Catastrophic failure of a polypropylene tank Part I: primary investigation
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Abstract

The creep rupture of a new polypropylene tank used for holding caustic soda solution is described from the primary evidence. The immediate cause of fracture was a pinhole in the centre of a weld, which initiated a brittle crack. The crack grew slowly during each loading until it penetrated the wall shortly after the fourth filling. The design of the structure fell short of the required data—rather than barrel-like form needed for resisting hydrostatic pressure. "1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Polypropylene is a popular material for applications where toughness, low density and environmental resistance are needed. It has been used for many years for constructing storage tanks (e.g., silos for storing bulk powders) and as a lining for large GRP tanks (e.g., for storage of corrosive fluids) [1]. However, good design demands that allowance must be made for the maximum stresses to which such products can be exposed in service. The example described in this case history offers some apposite lessons in using polymeric materials for highly stressed products, especially where failure can threaten life and property. The failure bears distant similarity with the failure of a steel silo reported earlier [2].

On 23 August 1994, a large storage tank containing concentrated caustic soda (NaOH) fractured suddenly along one of its welded seams, a jet of liquid shooting across the factory. The incident occurred without any prior warning of failure, and in a tank which had only recently been installed (6 March 1994) at a factory used to manufacture dairy detergent. The last full loading was only the fourth since installation. The tank was made of polypropylene (PP) panels welded together.

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Fig. 1. Sketch plan of the caustic soda tank (diameter ca 2.7 m), showing four vertical welds (W1-4) and their position relative to the bund wall. Three of the four plastic panels had a contour length of ca 2.5 m, the fourth being shorter, at about 1.2 m. An internal heating element lay below the critical crack, but had apparently never been used. The sight and overflow tube led to the top of the tank.

The jet of caustic soda could not be contained safely, since the fracture had occurred about 1.5 m from the floor of the tank (which itself was free standing on the factory floor), the jet projecting the liquid stream over the adjacent bund wall (Fig. 1). Since the initial fracture was only relatively small, the jet stream continued for several hours under hydrostatic pressure from the tank (which had only been filled that same morning by tanker) before the bund wall contained the liquid. The unconfined fluid spilled out over nearby equipment, and subsequently flowed into adjacent premises, which used specialised printing equipment. Severe damage ensued owing to the highly corrosive nature of the concentrated caustic soda, a fluid which degrades much organic and inorganic material very rapidly. Escape into local water streams could also have created a further hazard to animal and plant life as well as a potential danger to water supplies in the area, but was collected and safely disposed by the Fire Brigade and others. The tank apparently met the stringent conditions imposed by the only public standard available, the German Code of Practice DVS 2205 [3]. An English translation of the document only became available some time after onset of the investigation, and is discussed fully in Part II of this paper.

Preliminary analysis of the failure indicated that the critical fracture might have been caused by weld defects (blow holes), so that a programme of tests was undertaken on the weld material as
Fig. 2. Failed plastic tank, showing the bund wall in section (the front part was removed by the Fire Brigade). The jet of caustic soda flew from the tank wall near the right-hand edge in the figure, just above the top of the bund wall. It rose upward from a small crack in the weld, and landed some 4-5 m away from the exit point.

well as the panel plastic. They included DSC and FTIR to check material constitution, and simple tensile tests to measure directly the strength of the welds. The experimental part of the investigation was carried out by P.R. Lewis, the translation of the key standard (DVS 2205) covering such tanks being carried out by G.W. Weidmann.

2. The accident

Failure of the tank occurred at about 18:45 h, and was discovered by the Production Director at the factory. He was in the upstairs office at the factory, and was about to leave the premises at the end of his working day, when he heard a bang or ‘popping’ sound coming from the factory floor. It was followed by the sound of ‘rain’, and looking down through an internal window, he saw a jet spray of fluid issuing from the lower part of the recently filled black storage tank, situated in a further corner of the factory (Fig. 2). He observed that the jet was issuing in the form of an “...8 or 9 inch wide stream...” from the side of the tank facing a storage bay. The jet curved upwards, so easily clearing the top of the adjacent bund wall, and was about 4-5 m long. The end of the jet was hitting storage containers, and flowing down onto the factory floor.

