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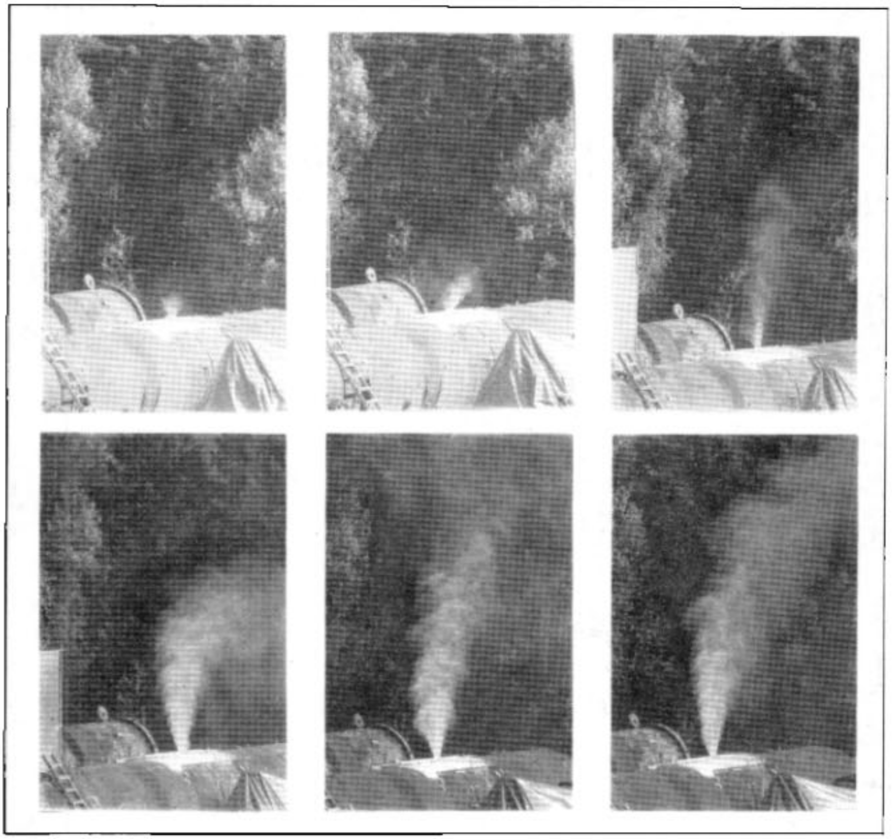
PREVENTION OF CATASTROPHIC FAILURE IN PRESSURE VESSELS AND PIPINGS



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PREVENTION OF CATASTROPHIC FAILURE IN PRESSURE VESSELS AND PIPINGS

Final Report of the NKA-Project MAT 570

Rauno Rintamaa
Kim Wallin
Kari Ikonen
Kari Törrönen
Heli Talja
Heikki Keinänen
Arja Saarenheimo
Fred Nilsson
Matti Sarkimo
Stig Wästberg
Christian Debel

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ABSTRACT

The fracture resistance and integrity of pressure-loaded components have been assessed in a Nordic research programme. Experiments were performed to validate the computational fracture assessment analysis. Two tests were also conducted on a large decommissioned pressure vessel from an oil refinery plant.

Different fracture assessment methods were developed and subsequently applied to the tested components. Interlaboratory round robin programmes with the participation of several laboratories were arranged to examine elastic-plastic finite element calculations and fracture mechanics testing. The transferability of material parameters derived from small specimens with simple crack geometries to more realistic crack geometries in real components has been verified.

KEY WORDS: Fracture mechanics, numerical analyses, engineering analyses, leak-before-break, testing, compact tension specimen, flawed steel plate, pipe, pressure vessel, acoustic emission, austenitic steel, ferritic steel

This report is a part of the safety research programme sponsored by NKA, the Nordic Liaison Committee for Atomic Energy, 1985-1989. The project work has partly been financed by the Nordic Council of Ministers.

SUMMARY

Cracking and subsequent catastrophic failure in pressure vessels and piping systems has a significant impact on the safety and reliability of operating process plants, including nuclear and fossil fired power plants. The result has been high economic losses, increased risks to personnel and concern regarding safe plant operation. By using validated fracture mechanics analyses and appropriate material properties, it is in most cases possible to determine if an existing crack, due to operation or manufacture, will remain static or grow slowly. If a detectable leak occurs prior to a complete break, catastrophic failure of a pressurized component can be avoided.

In order to assure the structural integrity of pressurized components, reliable knowledge of the relevant material properties must be available. Valid experimental and computational fracture analysis methods are then needed. In addition, because hydrotesting is normally used for integrity assessment of large pressure vessels, a crack can produce catastrophic failure during a hydrotest. To prevent this and to locate a crack or cracks, the accuracy of non-destructive testing methods such as acoustic emission is of major concern.

To improve the accuracy and validity of experimental and computational fracture assessment methods, a four year Nordic research programme was initiated 1985. The aim of the programme was to clarify how catastrophic failure can be prevented in pressure vessels and piping systems by developing the necessary elastic-plastic fracture mechanics analyses and by providing appropriate experimental data for their validation.

The reliability of fracture mechanical computation and materials characterization was validated by two round robin programmes on the elastic-plastic finite element calculation and fracture mechanics testing.

One laboratory each from Denmark, Norway, Sweden and Finland participated in the computational round robin. In this programme fracture mechanics parameters from one of the experimental round robin test specimens were calculated numerically and then compared to the experimental results. There was little difference in the computational results from each of the four laboratories. There was also good agreement between experimental results, values calculated using two-dimensional plane strain analysis and results from three-dimensional calculations.

In the experimental round robin programme, fracture resistance curves for two different materials were determined by seven testing laboratories. The first material was ferritic steel taken from the decommissioned pressure vessel that had been used for the full-scale pressure vessel tests. The second material was an aluminum alloy. Results indicate that most of the round robin scatter was due to differences in test performance between the seven laboratories, although some scatter may have been caused by the macroscopically inhomogeneous steel. By analyzing the slightly different methods used by individual laboratories in performing the tests, data scatter was diminished.

One of the major uncertainties in the reliability of fracture assessment analyses involves the transferability of experimental results which are normally obtained from small specimens to geometries and loading conditions encountered in actual components. To investigate this possible difficulty, the fracture behaviour was assessed of 1) single-edged notched specimens, 2) three-point bend specimens and 3) surface flawed plates in tension, in bending and in combined tension and bending loading. Numerous experiments and numerical calculations were made to this effect. The material used in all experiments was the steel taken from the decommissioned pressure vessel mentioned above.

Computational and experimental fracture assessment methods were verified by component tests. Small straight pipes with axial and circumferential flaws and a thin-walled pressure vessel with a circumferential surface flaw were pressurized to failure. Additionally, a major part of the programme consisted of two tests using a decommissioned pressure vessel having dimensions resembling those of a nuclear reactor pressure vessel.

The engineering fracture assessment methods (Battelle's limit load method, MPA's method) that were applied gave reliable and conservative estimates for rupture pressure and leak-before-break considerations in case of flawed thin-walled pipes. The factor with the largest influence on accuracy was the selection of a correct value for the flow stress of the material. For large pressure vessels the engineering R6-method developed in Central Electricity Generating Board, U.K., predicted more stable crack growth and lower rupture pressures than what was obtained in the experiments.

Fracture behaviour of the large pressure vessels was simulated more precisely by both elastic-plastic and geometrically nonlinear analyses based on the finite element method. The calculated strains, stresses and stable crack growth estimates from the three-dimensional analysis agreed well with the experimental findings.

This project has produced new insights into the structural integrity assessment of flawed pressurized components. Deeper knowledge of the limitation, accuracy and applicability of different fracture assessment methods was obtained. As a major outcome, extensive experimental data from the full-scale pressure vessel tests and fracture mechanics testing was produced for the validation of fracture assessment methods and for their further development. The use of acoustic emission testing during a hydrotest facilitates the locating of an existing flaw during the early loading stages. However, its application for crack growth monitoring requires preliminary fracture mechanics consideration before the correlation between the acoustic emission event activity and crack extension can be reliably expressed.

Typical industries which may benefit from the results are process industries including energy production as well as off-shore installations. The knowledge and capabilities of experimental and computational fracture assessment that were produced in this project can be applied for the design of new components and when considering the safety and reliability of main components in operating plants, thereby reducing the risk of catastrophic failure.

SAMMANFATTNING

Instabilt brott av tryckkärl och rörledningar förorsakar betydande ekonomiska förluster och säkerhetsanknytna risker inom t.ex. energiproduktion och processindustri. Genom lämpligt val av material och rätt dimensionering av komponenten är det ofta möjligt att garantera att ett existerande fel, som uppkommit vid fabrikation eller under användning, inte växer eller växer sakta på ett stabilt sätt, förorsakande läckage före brott. På detta sätt kan katastrofalt brott av en tryckbärande komponent undvikas.

Säkerhets- och hållfasthetsanalyser av tryckbärande komponenter kräver pålitlig kunskap angående de relevanta materialegenskaperna samt noggrannheten av experimentella och numeriska beräkningsmetoder. Dessutom utförs ofta tryckprov för säkerhetsgranskning av stora tryckkärl. En spricka i ett dylikt tryckkärl kan förorsaka katastrofalt brott även under tryckprovet. För att förhindra detta och för att lokalisera en spricka eller sprickor bör akustisk emission provning och annan instrumentering kunna användas.

För att förbättra noggranheten av experimentella och numeriska hållfasthetsanalyser, initierades ett fyra-årigt Nordiskt forskningsprogram, under ledning av Nordiska Kontaktorganet för Atomenergifågor, år 1984. Det huvudsakliga tekniska målet i programmet var att klarlägga hur katastrofalt brott kan undvikas i tryckkärl och rörledningar.

Den experimentella delen av programmet omfattade provning av små brottmekaniska provstycken, grova plåtar med sprickor, rör och fullskale tryckkärl innefattande en betydande instrumentering och materialkaraktärisering. Den numeriska delen bestod av utveckling samt verifikation av brottmekaniska analysmetoder och en detaljerad analys av experimenten som utfördes inom programmet.

Tillförlitligheten av brottmekaniska numeriska analyser samt materialprovning undersöktes via jämförelseprovning. I den numeriska jämförelseprovningen analyserades ett av provstyckena från den experimentella jämförelseprovningen av fyra deltagare från Danmark, Norge, Sverige och Finland. Jämförelseprovningen var tvådelad. I första delen utfördes två-dimensionella beräkningar med antagande av olika spänningstillstånd. I andra delen utfördes ingående tre-dimensionella beräkningar för en bästa estimatanalys av provstavens beteende.

I den experimentella jämförelseprovningen deltog sju provningslaboratorier. Jämförelseprovningen utfördes två gånger med två olika material. Materialen var en aluminiumlegering samt ett ferritiskt stål som tagits ur fullskale-tryckkärlen.

Grova plåtar med kantspricka, trepunkts böjprovstavar och plattor med ytspricka testades till brott under olika typer av belastning. Brottbeteendet undersöktes med ett flertal experimentella metoder. Numeriska beräkningar utfördes för att verifiera överföringen av resultat med små provstavar till mera realistiska sprickgeometrier i större provstavar.

Numeriska och experimentella brottmekaniska beräkningsmetoder verifierades genom provning av små raka rör med axiella och longitudinella sprickor, ett tunnväggigt tryckkärl med longitudinell spricka, och utgörande huvuddelen av programmet, två provningar av stora tryckkärl vilkas dimensioner motsvarar reaktortryckkärl. Under provens gång kunde brottbeteendet registreras via en omfattande instrumentering av tryckkärlen. Instrumenteringen av området intill sprickan gav realtidsinformation om sprickans beteende. Akustisk emissionsmätning (AE) antydde sprickans utveckling redan vid ett tidigt skede av provet, långt innan sprickan börjat växa. Proven analyserades med olika ingenjörsmässiga beräkningsmetoder.

Mer exakta beräkningar av brottbeteendet utfördes för de stora tryckkärlen. De beräknade töjningarna, spänningarna och mängden stabil spricktillväxt stämde väl överens med de experimentella resultaten i fallet av tre-dimensionella beräkningar. Före utförandet av en ingående tre-dimensionell finit elementanalys, måste man förvissa sig om rättfärdigheten och betydelsen av alla randvillkor som påverkar det slutliga resultatet.

Projektet har producerat nya kunskaper angående säkerhets- och hållfasthetsanalyser av tryckbärande komponenter. Genom användande av resultaten från de experimentella jämförelseprovningarna kan man utvärdera olika osäkerhetsfaktorer vid brottmekanisk provning. Användande av akustisk emission vid tryckprov möjliggör lokalisering av existerande sprickor i ett tidigt skede. Det mest betydande resultatet har varit en djupare kunskap beträffande tillgängligheten och användbarheten av olika brottmekaniska beräkningsmetoder.

Typiska industrier som gagnas av och som kan dra nytta av resultaten är basindustrier för energi, olja, petroleum, kemi osv. Förtida, framförallt katastrofalt brott i huvudkomponenten i ett dylikt industriverk förorsakar betydande ekonomiska förluster samt säkerhetsanknutna risker. En säker funktion är nödvändig under hela komponentens livstid för en del komponenter såsom tryckkärl i kärnkraftverk och kemiska reaktorer i raffineringsanläggningar, turbinrotorer, högtrycksrörledningar med explosivt eller giftigt innehåll. M.a.o. är försäkrandet av läckage före brott -beteendet viktigt i dylika komponenter och resulterar i betydande besparingar och ökad säkerhet.

CONTENTS

1. INTRODUCTION

The present final report summarizes the most important results of the NKA project MAT 570 elastic-plastic fracture mechanics. The program plan and results are described in more details in the publications and other reports and working documents [1 - 21].

The main objective of the project [1] was to improve the efficiency and economy of the energy production and process industry by optimizing the design of pressure retaining components which would result in fewer and shorter shut-down periods. The main technical objective was to clarify how catastrophic failure can be prevented in pressure vessels and pipings by considering particularly the leak before break concept.

