Fracture Analysis of a Pressure Vessel Rejected After Inservice Inspection

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1 INTRODUCTION

As part of a research project aimed to validate fracture analysis methods as used for structures containing defects (Rongen et al. 1990) a pressure vessel has been tested by pressurizing it till failure. This vessel (heat exchanger) was made available by DSM and was taken out of operation after defects had been found in the transition between the cylinder wall and the tube sheet of the vessel. Three different fracture analysis methods have been applied to predict the failure pressure of this vessel, viz. section XI of the ASME code, British Standards PD-6493 (1980) and CEGB R6-revision 3 (1986). To show the influence of the available information on the predicted critical load three information levels have been defined varying from minimal to maximal information. The main difference between these levels involves the extent and the accuracy of the information necessary for the failure analysis.

2 DESCRIPTION OF THE PRESSURE VESSEL

The geometry and the main dimensions of the vessel are shown in figure 1. The vessel is a heat exchanger with high pressure water flowing around the tubes and gas flowing through the tubes. The total number of tubes is 750 (outside diameter 25.4 mm; inside diameter 18.6 mm). After welding the vessel was fully stress relieved. The design pressure and the test pressure are 11.6 MPa and 17.4 MPa respectively.

During ultrasonic inspection defects were found in the transition region between the cylinder wall and the tube sheet with a thickness of 170 mm. These defects are along the entire circumference. Three defect zones can be distinguished as shown in figure 2. No defects were found in a zone of 40-50 mm from the outside (zone 1). A large number of defects with a depth of 3-10 mm were found in zone 2. The plane of these defects is parallel to the plane of the tube sheet. At the inside of the vessel the number of defects strongly increases making it impossible to discern between the separate defects (zone 3). This region

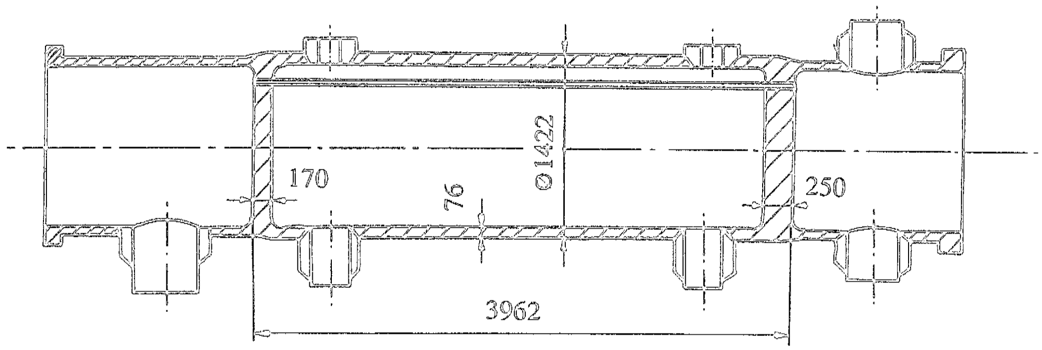


Figure 1. Geometry and dimensions of the vessel.

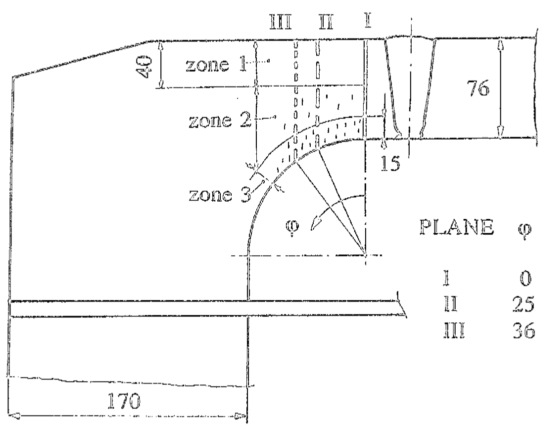


Figure 2. Defect zones and fracture planes.

covers a distance of 10-15 mm from the inner surface. Because of these defects it was decided to take the vessel out of operation.