The broken tank was simply a static storage container with a sight tube on one side, and pumping facilities (Fig. 2). By 22:00 h that evening, the level of liquid in the tank had fallen substantially, so lowering the hydrostatic pressure, decreasing the length of the jet stream, and causing it to fall within the bund wall. The load of caustic soda which escaped freely into the factory represented
almost half the total capacity of some 30 t, and had only been delivered to the premises that day. Pumping of the fluid from the tanker into the tank had been completed by about 09:15 h, and nothing untoward had apparently been observed by operators working in the factory, either at that time or later during the day before catastrophic fracture. It is worth observing that the corner of the factory where the tank stood was poorly illuminated (Fig. 2). Sub-critical cracks would have been difficult to spot, since they would simply have been fine hairline features against a black matte background of the polypropylene material of the panel walls. There was no evidence of any leakage of fluid before the accident near the critical crack—such leakage would have been relatively easy to see, owing to the contrast between the white deposit and the black surface of the tank.

2.1. Site inspection

A visit to the site showed that failure had occurred by a single crack apparently running the complete length of one of the four vertical welds directly visible on the exterior wall of the tank (Fig. 3). The crack was brittle and it was whitish in appearance in one large region near the centre of the panel. There was also extensive surface contamination from caustic soda crystals and sodium carbonate. The results of measurement of the tank are shown in Figs 1 and 4. Its circumference was also measured at two points. One was at a height about 1.5 m above the ground, approximately level with the centre of the crack, and the other at a location well away from the crack, at the top of the second buttress. The results were: circumference at crack level = 8.57 m; circumference at top of second buttress = 8.55 m.

The difference of 2 cm thus represented crump of the wall, plus any crack opening that may have occurred as a result of the fracture. Since the crack had only opened by about 1 mm, it was concluded that crump of the material accounted for most of the increase in circumference, of about 0.23%. Some bulging of the failed panel was in fact detectable by eye, as shown in Fig. 3 (the effect can be seen clearly by tilting the figure and looking along the edge of the tank). The tank had been created at crack level by welding four 12 mm thick panels together, three being of roughly equal contour length (2.43, 2.48 and 2.45 m clockwise from the cracked panel, Fig. 4) the panel adjacent to the cracked having 1.21 m contour length. The visible tank structure at first buttress level (i.e. below the crack) had been created in a similar way by welding three panels of about the same contour length (2.47, 2.49 and 2.48 m clockwise, offset by 0.71 m from the cracked panel weld). The final panel comprised a panel of contour length 1.31 m.

The surface of the tank was examined closely for any trace of surface damage, whether from impact or abrasion, which might have accounted for the catastrophe. None of any kind was found, the patterned exterior surface appearing pristine in condition, especially near the crack itself. If impact had initiated failure, then it was here that might show surface damage (Fig. 3). Even small impacts could damage the plastic, owing to its relative softness. It was decided to cut out several areas of the tank with a circular saw for further analysis of the fracture surface.

3. Fractography

The fracture surface was revealed by estimating where the ends were situated, and then carefully cutting through the double panels so as to leave a few mm of material holding the crack together...
Fig. 3. Face view of the failed weld in the plastic panels of the tank. The large white arrow indicates the position of the crack initiation point in the centre of the weld, the crack eventually widening to the points shown by the two smaller arrows. The surface surrounding the failed weld is pristine and totally undamaged, with no abrasive wear or traces of impact damage.

at each end of the specimen. It was then broken apart by a sharp bending movement, oriented so that the wide wings of the panel formed the arms of the beam. The material behaved in a totally brittle fashion, owing to the sharp ends of the crack.