Safety and integrity assessments of pressure vessels can be performed using complete 3D FEM analysis but the cost may become unacceptably large. Therefore different engineering analysis methods for such assessments are in use today. Examples of such methods are R6 and more advanced FAD methods, Kiefner's method and crack driving force diagrams in conjunction with EPRI Handbook formulae or even 2D FEM. The accuracy and validity of the engineering assessment methods is most appropriately evaluated by comparing the calculated results with those from experiments. The computational fracture assessment, on the other hand, is based on the reliable determination and application of the relevant material property parameter.

The participants in the elastic-plastic fracture project were Risø, Dantest and the Jydsk Teknologisk Institut from Denmark, the Technical Research Centre of Finland (VTT), Neste Oy and Imatra Power Co. (IVO) from Finland, Veritec/ Veritas Research and SINTEF from Norway, and the Royal Institute of Technology from Sweden. The project leaders in each tasks are given on page 3 of the cover.

The project was funded by the Nordic Council of Ministers, Technology Development Centre (TEKES), Ministry for Trade and Industry in Finland (KTM), Finnish Centre for Radiation and Nuclear Safety (STUK), Swedish Nuclear Power Inspectorate (SKI), Neste Oy, Imatra Power Co. (IVO), Helsinki Energy Board (HKE) and Technical Research Centre of Finland (VTT).

2. RELIABILITY OF FRACTURE MECHANICAL COMPUTATION AND MATERIALS CHARACTERIZATION

Fracture mechanics is commonly used for assuring the safety of flawed structures and components. The assessment is based on the calculation of an appropriate fracture mechanics parameter in a load-carrying component and on the comparison of it to the parameter determined by fracture mechanics testing. To verify computational and experimental fracture assessment methods, round robin programmes were arranged on elastic-plastic finite element calculation [4] and on fracture mechanics testing [5, 6].

2.1 Description of numerical J-integral round robin programme

One of the CT-specimens tested in VTT's Metals Laboratory for the experimental round robin was chosen to be simulated in the numerical calculations.

The participants in the numerical J-integral round robin programme were Kungliga Tekniska Högskolan in Stockholm, Risø (Denmark), Technical Research Centre of Finland (VTT) and Veritas Research (Norway).

2.1.1 Description of the problem and the solutions

The numerical round robin for the side-grooved CT-specimens consisted of two parts. During part one, two-dimensional finite element calculations using both plane stress and plane strain were made. For best estimate analysis of the specimen behavior, three-dimensional analyses were performed. Only two participants performed three-dimensional analyses, both with 20-noded volume elements. One of the three-dimensional analyses was made considering the side-grooves and in the other a smooth specimen with the total thickness was modelled.

The calculations were made keeping the crack size constant. The participants were asked to perform the analyses by imposing the load as a prescribed load point displacement. As a result of the calculation, the values of load, crack mouth opening, crack tip opening and J-integral values were reported. In the case of three-dimensional analysis, J-integral values were given as variations over the crack front and as integrated average values from the crack front.

2.1.2 Results and discussion

The differences between the two-dimensional results of different participants were rather small (Fig. 1). The most remarkable deviations, especially when the plane strain solutions are considered, were found in the solution where linear 4-noded elements were used in spite of second order elements. This model was stiffer than the other ones, though the number of degrees of freedom was the largest. Good agreement was obtained when the calculated plane strain results were compared to the net thickness normalized experimental results. Plane stress results were approximately the same as but slightly less than the effective thickness normalized experimental result. Three-dimensional results from the two laboratories were very close to each other and they agreed very well with the experiment (Fig. 2).

Calculated J-variations along the crack front are remarkably different in smooth and side-grooved specimens. When load, crack tip opening or average J-integral values integrated from the crack front are considered, the agreement between the calculated three-dimensional results and the experimental ones was very good, though one of the calculations was made without considering the side-grooves.

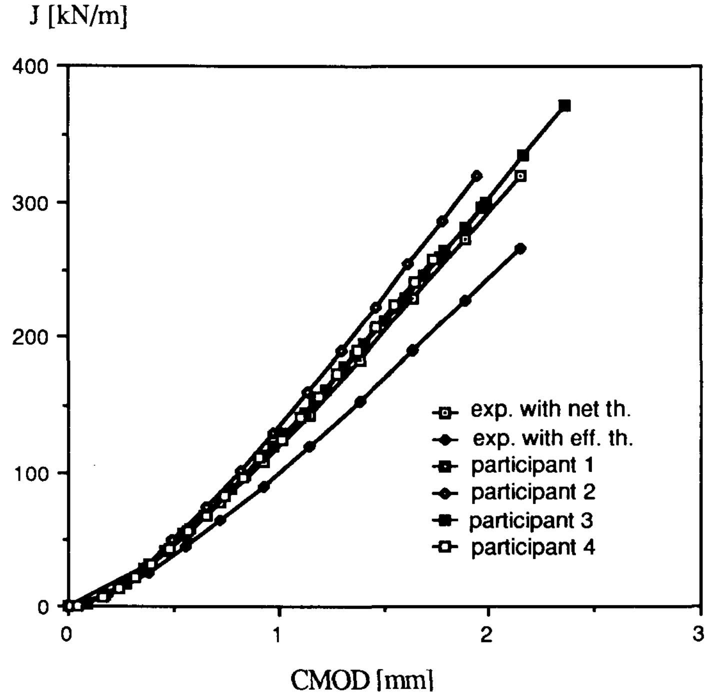


Fig. 1. J-integral as a function of load line displacement, results from two-dimensional plane strain calculations with the experimental ones [4].

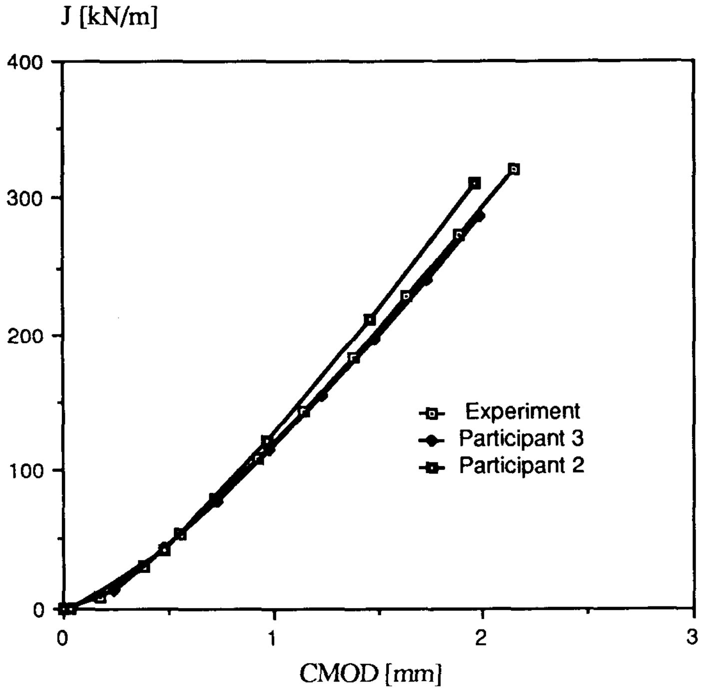


Fig. 2. Average J-integral from the crack front as function of load line displacement, results from three-dimensional calculations with the measured ones [4].

2.2 Description of experimental J-R round robin programmes

Experimental elastic-plastic fracture toughness testing has during recent years become more and more common in the Nordic countries. Most experience has been obtained with the British CTOD test procedure. CTOD is not, however, often used in nuclear structural integrity assessment. The usual parameter in nuclear safety assessment is the J-integral, but the J-integral based J-R-curve test is not widely used in all Nordic countries. In order to ensure the reliability of Nordic J-R-curve testing two special Nordic J-R-curve round robin test programmes were carried out.

2.2.1 The first round robin

The first J-R-curve round robin test programme [5] had seven Nordic materials testing laboratories participating. Each laboratory was supplied with material for ten 25 mm CT-specimens. The laboratories had to manufacture their own specimens and were free to perform the actual testing in any way they found convenient. The only demand was to meet the requirements in the ASTM J_{IC}-standard E813-81.

The participating laboratories were: Jysk Teknologisk and Risø from Denmark, Veritas Research and SINTEF from Norway, Royal Institute of Technology (KTH) from Sweden and VTT from Finland (Metals Laboratory and Reactor Laboratory).

The material used in the round robin was a 2 1/4 Cr 1 Mo steel taken from a decommissioned reactor pressure vessel of a Finnish oil refinery plant and used for the full-scale pressure vessel tests. The six laboratories called laboratory 1 - 6, were supplied with one of 6 pieces cut from the pressure vessel. The laboratories fabricated 25 mm thick standard CT test specimens from these plates.

One laboratory (laboratory 7) joined the round robin testing later and fabricated specimens from material extracted from a place located below the section used for the other laboratories. The specimens were numbered in the same manner as the others. Laboratory 6 tested ten additional specimens to perform a key-curve calibration.

These specimens were taken from the same location as specimens for laboratory 7. Laboratory 6 also tested 105 specimens to get a good multispecimen reference J-R-curve.

Preliminary tests on the material indicated upper shelf behavior at a temperature of +50 °C. The room temperature 0.2 % proof strength and ultimate strength were

$R_{p0.2}$ = 300 MPa
R_u = 532 MPa.

The round robin test temperature was chosen as +50 °C and the flow stress to be used in the analysis was estimated to be 416 MPa.

All laboratories applied essentially single specimen type methods to evaluate the J-R-curves. Mainly two types of methods were used, i.e., partial elastic unloading compliance and direct current potential drop. Besides differences in the testing methods, there were also differences in the performance and the analysis of the tests. The main differences are presented in Table 1. In order to minimize the differences, all the raw data was later reanalyzed with the multiple specimen method as well as a modified key-curve analysis method [22].

Table 1. Difference in the laboratories test performance.

	Laboratory						
	1	2	3	4	5	6	7
Method	comp.	comp.	comp.	DC-PD	DC-PD	comp.	comp.
Flat bottom holes	yes	yes	yes	no	yes	yes	yes
Close fitted pins	yes	yes	yes	yes	yes	no	no
SZ included in Δa	yes	yes	yes	yes	no	yes	yes
a_0 identified from	comp.	comp.	comp.	phys.	phys.	phys.	phys.
Rotation correction of compliance	no	yes	no	-	-	yes	yes
Crack growth correction of J	no	no	yes	no	no	yes	yes
Negative crack growth correction	yes	no	no	no	no	no	no

comp. = compliance

2.2.2 The second round robin

The second round robin [6] had the same participants as in the first round robin with exception of the Reactor Laboratory at VTT. The specimen geometry was the same as in the first round robin. Contrary to the first round robin, each laboratory was supplied with ready made specimens. Also the primary test method was fixed as being based on the multiple specimen technique. As a secondary method, each laboratory was free to use an additional crack length monitoring technique so long as the requirements in the ASTM J_{IC}-standard were not violated.

Two different materials were used in the round robin. Firstly, a 2 1/4 Cr 1 Mo steel taken from the reactor pressure vessel used for the second full-scale pressure vessel test (HC2). Secondly, an aluminum alloy ISO AlSi1Mg supplied by Norsk Hydro. The aluminum specimens were fabricated by SINTEF and the steel specimens at VTT. The specimens were divided randomly between each laboratory, in order to limit the effects of possible macroscopic material inhomogeneities.

The room temperature tensile properties for the two materials are presented in Table 2.

Table 2. Tensile properties of round robin materials.

Material	$\sigma_{0.2}$ [MPa]	σ_u [MPa]	E [GPa]
2 1/4 Cr 1 Mo	329	522	200
Al Si 1 Mg	318	338	70

The testing temperatures were chosen as +50 °C for the steel and room temperature for the aluminum alloy.

2.2.3 Results and discussion

The primary results of the first round robin were not at all promising [5]. A centralized key-curve based reanalysis of the data made the situation somewhat better, but still the results showed a large amount of scatter. When the results are treated by multiple specimen analysis (Fig. 3) and fitted with a square root expression $J = C\sqrt{\Delta a}$ the mean and standard deviation of C is 489 and 58 $kJ/(m^2\sqrt{mm})$, respectively (Fig. 4). This means that the standard deviation of C is less than 12 %. Such a scatter could well be attributed to material inhomogeneity considering that the material had been manufactured and been put in use more than 20 years ago.

Some questions remained, however, as to how much of the scatter was due to material inhomogeneity and how much to test performance variation.

The additional 105 tests performed for the multiple specimen reference J-R-curve showed approximately half of the round robin scatter. This would indicate that part of the round robin scatter is due to differences in test performance between the different laboratories. However,since 105 specimens were extracted from one place whereas the round robin material was more scattered, it is possible that the pressure vessel material is macroscopically inhomogeneous. This could explain the larger amount of scatter in the round robin results. But differences due to the laboratories could not be ruled out. The primary results indicated that some laboratories had severe friction problems in their tests. Such friction will automatically affect the load-displacement behavior causing excessively high J-values and inflated J-R-curves to be measured.

The results of the second round robin [6] confirmed that the main source for scatter and systematic differences is the test performance.

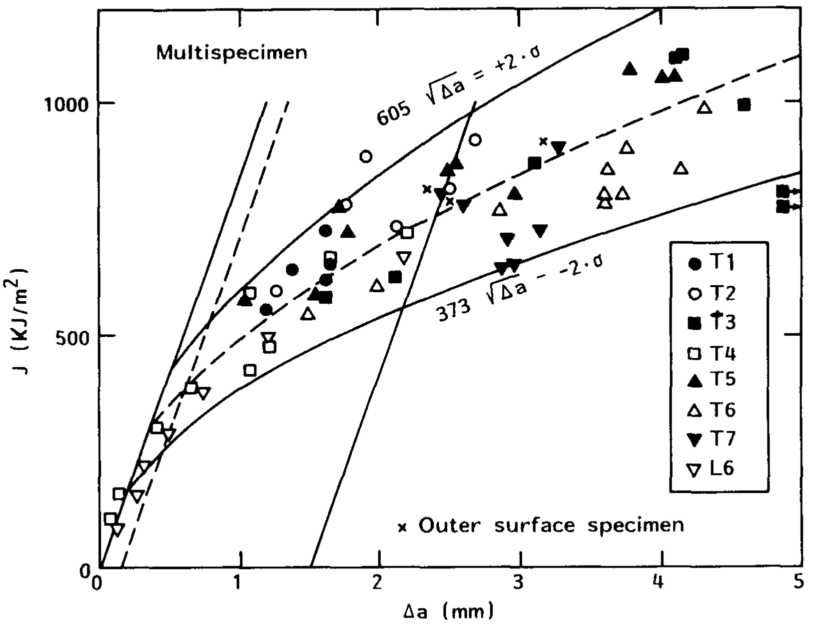


Fig. 3. Multiple specimen presentation of first round-robin results.

