Case study

Catastrophic failure of a carbon steel storage tank due to internal corrosion

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1. Introduction

Catastrophic failure of a 10 m high, 8 m diameter steel storage tank containing approximately 350 m³ of waste solvent led to a significant environmental incident in 2009. An investigation was carried out to establish the root cause and to learn lessons that might prevent a reoccurrence.

2. Site investigation

The failed tank, one of a number within a concrete bund, Fig. 1a and b, had catastrophically collapsed. The shell, fabricated in five welded courses each 2 m in height, appeared to have fractured approximately vertically on the North East side, probably under the action of the head of liquid contents. The shell plates had separated laterally about the fracture and the tank had collapsed once the shell plate support had been removed. Collapse of the tank to the North East had resulted in large stresses on the shell – floor welded joint around the base of the tank causing this to fracture, Fig. 1c.
The failure of the shell had caused some damage to the concrete bund, Fig. 1d, and a significant proportion of the contents (thought to be primarily toluene and water) had escaped the bund. A nameplate on the tank provided details consistent with those on an engineering drawing, see below, and showed that the tank had been manufactured in 1998.

The engineering drawing of the failed tank listed the following details:

- **Design code:** BS 2654:1989
- **Design pressure:** 7.5 mBar
- **Plates and sections:** BS EN 10025 S275
- **Corrosion allowance:** Nil
- **Shell height:** 10,000 mm
- **Base diameter:** 7710 mm
- **Shell thickness:** 5 mm

The fracture of the shell is shown in more detail in Fig. 2a and b. Visual examination of the plate close to the fracture surface suggested that, in many places the wall thickness was significantly less than the 5 mm specified on the engineering drawing. The fracture surface itself was covered in a corrosion deposit and therefore no fine details were visible. On the fracture surface where the plate was thickest, the fracture was slanted, consistent with a shear failure.

The shell fracture surfaces were marked, from the junction with the floor plate, at 200 mm intervals and two sets of thickness measurements were taken using a calibrated ball micrometre. Measurements were taken firstly within 2 mm of the fracture surface and secondly, 20 mm from the fracture surface to account for any plastic deformation associated with the failure process, the results are shown in Fig. 3. The process was repeated for the mating fracture surface. The data, in both cases, showed that the shell plate was less than 1 mm thick at course 2 and generally increased in thickness more remote from course 2. The minimum thickness recorded was 0.59 mm close to the centre of course 2.

Wall thickness measurements taken around the shell – floor fracture, in the area shown in Fig. 1c, gave a minimum wall thickness of 4.75 mm and the general appearance of the fracture surface suggested failure had occurred by a shear mechanism.

The tank level gauge was examined for the period during which the tank failed and this showed, that the tank had been approximately 75% full immediately prior to the incident and the level fell almost instantaneously to approximately empty at the time of the incident.

The fracture surfaces and the N5 nozzle shell plate were marked for recovery to the laboratory. In addition, a 200 mm wide circumferential section from the centre of course 2 was requested to establish whether the reduced wall thickness was localised at the position of failure or more widespread.
3. Laboratory analysis

3.1. Visual examination

Sections of plate including the vertical fracture surfaces and a 200 mm wide circumferential strip from course 2 were cut out on site for laboratory analysis.
The fracture surfaces were photographed in the laboratory and a montage, Fig. 4, was created. The plate sections, were approximately 200 mm wide and between 0.3 m and 2.5 m in length. In general, the plates had been mechanically cut at the positions of the circumferential welds.

The external surface of the plates had been coated with a blue paint, under which both white and red layers were visible in places. The area immediately adjacent to the fracture was largely free of paint and it is likely that the paint had become disbonded during the plastic deformation of the substrate material when fracture occurred. The reverse sides of the plates (the internal surface of the tank) had a rough, brown corrosion layer over all of the surfaces. The fracture surfaces were coated in an adherent corrosion product and therefore no detailed features could be observed. Macroscopically, the fracture surfaces had a slanted appearance, consistent with shear, where the plates were thickest, in other areas the plates were too thin to assess the mode of failure.

3.2. Thickness measurements

In addition to the thickness measurements made on site, further measurements on the plates containing the vertical fracture were made approximately 200 mm from the fracture using a calibrated ball micrometre. The results showed that the thickness of the plates, at 200 mm from the fracture surfaces, closely mirrored the fracture surface measurements taken on site, and shown in Fig. 3.