The fracture surface proved to be relatively simple, with a central whitened zone at the outer weld edge on which were situated several small voids. One of these features appeared more prominent than the others, being surrounded by several concentric zones of slightly different greyish hue. Examination of the centre of this origin showed there to be a small hollow pit oriented at right angles to the major axis of the weld, and meeting the outermost surface at one end (O₁ on Fig. 5). The inner surface appeared highly reflective, almost polished, very similar to that produced by melting a free surface. There was also a thin flap of polymer partly concealing the outer part of the hole from external view. Measurement of the pit showed it to be 1.0 mm in length from the
Fig. 4. Sketch section of the failed caustic soda tank from the office side of the factory floor. It consisted of rectangular thermoplastic panels welded together, and reinforced with three extra horizontal buttresses (shown by the bold lines). The critical crack started (point O) in a vertical weld (W1) in the lower of the two un-reinforced parts of the tank, and the jet rose in a gently curving arc above the bund wall.

surface, 0.6 mm wide at the outer surface of the weld and about 0.15 mm deep. Matching the two halves of the fracture showed that the critical crack had bisected the pit along its longer cross-sectional dimension. Thus the cross-section was roughly elliptical, of minor axis 0.3 mm, and major axis 0.6 mm. The were similar, but sub-critical pits discovered elsewhere on the fracture surface (Fig. 6).

Since the fracture surface had been washed with water to remove the white crystals of caustic soda and sodium carbonate, the white zone at the centre of the failed panel cannot be contaminant, so what does it represent? Almost certainly, it is crazed material present ahead of a slowly growing crack, polymer material which has been diluted by stress, and thus retains minute voids which scatter light and hence appear white. The four main zones present around the largest defect (Fig. 5) on this hypothesis, thus represent four periods of slow crack growth, corresponding to the four full loadings of the tank with caustic soda. It may be noted that each region shows progressively greater size, due to the greater stress concentration exerted after each full loading. The smaller surface defects also initiated slowly growing cracks, which never reached critical size for catastrophic propagation, but were instead intercepted by that of the critical crack (Fig. 5).

What then, of the roughly vertical lines seen on the matte black portion of the fracture surface (not shown in the figures here)? Each was clearly visible against the black surrounding by a faint trace of whitening. Such lines probably represent crack arrest points, which either occurred after
Fig. 5. Close-up of the origin of the critical crack in the main fracture surface, taken using oblique lighting to highlight surface features. There are four propagation zones (1–4) visible around the large pit (O) which opens to the outer surface of the 12 mm thick section through the skin of the tank.

Fig. 6. Close-up of set of pits (arrows) on the outer surface of the critical weld, with brittle crack zone connecting the set, created during one of the early loadings. The pits are pin-holes created by thermal welding and not detected by subsequent spark testing. The sub-critical crack zone was intersected by the critical crack during the final catastrophic failure.
the first penetration of the crack to the interior of the tank, or some time afterwards, when the crack was examined by firemen, inspectors and workmen. The in situ crack could be opened by hand pressure against one of the adjacent panels, and it is likely that inspections simply extended the size of the brittle crack. It is important to note that this hypothesis would explain why the initial size of the jet was only \( .8 \text{ or } 9 \text{ inches } \) wide. This visual estimate corresponds not unreasonably with the actual 134 mm (5.25 in) length of the central white zone. Alternatively, other crack arrest lines in the proximity of the white zone give measurements of 7.25 in (184 mm) and 8.75 in (222 mm), which may indicate that the critical crack had grown somewhat after the first penetration of the tank. The crack would have then been wetted by the caustic soda, and further crack growth enhanced through the lowering of surface energy.