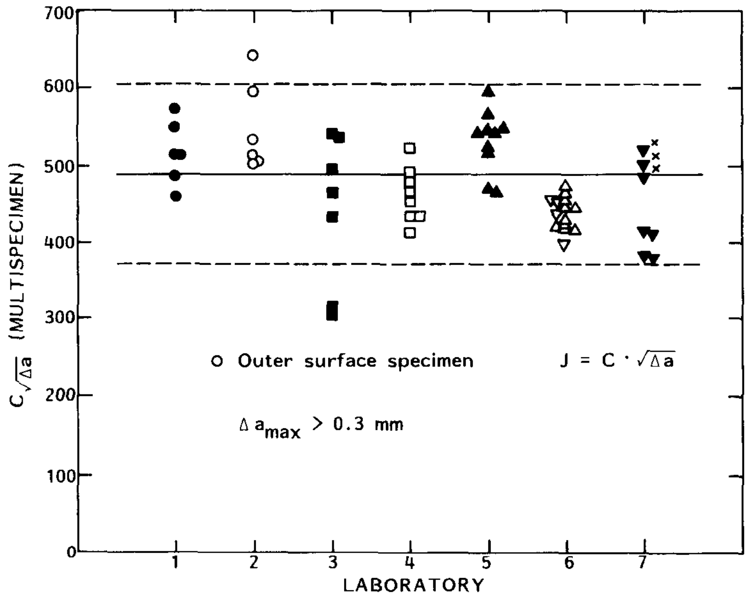


Fig. 4. Square root fit of first round-robin end point results.

It is interesting to note that the simple square root fit yielded less scatter than the more refined power law fit, for all examined parameters. It was found that the power law fit parameters had an inverse relationship. The same trend is to be seen in the ASTM E318-81 J_{IC} and T_{mat}. This indicates that the power law fit and the ASTM E813-81 procedure does not describe the J-R-curves unambiguously. It is thought that it might be valuable to further investigate the possibility of using a simpler and more straight forward fitting procedure such as the square root fit. With this kind of one parameter fit the description of the J-R-curve is simple and the result would be closer to a mean description of the curve. Whether a square root or some other value of the exponent fits the data better is open for discussion. The important thing is that a one parameter fit makes J-R-curve data much more readable.

2.3 Conclusions on the reliability

The scatter of the results of the Nordic finite element round robin was much smaller than in the round robin [23] arranged by the European Group on Fracture in 1983. One explanation that in the European round robin the number of participants was much larger. The analysis expertise and capabilities might also have been improved in recent years.

One can draw conclusions on the J-integral testing procedures by comparing the experimental J-values to calculated average values from crack front. Experimentally and numerically derived J-values were in good agreement as were the loads at a defined load point displacement. This is not surprising since experimental J-values are based directly on the measured load vs. crack mouth opening result. Comparable accuracy of both load and J-values confirms the applicability of the testing method. Another possibility to consider in the testing procedure is to use the numerical values calculated for a side-grooved specimen, and to compare average J-integral values with J-integral values calculated from experimental load and CMOD results. When the calculation is repeated using both the net thickness and the effective thickness, one can draw conclusions as to, which thickness value is the most appropriate in elastic-plastic J-integral testing. The present analysis confirms the use of net thickness which has been used during experimental measurement (Fig. 5).

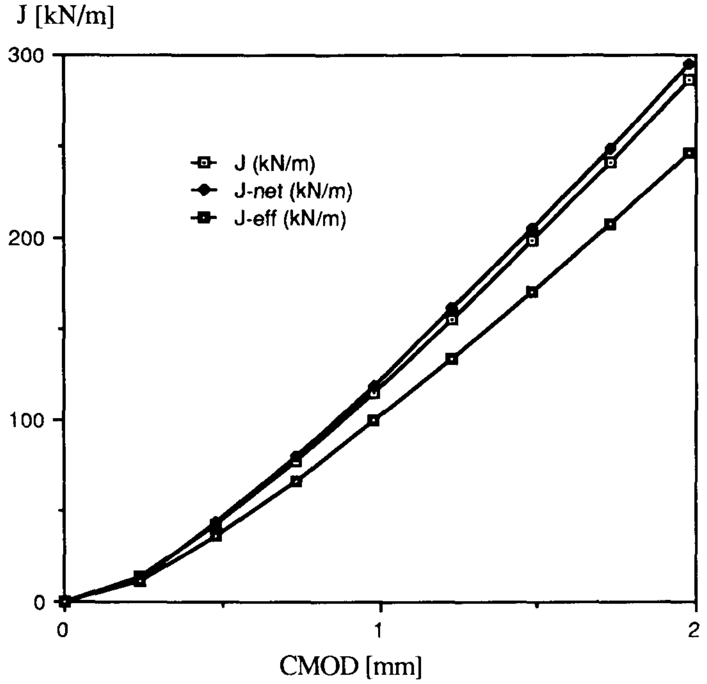


Fig. 5. Comparison of average J-integral from the crack front in the side-grooved specimen with the values calculated from load vs. load point displacement result as a function of load line displacement [4].

3. FRACTURE ASSESSMENT OF SURFACE FLAWED PLATES IN TENSION AND BENDING

3.1 Experimental procedure

The most widely used parameter for characterizing the crack tip state under elasto-plastic conditions is certainly the J-integral. Numerous experimental investigations have been carried out to explore its relevance to crack growth description. However, the majority of these studies have been concerned with a few geometries, suitable for laboratory work and materials testing. Much research remains in order to verify the transferability of results obtained from such specimens to geometries encountered in actual failure assessment situations.

The main object of the investigations [7] at the Department of Solid Mechanics at KTH was to compare results obtained from typical laboratory specimens with those obtained from experimentation on larger specimens with more realistic crack configurations. Another question that has not been sufficiently studied is the effect of more complicated loading situations. In most experimental investigations only one loading system is applied so that at least approximately a state of proportional loading prevails. In the present work load history effects of this kind are investigated for three-dimensional crack configurations.

The material used in all experiments was the 2 1/4 Cr 1 Mo steel taken from the decommissioned pressure vessel used for the full scale testing of this project. All tests here were performed at room temperature (~ 21 °C). The specimens were prepared so that in all cases the crack front was perpendicular to the rolling direction.

The two-dimensional test specimens were of two basic types, a single-edged notched tensile specimen and a three-point bend specimen. In order to study the effects of side-grooves, some of the specimens were grooved. The thickness of the specimens was varied, the normal alternative had a thickness of 25 mm, while a variant with a thickness of 50 mm was also tested. In order to maximize the difference between the tensile and bend specimens, the tensile ones were loaded by clamping the edges with jaws that prohibited rotational movements. As a result of this constraint a reaction in form of a bending moment tending to close the crack was present besides the tensile load. This moment was determined by strain measurements on gauges placed along a line near the edge of the specimen.

The loading of the specimens was done in accordance with ASTM E-813 with partial unloadings used to facilitate the crack growth determination by the compliance technique. J was evaluated for the experiments from the experimentally observed data. The experimental determination of J for the bend specimens was performed according to ASTM E-813. For the SEN-specimens there is no standardized procedure for experimental J-evaluation and a procedure developed by Kaiser for determination of J under combined tension and bending was used.

A series of four experiments with a more complex crack geometry and loading was performed. The specimen is shown in Fig. 6 and is a 50 mm thick plate that is somewhat curved, the midpoint of the cracked section being offset a distance e from the midpoints of the ends of the specimen.

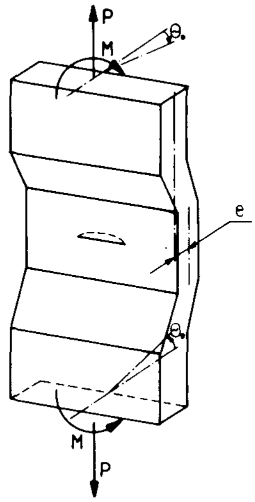


Fig. 6. The specimen for the surface crack testing.

The object of this design is to induce a bending moment tending to open the crack by tensile loading of the specimen. The specimen ends are welded to circular thick plates which in turn are mounted by screws along the periphery to a servo-hydraulic testing machine. In addition to the tensile loading, the specimen is mounted to the machine with a initial slant angle θ_o which induces an initial bending moment. Thus, the specimen is subjected to two loading systems. The applied tension can be regarded as a primary loading which induces both tensile and increasing bending loads. The initial displacement can be considered as secondary bending load. By varying the offset e and the angle θ_o different M-N histories can be obtained where M and N are the moment and the membrane loads respectively as referred to the cracked section. One of the objects of this investigation is to study whether the path in the M-N-diagram has any influence on the crack growth initiation behavior. In the course planning, a simple beam model of the system was considered. The M-N histories for different e and θ_o were obtained by running this model with the program system

ABAQUS taking plastic behavior and large deformation effects into account. In addition to these four experiments two tests were made with the offset e equal to zero. One of these were tested under pure tensile loading while the other was tested under three-point bending.

The crack was produced by first machining a semi-circular slit perpendicular to the surface. After fatigue loading in bending the cracks assumed approximatively semielliptical shapes. The depth was kept around 25 mm and the surface length around 85 mm.

During the testing the specimens were instrumented with strain-gauges at different locations for measurement of loads and crack length. The crack length measurements were made by partial unloadings and strain measurements in the vicinity of the crack. In addition a color-marking technique was employed. Different colours were injected into the crack at some occasions during the loading process.

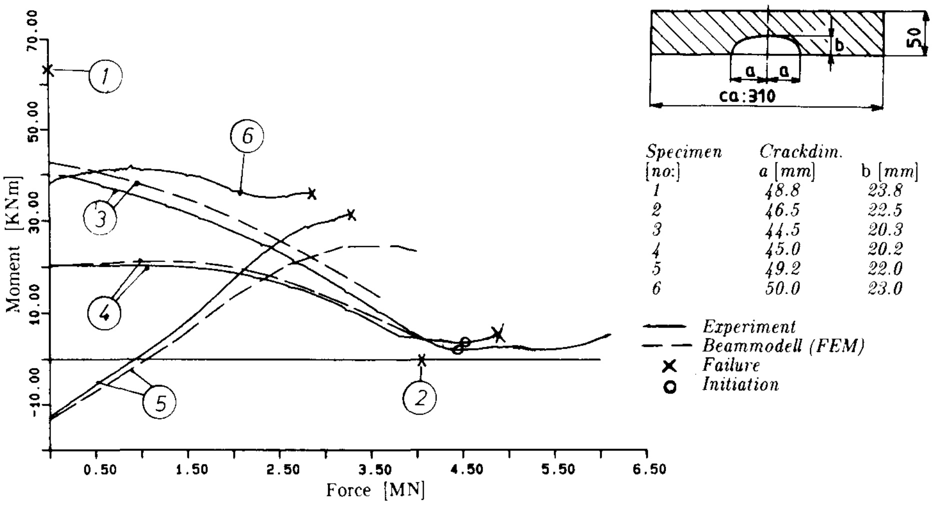
3.2 Experimental results and discussion

In the two-dimensional tests stable crack growth generally occurred. The agreement between the tensile and bend tests without side-grooves was fairly good in view of the difficulties in obtaining reliable crack lengths for the tensile tests. The side-grooved bend tests, however, differed from the smooth tests in that the J_R-values were markedly lower than for the smooth specimens.

In the six experiments with surface cracks, unstable crack growth followed immediately after initiation of crack growth in all experiments but one. The result of the previously mentioned beam type calculations for the experiments with the offset e greater than zero are shown in Fig. 7. together with the behavior observed during the actual experiments. As can be seen the agreement between the predicted and the observed behavior is good, except perhaps at the highest load levels where plastic effects relax the bending moment very rapidly. An observation that can be made from the figure is that the path to the critical point in the M-N space is of minor importance. The presence of a secondary bending of the present nature here seems to have little importance for crack growth initiation under ductile conditions.

An evaluation of tests by the R6-method was performed using global collapse load solutions and the K_{IC}-value measured from the two-dimensional tests with side-grooves. The R6 option 1 was assumed and the results from the evaluation are shown in Fig. 8. As can be seen from the figure some scatter is evident and also that some points fall below the assessment line. By comparing experiments 5 and 6 it seems that the R6 procedure of accounting for secondary stresses is not satisfactory. From Fig. 7 it is seen that these two specimens failed at approximately the same instantaneous loading conditions although the initial bending was very different. In the R6-procedure this initial difference causes the points for 5 and 6 to fall widely apart in the assessment diagram.

In addition to this evaluation, more accurate three-dimensional elasto-plastic FEM-calculations with the program system ABAQUS are in progress.



Specimen [no:]	Crackdim. a [mm]	b [mm]
1	48.8	23.8
2	46.5	22.5
3	44.5	20.3
4	45.0	20.2
5	49.2	22.0
6	50.0	23.0

Fig. 7. Moment versus force histories for complex testing of flawed plates [7].

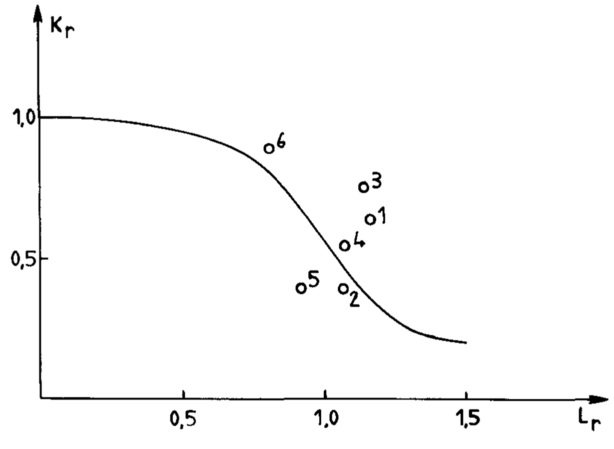


Fig. 8. Failure assessment by the R6-method [7].

