AN ENGINEERING CRITICAL ASSESSMENT OF A SPHERICAL LIQUID AMMONIA STORAGE VESSEL

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A major investigation of the structural integrity of a 16m diameter ammonia storage sphere has been undertaken. The work included a finite element analysis of the structure and a comparison with stress-strain data obtained during a hydrotest, a defect survey carried out using NDT data obtained during previous inspections and a comparison with sections of plate removed from the vessel. Data were also obtained on the morphology and growth of stress corrosion cracks and fracture toughness data were obtained from the relevant microstructural components.

A structural assessment using British Standard Published Document PD6493 was carried out in order to establish tolerable defect sizes.

INTRODUCTION

The work reported here was initiated in order to evaluate the stress-strain response of selected welds and legs on a spherical ammonia storage vessel during a full scale hydrotest for comparison with finite element predictions. The investigation also considered the influence of peaking and mismatch at welds on the vessel behaviour and on the propensity to form stress corrosion cracks. A quantitative description of the occurrence of stress corrosion cracks in selected areas of the vessel was also obtained. These data were used to perform an engineering critical assessment of the vessel based on British Standard Published Document PD6493(1).

STRESS ANALYSIS

The vessel had been constructed from plates of a low alloy, weldable structural steel, nominally 11.5mm in thickness. The plates had been shaped and welded forming a number of circumferential(C) and vertical(V) welds. The vessel had not been post-weld heat treated. The lower half of the vessel is shown schematically in Fig 1.

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Finite Element Analysis

The finite element (FE) method is a numerical method of structural analysis which calculates the stress field present in the structure for the specified loading and boundary conditions. The ammonia storage sphere was supported on ten equi-spaced legs and Figure 2 shows the mesh of the FE model of the whole vessel. However, only one tenth of the vessel was analysed because of the inherent geometrical symmetry and symmetrical loading patterns of the structure. The FE analysis assumed that there was no mismatch or peaking (rooftopping) at the welds which joined the adjacent plates and that the whole vessel was perfectly spherical. Two main load cases were analysed; these were for the hydrostatic pressure produced when the vessel was full of water and secondly for an internal design hydrotest pressure of 0.48 MPa. Other load cases were derived from these two load cases.

Finite Element Analysis Conclusions

The main conclusions were that:
1) The stress patterns predicted by the analyses showed shallow stress gradients remote from the support leg intersection compared with steep stress gradients around the intersection area. 2)Where suitable formulae exist to perform check calculations these were made, and the predicted values of deformation and stress from the FE analysis were close to the values obtained by these check calculations. 3) For most of the spherical shell the stresses induced were membrane stresses, but at the support leg intersection area the stresses were a combination of both membrane and bending.

Experimental Stress Analysis

The area of sphere investigated was restricted to that lying between a leg intersection and the mid-line between adjacent legs. Strain gauge rosettes were used to monitor strain changes during filling with water and during three subsequent hydrotests, each to 0.48 MPa. The triaxial rosettes were fixed to both the inside and the outside surfaces of the sphere. This arrangement enabled principal, shear, longitudinal, and circumferential strains and their respective membrane and bending components to be calculated from the measurements.

Experimental Analysis Conclusions And Correlation With FE Analyses

1) The experimental stress values showed that the effect of the leg intersection produced significant compressive circumferential bending stresses in the sphere but that the bending stress became tensile a relatively short distance from the leg intersection as illustrated in Fig 3, which is for an internal pressure of 0.48 MPa. This was in broad agreement with the findings of the FE analysis.

2) Away from the leg and the vertical weld the stress levels were mainly of a membrane nature and this again accorded with the FE analysis.

3) On the internal surface there were high tensile bending stresses, Fig 3, close to the weld and subsequent measurement of the plate profile showed that there was about 8 mm of peaking and some mismatch at these locations. The FE analysis was based on a geometrically perfect sphere and hence could not predict such high bending stresses. A more refined FE analysis with the actual geometry modelled accurately would be required to reveal the increased stresses caused by such effects.