4. Re-examination of the failed tank

Since the mechanism of failure of the panel had now been identified as brittle fracture through slow crack growth from pre-existing flaws (pits) within the weld zone, it was now thought essential to determine why only one of the four vertical welds had failed in this way. The problem could be tackled in two ways. Firstly, was it true that the other panels were completely unaffected by the high loading stresses? Examination on site had been necessarily made under poor lighting conditions, and some of the welds were physically difficult to access. The analysis of fracture clearly indicated that catastrophic failure must have been preceded by the slow growth of hairline cracks from defects on the outer surface of the weld, so that close examination of the other welds should reveal similar, but sub-critical features either if they had been welded under the same conditions, or if there was more general problem with the basic design of this tank. It was therefore decided to re-visit the site before the tank was destroyed totally, and inspect the other welds directly.

Secondly, the behaviour of good versus poor weld material had been roughly tested by comparing the behaviour of sections cut from the two large panels. Both specimens fractured in a brittle manner along the weld, the fracture surface from the poor weld showing a distinctly greater number of internal defects than the good weld material. So it was natural to place such a result on a more systematic basis by cutting tensile specimens for rigorous analysis. Further, tests of each weld and surrounding panel would be required to ascertain whether or not there were any material differences between "good" and "poor" welds which could explain the differences between them.

The prime objective of a second visit to the site was to inspect the final two vertical welds which had not been examined earlier, for hairline cracks. The first weld examined was that one lying partly under the HazChem warning notice (Fig. 2), and it showed an irregular bead smoothing mark, but otherwise no hairline cracks were detected. Fine grade talcum powder was smeared over the weld to highlight any cracks. The second weld proved more difficult to access, since it lay on the side of the tank nearest the outside wall of the factory, and was therefore in almost complete darkness. The band wall was also very close to it, so making access extremely difficult. There appeared to be numerous linear features along the weld zone, so the whole weld was taken away for closer examination.

4.1. Confirmatory microscopy

Inspection of the two welds extracted with a small part of the adjacent panels confirmed the results obtained in the factory. The whole weld sections showed numerous hairline cracks in the
second weld, where they were seen to bisect the complete weld, being almost perfectly aligned with the major weld axis (Fig. 7). This crucial piece of evidence allowed the cracks to be identified and distinguished from the striations caused by bead smoothing. The latter marks tended to wander slightly in direction, while the hairline cracks were perfectly straight in their alignment.

Low power examination in an optical microscope showed that the weld possessed no less than about 10 hairline cracks, varying in length from about 3 mm to more than 40 mm, the longest one being situated at the approximate centre of the panel. Direct measurement of crack width from these plates show the cracks to be about 0.3 mm wide at the top surface. Many of the cracks also had small parts which appeared to be slightly wider than the rest of the crack, especially towards their centres.
The appearance of sub-critical cracks on the outer surface of an intact weld confirmed the picture which had emerged from the study of the fracture surface, namely that cracks had been initiated at pre-existing defects in the welds (small pits at the outer surface), and had grown slowly as a result of superimposed pressure from the full tank. As the tank was emptied, the pressure fell, and slow crack growth stopped. With time, as the cracks grow in size, the stress concentration at their ends became more severe, and when crack growth resumed on refilling the tank, the speed of crack growth increased. This would account for the increasing area under each of the zones shown in Fig. 5. Sub-critical cracks were found elsewhere on the main fracture surface (Fig. 6), and represent cracks which had grown but not propagated catastrophically. It remained to investigate what extra information could be gleaned from closer examination of the welds themselves, particularly comparison of welds which showed no cracks whatsoever (despite being exposed to similar pressures to those which failed) and the intact welds.

5. Mechanical testing of welds and panels

An initial test made on large lengths of panel material cut across the welds had indicated that the fracture surface of the intact weld possessed fewer defects in the weld than that from the critical weld. The samples were simply cut using a circular saw, and bent over with the textured, external surface subjected to the greatest tensile stress, to cause failure in the weakest part. In both cases, one bend was insufficient to break the samples. Both samples broke essentially in the same way, by brittle fracture along the centreline of the weld. The resultant fracture surfaces were very different, however, with a greater density of visible defects from the failed weld. Tensile tests on two dumbbells from each of the two types of weld was conducted to confirm the hypothesis.

