Numerical Analysis of Cracked Pipe Experiments within the IPIRG-Program

Björn BRICKSTAD
The Swedish Plant Inspectorate, Stockholm, Sweden

ABSTRACT

Numerical studies with non-linear FEM-analyses have been used for evaluation of a number of cracked pipe experiments conducted within the IPIRG program. Some verification tests are presented which demonstrate the capability of the ABAQUS-program to calculate different crack parameters for both surface cracks and through wall cracks in pipes. Numerical results are then compared with experiments for a number of IPIRG-experiments involving both monotonic and cyclic loading as well as quasistatic and dynamic loading. The numerical results confirm the experimental trends that dynamic loading will here degrade the fracture properties for carbon steel. They also indicate that the apparent J_R curve evaluated for large cyclic loading at R=-1 is not a unique material property but depend on the loading history.

1 INTRODUCTION

The International Piping Integrity Research Program (IPIRG) has been initiated to develop data that are needed to verify engineering methods for assessing the integrity of nuclear power plant piping that contains circumferential defects. An overview of the program can be found in a paper by Schmidt et al 1991 [1]. In this paper some results are presented within a nationally funded analysis project where the scope is to evaluate some of the IPIRG-experiments with numerical finite element technique that goes beyond the engineering methods.

2 NUMERICAL VERIFICATION TESTS

The finite element program ABAQUS (1988, [2]) is here verified by comparison with the elastic-plastic J-solutions for circumferential through-wall cracks (TWC) and surface cracks (SC) in pipes, developed by EPRI (Norris 1988 [3]). Fig. 1 shows this comparison for pure bending of a deformation plastic pipe containing a TWC along one fourth of the circumference.

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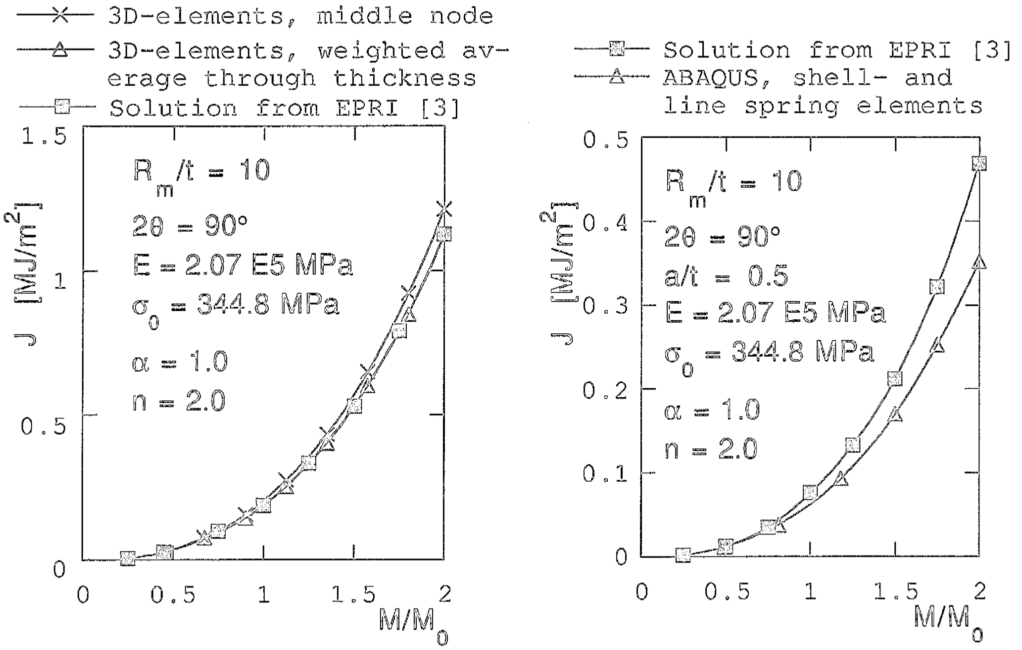

Fig. 1-2 Verification tests. Bending of a deformation plastic pipe containing a through wall and a surface crack, respectively.

M_0 is the limit load for a perfectly plastic pipe with yield stress σ_0. An excellent agreement is seen between the EPRI-solution and the ABAQUS-evaluation using one layer of 20-node solid elements (C3D20R). Fig. 2 shows the corresponding comparison for a surface cracked pipe with a constant depth equal to half the pipe thickness. For the numerical solution 8-noded shell elements and 3-noded non-linear line-spring elements were used. Here the EPRI J-solutions are somewhat larger than the line-spring results.