4) The high tensile stress changes near the weld suggested that any tensile circumferential residual stresses would tend to be partially relieved during the hydrotest.

ASSESSMENT OF DEFECTS

Prior to decommissioning, the lower half of the sphere had been subjected to a magnetic particle inspection in May and July 1988, and a report was issued listing all the defects found(2). At HSE's Sheffield laboratories magnetic particle non-destructive testing was carried out on four sections(HSE1 to HSE4) cut from the strain gauged area of the sphere for comparison purposes.

Historical Data

Defect assessments(2,3) carried out in 1985 and 1988 were used as a basis for a defect survey. It was envisaged that this would identify areas of the vessel with high populations of defects and these might then be related to the results of experimental stress analysis based on strain gauge measurements and finite element work. Only the lower hemisphere of the vessel was considered for this exercise.

Separate surveys were produced by HSE for the 1985 and 1988 inspections. The data from the 1988 inspection were analysed to differentiate between those defects which occurred in areas previously found to have defects, in the 1985 inspection, and those occurring in previously crack free areas.

This information was used firstly to determine where cracks had initiated or grown in the period between the two inspections, secondly to determine any propensity to form defects in previously ground or weld repaired areas and finally to determine the significance of weld orientation on the susceptibility to stress corrosion cracking.

Results. Examination of the 1988 data produced a number of interesting results (Table 1). The distribution of defects was clearly non-random. Approximately 70%

of the defects were concentrated in the lowest welds (C1, C2, V1-16). This is surprising in one respect since the total length of these welds (142m) is less than the total length of the remainder of the welds in the lower hemisphere(169m). The majority of the defects on circumferential welds were concentrated on the C2 weld. Another unusual feature observed here was the distribution of defects in the vertical welds between C1 and C2, where the odd numbered welds contained only 7% of the total number of defects on these welds.

TABLE 1- Comparison of 1985 and 1988 NDT Examinations

Weld	Year	Total Defects	% difference Total Defects	Defects- Ground Regions	Defects- Unground Regions	Defects/m
Vertical welds (V1-V16)	85	141	53.2	*	*	1.51
	88	216		104	112	2.31
C1	85	19	-10.5	*	*	2.22
	88	17		2	15	1.99
C2	85	236	-0.8	*	*	5.93
	88	234		181	53	5.88
Vertical Welds (V1-V20)	85	278	-63.6	*	*	2.38
	88	101		65	36	0.86
C3	85	129	-34.9	*	*	2.47
	88	84		77	7	1.61

* Note that data prior to 1985 were not available and therefore defects cannot be divided into those found in ground and unground areas.

Examination of the 1985 data shows some similarities with the results obtained in 1988. The majority of defects in the circumferential welds were found on C2 and odd numbered vertical welds between C1 and C2 contained less than 15% of the defects on these welds. The data obtained from the 1988 and 1985 examinations show that defects formed preferentially(65%) in areas ground to remove defects after previous examinations.

Discussion. The propensity to form stress corrosion cracks is primarily dependent on the environment and the level of stress. Since the environment, in this case, may be considered to be constant (below the liquid surface level), then the high concentration of defects in welds C1, C2 and the vertical welds between C1 and C2 is likely to be due to higher stresses in these areas. The other welds(C3, V1-20) may benefit, in terms of a reduction in applied stresses, from the support of the legs spaced around the circumference of the sphere. The tendency for defects to occur on the odd numbered vertical welds may be due to fabrication methods (i.e. some welds manufactured in workshops and others manufactured on site). Weld peaking and mismatch described earlier have been shown to give rise to additional stresses.