5.1. Etching of weld zones

It was of interest to see if the weld zone could be revealed by an appropriate etching method applied to the cross-section produced by polishing. Several reagents were evaluated on a separate sample, including hot chromic acid of various strengths, nitric acid and, finally, organic fluids known to swell or partially dissolve polypropylene. When xylene was used as a polishing medium for the final stage of the polishing process, it was found to show the weld zone very clearly. The method was applied to standard samples of the weld taken from the failed and unbroken panels (Fig. 8).

The etching revealed the internal structure of the form of the welds, both macrographs showing the weld to be wider at the external surfaces, and narrowing down to a reasonably uniform band of material within the bulk of the weld. Both samples also showed a centreline extending from head to head, which presumably represents the direct contact surface between the original panels when they were brought together during the thermal welding process. It also represents the zone along which fracture occurred during failure of the tank. There seemed to be a significant difference between the two weld regions, however. That from the failed weld appears to be thinner in width in the narrow, middle portion than that from the intact panel. Direct measurement from the samples with a lupe and graticule gave the width of the failed weld as about 0.6 mm, while the width of the intact weld is about 0.8 mm. It was concluded that the welding process was such as
to give some variability in the size of the heat-affected zone (HAZ), and that there was probably a direct connection between size of the HAZ and the liability of the weld to fail.

5.2. Tensile tests

Specimens were tested in tension at a crosshead movement rate of 10 mm min\(^{-1}\). Failure of all the weld specimens occurred in a completely brittle fashion at the centre of the welds, clean and sharp fracture surfaces being obtained. By contrast, the panel specimens could not be broken within the limited elongations available with the machine used in the tests. In the bulk panel samples, the material showed cold drawing after a yield point, normal behaviour for polypropylene material. The weld samples, however, broke during initial straining, before or near the yield point, when the load/elongation curve turns. The results of detailed analysis of the load/elongation curves are shown in Table 1. The panel materials exhibited no sign of brittleness (so they are not included in the table), but both kinds of weld material failed by brittle cracking at relatively low strains.

When it comes to comparing the numerical data large differences emerged. Thus although the ‘poor’ weld material was only 4% weaker than ‘good’ weld material (when evaluated in terms of tensile strength), it showed a mean failure strain nearly 32% lower than that of good weld material. Thus the total work of fracture (the area under the load/elongation curve) is significantly less. The experiment demonstrated rather clearly that the poor welds comprised material weaker than one
of the alternate welds which had shown no sign of cracking. It is also important to appreciate that the whole weld specimens were taken in the case of the poor weld, well away from the failure zone itself, suggesting that whatever was wrong with the failed weld seems to have been a property of the whole weld rather than, for example, a small restricted zone of the feature. One key property of the PP sheet, tensile strength at yield, was consistent with the values measured directly on weld material from the failed tank. The figure from the manufacturer's technical literature is 20 MPa, compared with slightly greater values shown in Table 1 (20.1–21.7 MN m⁻²).

6. Inspection of the welding method

It was now reasonably clear that defects present in the outer surface were the direct and immediate cause of fracture of the tank. Analysis of the four welds on the unbuttressed lower portion of the tank had also indicated that the welds varied in defect density, and hence intrinsic strength. It was therefore relevant to examine the welding process used in tank manufacture.

The welding apparatus itself comprised two tables separated by a central gap, where welding would be effected. The surfaces to be joined were first clamped on each side of the table, aligned together in the way intended for the butt weld. The two tables then slid out under hydraulic control, and the hot blade rose from beneath the central gap. The panel edges moved up against either side of the hot blade to start the fusion process, for a time of contact and pressure determined by the operator. He stated that he controlled the heating time by simply observing the state of the two edges: when a bead started to form by melting of the contact surfaces, it was judged that the panels were ready for the next step in the process. The exact time would depend mainly on panel thickness.