4. FRACTURE ASSESSMENT OF FLAWED PRESSURE COMPONENTS

To verify computational and experimental methods used for fracture and catastrophic failure assessment, pipes and full-scale pressure vessels were tested up to rupture.

4.1 Pipe tests

Pipe tests [9, 10] were performed by Imatra Power Co's Energy Laboratory in Helsinki during years 1985 and 1986. A total of 122 straight small diameter and thin-walled pipes representing two materials were tested. All pipe materials were ductile. The first test pipes were without flaw. The flawed pipes were made by machining axial and circumferential flaws in the inner and outer surface of the pipe walls. Circumferential flaws were made also by welding two pipes together giving a flaw geometry more similar to a natural sharp crack than in cases where the flaws were machined. The radius of the machine crack bottom was about 1.1 mm in most cases. The load was pure internal pressure, but in some pipes also a bending moment relative to the internal pressure was superposed. Some tests were performed with pure bending moment load only.

4.1.1 Experimental procedure

The length of the pipes was about half a meter and the pipes were closed at the ends by flat plates. The pipes were pressurized by water, but because of the small volume of water and rapid decrease of the pressure after a burst of the flaw, nitrogen was also often introduced into the pipes before the water. In this way it was possible to simulate the stability of a flaw in long steam containing pipes, where the pressure decrease is not rapid. Because of the limited instrumentation, only the burst pressure of each pipe was measured. In those cases with leaks, the leak area was measured after test completion. Stress strain curves for each materials were determined after pressure testing.

4.1.2 Analytical calculations

Analytical considerations [8] were done by applying the Battelle's limit load method [24] and also in some cases MPA's method [25]. In addition to the rupture pressure, the stability of the burst surface crack was estimated and compared to the experimental findings. In cases where the critical pressure, i.e. the pressure at which a crack became unstable, of the surface crack was greater than that of a trough-the-wall crack, catastrophic failure occurred. In the absence of a pressure drop, the crack would extend unstably at both ends.

4.1.3 Results and discussion

From the results it can be concluded that if the material is ductile, as it was in all the pipe tests, one can accurately estimate the rupture load. The stability of a burst crack can also be determined by using Battelle's and MPA's limit load methods. Some of the results are presented in Figs. 9 - 13, where the lines indicate rupture loading ratios (stress in the ligament normalized by the flow stress of a material) are shown as a function of crack geometry (crack length C/radius of a pipe R). The lines for through-the-wall crack indicate the boundary of instability for the through-wall cracks of same length as the surface crack. More extensive description of the piping programme has been presented in the report by Ikonen et al. [8].

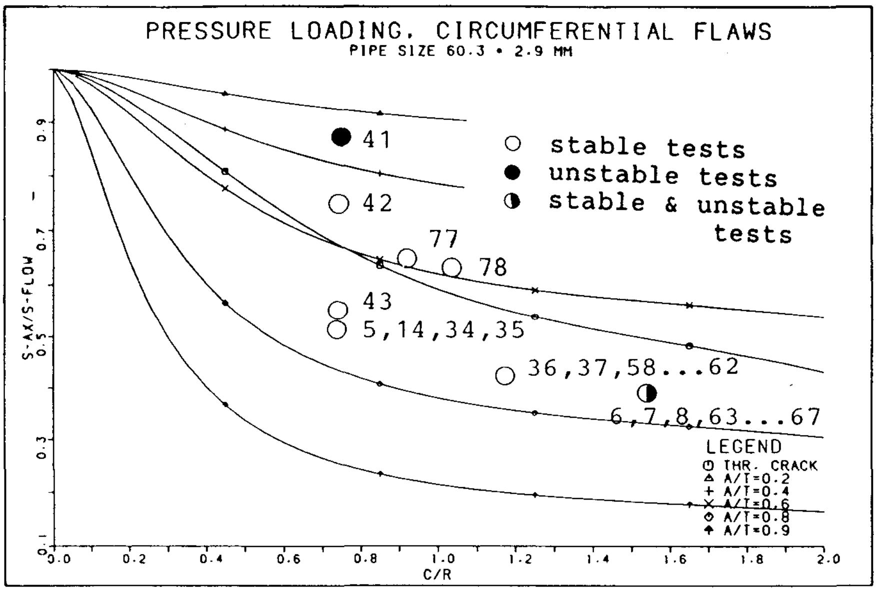


Fig. 9. Results from tests, where pipe material was Fe 37B, flaw was circumferential and pipes were loaded by pure internal pressure. The line of the through crack divides the area into stable and unstable areas [8].

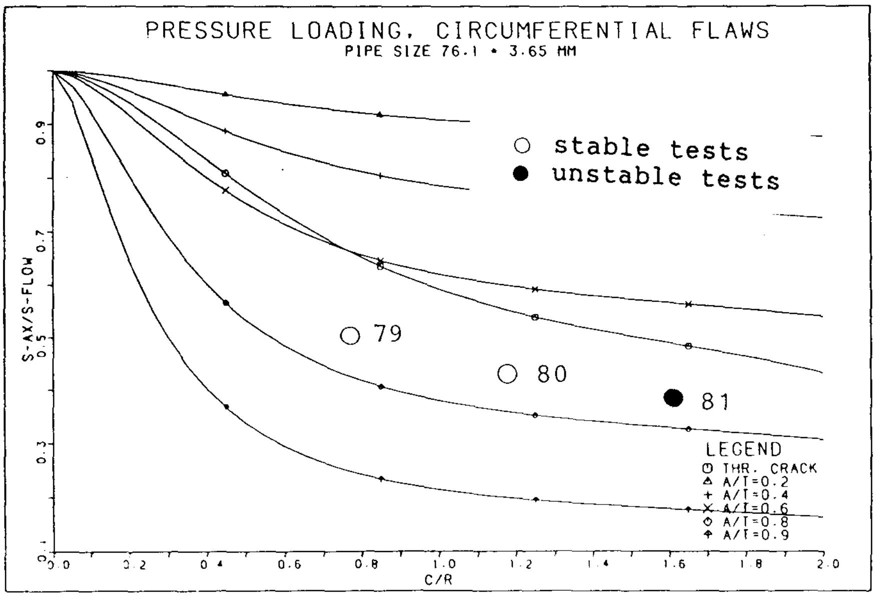


Fig. 10. Results from tests, where pipe material was AISI 304, flaw was circumferential and pipes were loaded by pure internal pressure. The line of the through crack divides the area into stable and unstable areas [8].

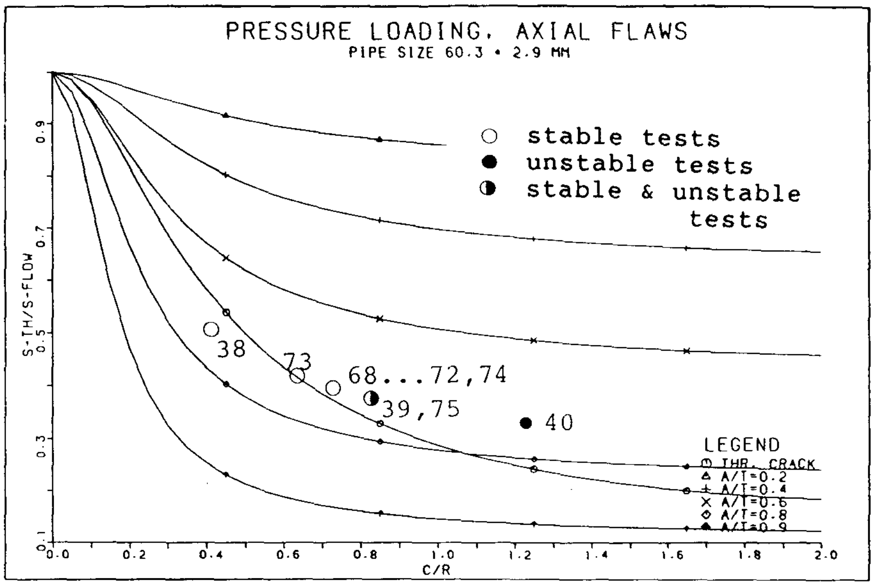


Fig. 11. Results from tests, where pipe material was FE 37B, flaw was axial and pipes were loaded by pure internal pressure. The line of the through crack divides the area into stable and unstable areas [8].

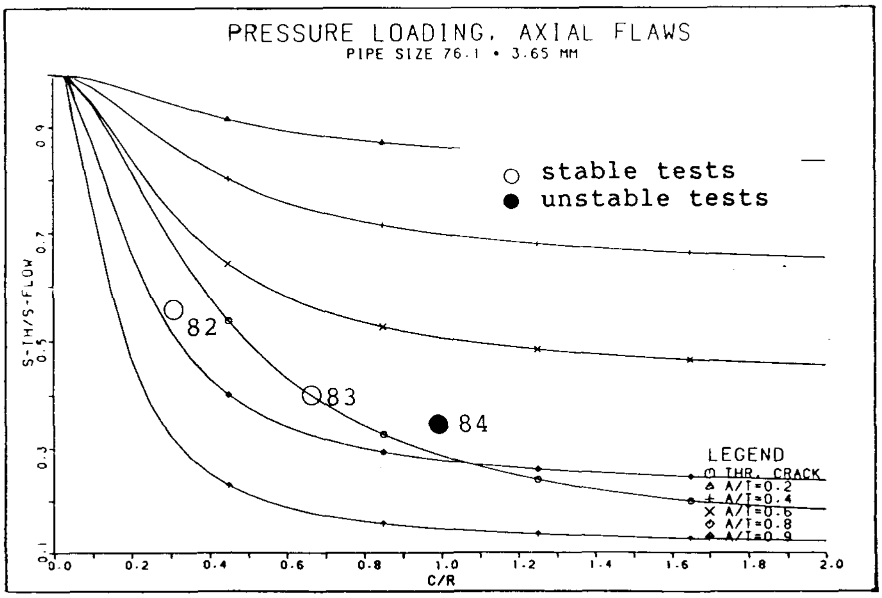


Fig. 12. Results from tests, where pipe material was AISI 304, flaw was axial and pipes were loaded by pure internal pressure. The line of the through crack divides the area into stable and unstable areas [8].

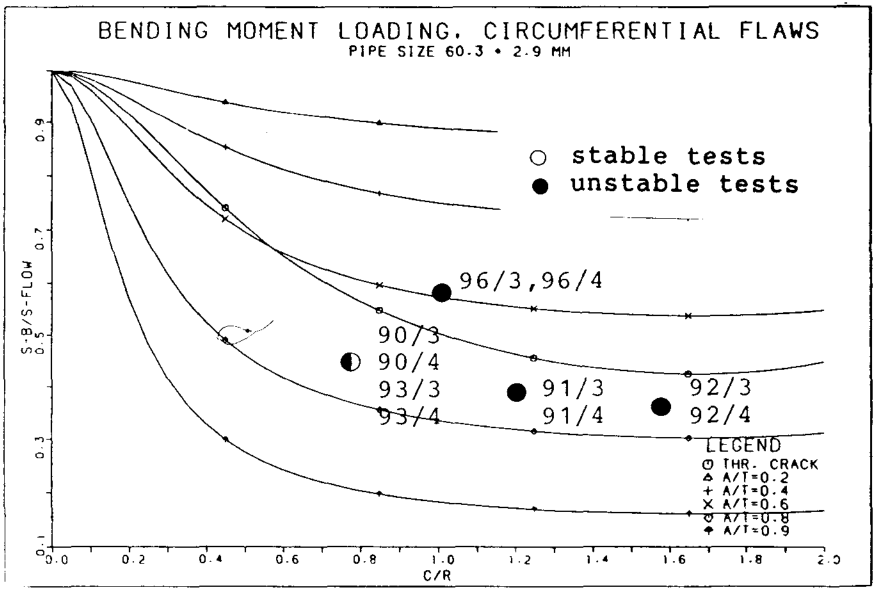


Fig. 13. Results from tests, where pipe material was FE 37B, flaw was circumferential and pipes were loaded by bending moment. The line of the through crack divides the area into stable and unstable areas [8].

4.2 Full-scale pressure vessel tests

Theoretical and experimental fracture assessment methods were verified by performing three tests with full-scale pressure vessels. The first test [11] was carried out in Espoo at VTT in winter 1986, the second [12] and third one [20] in Sköldvik at Neste Oy's Oil Refinery Plant in September 1986 and in August 1988. The experiments were planned and conducted by VTT.

4.2.1 Experimental procedure

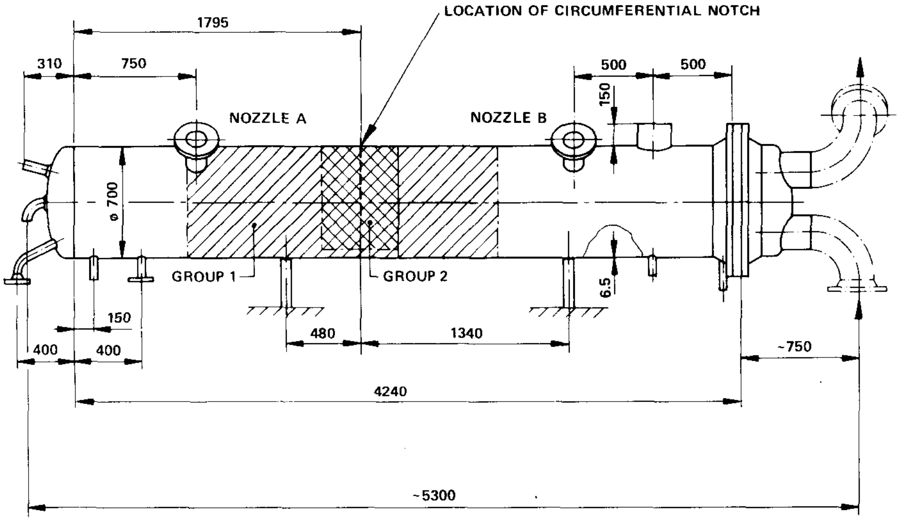
Pressure vessels

For verifying the experimental arrangements and instrumentation a preheater (PH-test) from a coal-fired power plant was tested first [11]. The vessel had been in operation from 1963 to 1984; the design pressure and temperature were 6 bar and 250 °C. Before the test the vessel was mechanically degraded by a circumferential notch (Fig. 14). The vessel was tested at 20 °C using water for pressurization. The material used in the preheater was a boiler vessel steel (HII).