Previously ground weld areas contained approximately 65% of all defects. It is not known what proportion of the total weld length had been ground prior to the last inspection, however it might be postulated that an increase in crack initiation and growth may occur in the ground areas due to a number of factors: firstly, ground areas were found to have a reduced wall thickness and as such a higher membrane stress might be expected; secondly, the grinding operation used to remove defects may induce tensile residual stresses in the plate surface thus increasing the possibility of cracking; thirdly, where deep defects had been ground out weld repairs had been carried out. The weld repairs are likely to have been performed without the benefit of post-weld heat treatment and it might then be expected that residual tensile stresses would promote an increase in crack initiation and propagation rates.

Defect Assessment of Selected Welds

A magnetic particle inspection technique was employed and the 1988 report(2) was used for comparison purposes. The HSE examination located the majority of defects indications found on site together with additional smaller indications not previously found. Indications were found to be transverse, longitudinal and diagonal with respect to the weld direction. It could not be determined with any certainty whether the defects were located within the heat affected zone or the weld. Indications varied in length from 1 to 6mm. All indications of greater than 5mm in length had been identified by the previous inspection(2).

A number of the longest cracks were sectioned and were found to have a maximum depth of 0.5mm. In some cases cracks existed with little evidence of branching. In others a considerable amount of branching was observed. The cracks in all cases had initiated in the HAZ immediately adjacent to the fusion boundary. In some cases cracks had initiated in the HAZs of repair welds. The crack aspect ratio (the crack depth divided by half crack length) was approximately 0.2 in most cases. The crack growth, in most cases, was clearly intergranular along prior austenite grain boundaries. The cracks were in all cases "tight", less than 2μm in width, with little evidence of subsequent corrosion after the crack tip had passed.

The influence of oxygen content on stress corrosion cracking(SCC) has been investigated(4) by the Institute for Energy Technology(IET) in Norway (work co-sponsored by HSE) and the results suggest that O_2 contents of 3ppm produce narrow, branched cracks. Higher O_2 contents (10ppm) produced wide cracks with considerable amounts of oxide corrosion products. In general this investigation showed that intergranular cracking occurred at low growth rates and in coarse grained HAZ structures. Transgranular crack growth occurred at high growth rates in weld metal and fine grained HAZ structures. This implies that the cracks observed in the present investigation grew at low growth rates and low O_2 concentrations.

Crack Growth Mechanisms

The mechanism of crack growth in ammonia was also investigated by IET(4). It is known that stress corrosion crack growth rates in ammonia are enhanced in the presence of 3 to 10ppm oxygen(5). SCC cracks may initially grow quickly but become retarded as the cracks become longer. Reductions in crack growth rate as cracking progresses are thought(6) to be due to a reduction of oxygen content or changes in electrochemical conditions at the crack tip.

Clearly, if continued crack growth is dependent upon the transport of an active species, e.g. oxygen, to the crack tip then the 'transport distance' or crack length might be rate limiting. Crack growth could however, continue at the surface. This implies that cracks that initiate from, say, a corrosion pit, with an initial aspect ratio of approximately one, may continue to grow but with a continuously diminishing aspect ratio. This obviously has implications for tolerable defect calculations and leak before break arguments.

MATERIALS PROPERTIES

Chemical Analysis

The structure had been manufactured from a low alloy weldable structural steel. The chemical analysis of HSE1 is shown in Table 2. The material conforms to Grade 400 in BS 1501 : Part 1 : 1980 "Steels for fired and unfired pressure vessels : plates".

TABLE 2- Chemical analysis of plate HSE1 (Weight %)

C	Si	Mn	P	S	Cr	Mo	Ni	Cu	V
0.144	0.210	0.280	0.024	0.021	0.085	0.046	0.190	0.219	0.002

Microstructure and Tensile Properties

The parent plate material consisted of a fine grained ferrite-pearlite microstructure and was in the hot rolled condition. The welds had been built up in a number of weld runs. The final runs had a coarse grained cast structure. The structure of the heat affected zone was consistent with observations on other similar vessels. The parent plate had a measured 0.2% Proof Stress of 300-316 MPa and a Tensile Strength of 476-496 MPa. The weld metal and HAZ had Tensile Strengths of 570 MPa and 680 MPa respectively. The strength of the parent plate material conforms to the requirements of Grade 400 in BS 1501 : Part 1 : 1980 and is consistent with the chemical analysis and the microstructural observations. The approximate tensile strengths of the heat affected zone and the weld metal are consistent with their respective microstructures.