The blade withdrew beneath the table, and the tops then slid together, carrying the hot edges together under controlled hydraulic pressure. Fusion between the two panels occurred, the time of contact under pressure again being determined by the operator. A spark test was conducted on welds, the method involving holding a small spark generator immediately above the weld and observing the behaviour of the spark as it was moved along the weld. The joint was supported on a metal conducting table, so that should a pinhole void connecting upper and lower surfaces be
present, the spark would travel through the gap and the defect be discovered. The method was relatively crude, and could not detect pinholes which did not connect the two opposite surfaces of the weld, for example.

The large circumferential hoops are created first, in the following way. Flat sheets previously cut to the appropriate length with the table saw are welded up until the last joint is ready to be made. The ca 8.55 m length (in the case of the failed tank) is then bent round by hand to form a complete circle, and the ends thermally welded by the machine to make the hoop (Fig. 9). The hoop is therefore under a continuous bending stress, with a large tensile component in the outer surface, and a compressive component on the inner. This is discussed further, especially the effect on the gross stress to which the welds are exposed as a result, in Part II of this investigation.

Similar hoops made in the same way are then stacked and welded to create the tower. The operator thought that the horizontal welds thus made were somewhat weaker than the butt welds made initially, but certainly much stronger than hand made welds.

7. Materials analysis programme

Material from both panels and welds was also tested for its chemical integrity. The tests employed included infra-red spectroscopy (using a Fourier Transform or FTIR spectrometer) and melting behaviour (using a Differential Scanning Calorimeter or DSC). The objective in these tests was to see if there were any perceptible differences in chemical behaviour between 'good' and 'poor' weld material, between weld and panel material and between independent samples of polypropylene and material taken from the tank.

FTIR spectroscopy showed that the tank material was an ethylene–propylene copolymer. Little variation in chemical composition could be detected from several weld sample and normal tank material. Moreover, there was no evidence of oxidation, especially in the welds. The results of various DSC experiments conducted on the various tank materials are shown in Table 2.

The thermograms showed that both sets of samples had very similar endotherms, with melting
maxima at about 165 °C. However, there are differences between the two samples, that from the cracked weld showing a slightly higher melting point just above 165 °C, while the uncracked weld has a melting point just below. The cracked weld also possesses a slightly lower level of crystallinity, judging by the computed areas under each curve. It was reasonably clear that, overall, the melting behaviour of the different panels and welds were very similar to one another and to that of a reference material, and that the material does not appear to be sub-standard.

8. Discussion

The material appeared to be normal, although the welds did show differences, so what could be inferred about the cause or causes of failure?

8.1. Tank failure

Examination of the cracked panel which caused the leak of caustic soda showed that leakage occurred from a single 12 mm thick panel of polypropylene about 1.5 m from the base of the tank. The open crack initially was about 200–230 mm in length and was vertically oriented along the mid-centre of one of the four welds used to fabricate the circumference of the tank at this point above the base. Detailed examination of the fracture surface showed that the crack had been initiated during one of the four previous full loadings of the tank since its installation on 5 March 1994. Initiation had occurred from a pinhole defect on the outer surface of the weld near the centre of the panel, and at least three regions of growth had occurred since installation. The periods of growth appeared to correlate reasonably well with the four full loadings, the extent of each area increasing with each successive loading owing to the increasing size of the sub-critical crack. It is also clear that several other cracks were also initiated following installation from similar surface defects on the outer surface of the weld. Although the cracked panel as extracted from the tank appeared to span the entire length (about 0.82 m) of the single thickness panel from lower to upper
reinforcing buttresses, the occurrence of several crack arrest lines on the fracture surface indicated that the crack extended after the initial fracture, either while fluid was still issuing from the tank, or at a later stage when the crack was investigated by the firemen and others at the scene of the accident. Simple hand pressure on the side panel revealed the fracture surface, the act of doing so putting extra stress on the long crack which already existed.