The plates from the circumferential section of course 2 were measured in the same way and the results are presented in Fig. 5a. The data showed that the vessel shell was approximately 2.5 mm thick around the majority of the circumference at the level of the C2 course. Close to the position of the vertical fracture, the shell thickness was reduced to approximately 1 mm. On the basis of this data, the thinned area, below the background 2.5 mm, was around an arc of approximately 2 m.

3.3. Chemical analysis

Five samples, one from each course were selected for chemical analysis; the results are shown in Table 1. The analysis was carried out using a combination of inductively coupled plasma optical emission spectrometry (ICP OES) and thermal conductivity fusion techniques.

An engineering drawing for the tank specified that plates be manufactured to BS EN 10025 S275 [1]. Each of the samples from the five courses complied with the chemical analysis requirements of the Standard.

3.4. Metallography

Samples from each course were cut from positions adjacent to the fracture surface for metallographic examination. In each case these were mounted, polished to a 1 μm finish and etched in 2% nital. This showed that the material of each plate
had a ferrite and spherodised pearlite microstructure consistent with a structural steel, Fig. 5b. The proportion of pearlite indicated a carbon content of approximately 0.2%. The microstructure was heavily aligned and the spherodied pearlite indicated that the plates had been hot rolled.

At the position of the fracture surface, Fig. 5c and d, some additional deformation of the microstructure indicated that plastic deformation, consistent with a ductile failure mechanism had occurred. The internal surface of the tank had a pitted appearance and a layer of corrosion product was apparent. In the case of the course 2 sample, the thickness of the remaining material remote from the fracture surface varied from approximately 0.5 mm to 1 mm.

Sections through the C2/C1 weld and the C3/C2 weld were examined. The welds had been manufactured using a fusion welding process and had a coarse grained cast structure. The fracture surfaces had been corroded in the time interval between the failure of the tank and examination of the surfaces and, although attempts were made to remove the corrosion product using commercial cleaning agents, no additional fracture surface features could be observed.

The paint thickness on the external surface of the tank was examined on a section of plate from course 2 and showed that the paint layer was approximately 0.3 mm thick.

### Table 1
Chemical analysis (mass%).

| Sample     | C  | Mn | Si  | P  | S   | N  |
|------------|----|----|-----|----|-----|----|
| C1 (05803) | 0.20 | 1.22 | <0.02 | 0.012 | 0.004 | 0.0074 |
| C2 (05804) | 0.18 | 1.18 | <0.02 | 0.010 | 0.003 | 0.0076 |
| C3 (05805) | 0.20 | 1.20 | <0.02 | 0.011 | 0.004 | 0.0070 |
| C4 (05806) | 0.18 | 1.17 | <0.02 | 0.010 | 0.004 | 0.0068 |
| C5 (05807) | 0.17 | 1.14 | <0.02 | 0.010 | 0.004 | 0.0070 |
| Tolerance  | ±0.01 | ±0.03 | ±0.005 | ±0.002 | ±0.002 | ±0.008 |
| Grade S275 | 0.21–0.24 max | 1.60 max | – | 0.045–0.055 max | 0.045–0.055 max | 0.011 max |
3.5. Hardness measurements

Hardness tests were carried out in accordance with BS EN ISO 6507-1:1998 "Metallic materials – Vickers hardness test". The reported results had an accuracy of ±3%. Conversions of hardness data to tensile strength were based on Table A1 of BS EN ISO 18265:2003 [2].

Hardness data was obtained on microsections from each of the courses and the results are shown in Table 2. Table 5 in BS EN 10025 specifies minimum yield strength for Grade S275 as 275 MPa. Although the approximate tensile strength, rather than yield strength, is estimated from hardness data, the results were entirely consistent with Grade S275.