The main full-scale pressure vessel tests consisted of two destructive hydrotests [12, 20] carried out on a large decommissioned pressure vessel (Fig. 15) which had been used as a hydrogen cracking reactor in Neste Oy's oil refinery plant from 1965; the design pressure and temperature were 144 bar and 471 °C. The vessel was fabricated of hot-formed and welded (axial weldments) rings and two hot-formed heads. The material used was a heat resistant high strength steel 2.25 % Cr 1 % Mo.

The wall thickness (without cladding) of the rings and heads was 152 mm and 60 mm, respectively. The inside wall of the vessel was cladded with a ~7 mm thick stainless steel layer which was partly separated from the base metal during the operation. Hence the cladding was thought not to influence the fracture behaviour of the vessel.

For fracture mechanics purposes, an artificial but sharp axial flaw was introduced into the inner wall of the vessel. The flaw was prepared by applying a special grinding and welding technique in three stages. In the first stage rough machining was done by carbon arc gouging to produce a deep prenotch. In the second stage the prenotch was deepened by a grinding wheel to produce a smaller notch (depth 20 mm, width 12 mm). In the last stage this notch was filled by three weld deposits. Immediately after welding, a long sharp crack was produced by hot cracking in the middle of the weld. The dimensions of the flaws in the HC1 and HC2 tests are given in Fig. 15.



NOTCH DIMENSIONS (PH-TEST)

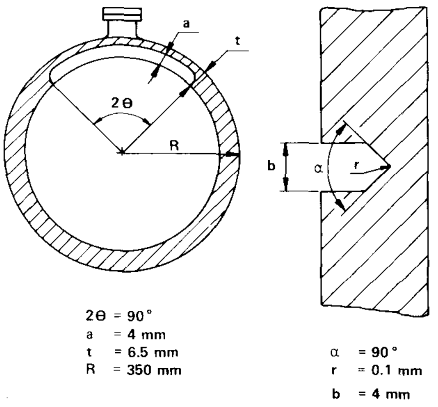


Fig. 14. PH pressure vessel and dimensions of the circumferential surface flaw produced into the vessel wall.

The same pressure vessel was used for both tests. After the HCl-test, the vessel was repaired by installing a repair piece from the sister vessel. Welding was done by applying temper bead technique and performed by Rauma-Repola Mäntyluoto Works.

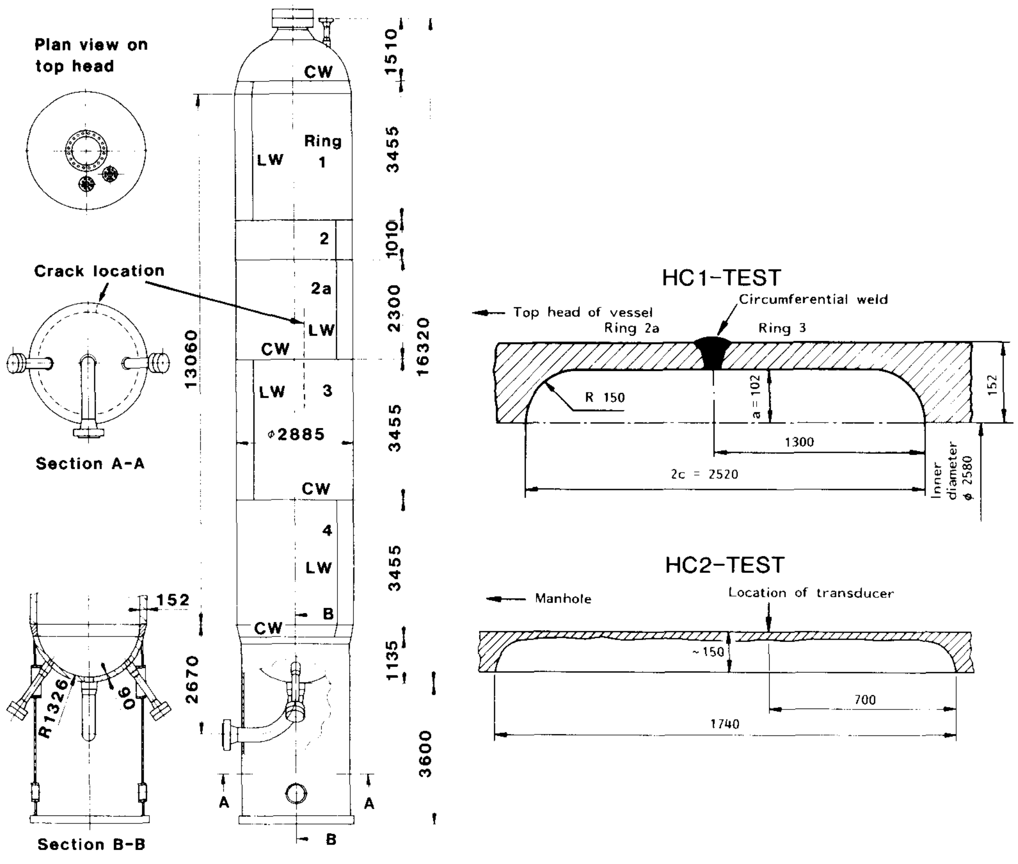


Fig. 15. Decommissioned HC-reactor pressure vessel of an oil refinery plant and dimensions of the axial surface flaw produced into the pressure vessel.

Test instrumentation

The instrumentation used during the tests allowed the determination of membrane stresses (strain gauges), crack opening displacement (LVDT, omega-type clip gauges), vessel ovalization (LVDT), crack initiation and crack growth (strain gauges, DC potential drop technique and acoustic emission), pressure and temperature [12, 20].

The potential difference across the crack, near the crack faces, as well as COD were measured at three positions.

The acoustic emission (AE) instrumentation of the pressure vessels [17, 18] was planned so as to monitor the entire vessel, as in a normal hydrotest, and also to more precisely monitor the defect area by using extra transducers. The main task of the AE system during the measurement phase was to store all raw emission data (arrival time and amplitude of AE events on each channel) on floppy discs. The AE activity on each channel (total of 64 channels) as well as the results of real-time analysis were shown on the computer terminal during the test period. Afterwards a more comprehensive and time-demanding analysis was carried out by the system computer to obtain the final results. The mean resonance frequency of the transducers used was about 100 kHz. Preamplifiers gave an amplification of 60 dB. The sensitivity of all transducers was checked and yielded the pulse velocity of 3.0 mm/µs, which was used for AE source location calculations.

4.2.2 Analytical and numerical calculations

Rupture pressure estimation of the preheater pressure vessel (PH-test)

The rupture pressure and leak-before-break condition was calculated by using the Battelle's method. The yielding stress of the material was 296 MPa and the ultimate strength 455 MPa. The flow stress was calculated as an average of the yielding stress and the ultimate strength giving thus a flow stress value of 376 MPa.

Precalculations of the first test with HC reactor pressure vessel (HC1-test)

The aim of the precalculations [11, 12] was to choose suitable flaw dimensions and estimate the leak-before-break condition in the test. Precalculations were performed using the Battelle's method [24], tangent method [27] and R6-method [26]. As a result of the calculations made by using the Battelle's method, a flaw with the length of 1.6 m and the depth of 110 mm of was recommended. Due to fabrication problems, however, crack depths greater than 100 mm were not possible. To keep the burst pressure below about 200 bar a flaw with the length of 2.5 m and the depth of 100 mm was produced.

The unstable crack extension in the length direction after ligament rupture was also estimated by taking into account the pressure drop in the vessel and the enlargement of the leak area.

Precalculations were performed by Technical Research Centre of Finland (VTT), Veritas Research (VR, Norway) and Fraunhofer - Institut für Werkstoffmechanik (IWM, Federal Republic of Germany).

Postcalculations of the first test with HC reactor pressure vessel (HC1-test)

The postcalculations [14, 15, 19] were elastic-plastic and geometrically nonlinear finite element analyses. They were needed because in engineering analyses it was not possible to consider the effect of the brittle weld intersecting the flaw nor the effect of the maintenance deck which was not totally removed before the test. The analyses were carried out using the 84-version of the ADINA code and the J-integral values were calculated using a post-processor program VTTVIRT.

Due to the different material properties and the premature failure of the ligament (Fig. 21), three-dimensional effects were essential. Because of two symmetry planes, only one quarter of the pressure vessel had to be modelled, Fig. 16. The length of the model was limited to 3.5 m in the axial direction. The model shown in Fig. 16 contained over 16 000 degrees of freedom. There were 20-noded and 15-noded three-dimensional volume elements and one beam element which was needed to describe the effect of the maintenance deck [19]. The crack tip was modelled by collapsed elements causing an 1/r-singularity in the strains near the crack front.

Two different analyses with stationary cracks were carried out. The aim of the first one with original surface crack geometry was to locate where the crack starts to grow and to estimate the amount of the stable crack growth along the artificial crack front. The aim of the second analysis with the through-the-wall crack geometry was to study whether a narrow through-the-wall crack in the surface crack ligament tends to grow in the axial direction, i.e. into the base metal. Also the shape of the crack at the end of the test was roughly assessed.

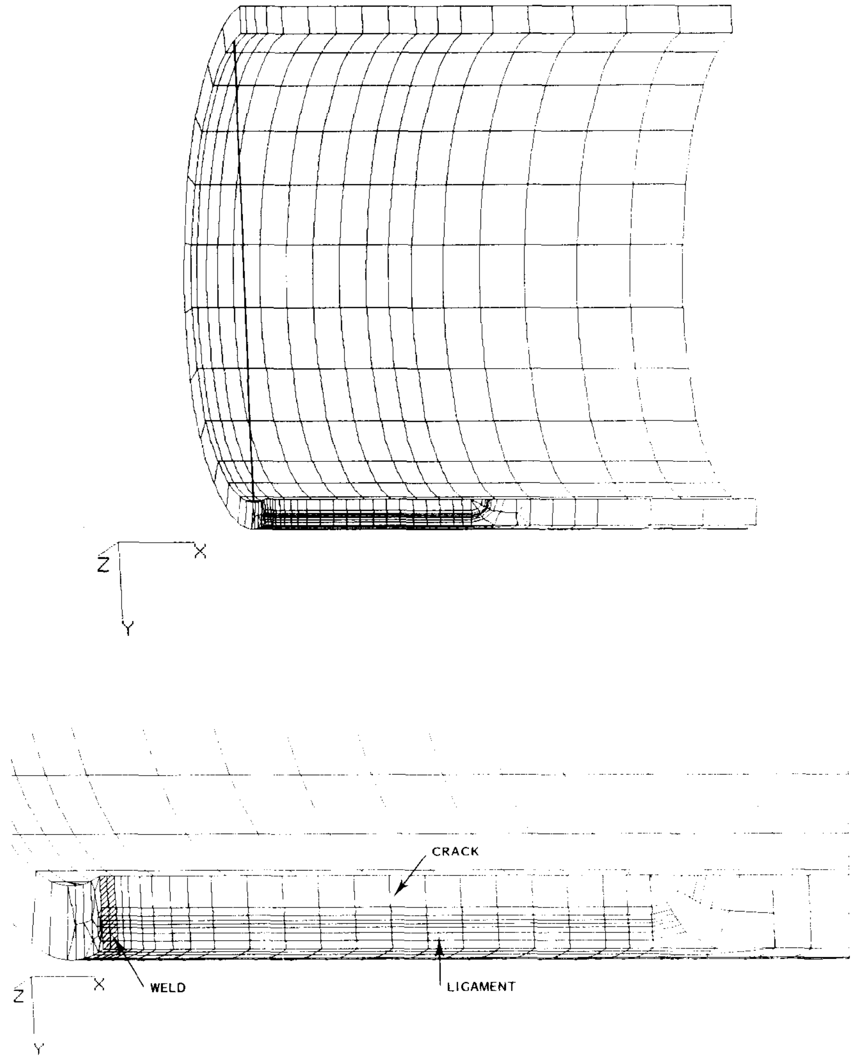


Fig. 16. Finite element model used for the three-dimensional fracture assessment of the HC1-test [19].

Precalculations of the second test with HC reactor pressure vessel (HC2-test)

The flaw geometry for the second test was chosen on the basis of the engineering analyses for the first test. The flaw was deeper and shorter than in the first test so that a leak before break situation was expected. The aim of the precalculations was to investigate the phenomena in the test. Precalculations [20] were performed by Technical

Research Centre of Finland (VTT) and Institut für Werkstoffmechanik (IWM, Federal Republic of Germany). Precalculations were performed using the Battelle's method and R6-method.

Postcalculations of the second test with HC reactor pressure vessel (HC2-test)

Postcalculations [21] were at first aimed to consider the effect of residual welding stresses, which were not considered in the pre-test calculations. The postanalyses were done by using engineering methods and two-dimensional finite element models.

Due to the welding of the repair piece (size 2 x 3.5 m) into the vessel used for the HC1-test, a crack mouth opening displacement (COD) of -0.8 mm and hoop strain of 1800 microstrains in the ligament at the middle of the crack length were measured after the welding procedure (Fig. 17). This crack closure was compensated according to the COD measurements during the test. The pressure range which exceeded the COD value of 0.8 mm, was assumed to cause the rupture when the Battelle's method was applied.

Two-dimensional FEM-analyses were carried out in order to simulate the vessel behaviour due to the residual stresses and to estimate the effect of the repair welding. The main purpose of these calculations was to find correct boundary conditions for later three-dimensional analysis.

