral-values which are calculated to determine the possible amount of stable crack growth, most attention is given to the calculation of leakage areas with respect to the applied loading, where values between about 400 mm^2 (pressure loading only) and 2000 mm^2 (pressure and bending) were found.

INTRODUCTION

To evaluate the fracture mechanics behaviour or to gain structure mechanics results as for instance the leakage area of a through crack for a component of a piping system, it is necessary to model the cracked component by shell or continuum elements, when the finite element method ist applied. Mostly it may be reasonable to know the global deformation behaviour of the complete piping system.
Modelling the whole piping system with shell or continuum elements would lead to a very large finite element model. More effective is a combined use of simple, but ovalizing beam elements (so called pipe elements) and of continuum (or shell) elements.
One possible way of performing studies of piping systems with a cracked component is described in our paper. The following steps were carried out:

- Finite element calculations of the complete piping system without crack using pipe element models.

- Three dimensional finite element calculations of the cracked component loaded by global deformations gained from the pipe element models.
- Evaluation of leakage areas and rates using the results of the three dimensional calculations with crack.

As basis for our calculations an experimental study of a relatively simple piping system was chosen, which is shown schematically in Fig. 1. The experiment was carried out in the frame of the HDR (overheated steam reactor)-Safety-Program, Phase 2 (Katzenmeier, 1987).

The experiment was performed at conditions (p = 10.5 MPA, T = 240 °C) similar to those in the primary circuit of a pressurized water reactor. During the experiment the end cap was cyclically moved in horizontal direction ($u_x^!$ in Fig. 1) by means of a hydraulic cylinder. Thereby an inplane bending moment with a periodic opening of the elbow was generated.

By this kind of fatigue loading supported by corrosion processes a longitudinal crack was generated in the flank of the elbow, which finally penetrated the wall with an outer length of 400 mm, while at the inside the total crack length was about 650 mm. More details of the experiment may be found in (Katzenmeier, 1987), contribution of DIEM et al.

In our analyses the leakage area and leak rate of the final state of the crack was calculated.

PIPE ELEMENT CALCULATIONS

As mentioned before the first step of the study consisted of a pipe element analysis of the complete piping system without crack. Internal pressure, gravitational loads and the prescribed displacement $u_x^!$ were included in this analysis. The piping system consists of several components with different radii and wall thicknesses and is made of different ductile steels. More details are given in (Katzenmeier, 1987). The calculation was carried out using ADINA (1984) with a bilinear modelling of the elastic-plastic behaviour.

The global deformation of the pipe element model at maximum load ($u_x^!$ = 500 mm) is shown in Fig. 2. The distribution of the bending moment along the axis of the piping system ist presented in Fig. 3. The maximum values of the moment are found near by the middle of the pipe elbow, and values up to 1740 kNm are achieved. Fig. 4 shows the circumferential distribution of the Von Mises effective stress in the 45 degrees cross section of the pipe elbow for $u_x^!$ = 350 mm.

A comparison of the pipe element calculations with the experiment may be drawn for the first cycles, where cracks were not yet present. Thereby the global longitudinal and transverse forces at the end cap of the piping system may be compared. For a relative displacement of the end cap of 350 mm (between $u_x^!$ = 150 mm and $u_x^!$ = 500 mm) the difference of the measured forces is 225 kN for the longitudinal and 365 kN for the transverse component. The corresponding values of the calculation are 219 kN and 387 kN, respectively, so that a good coincidence is found.

THREE DIMENSIONAL ANALYSIS OF THE ELBOW

The three dimensional model used for the evaluation of the cracked pipe bend is shown in Fig. 5. The model consists of 380 elements with

20 nodes each and has about 8000 unknown degrees of freedom. The walls of the pipes and the pipe elbow are modelled by one element layer, the through crack considered has the same length (2a = 400 mm) at interior and exterior. Pipe elbow and straight pipe pieces have different, but each constant wall thicknesses.
The calculations again were carried out using ADINA. In this case a version of the program with fracture mechanics extensions was used, which gives the possibility to calculate J-integral values as introduced in (Rice, 1968) or in a formulation according to (DeLorenzi, 1982). Multilinear approximations of the stress strain curves were used.
The relatively simple model was used in order to limit the computational costs. From parametrical studies and other calculations the conclusion may be drawn, that the results gained with this model are sufficiently accurate.
The end cross sections of the straight pipe pieces are loaded by prescribed displacements of the nodes, calculated from the global deformations of the corresponding nodes of the pipe element analysis. Also, the three dimensional model was loaded by constant internal pressure (10.5 MPa).
Results of the calculation are presented in Figs. 6 to 10. In Figs. 6 and 7 the plastic zones (i.e. the region where $\sigma_V \geqq \sigma_Y$) are shown at maximum load. In addition to the plastic zones at the crack tips, which are rather unsymmetric at the outside surface, plastic zones originate at intrados (at the outside surface of the pipe elbow) and at the crown of the elbow (at the inside surface), which are due to the bending of the elbow.
The opening of the crack (COD) in the 45 degrees cross section of the elbow is presented in Fig. 8. As long as only internal pressure loading is valid, the COD-value at the outside surface is higher. With increasing bending the situation is changing to the opposite. A similar behaviour is found for the leakage area, as shown in Fig. 9. Though the crack is rather large and the loading applied very high, the leakage area is not larger than 1.5 percent of the cross sectional area enclosed by the bend.
Finally, Fig. 10 shows the increase of J-integral for a midsized integration volume surrounding the crack tip, which is located closer to the pressure vessel. In (Katzenmeier, 1987) the initiation value of stable crack growth of the pipe elbow material is estimated to about 80 N/mm. From Fig. 10 it may be expected that stable crack growth should have occurred.