3 NUMERICAL EVALUATION OF IPIRG-EXPERIMENTS

In this section some results are given for the evaluation of some IPIRG-experiments within subtask 1.2. In this subtask stainless and carbon steel TWC pipes were subjected to displacement controlled four-point bending. The load line displacement Δ_P was applied both quasi-static (QS) and dynamic (DYN) and in some experiments also cyclic with different R-ratios. The objective was to investigate the influence from the loading history on the fracture properties. The numerical evaluations are all made in a generation mode, i.e. the prescribed load line displacement together with measured crack growth increments are used as input in the analyses.

3.1 IPIRG-test 1.2-8

In this experiment a A 106 grade B carbon steel pipe at 288 °C was subjected to a high loading rate, $\dot{\Delta}_P$=25.4 mm/s. Outside diameter

D_y was 167.4 mm and wall thickness t=13.7 mm. The initial TWC was 37.2 % of the pipe circumference. The finite element mesh contained one layer of 131 20-noded solid elements (C3D20R) and an enlargement of the cracked section is shown in Fig. 3.

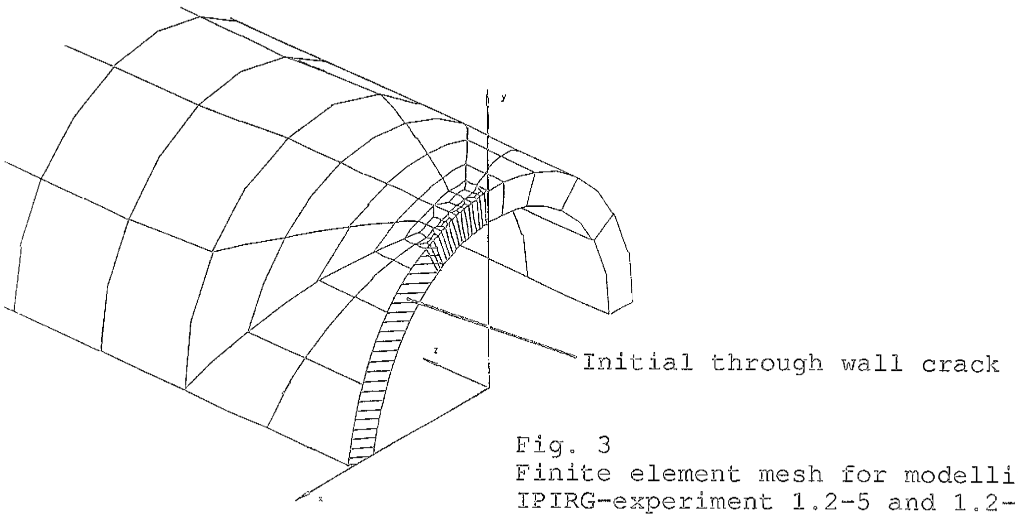

Fig. 3
Finite element mesh for modelling IPIRG-experiment 1.2-5 and 1.2-8.

The smallest element size along the crack growth path was 2 mm. Not shown in Fig. 3 are the saddle fixtures and the elastic spring to model the stiffness of the loading machine. Fig. 4-5 show the computed total load response and crack opening displacement COD at the centerline versus applied load line displacement.

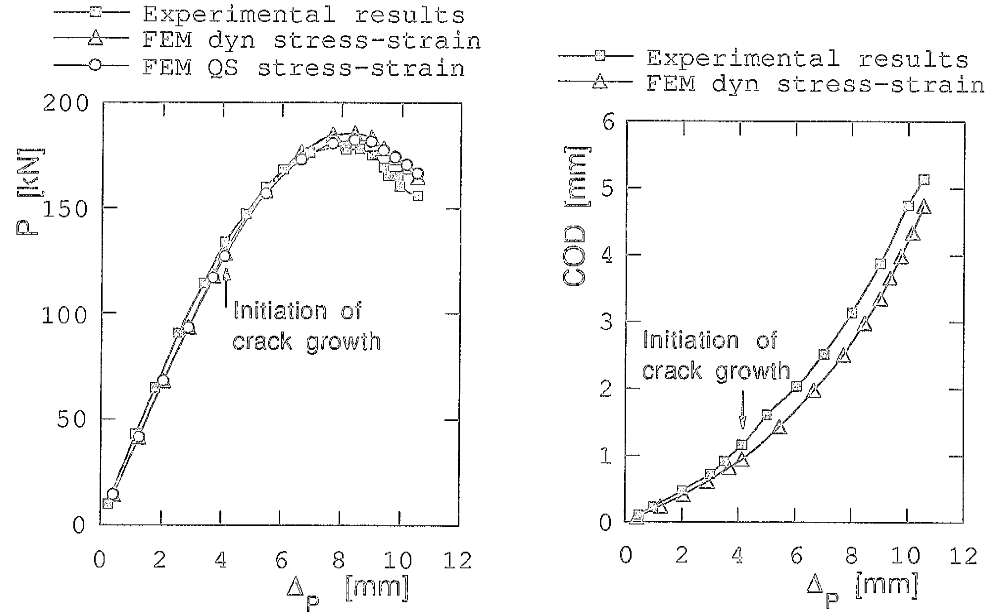

Fig. 4-5 Load and COD versus Δ_P for IPIRG-experiment 1.2-8.