Fracture Toughness

Fracture toughness data were obtained with the external weld bead intact. It was recognised that this would inevitably produce a certain amount of scatter in the fracture toughness results since weld bead shape and size was variable. Full plate thickness, three point bend crack tip opening displacement(CTOD) fracture toughness specimens were manufactured from parent plate, HAZ, and weld metal. The tests were conducted in accordance with BS 5762:1979(7) where possible. Values of CTOD were obtained at either maximum load, at the onset of unstable fracture or onset of "pop-in".

The CTOD toughness values obtained in the parent plate material at room temperature were between 0.21mm and 0.68mm. Specimen orientation effects were apparent. Heat affected zone(HAZ) and weld toughness values at room temperature showed considerable scatter. This was partly due to the variable geometry of the welds and partly due to the effects of microstructural inhomogeneity at the crack tip. The four lowest values of CTOD obtained in the weld were associated with pop-ins. The HAZ CTOD values ranged from 0.13mm to 0.73mm and weld metal CTOD values ranged from 0.06mm to 1.06mm. Some ductile tearing preceded brittle failure in all cases. The toughness of the parent plate material at -30°C was similar to that obtained at room temperature. Consistently lower toughness values were obtained in both the HAZ and the weld metal at the lower testing temperature. The lowest toughness values (0.03mm - 0.44mm), obtained in the weld metal, were associated with pop-ins. The proportion of ductile fracture prior to brittle failure was generally lower in the weld metal.

DISCUSSION

Detailed experimental stress analysis of the support legs and surrounding structure confirmed the presence of high bending stresses in the welds. These data were correlated with peaking and mismatch measurements.

Analysis of NDT data(2,3) showed that the defect distribution was non-random. This may be due to a number of factors acting singly or in combination: the sphere support legs were thought to produce inhomogeneous stresses in the areas surrounding their attachment points; fabrication methods may have produced welds with different levels of residual stress; the practice of grinding out defects and repair welding may produce additional residual stresses.

An NDT examination of the plates HSE1 to HSE4 indicated that all defects greater than 5mm in length had been found during the last inspection(2) and, by implication, all cracks deeper than 0.5mm had been detected. The cracks were intergranular, with respect to the prior austenite grain boundaries, and tight. This suggests that the stress corrosion crack growth rate, in this structure, was slow or that cracking had occurred during commissioning and not grown subsequently.

Tolerable Defect Size

A defect assessment in terms of the BSI published document PD6493 (1990)(1) was carried out in order to determine tolerable defect sizes for the ammonia sphere under appropriate operating conditions.

In all cases conservative data were used in the analysis. Approximate tensile properties of the heat affected zone were used together with the lowest CTOD values in the HAZ. The stresses acting on the structure were obtained from the experimental stress analysis and finite element prediction described above. Secondary stresses due to welding and peaking stresses have been assumed to be of yield magnitude in total. For a through-thickness defect a maximum tolerable defect length of 22mm was calculated.

A plot of crack depth against half the crack length, Figure 4, shows the limiting defect contour for the HAZ material. The minimum defect size that can be reliably detected is of the order of 5mm long. If it is assumed that the longest defect which may be missed is 10mm long and the defect continues to grow with an aspect ratio of 0.2 then the limiting flaw size will be approximately 50mm long and 4.5mm deep. This gives a factor of safety of 5 on defect length.

An allowance must also be made for crack growth during the inter-inspection period. The longest defect found during the 1988 survey was 13mm in length but it is not known from what length it grew. If 13mm of growth is assumed on a 10mm defect then a factor of safety of 2 is obtained for three yearly inspections. A leak before break criterion for fracture avoidance would be inappropriate in this case where defects may continue to grow with a small aspect ratio.