DISCUSSION OF THE RESULTS, CONCLUSIONS

The pipe element results may be compared to the experimental values at the beginning of the experiment, where no cracks were present. Unfortunately only global forces may be compared. These were measured in the experiment only at one position (at the end cap) in two directions.
As shown above the coincidence between experiment and calculation is very good. Also the location of the calculated maximum effective stress in the pipe elbow is very close to the location, where the crack originated.
A comparison of the results of the three dimensional analysis with the experiment ist not possible, as neither the crack opening nor the leak rate were measured after penetration of the crack through the wall. From other calculations and from parametrical studies it

may be concluded that structure and fracture mechanics results are obtained with sufficient accuracy.
In general, the crack opening and leakage areas calculated are disproportionately high, due to the high bending moment applied and to the large plastic deformation obtained. Most probably they are higher as in the case of a leak in a real piping system.
To summarize it may be concluded that a piping system with a cracked component may be studied, using the procedure described here, with a limited amount of computer costs and man power.
More possibilities to verify the leakage area calculations are expected in connection with the leak experiments performed in phase 3 of the HDR safety program.

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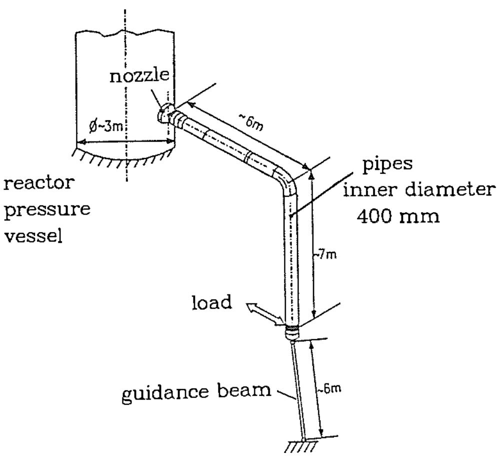

Fig. 1: Experimental arrangement - schematically

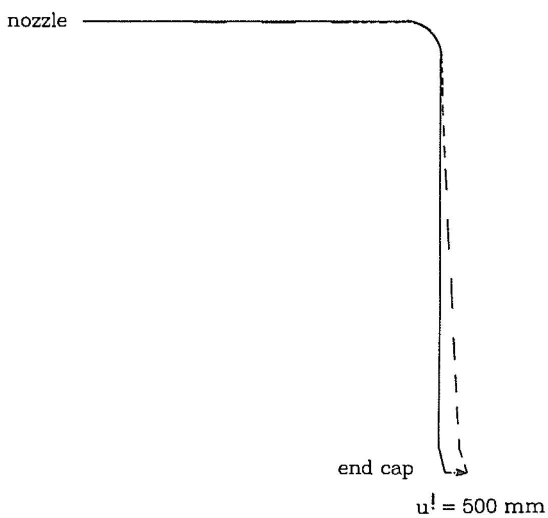

Fig. 2: Global deformation of the pipe element model

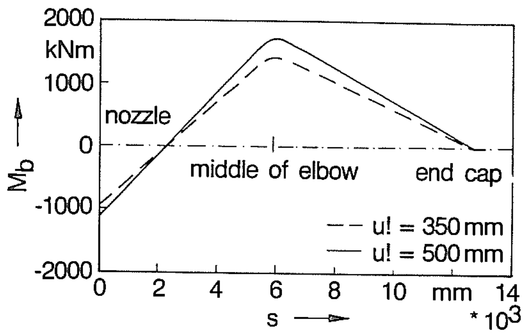

Fig. 3:
Bending moment along the longitudinal axis of the piping system

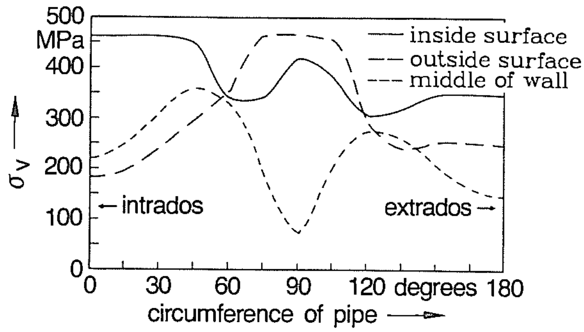

Fig. 4:
Effective stress in the 45 degree cross section of the elbow ($u_x^! = 350$ mm)