The vessel was tested by pressurizing it till failure. Failure occurred at an internal pressure of 53 MPa due to crack initiation and unstable crack propagation in the transition region between cylinder wall and tube sheet with a thickness of 170 mm, plane III in figure 2. The fracture surface was completely brittle and showed no shear lips. Examination of the fracture surface showed a lot of small defects in the region of crack initiation. It was not possible to determine the crack that initiated fracture. After characterization of these defects according to the ASME code the most severe defect appeared to be a semi-elliptical surface defect with depth a = 5.9 mm and length l = 11.8 mm.

3 FRACTURE ANALYSIS METHODS

Three different fracture analysis methods have been applied to this vessel, viz. ASME XI, BS PD-6493 and CEGB R6. To calculate the critical load in connection to fracture according to ASME XI the requirement for emergency and faulted conditions (article IWB-3600) given by $K_I \leq K_{IC}/\sqrt{2}$ has been applied. Neglecting the assumed safety factor of $\sqrt{2}$ the critical load was calculated by solving the equation $K_I = K_{IC}$. The stress intensity factor is calculated with the formula given in the code.

The results obtained by BS PD-6493 are based on the design curve characterized by K_{IC}.

For the CEGB R6 method a category 1 analysis with the analytical assessment curve was applied. The stress intensity factor was calculated with the solution for a wide plate under tension and bending (Newman and Raju 1981). For the plastic collapse no solutions exist for the cylinder case, therefore a flat plate solution was applied (Miller 1988).

To show the influence of the available information three information levels have been defined. The analyses at the minimal level (level A) and at the intermediate level (level B) are based on information available before pressurizing the vessel till failure. The analysis at the maximal information level (level C) is based on information after failure of the vessel.

Level A: Minimal information.

- Defects;
  Because the ultrasonic testing method used could not discern between the separate defects in a region of 10-15 mm from the inside this evaluation is based on a circumferential defect with depth a = 15 mm in plane I and II, shown in figure 2. Plane II was chosen because the finite element (FE) results showed a maximum in the stress near the inner surface at $\varphi = 25°$.
- Fracture toughness;
  K_{IC} = 1600 MPa $\sqrt{mm}$; derived from Charpy tests.
- Stress analysis;
  The stresses were derived from simple analytical equations.

Level B: Intermediate information.

The stresses are calculated with the FE method, while the defect configuration and the fracture toughness are the same as for the minimal information level specified above.

Level C: Maximal information.

- Defects;
  Of the defects present in the real fracture plane (plane III) the most severe appears to be a semi-elliptical surface defect with a depth a = 5.9 mm and a length l = 11.8 mm.
- Fracture toughness;
  K_{IC} = 2070 MPa $\sqrt{mm}$ (lowest value), K_{IC} = 2680 MPa $\sqrt{mm}$ (highest value); determined with fracture mechanics specimens fabricated from material near the defect location.
- Stress analysis.
  The stresses were derived from FE calculations.

4 STRESS ANALYSIS

Application of the fracture analysis methods mentioned above requires the determination of the stresses at the location of the postulated or observed flaws. For the minimal information level the stresses are based on simple analytical formulas where the tube sheet is assumed to be rigid, so the end of the cylinder is assumed to be built in. Solving this problem results in a membrane stress of 3.76 MPa and a bending stress of 16.08 MPa (internal pressure: 1 MPa) in case the pipes do not contribute to the axial equilibrium. To take into account the stress concentration in the transition region at the position of plane II the membrane stress and the bending stress are corrected with stress concentration factors according to the WRC bulletin 107. The stress concentration factor for tension is given by $K_t = 1.52$ and for bending by $K_b = 1.29$.

For the information level B the stresses are derived from a FE calculation of the uncracked geometry. The pipes inside the vessel are not modelled. According to article A-8000 of section III of the ASME code the perforated tube sheet was modelled as a solid plate, which has modified elastic constants. The calculated axial strains at the outside of the cylinder wall are presented in figure 3 together with the measured strains at an internal pressure of 1 MPa. This figure shows that the calculated strains do agree very well with the measurements, so it is concluded that the contribution of the pipes to the stiffness of the vessel can be neglected.