The material model used was incremental theory of plasticity with von Mises yield criterion and isotropic hardening. Allowance for large displacements and strains was made in the calculations. Crack growth was simulated by gradual node relaxation. For the material, stress-strain data at 288 °C was available for specimens tested both under quasi-static ($\mathring{\varepsilon}=4.10^{-5}$ s^{-1}) and dynamic ($\mathring{\varepsilon}=11.6$ s^{-1}) conditions. For higher strains the dynamic σ-ε curve was substantially lower than the quasistatic curve. In the numerical results in Fig. 4-5 this effect did only play a minor role. The agreement between the experimental measurements was here quite satisfactory. Fig. 6 shows the computed J-resistance curves using dynamic σ-ε data, evaluated for contours both near the crack-tip as well as further away and outside the dominant plastic zone.

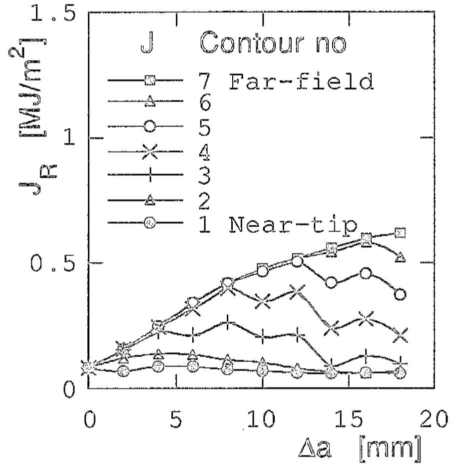

Fig. 6 Computed J_R for different contours in IPIRG 1.2-8.

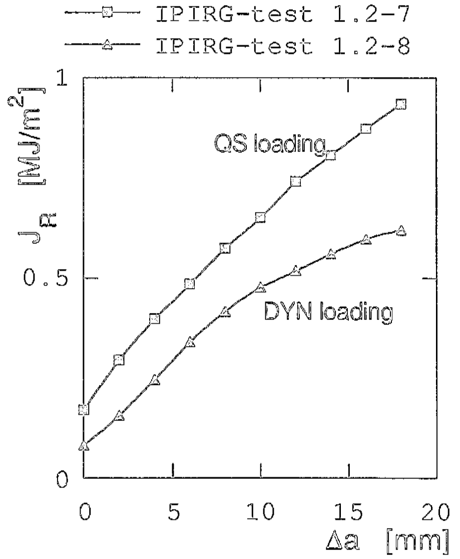

Fig. 7 Influence of dynamic loading on J_R for carbon steel.

It is seen in Fig. 6 that J loses its path-independance after some amount of crack growth. The near-tip J will approach zero in the limit of vanishingly small integration contour (decreasing element size). This is consistent with other investigations, cf Brocks and Yuan 1989, [4]. The far-field J may serve as a measure of the external loading work but it does not in general control the state at the growing crack-tip.

Fig. 7 shows the result in terms of the far-field J_R-values also for IPIRG-test 1.2-7, which is identical to 1.2-8 with the difference that the loading was applied quasistatically. It is seen that the dynamic loading rate here appears to decrease the fracture properties both at initiation and during stable crack growth.

3.2 IPIRG-test 1.2-5

In this experiment almost the identical geometry as in the 1.2-8 test was used, the difference being that a SA-376 TP304 stainless steel pipe subjected to slow cyclic bending with R=-1 at 288 °C was investigated. Fig. 8 shows the prescribed loading cycles.

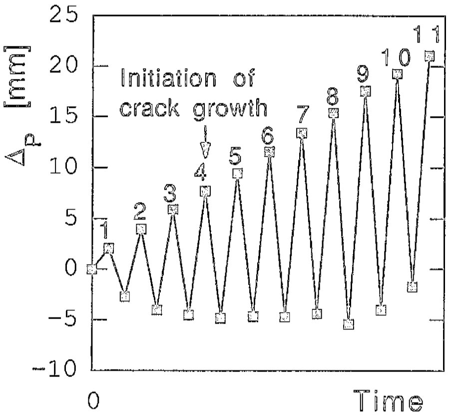

Fig. 8 Prescribed history for Δ_p vs time for IPIRG-test 1.2-5.