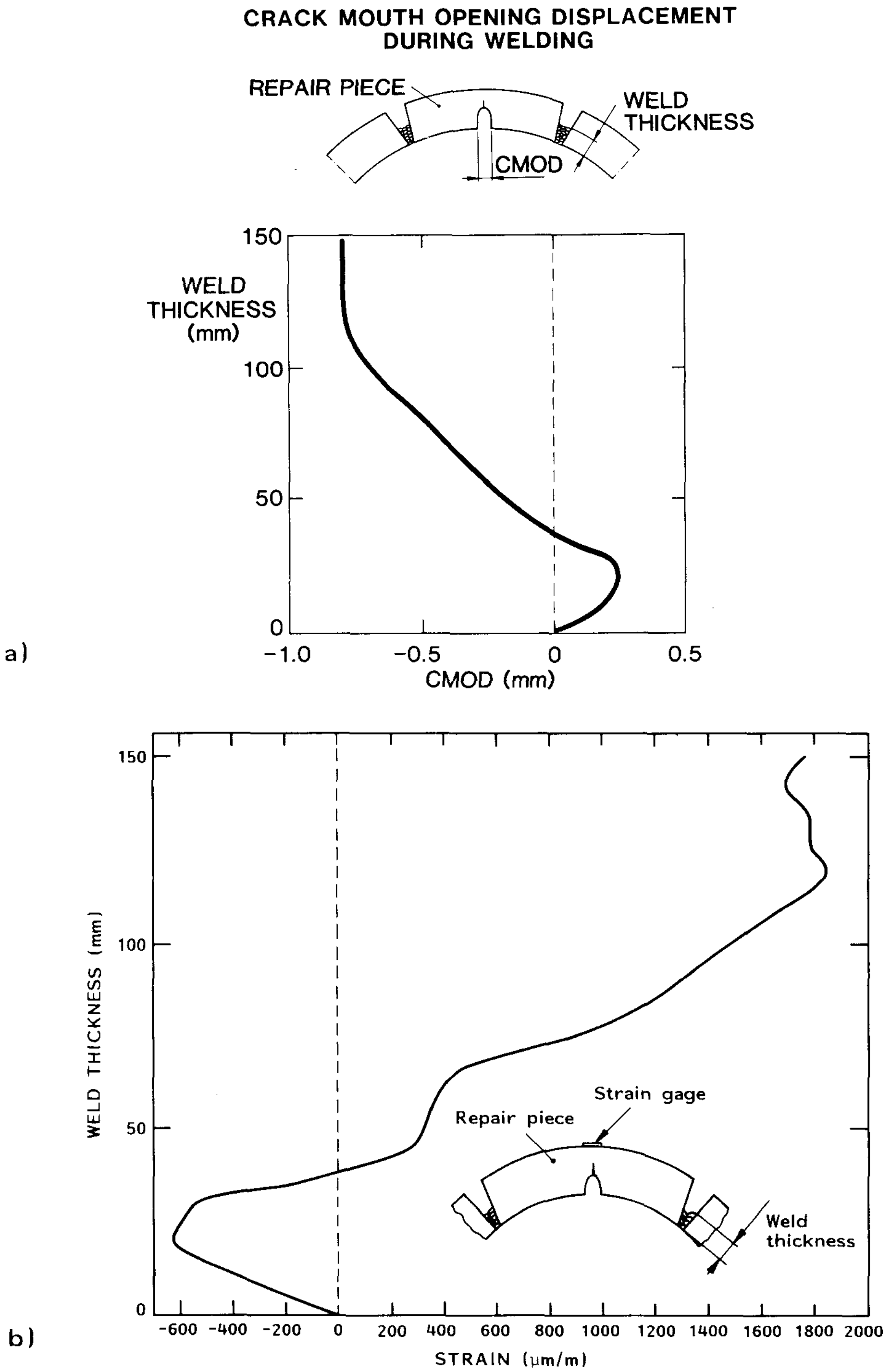


Fig. 17. Generation of the crack mouth opening displacement (a) and ligament hoop strain (b) during the repair welding of the vessel before the HC2-test [20].

4.2.3 Results and discussion

Rupture behaviour

The failure mechanism of the thin-walled PH pressure vessel as well as HC reactor pressure vessel was through plastic collapse of the ligament. In the PH test where a mechanical notch was used, the notch did not grow but the ligament was only necked and finally ruptured at 64 bar pressure. Due to the pure plastic collapse of the notch ligament, the real rupture pressure agreed quite well with the calculated value of 58 bar. The crack extension in the length direction was only about one millimeter, and hence the LBB condition was valid, even if the Battelle's method indicated slightly unstable crack extension. Similar fracture behaviour was found in the HC2-test as shown in Fig. 18.

In the HC2-test, in addition to extensive necking in the outer surface (Fig. 19), stable crack growth and in some local regions brittle crack extension was preceded before ductile tearing of the ligament at the ultimate pressure of 189 bar. The crack was also extended in a brittle manner at one end of the crack, as can be seen from Fig. 20.

In the HC1-test, when the pressure of 170 bar was reached, a local leak occurred in the half-way area of the crack length, where one of the circumferential welds of the vessel was located. After the leak the pressure could be increased further up to 186 bar, at which point the leak rate became equal to the capacity of the pumps. The reason for the local leak was the weldment with lower toughness than parent metal. Outside of the leak area stable crack growth of 1 - 2 mm was detected.

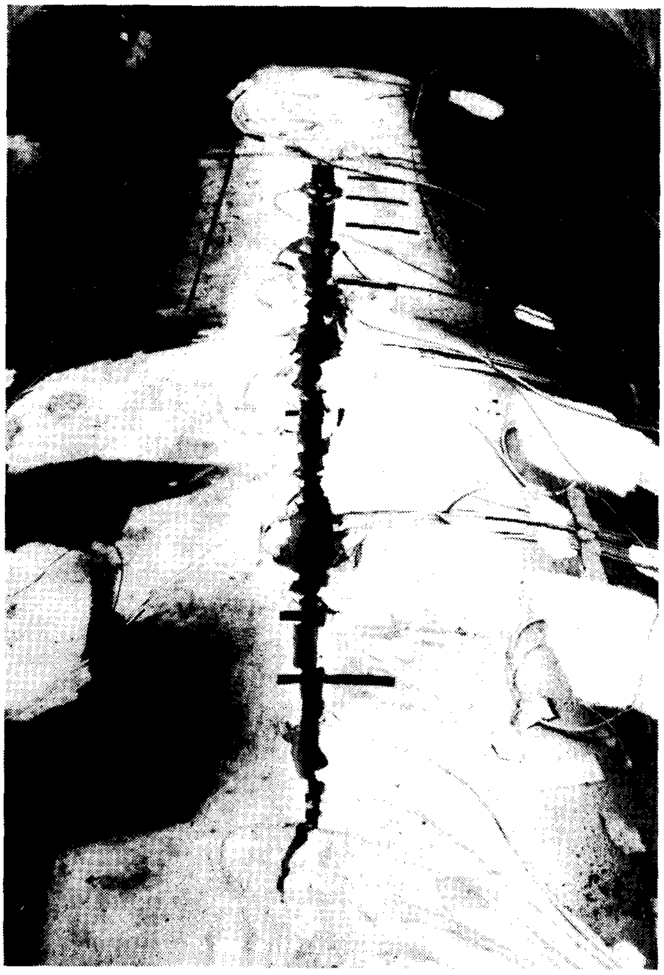


Fig. 18. An overview of the leak region in the HC2-pressure vessel test [20].

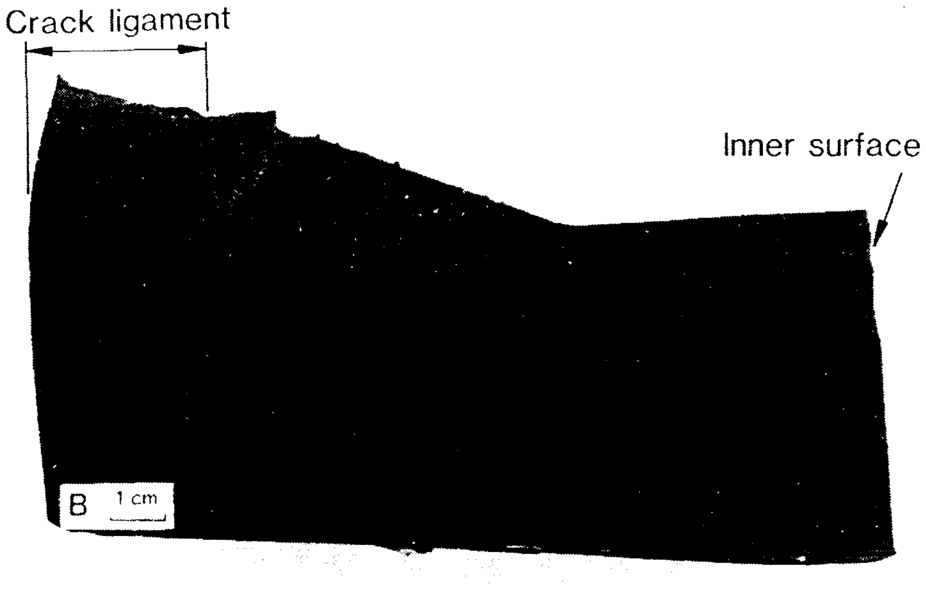


Fig. 19. Profile of the vessel wall after the HC2-test.

Fig. 20. Brittle crack extension at one end of the crack in the HC2-test.

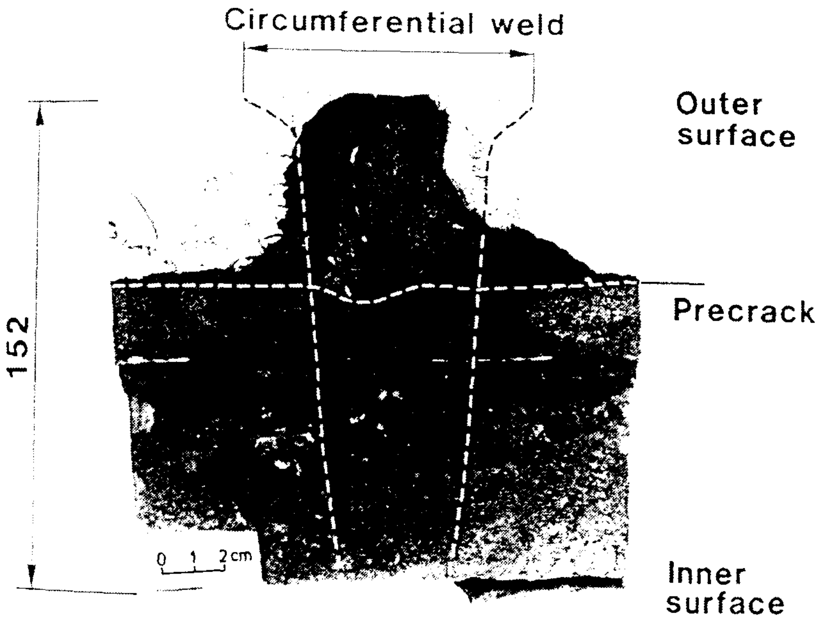


Fig. 21. Fracture contour of local rupture in the crack ligament of the HC1-test [12].

Experimental detection of crack initiation and growth

The instrumentation of the crack field area by strain gauges, COD sensors, PD sensors and AE detectors was aimed to detect crack initiation and crack growth in each test, except PD in the HC2-test [12, 20].

According to the measurements, outer surface hoop strains in the crack ligament were localized in all tests. The strain exactly opposite to the crack tip (K3) was first compressive reaching maximum compressive value in the 75-85 bar pressure range. The strains at the distance of about one ligament thickness from the crack plane (K4 and K5) were increasingly tensile with rising pressure but showed sharply accelerated increase at the same pressure where the strain on the ligament reached its maximum compressive value. This phenomenon was independent whether an axial or circumferential part-through-wall crack was considered.

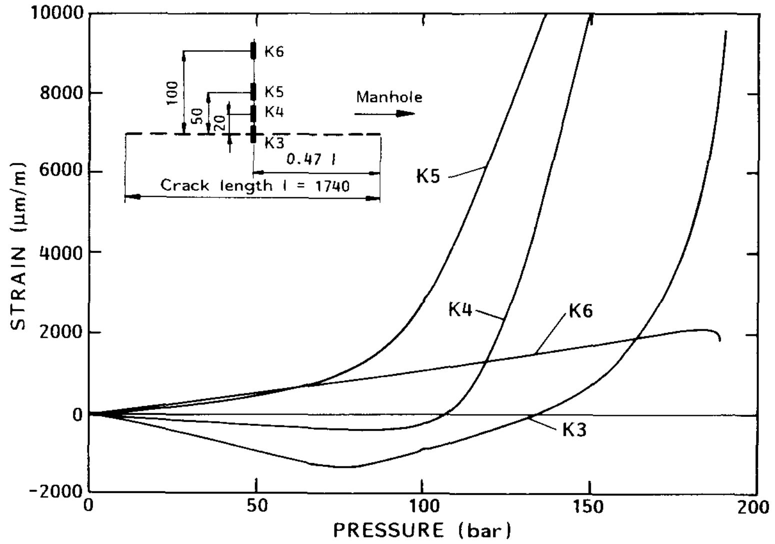


Fig. 22. Typical crack ligament straining in all flawed pressure vessels with axial or circumferential surface flaw (as an example HC2-test) [20].

By applying the acoustic emission monitoring system the flaws could be located already in early stages of the test in spite of heavy background noise level which was mainly due to the partially loosened cladding in the tested vessel.

The AE testing revealed some trends which could be correlated with the other experimental measurements. In that phase of pressurization where strain and COD values were linear, the rate of AE events was very high as can be seen from Fig. 23. In the HC2-test this range corresponded approximately to the pressure of 60 bar. In the pressure range exceeding 60 bar, the ligament started to plastify. Simultaneously the AE event rate along the crack ligament decreased to a relatively low value and remained low until the pressure of 150 bar was exceeded. Approximately at this pressure, the rest of the ligament (elastic zone in the ligament close to the outer surface) started to plastify causing an increase of the AE event rate. The same tendency was not seen at the crack end regions, where plastification was found to be small and the AE rate was low.

Amplitude distribution of the registered and located AE events (Fig. 24) revealed that the events with high amplitude were coming between the pressure of 150 bar and the rupture pressure, which was 189 bar for the HC2-test.