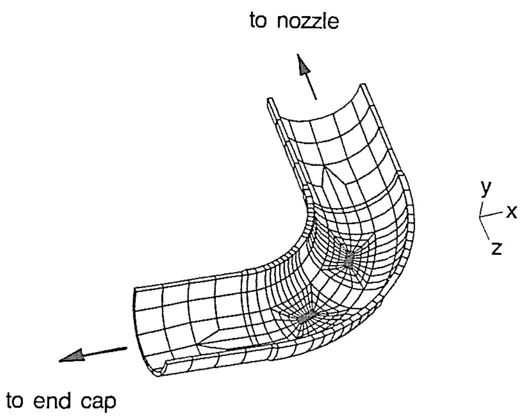

Fig. 5:
Three dimensional model of the elbow

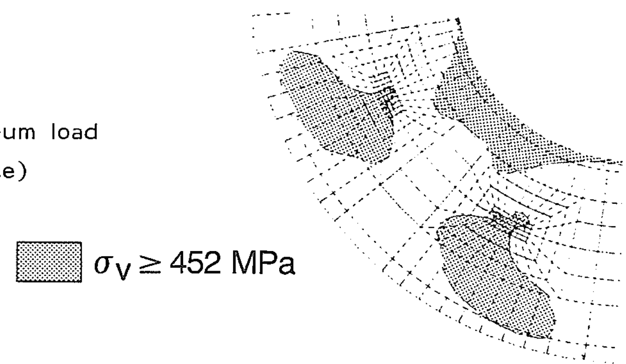

Fig. 6:
Plastic zones for maximum load (view to outside surface)

Fig. 7:
Plastic zones for maximum load (view to inside surface)

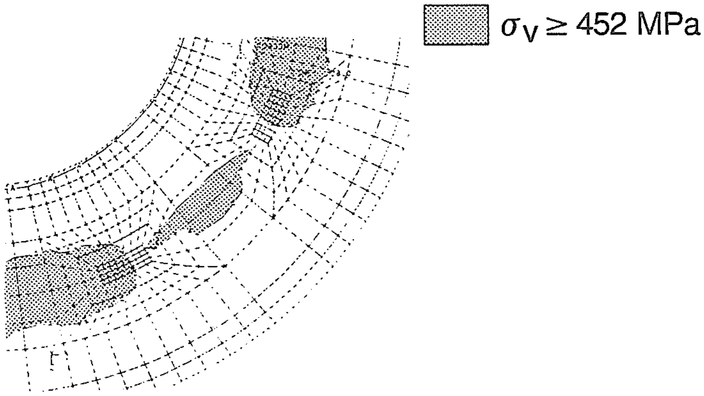

Fig. 8:
Crack opening displament (COC) at the middle of the crack

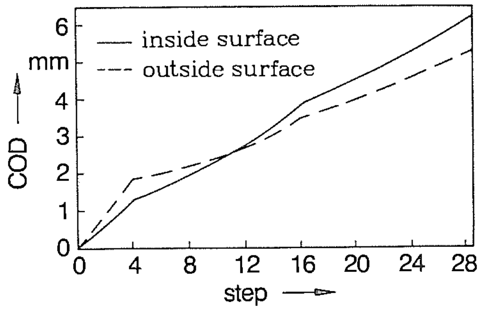

Fig. 9:
Leakage areas as functions of the hydraulic cylinder displacement

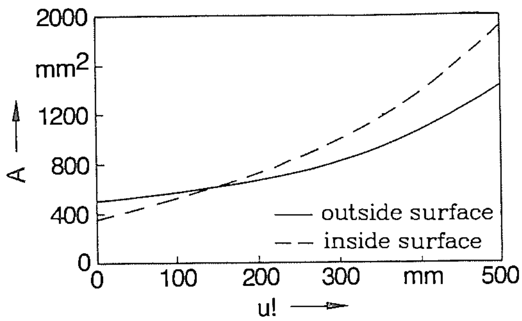

Fig. 10:
J-Integral values at crack tip closer to pressure vessel