CONCLUSIONS

1. The experimental stress analysis produced results in broad agreement with finite element predictions.

2. High tensile bending stresses were measured at the plate welds and were correlated with peaking and mismatch measurements.

3. An examination of defect assessment data showed that the defect distribution is non-random. Inhomogeneous stress distributions in the welds were thought to be the primary cause.

4. Magnetic particle inspection of a number of welds suggested that defects, greater than 5mm in length, were detected during on site defect assessment.

5. Stress corrosion cracking in this environment produces shallow, intergranular cracks typically with an aspect ratio of 0.2. The cracks had a similar morphology to those reported elsewhere(4).

6. If an aspect ratio of 0.2 is assumed then a tolerable defect 50mm long and 4.5mm deep is calculated. For a through thickness defect a maximum tolerable defect length of 22mm is calculated.

7. A factor of safety of 2 on defect length can be expected for an inspection interval of 3 years.

REFERENCES

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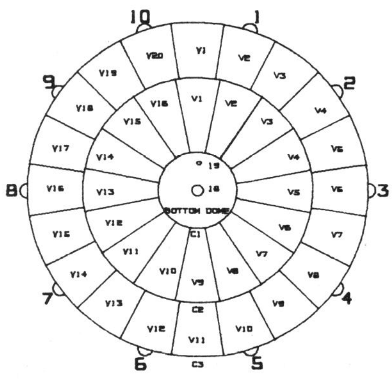

Figure 1 Schematic of ammonia sphere construction

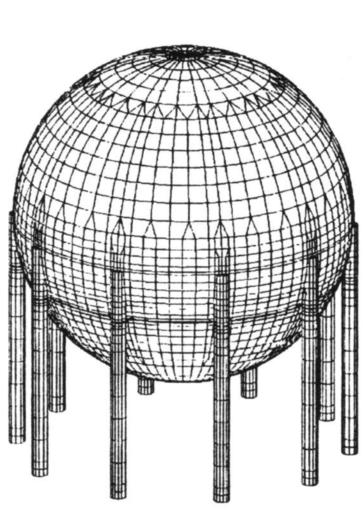

Figure 2 Finite element mesh of ammonia sphere

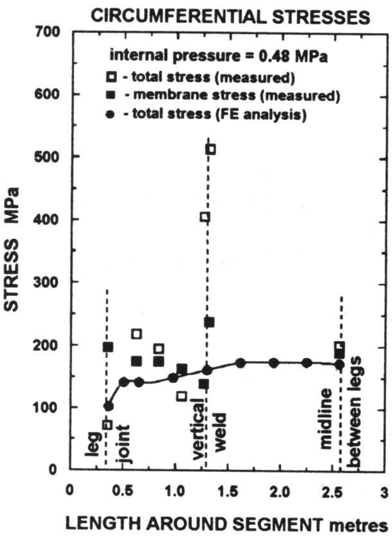

Figure 3 Comparison of FE and experimental stress analysis

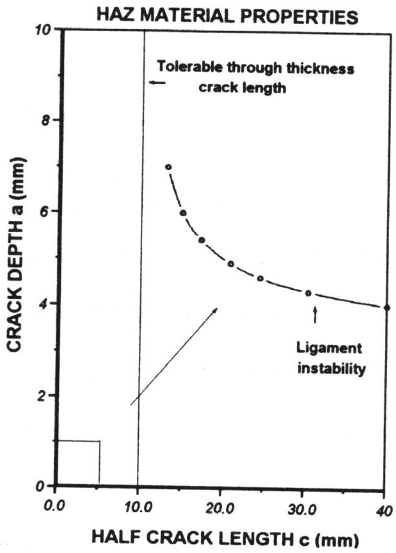

Figure 4 ECA limiting defect contour