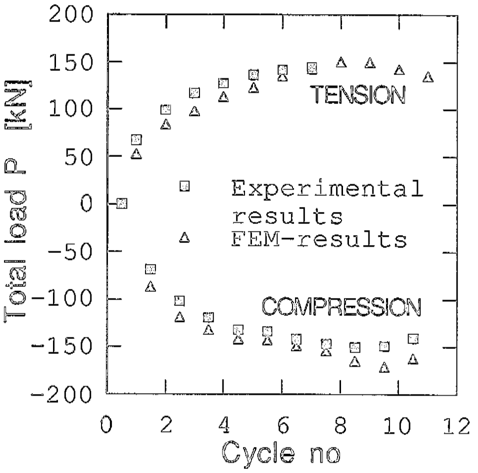

Fig. 9 Computed peak loads for IPIRG-test 1.2-5.

Initiation of crack growth was estimated to start at the 4:th loading cycle and after the 11:th cycle the total measured amount of crack growth was estimated to 23.5 mm. Fig. 9 shows the computed peak loads at tension and compression versus loading cycles.

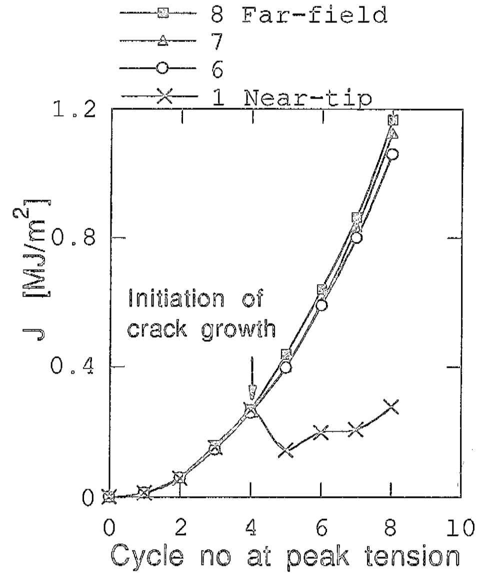

Fig.10 Applied J at peak tensile loading cycles for IPIRG 1.2-5.

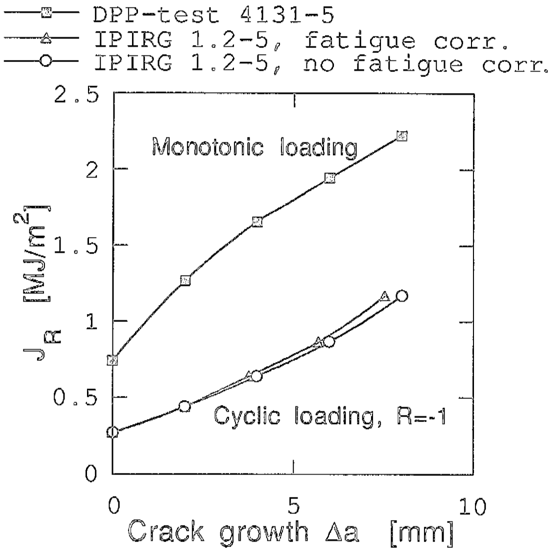

Fig.11 Influence of cyclic loading on J_R for stainless steel.

In the numerical evaluation, crack growth was only assumed during the increasing part of the loading cycles. Simple contact elements in combination with gradual node relaxation was used to simulate cyclic crack growth. The FEM-mesh is shown in Fig. 3. The applied J at peak tensile load in every cycle is shown in Fig.10. Admittingly, there is little theoretical basis for using the J-integral when unloading takes place. As the crack continue to grow and as more cycles are applied, the path-independance is successively more destroyed even for the far-field contours. In Fig. 10, J is only plotted up to a point where a reasonable path-independance is observed for the far-field contours. Another characterizing fracture parameter such as CTOD may here be needed. In Fig. 11 the computed (far-field) J_R-curves are plotted both for IPIRG-test 1.2-5 and the corresponding monotonically loaded test DPP 4131-5. Even if a fatigue correction is made for test 1.2-5, with fatigue growth data from ASME XI, Fig. 11 indicates that large fully reversed cyclic loading at R=-1 may degrade the fracture properties.

4 CONCLUSIONS

The results presented in this paper have demonstrated that numerical analyses by FEM can be a useful tool to obtain information of the fracture behaviour in cracked pipe experiments under complex loading situations. The results obtained sofar have indicated that both dynamic loading (carbon steel) and large cyclic loading at R=-1 (stainless steel) may have a negative influence on the apparent J_R-curve.

ACKNOWLEDGEMENTS

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