8.2. Pressure conditions in the failure tank

The exact stress on the lower tank panel where fracture occurred can be calculated relatively easily, since the volume of the contents is known and the height of the top level of the contents is also known, within reasonably close limits. Together with a knowledge of the density of the caustic soda, the hydrostatic pressure acting on the panel at the failure locus can be determined from the simple formula

\[ P = h \rho g \]  

where \( h \) is the height from the origin of the fracture to the top level of the liquid when fully loaded just prior to the accident, \( \rho \) is the density of caustic soda at ambient temperature and \( g \) is the gravitational constant \( (g = 9.81 \text{ m s}^{-2}) \).

The thickness of the panel at the origin of fracture is about 12 mm, and the ratio to the radius of the tank (of about 1.35 m) is 112.5. A figure well in excess of the figure of about 10 normally regarded as the threshold ratio between thick and thin walled pressure vessels [4]. The failed tank can therefore be regarded as a thin-walled vessel, subjected to simple hydrostatic pressure.

Neglecting for the moment the self weight of the vessel and any creep in the plastic wall, the situation is that described by Roark [4] in his Table 28 (case 10). There is only one important stress acting in the wall, the hoop stress, \( \sigma_h \), acting around the circumference of the wall. There is no stress acting in a vertical direction. It is therefore a force tending to extend the circumference in tension, and hence acting on the vertical welds. This hoop stress can be calculated at the origin of the fracture using the simple formula

\[ \sigma_h = \frac{PR}{t} \]  

where \( P \) is the pressure as determined above, \( R \) is the radius of the tank, and \( t \) the wall thickness.

Taking the design height of the failed tank as 3.5 m and the measured height of the crack origin from the base of the tank as 1.486 m, then the height, \( h \), of fluid lying above the origin of the critical crack is 2.014 m. This assumes that the last load delivered of 22.32 t came up to the top of the vertical section of the tank. In fact, there is an overflow valve fitted just below this junction, so the estimate of 2.014 m is probably slightly exaggerated. A round figure of \( h = 2 \) m will be taken as a reasonable estimate of the total height of caustic soda above the origin. The specific gravity of aqueous caustic soda of 47% concentration lies between 1.4873 and 1.5065 [5], so that a mean value of 1.4969 may be rounded to a density value of about 1.5 g cm\(^{-3}\) (or 1500 kg m\(^{-3}\)) at about 20 °C. The pressure at the origin of fracture is therefore

\[ P = 1.500 \times 2.0 \times 9.81 = 29.41 \text{ Pa} \]

hence, from eqn (2).
Knowing the mean failure stress of weld sample under the controlled conditions of a simple mechanical test (Table 1), it was now possible to determine the stress concentration factor, \( K_c \), which was present at the side of the critical pinhole. Thus,

\[
K_c = \frac{\text{failure stress under test conditions of weld}}{\text{actual stress at origin}}
\]

(3)

Hence,

\[
K_c = \frac{29.4}{3.4} = 6
\]

It is possible to test this conclusion in a very simple way by evaluating the stress concentration factor for the specific dimensions measured on the pinhole directly. The cross-section of the pinhole was ellipsoidal in shape with axes roughly 0.6 x 0.3 mm. Using Inglis's evaluation of this configuration, as given by Peterson [6], then the parameter \( h = 0.6 \times 0.3 = 2 \). Interpolation on Peterson's figure gives a value of

\[
K_c = 5
\]

The agreement between theory and practice is good, bearing in mind the errors of measurement from the fracture surface as well as the errors associated with experimental tensile analysis, sampling error, and so on.

The above analysis is the simplest possible for this situation, and there are some known deviations from the simple assumptions underlying the various calculations given above. For example, creep had occurred in the exposed lower single panel where the fracture happened. Figure 3 shows the bulging caused by the pressure from the caustic soda contents, a fact confirmed by direct measurement of the circumference at two points on the tank, when a creep strain of about 0.2% was recorded. It may also be borne in mind that the tank by the time of investigation and measurement had been empty for about a month, so that some considerable strain recovery will have occurred. Such bulging will of course have added a small but not insignificant bending moment to the critical weld, adding an extra tensile component to the stress system acting on the pinhole.