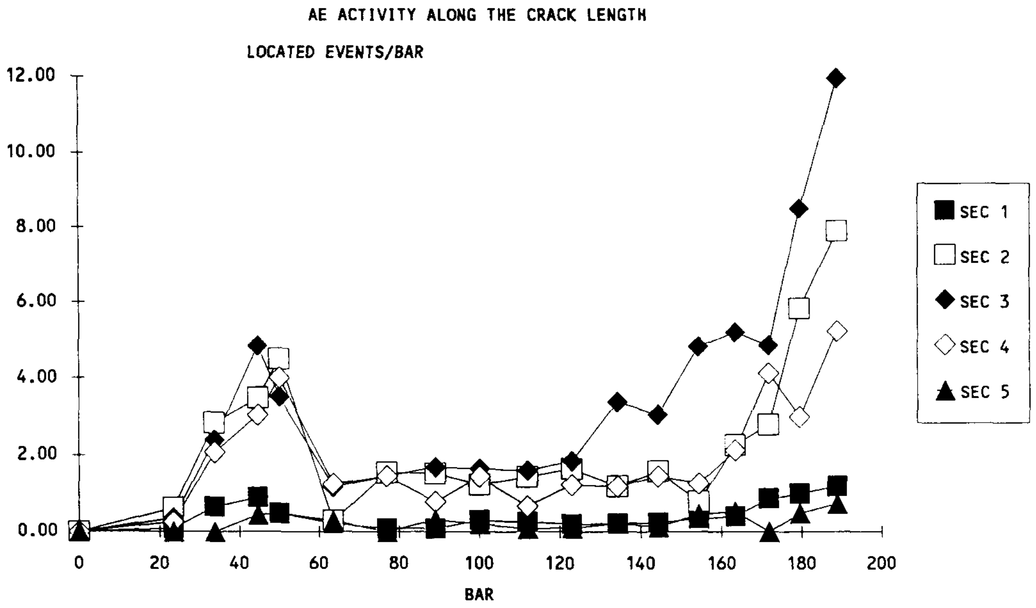


Fig. 23. Acoustic emission activity of the HC2-test using events located not further than 150 mm on both sides of the crack line [20]. The total crack length is divided into five sections (length 450 mm) numbered from 1 to 5 to demonstrate AE event rate along the crack length. Sec 3 corresponds to the midsection and sec 1 & 5 to the ends of the flaw.

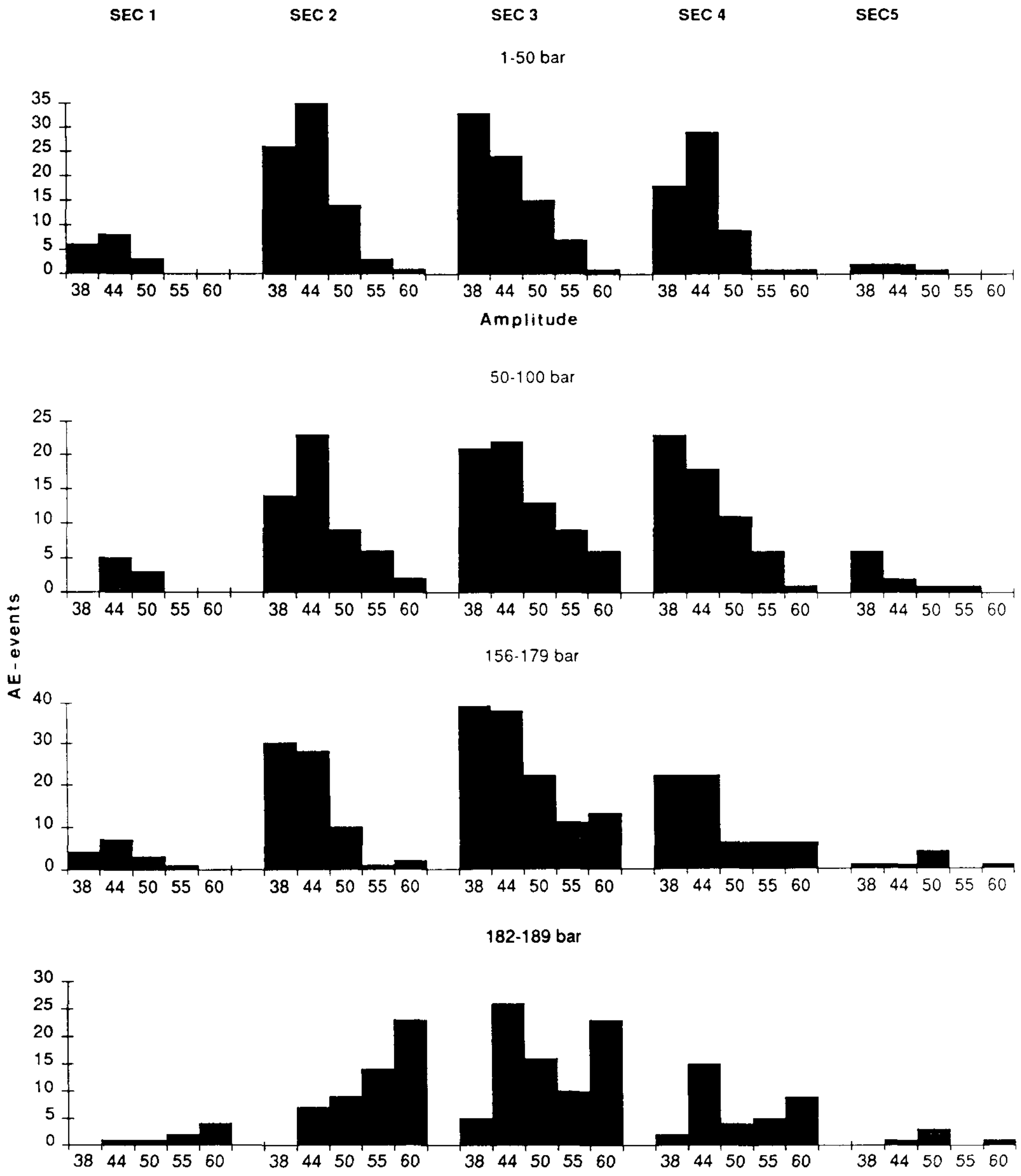


Fig. 24. Amplitude distribution of the AE-events registered in five sections along the crack length in different pressure ranges of the HC2-test [20].

Deformation of pressure vessel circumference

Because of the flaw, the vessel wall was subjected to bending. The flaw area deflected to the inside of the vessel causing the ovalization of the vessel as shown in Fig. 25. The diameter as measured parallel to the crack decreased while the diameter measured perpendicular to the crack plane increased.

Calculated hoop strains from a three-dimensional analysis along the outer and inner surfaces of the vessel circumference agreed well with the measured ones [15, 19]. Measured and calculated hoop strains along the inner surface were higher than those along the outer surface at 90° (Fig. 26a). At 45° (Fig. 26b), however, the situation was reversed indicating significant influence of the crack on the stress field. In Fig. 26 the 0° reference plane is the crack surface plane.

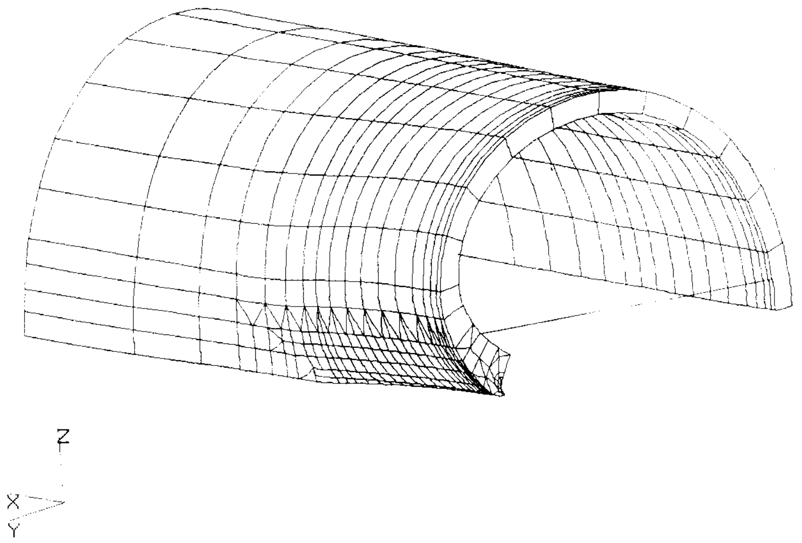


Fig. 25. Deformations of the pressure vessel in the HC1-test (exaggerated) [15].

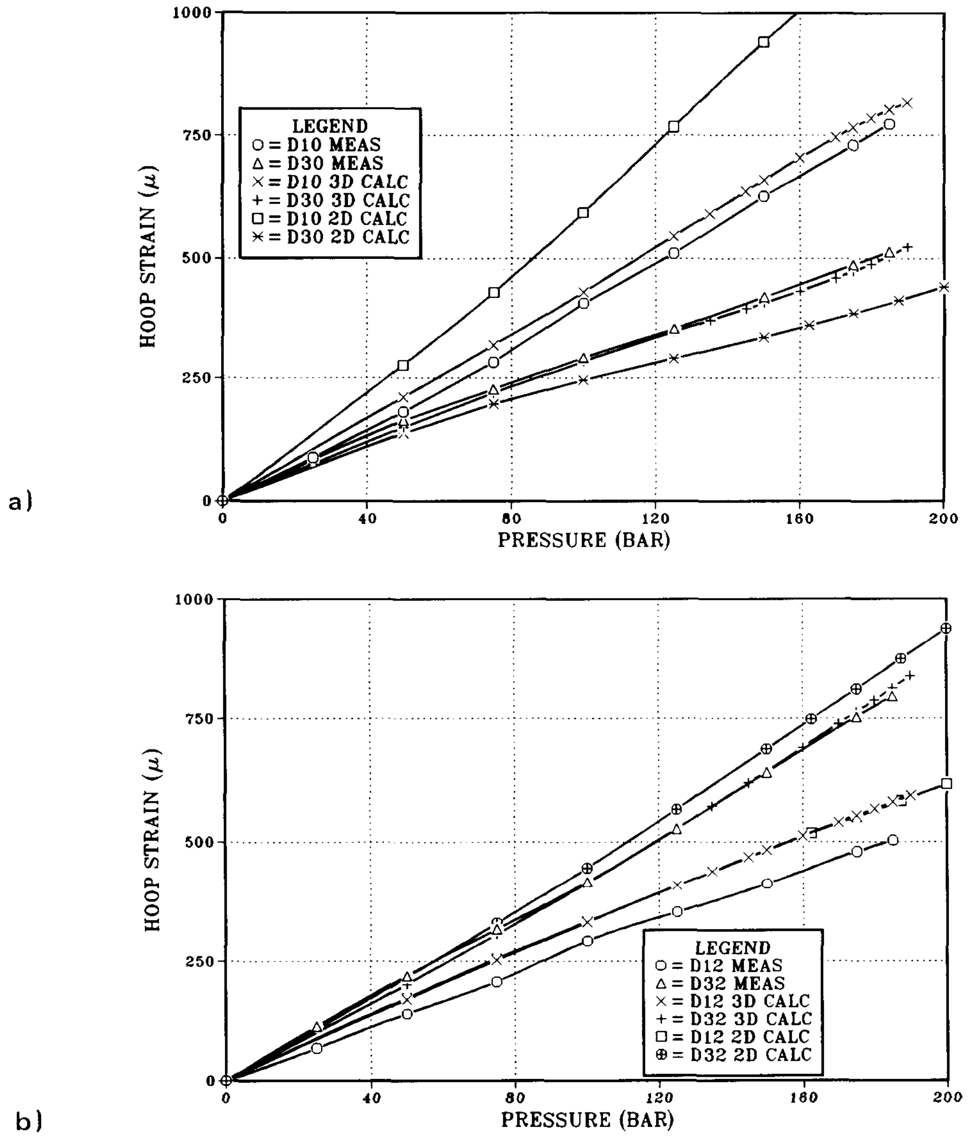


Fig. 26. Calculated and measured inner surface (D30, D32) and outer surface (D10, D12) hoop strains along the pressure vessel circumference, at the orientation of the 45° in a) and 90° in b), and crossing the crack ligament at one third of the crack length (HC1-test) [15].

Fracture behaviour assessment

The rupture pressure in the PH test was estimated only by Battelle's method. The calculated value of 58 bar agreed well with the measured rupture pressure of 64 [11]. Battelle's method predicted the case to be a catastrophic failure. The test result was a leak without break because of small energy content in the system.

Precalculations of the HC1 according to the Battelle's method resulted that the dimensions of the flaw should have led to a catastrophic failure at the pressure of 194 bar. The estimates for the unstable crack growth at through-the-wall crack ends varied between 1.4 and 3.0 mm. In the test no unstable crack growth occured due to the relatively brittle weld in the middle of the pressure vessel which allowed a significant leak before the critical burst pressure could be achieved.

The results of the preanalyses [11-13] are summarized in Tables 3 and 4 and compared to the experimental findings in Fig. 27.

Table 3. Results of the preanalyses of the HC1-test.

		Crack initiation pressure (bar)	Stable crack growth in thickness direction (mm)	Rupture pressure (bar)
Battelle's formula		-	-	200
EPRI method:	2D	110	8	140
	3D	195	9	200
R6 method:	IWM	122	5	133
	VR	173	1.5	173
	VTT	135	-	-
R6 and EPRI:	IWM	141	10	189
EPRI method:	2D	90	2	130

Table 4. Results of the preanalyses of the HC2-test.