3.6. Estimation of hoop stresses

A finite element model was developed to estimate the hoops stresses associated with the thinned plates at the time of failure.

| Sample no. | Course | Mean hardness (HV10) | Estimated tensile strength (MPa) |
|------------|--------|-----------------------|---------------------------------|
| 05803      | C1     | 183                   | 595                             |
| 05804      | C2     | 150                   | 480                             |
| 05805      | C3     | 161                   | 510                             |
| 05806      | C4     | 179                   | 575                             |
| 05807      | C5     | 152                   | 480                             |

Fig. 6. (a) FE model of equivalent stresses in tank, shell elements, (b) equivalent stresses in tank with a 1 mm wall thickness, shell elements, (c) schematic representation of material removed (shaded) in thin walled FE model and (d) equivalent stresses in model with a gouge of depth 4.5 mm.
3.6.1. Uniform thickness models

Two different methods were used to create the uniform thickness models; using solid elements and shell elements. The shell element approach had the advantages of being computationally more efficient, and having the facility to change the thickness easily without changing the geometry or remeshing. The models consisted of the wall and the base of the vessel. The base was 6 mm thick. The roof and other connections to the tank were not modelled. Material properties used were a Young’s modulus of 200 GPa and a density of 7850 kg/m³. No yield or strength levels were included in the model, as it was not anticipated that stress levels would reach this magnitude.

The tank was loaded by applying a hydrostatic load to the inside surfaces of the tank. The hydrostatic pressure assumed a fill level of 7.5 m from the base, a fluid density of 1000 kg/m³ and a standard gravitation acceleration of 9.81 m/s². The bottom surface of the base was constrained in all directions.

The results for the model with a 5 mm wall thickness are shown in Fig. 6a. There was good agreement between the results for the two models, although the model using the shell elements, showed more stress variation, probably due to the much coarser mesh used in this case. Maximum hoop stresses in the wall of approximately 50 MPa were obtained in both models.

The thickness of the shell elements was reduced to 1 mm for the third model. In this case, the hoop stresses increased to approximately 170 MPa, shown in Fig. 6b.

3.6.2. Thinned models

Further models were created to represent a tank with a wall thickness of 2.5 mm containing a thinned area. The thinned area was created by subtracting the arc of a cylinder of radius 2 m and height of 4 m from the wall of the tank, illustrated in Fig. 6c; the base of the cylinder being 1 m above the bottom of the tank. Two models were created, with the cylinder positioned to remove 4 mm and 4.5 mm from the wall thickness, therefore thinning the tank to a minimum thickness of 1 mm and 0.5 mm for the two models. For the thinned models, the base was not modelled. Constraints in all directions were added to the bottom surface of the tank wall. Hydrostatic pressure loading was applied to the internal surfaces of the tank as in the uniform thickness models.

The maximum stresses in the wall were obtained at a position mid-way up course 2, with values of 153 MPa and 299 MPa for the 1 mm thick and 0.5 mm thick models respectively, the latter is illustrated in Fig. 6d. An additional model was created where a vertical downward load was applied on the top of the tank wall to represent the weight of the roof. In this case, the maximum stress increased by 0.05 MPa, indicating that roof loading was not significant.

4. Discussion

The site analysis indicated that the tank had failed initially, at the thinnest section of the shell in the region of course 2. The initial fracture had then propagated vertically in both directions, to the full height of the shell. The shell had then separated laterally, at the position of the fracture, as a result of the hoop stresses induced by the liquid contents. The roof collapse at the circumferential position of the vertical fracture had probably induced large tensile forces in the shell, on the opposite side of the tank and resulted in the failure of the shell/base weld.

The engineering design drawing for the tank specified that each of the five courses should have been manufactured from 5 mm thick plate. Thickness measurements made on the circumferential plate sections showed that at the level of course 2, the vessel was approximately 2.5 mm thick around the full circumference, except at the position of the vertical fracture where it was significantly thinner. Measurements made close to the fracture surface showed that the tank was, over the majority of the area, less than 1 mm thick at the level of course 2 and progressively increased in thickness more remote from course 2. However, at no point were the measured shell plates 5 mm thick as specified. Stress analysis based on the finite element models showed that the hoop stress associated with the thinned plate (0.5 mm) at C2 was approximately 300 MPa. The models assumed a uniform thickness at the point of failure, in reality corrosion pitting would have produced a stress concentration factor resulting in a significant elevation the local stresses, probably to a level that exceeded the tensile strength of the material. The model also neglected other modes, such as wind loading, which would have contributed to stress in the tank wall.