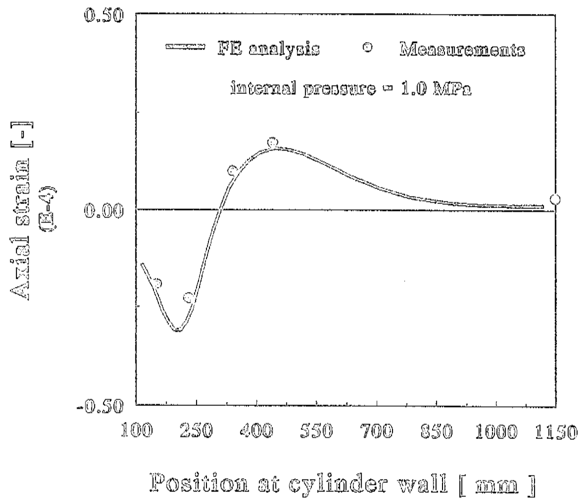
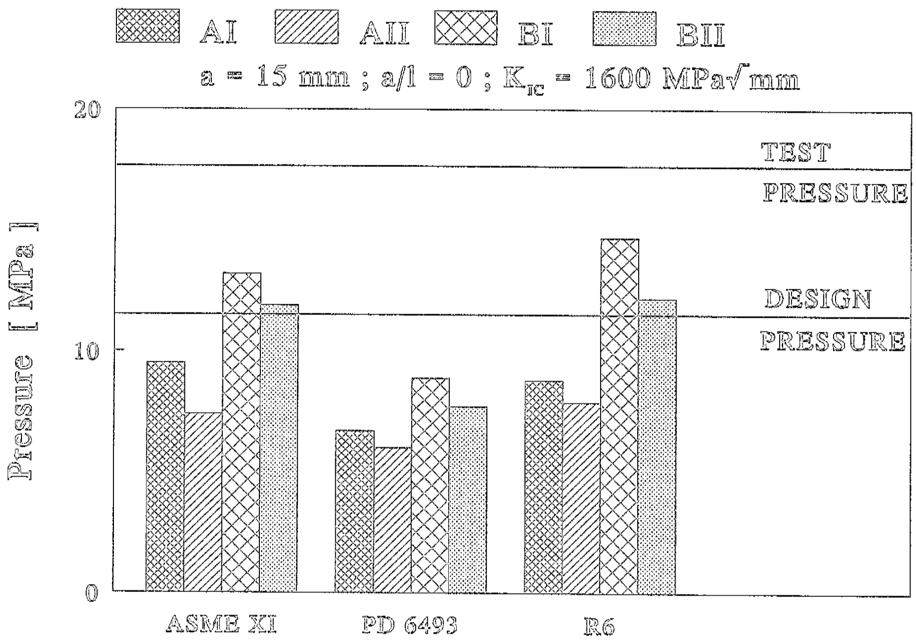


Figure 3. Axial strain at the outside of the cylinder wall.