		Crack initiation pressure (bar)	Stable crack growth in thickness direction (mm)	Rupture pressure (bar)
Battelle's method		-	-	130
R6-method	IWM	102	2.4	108
	VTT	124	2	125

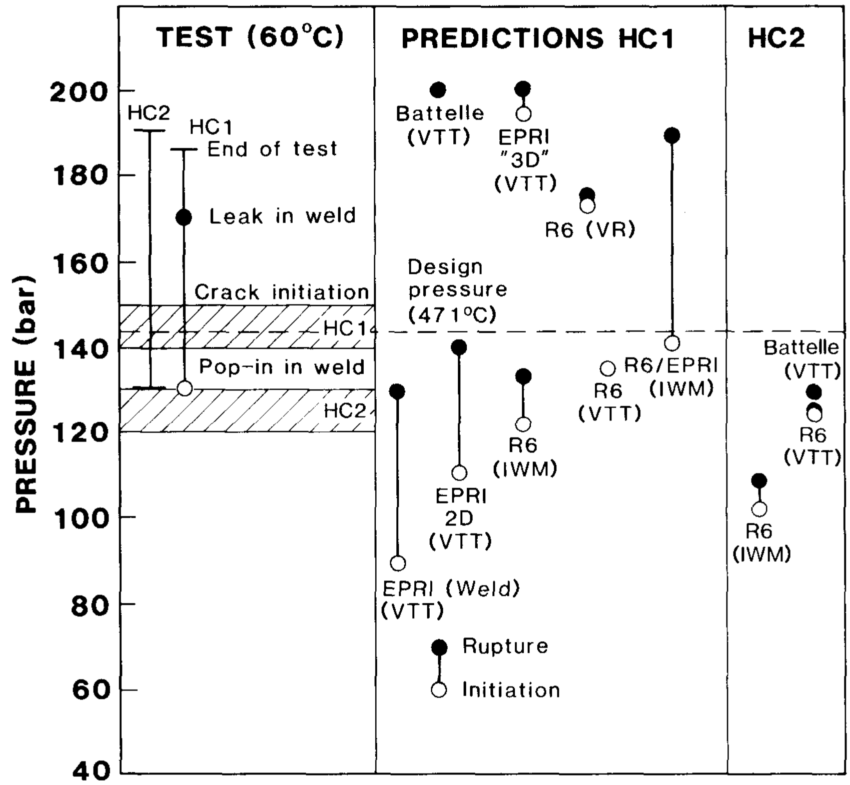


Fig. 27. Comparison of measured and calculated crack initiation and ultimate rupture pressures in the tests HC1 and HC2 with full-scale chemical reactor pressure vessel.

In order to ascertain the accuracy and applicability of the FE-analysis on the fracture behaviour assessment, calculated strains and crack opening displacements were compared to the experimental ones [15, 19].

Adjacent to a crack cross-section at the 1/4 crack length position the measured and calculated hoop strains in the ligament had a similar trend, but there were some differences between the absolute values (Fig. 28). Near the ligament, the outer surface hoop strains had a high gradient as a function of the distance from the crack plane, hence small inaccuracies in gage locations may be one reason for the differences between calculated and measured strains.

The measured and calculated crack mouth opening displacement (COD) values at one quarter of the crack length were in good agreement (Fig. 29). The calculated CTOD value, which is also shown in Fig. 29, reached a value of 1 mm corresponding roughly the J_{Ic} at a pressure of 150 bar. The J-values along the crack front are presented in Fig. 30 at different pressure levels. The maximum J-value occurred in

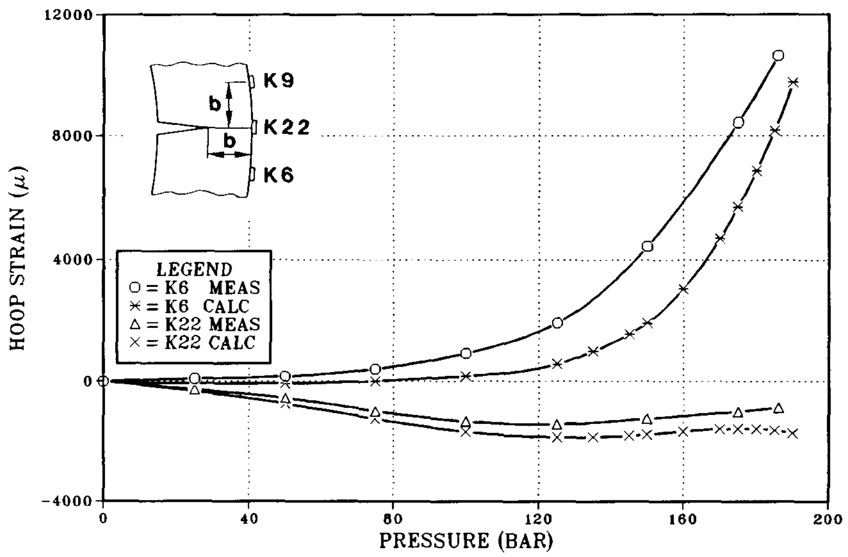


Fig. 28. Calculated and measured outer surface hoop strains of the ligament cross-plane located at one quarter of the crack length (HCl-test) [15, 19].

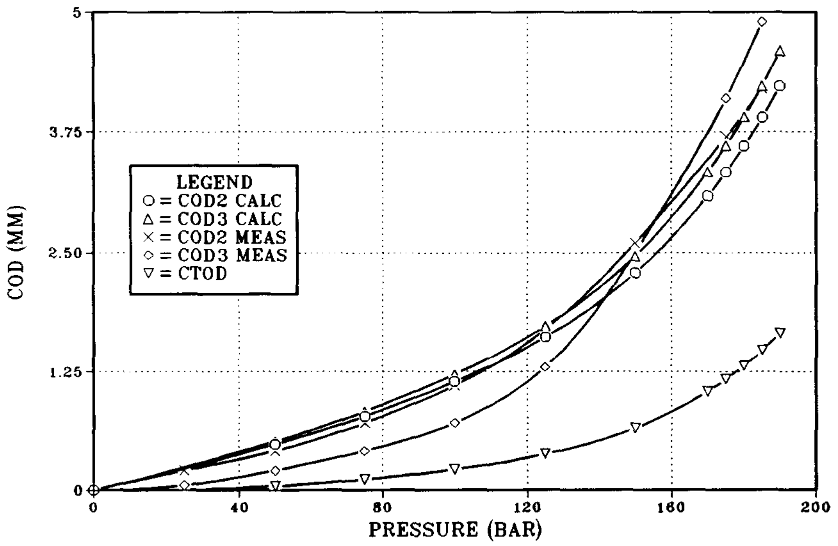


Fig. 29. Calculated and measured crack mouth opening displacements at the 1/4 (COD2) of the crack length as well as calculated crack tip opening displacements (CTOD) at the COD2 position (HCl-test) [15, 19].

the weld and was about 10 % higher than the corresponding value in the neighboring base material. The higher yield strength of the weld material caused higher J-integral values in the weld. The J_{Ic} value of 378 kN/m was reached at 150 bar, which was found to be the approximate pressure for the onset of stable crack extension in the thickness direction in the HC1-test.

On the basis of the material J_R-curve and the calculated J-values one can estimate stable crack growth at the end of the test (186 bar). According to the analysis [15] presented in Fig. 30, the estimated crack growth in the base material was 3.5 mm in the vicinity of the weld and 2.5 mm at one quarter of the crack length, and at the crack's end no crack growth in axial direction was expected. Fracture surface investigations [11] indicated about 2 mm crack growth over a length of approximately 500 mm on both sides of the leak. The J-level in the weld is much higher than weld material J-R-curve values, which could indicate instability or at least considerable crack growth through the weld. A very sharp peak in the J-distribution along the front of the trough-the-wall crack occurred in the crossing of the initial and new crack fronts. It showed that the through-the-wall crack tends to grow much faster near the inner surface, where it should extend considerably into the base material as supported by the shape of the experimental through-the-wall crack (Fig. 21). Estimated and measured crack growths are compared in Fig. 31. If the crack had been located entirely in the base material, it would have presumably penetrated the wall along most of its length thus causing a catastrophic failure. The failure pressure would probably have been slightly over 200 bar.

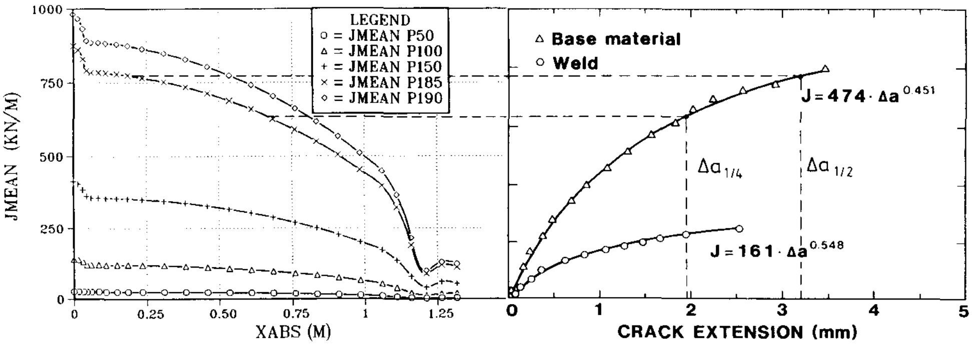


Fig. 30. Distribution of the J-integral value along the surface crack front at different pressure levels and determination of stable crack growth based on the application of the material's fracture resistance curve (HC1-test).

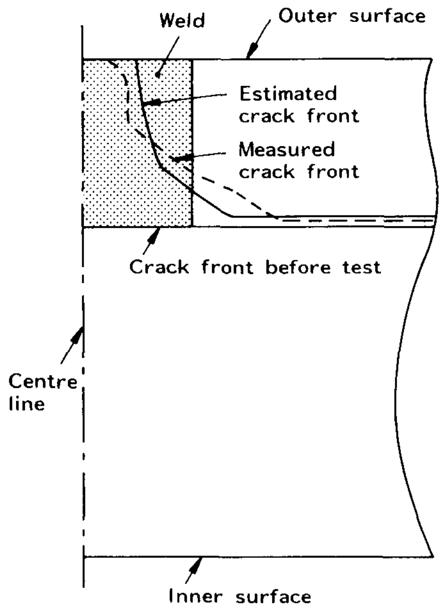


Fig. 31. Estimated and measured crack front location in the local leak region (HC1-test) [19].

In spite of the complicated geometry, the overall agreement between experimental and calculated displacement and strain results was good. Conservative estimates were obtained for stable crack growth. Extensive three-dimensional analyses were necessary to explain the failure behavior in the test.

In the precalculcations of the HC2-test [20] the residual stresses due to repair welding were not taken into account which was probably the reason for the large discrepancy between the actual rupture pressure (189 bar) and the average estimate rupture pressure (120 bar). Because the pressure vessel in the HC2-test behaved primarily elastically, i.e. the plastic zone near the flaw was small with respect to the vessel size, the crack closure (COD-value of -0.8 mm) after welding can be compensated for by adding the pressure load which corresponds to the COD value of 0.8 mm. During the test the COD value of 0.8 mm was reached at the pressure of 60 bar which meant that the COD value was actually zero at this loading level. In applying the Battelle's method it can be thought that the portion of the total pressure exceeding 60 bar causes the final rupture. Thus, adding 60 bar to the value of 130 bar evaluated in Table 4 without the welding residual stresses, a value of 190 bar is obtained, which is the same as the ultimate rupture pressure achieved in the test.

The effect of welding residual stresses on the fracture behaviour is currently being investigated by two-dimensional finite element analysis [21]. The emphasis of this analysis is to assess correct solutions for appropriate boundary conditions which are essential in three-dimensional analysis.

4.3 Conclusions on the applicability of fracture assessment methods

The fracture behaviour of flawed pressure-containing components can be assessed in different ways. The proper instrumentation of the flaw ligament region by strain gauges gives early information on the possible extension of the flaw. Additional instrumentation with an acoustic emission monitoring system can locate the flaw already in early loading stages. The application of AE testing for crack growth monitoring requires preliminary fracture mechanics considerations of the case concerned, before the correlation between the AE event activity and crack extension can be reliably expressed.

The engineering methods which were applied on the cylindrical pressure vessels, were Battelle's limit load method and the R6-method. The finite element method calculations consisted of two- and three-dimensional linear, elastic-plastic and both elastic-plastic and geometrically nonlinear analyses.

If the material is ductile and the geometry and loading situation are simple, Battelle's limit load method gives the ultimate rupture pressure with reasonable accuracy and low cost. The R6-method was useful because it could be used to estimate the degree of stable stable crack growth prior to rupture when the J-R-curve of the material was known.

In the case of a realistic finite flaw in a simple structure, as in a cylindrical vessel, three-dimensional effects are essential and three-dimensional finite element calculations are necessary. Even with the complicated geometry in the first test (HC1-test) of a decommissioned reactor pressure vessel, the overall agreement of displacement and strain results between the experimental and numerical values from three-dimensional finite element analyses was good. Conservative estimates were obtained for stable crack growth. Extensive three-dimensional analyses were necessary to explain the failure behaviour of the vessel in the test.

5. RECOMMENDATIONS

The test programme was comprised of tests with two large pressure vessels, semi-scale pressure vessel wall, one small pressure vessel, CT-specimens and 122 small pipes. The theoretical methods applied on the analysis of pressure vessels, specimens and pipes can roughly be divided into so called engineering methods and into methods based on the finite element method.

The engineering methods which have been applied on the cylindrical pressure vessels and pipes, have been Battelle's limit load method, MPA's method (Materialprüfungsanstalt, Stuttgart), the R6-method and failure assessment diagram. The finite element method calculations have consisted of two- and three-dimensional linear, elastic-plastic and both elastic-plastic and geometrically nonlinear analyses.

The following conclusions concerning the engineering methods can be drawn: If the material is ductile, as it was in the performed tests, and the geometry and loading situation are simple, i.e. cylindrical geometry and axial or circumferential crack orientation, Battelle's and MPA's limit load methods give the bursting load and the stability of a burst crack with low costs and quite reasonable accuracy. One of the biggest problems is how to choose the flow stress for the calculations. The smallest value is the yield stress of the material and the highest possible value is the true ultimate stress. One recommendation might be to make a test by pressurizing a cracked cylinder and determine the flow stress from the burst pressure. Certainly the flow stress determined in this way depends on the geometrical dimensions and their ratios, and probably even on the crack geometry.

The R6-method is useful because it can be used to estimate stable crack growth before bursting if the J-R-curve of the material is known. The R6-method is also useful, when the material is not fully ductile.

Conclusions of the application of the finite element method on cracked pressure vessel and pipe analysis are as follows: In case of a realistic finitely long flaw even in a simple structure, as in a cylindrical vessel, three-dimensional effects are essential and three-dimensional finite element calculations are necessary. This is usually very expensive but gives very detailed information, e.g., stresses and strains at every interesting point and J-integral distributions along the crack front at different load levels. The amount of stable crack growth and the fracture behavior can be assessed based on the calculated J-variations and the measured J-R-curves. In more complicated cases such as would be caused by a more complicated geometry, combined loading, or multiple materials (as in cladded pressure vessels or weldments), extensive three-dimensional finite element analyses are possibly the only way to explain the failure behavior of a pressure vessel or piping. The proper consideration of boundary conditions and availability of the relevant material parameter data are very essential for achieving good results. Automatizing of the finite element mesh generation and access to super computers greatly decreases the time needed for such computations.

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