A more serious deviation is that posed by the bending stress imposed by the need to form the final weld. Although the details of analysis of the problem are reserved for Part II, it is very evident that a tensile stress in the outer surface of the panels will enhance the possibility of failure from weak zones such as welds. Although there will be some stress relaxation after welding, there will be a substantial contribution to the gross stress acting on the weld defects. In addition, panels cut from the tank will tend to relax back to flatness. This was confirmed by re-measuring the dimensions of the portions of cut panel still retained after sampling. Three substantial samples (chord length ca 76 cm) were measured for their radii of curvature:

- sample 1 (single sheet from butress near good weld), \( R = 2.0 \) m
- sample 2 (double sheet near good weld), \( R = 1.6 \) m
- sample 3 (double sheet near poor weld), \( R = 1.64 \) m
These values may be compared with an original radius of the tank of 1.35 m, showing that these sections had relaxed substantially over the ca. 4 month period since extraction from the failed tank.

8.3. Cause of failure

A particularly important design point was evident early in the investigation, broadly confirmed by the classical analysis already presented. In vessels subject to simple hydrostatic pressure, the pressure increases in a linear way with height, so that the safest way to build supporting walls to resist the pressure from the contents is to increase the wall thickness in a correspondingly linear way. This well-known engineering principle is of course applied in dam walls for example, where the walls increase in thickness approaching the base (Fig. 10). That same principle had not been applied to the design of the failed tank, where the wall thickness was intermittently uniform, the three buttresses increasing the wall thickness, but only within three specific zones. They seem to have been designed to protect horizontal welds, rather than the vertical welds, which are in tension.

The horizontal welds hidden below the buttresses are probably in a state of compression, from the superimposed load of the tank above, and less likely to fail since the compressive strength of most materials, polymers included, is almost always greater than their tensile strength. This is despite the perception that such extrusion-welded joints are weaker than butt-welded joints. So the design of this tank leaves the lower panel circumference exposed to very high hoop stresses, which will naturally tend to be felt most severely at the weakest points, viz, the four welds connecting the panel sections together. The design issue is discussed further in Part II of this joint investigation.

8.4. Other installations

Other tanks holding corrosive fluids had been installed at a similar time to the failed tank, using essentially the same design philosophy, materials and method of welding. They were therefore examined for weldline cracks. Some small hairline cracks were found, but were far from criticality, largely because few of the tanks had been fully used to their maximum capacity. In one alarming
case an installation with a concentrated caustic soda tank adjacent to a concentrated ferric chloride tank, an access bridge could not support the supply vehicles, so the tanks were always kept well below capacity! It is understood that the tanks concerned have now been brought up to an acceptable standard.

Despite an extensive literature search for other examples of failure in such tanks, only one relevant example was found. References to earlier tank failures are exclusively concerned with GRP rather than thermoplastic vessels [7], or are theoretical exercises for comparison of different plastic tanks for fatigue resistance [8]. There is a report of a test tank which failed during a second fill of water to test the particular design calculations used [9]. The tank was under-designed with a barrel-like structure of the kind already discussed here. Unfortunately, details of how exactly the tank failed remains unclear, although the paper remains a good basis for the estimation of design stresses. Designing the wall to resist the creep strain developed by hydrostatic pressure is discussed, but without explicit mention of the need to increase the wall thickness towards the base, a point which receives greater emphasis in DVS 2206. It is also discussed in detail, with tables of recommended wall thickness, in a publication from Forbes Plastics Ltd [10]. The publication presents a good basis for design of plastic tanks, and should help to prevent future failures of the kind discussed in this article, especially in the more stringent regulatory environment for bulk storage of materials [11].

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