Generally, the external paint layer and the external metallic surface were in satisfactory condition and both vertical and circumferential weld beads were intact. This indicated that the loss of material had occurred on the internal surface.

The condition of the internal surface was consistent with both general and pitting corrosion. It is not known with certainty what the contents of the tank had been throughout its life and therefore whether the corrosion had been occurring uniformly throughout the period. Contents analysis information covering a 3 month period prior to failure showed that the inventory had been principally toluene but also included a range of organic constituents in smaller quantities including methanol, ethanol, acetone, methyl acetate, hexane, ethyl acetate, tetrahydrofuran, butanol, heptane, butyl acetate, methyl ethyl ketone, methyl isobutyl ketone and xylene. In addition to the organic content, the water content varied between 1.2–3.2% at the bottom and 58.3–60.3% at the top. The pH varied from 3.3 to 4.4.

The Engineering Equipment and Materials Users Association (EEMUA) produced guidance on the maintenance of storage tanks [3], which included data on corrosion rates for a range of environments. The guidance suggested that in neutral liquids, including toluene, corrosion rates of 0.1–0.25 mm per year could be expected. Given that the pH was towards the acidic end of the spectrum it is probable that the actual corrosion rate was at least towards the higher end of this range (or higher) due to increased hydrogen ion availability and also, in part, to the influence of acid on the solubility of corrosion products.
Given that the tank was approximately 10 years old, a corrosion rate of 0.25 mm per year would result in a reduction in wall thickness of 2.5 mm and consequently, a residual wall thickness of 2.5 mm.

The fact that the wall thickness in one specific area was less than 1 mm indicates a higher corrosion rate. The area of highest corrosion appeared to be in a vertical band extending from course 1 to course 4, based on the site thickness measurements, with the maximum loss of wall thickness at course 2. The thinned area, based on the circumferential measurements, probably extended circumferentially approximately 2 m at the level of C2.

The tank had contained three jet mixers spaced at equal distances around the circumference. Reference to engineering drawings suggested that one of the jets had been located close to the position of the locally thinned area, however, it was not possible to confirm the original position of the jet mixers following the incident due to the large scale deformation of the tank. The explanation for the localised corrosion may be associated with the position of the jet mixers in the tank.

Jet mixers, intended to ensure that the contents remain homogeneous, potentially cause increased flow rates over the surface of the tank, where the velocity is inversely proportional to the distance from the nozzle. This leads to a mechanical scouring effect on the corrosion product where the jet is sufficiently close to the internal surface. In effect, the corrosion product would have been removed more readily leading to the exposure of fresh metal to the corrosion process. In the absence of the mechanical effect, the corrosion process would have been limited by the transport of active species through the layer of adherent corrosion products.

The design drawing for the tank indicated that the design contents were to be “various solvent waste” and that the corrosion allowance was nil. Published corrosion data (EEMUA) indicates that a corrosion rate of 0.25 mm per year could be expected for neutral organic chemicals. Given this, it is difficult to see how a nil corrosion allowance could be justified. A note in the EEMUA document indicates that for contents with a pH less than 5 (as in this case); tanks are predominantly manufactured from stainless steel.

Inspection periodicity is normally based on a range of factors including: the nature of the stored product, corrosion allowances and corrosion rate, condition at previous inspections, etc. and can be assessed on an individual basis. EEMUA provides some generic guidance for tanks based on service conditions and these range from 1 year, for corrosive or aggressive chemicals, to 5 years for non-aggressive chemicals. Even if a 5-year period had been selected for the tank it should have been apparent, given a suitable inspection, that significant corrosion had taken place. A maintenance/inspection plan could then have been established to address the issue.

The investigation has highlighted some of the risks associated with the storage of hazardous materials and, in particular, the need to consider materials of construction, degradation mechanisms, operational factors together with robust inspection and maintenance procedures. The tank operator was prosecuted by HSE and fined £150,000.

5. Conclusions

Failure of the tank had occurred under the action of the hoop stresses imposed by the weight of the liquid contents. Failure occurred due to a combination of general internal corrosion and more localised corrosion, probably associated with the action of a jet stirrer.

An adequate scheme of wall thickness monitoring, in terms of reliability, scope and periodicity, during service would have identified the loss of wall thickness prior to failure.

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