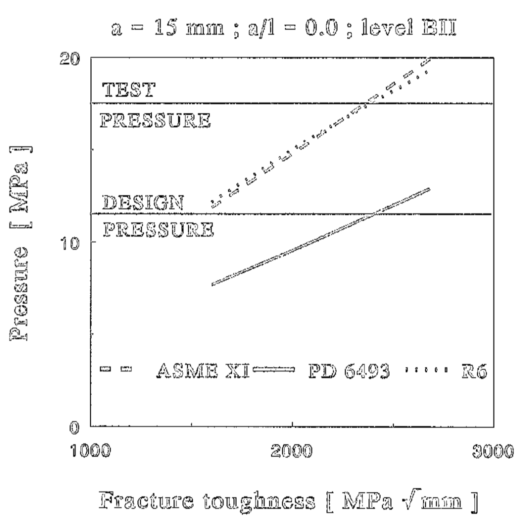
5 RESULTS

The most striking results are shown in the figures 4 to 6. In figure 4 the predicted pressures are given for plane I and II and the information levels A and B. This figure shows that for information level A all predicted failure pressures are below the design pressure. Clearly higher predictions are obtained when the fracture analyses are based on the stress distribution obtained with the FE method (information level B). Apparently the application of the FE method is appropriate to make a better estimation of the level of the failure pressure. However the use of the FE method still results in predictions which are less than the test pressure of 17.4 MPa, so the decision to take the vessel out of production was right. The results of ASME XI and R6 do agree quite well, while the predictions with PD-6493 are lower. This can be explained by the fact that for the PD-6493 method use was made of the design curve, which may be assumed to contain a safety factor.

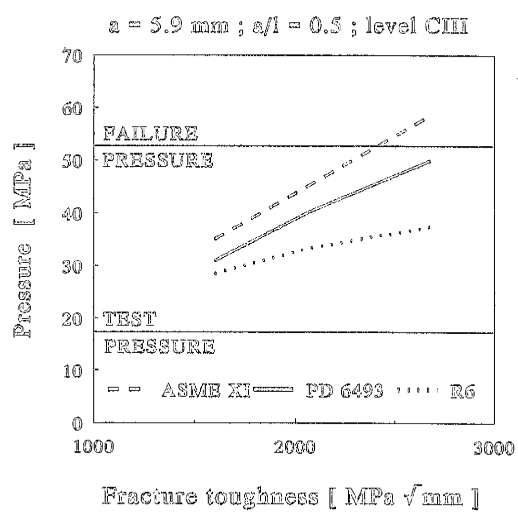
The influence of the fracture toughness is shown in figure 5, presenting the critical pressures for plane II and information level B. For the fracture toughness derived from Charpy tests (1600 MPa $\sqrt{mm}$) the predicted failure pressures are below or very



<u>Figure 4.</u> Predicted failure pressures.



<u>Figure 5.</u> Predicted failure pressures.



<u>Figure 6.</u> Predicted failure pressures.

close to the design pressure. At the minimum measured fracture toughness (2070 MPa √mm) the predicted results are below the test pressure. Consequently exact information concerning the fracture toughness could not have prevented the rejection of the vessel.

Figure 6 gives the results for the maximal information level where the real defect dimensions (a = 5.9 mm, l = 11.8 mm) are used. For reasons of comparison the results for K_{IC} = 1600 MPa √mm are given too. For the minimal measured fracture toughness all three methods make conservative predictions. The R6 method gives the most conservative predictions contrary to the level A and B analyses, which showed a good agreement between the ASME XI and the R6 results. This is caused by the fact that for the semi-elliptical surface defect as used in the level C analysis the plastic collapse criterion in R6 becomes more important leading to lower predictions. Taking into account the scatter in the measured fracture toughness (2070-2680 MPa √mm) the predicted failure pressure with ASME XI does correspond with the actual failure pressure. It is clear that even for the fracture toughness derived from Charpy tests the predicted critical pressures are above the test pressure. So, in the case of this vessel, the only factor that could have prevented rejection of the vessel was knowledge of the real defect dimensions.

6 CONCLUSIONS

Analyzing the DSM vessel with three different fracture analysis methods on the basis of the minimal and the intermediate information level leads to the decision to take the vessel out of operation. Rejection of the vessel could only have been prevented if the actual size of the defects in the material had been considered. Unfortunately the ultrasonic inspection method used to inspect this vessel was not able to discern between the separate defects.

Application of stresses obtained from FE-calculations (compared with stresses from a simple analytical analysis) or application of fracture toughness values obtained from fracture mechanics tests instead of Charpy tests leads to a substantial increase of the predicted failure pressure. However this can not prevent the rejection of the vessel.

On the basis of the maximal information level which uses the real defect geometry conservative prediction of failure load are made with PD 6493 and R6. ASME XI shows a good agreement with the actual failure load when the scatter in fracture toughness is taken into account.

REFERENCES

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