PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Material Defects and Service Performance

G. P. Smedley

*Phil. Trans. R. Soc. Lond. A* 1981 **299**, 7-17
doi: 10.1098/rsta.1981.0005

*Phil. Trans. R. Lond.* A **299**, 7–17 (1981) [ 7 ]
*Printed in Great Britain*

# Material defects and service performance

By G. P. Smedley
*Offshore Services Group, Lloyd's Register of Shipping,*
71 *Fenchurch Street, London EC3M 4BS, U.K.*

[Plate 1]

Since the early application of iron and steel to marine and land transportation, and large land constructions, brittle fracture has posed problems in service operation. From time to time such failures have been matters of public concern.

Following consideration of some serious failures, current engineering practice is examined for the avoidance of catastrophic fracture. The question arises: Have recent brittle fractures stemmed from misinterpretation of the results of major researches undertaken since World War II, or from deficiencies in the scope of these researches?

## 1. Introduction

In 1869, John Percy, F.R.S., stated 'There is no subject of greater importance to Civil and Mechanical Engineers than the properties of iron and steel which fit them for application to useful purposes; and there is no subject of the kind which more deeply concerns the general public. The lives of the many thousand daily travellers by railway are in no inconsiderable degree at the mercy so to speak of iron and steel; and the same may be said of voyagers in ships made of these materials' (Percy 1869). At the time, there was concern about brittle fractures of iron and steel constructions during the winter months in northern Europe. In the winter of 1865, when express trains were introduced between Stockholm and Gothenburg, the general public became aware of the hazards. Three serious accidents occurred when the temperature fell to about $-25$ °C, and all arose from brittle fractures. One accident was precipitated by the sudden fracture of a wrought iron tyre on the royal coach of an express train carrying King Charles XV. A Committee of Inquiry was established in Sweden and attention was focused on the properties of the materials.

It was established by drop weight tests at temperatures down to $-20$ °C that cold brittleness of iron and steel was governed by the chemical composition and the sizes of defects (inclusions) inherent to these materials (Percy 1869; Sandberg 1969). Efforts were concentrated on improvements in the processes of manufacture, and controls of the qualities of products. Special tests such as the explosion bulge test on steel plate were also made to determine the grades that offered maximum resistance to fracture during service (Jeans 1880).

A century has elapsed since these basic discoveries were made of the causes of brittle fractures. During the last 30 years, vast researches have been devoted to the avoidance of major fractures. Why do catastrophic brittle fractures of steel structures and component parts of engineering plant and equipment still plague industry and cause concern to the public? Have research and development neglected vital aspects of the technology, or have engineers failed to apply the findings to modern steel constructions? This paper attempts to answer these questions.

## 2. General considerations

Well before the turn of the century, engineers had devised riveted seams, which permitted the construction of structures, tanks and pressure vessels working at nominal tensile stresses of up to 90 $N/mm^2$. These seams were discontinuities that acted as crack arresters unless the stress increased unduly on the residual section. For example, fractures initiated in ships' hulls were invariably arrested at the riveted seams. As 'all-riveted' construction provided 'fail-safe' design for most structures, there was no incentive to improve the toughness of the steel. However, early steelmakers recognized the importance of the toughness of forged steel for highly stressed component parts of plants where brittle fracture could cause destruction. Before 1940 the relatively small ruling sections of forgings permitted the provision of satisfactory defect tolerance by suitable combinations of composition, heat treatment and tensile strength of the steel.

The rapid increase in the size of single turbo-generator units in power stations in recent years was a typical example of advance in design without a parallel advance in the quality of steel forgings for rotors and disks (British Engine Co. Ltd 1962; Kalderon & Gray 1972). The lesson had to be learned that where design cannot provide redundancy, integrity depends on good defect tolerance (i.e. high notch toughness). The benefit of high toughness of steel for shrunk-on turbine disks was demonstrated in certain marine steam turbines. L.p. turbine disks at the dew point of the steam suffered gross radial stress corrosion cracks extending from the bore. The cracks were caused by the concentration of alkaline salts carried over from the boiler, and were so numerous and large that the type of failure was referred to as 'sun-burst cracking' (Smedley 1963). Yet few disks burst and those that did were retained within the casings. When a similar type of cracking was encountered at the bore of a larger and thicker l.p. disk of a land turbine, the steel was so brittle that small cracks initiated brittle fracture. The fractured disk broke through the casing and wrecked the turbo-alternator set (Kalderon & Gray 1972).

In structural applications, when riveted construction was superseded by all-welded construction, structures were no longer fail-safe. This had a disastrous effect on structural durability as evidenced by casualties to U.S. Liberty ships and T2 tankers built in the 1940s (U.S. Ship Structures Committee 1953). It was soon established that the brittle fractures arose from a combination of severe notches and notch brittle steel. While some improvements were made to design detail, these did not provide the solution. Riveted crack arresters were fitted to existing ships to limit the propagation of brittle fractures. They reduced incidences of major casualties but were ineffective in a few cases because of the long intermediate lengths of notch brittle steel of the welded parts of the hull, and the severity of storm loadings. The solution to the problem was the development and production of ship steels with good notch ductility.

Inquiries into the casualties to all welded ships were conducted in the U.S. and the U.K. (U.S. Ship Structure Committee 1953; N.D.A.C.S.S. 1970). The investigations also revealed that major brittle fractures were not confined to ships' structures. Catastrophic brittle fractures had also occurred to welded bridges, penstocks, storage tanks, pressure vessels and pipelines (N.D.A.C.S.S. 1970; Pellini & Pusak 1963; Shank 1953). In all cases the steels were notch brittle at the casualty temperature. Clearly the development of notch tough steels was essential to safe design for all these different types of weldments. Steps were also taken to improve the toughnesses of weld metal and heat-affected zones.

The problem that confronted engineers was the level of toughness necessary in each application to avoid catastrophic fracture. Development of the theory of elastic fracture mechanics proved of enormous benefit in the design of short life, highly stressed items for the aerospace industry (A.S.T.M. 1965). It also permitted reasonable assessments to be made of fatigue crack propagation. In the heavy engineering industries, relatively large cracks had to be tolerated often in regions of stress concentration, to provide reliable service for 25 years or more at nominal design stresses between one-half and three-quarters of the minimum specified yield stress of the steel. Yielding fracture mechanics is not sufficiently advanced to permit the proper determination of minimal toughness requirements for rules and codes of practice governing the design and construction of important weldments.

## 3. Marine structures

In the 1950s, the welded steel hull of a tanker 200 m long and 38000 d.w.t., in the ballast condition, broke in two during a winter storm with mountainous seas. The fracture was close to the aft bulkhead of no. 6 tank. At the time of the casualty the sea and air temperatures were about +10 °C.

The design of the hull incorporated riveted stringers at the port and starboard gunwales. The steel plates that formed the bilge strakes, shearstrakes and deck stringers had been supplied to a grade expected to display notch tough characteristics. However, virtually the whole of the fracture was brittle with typical chevron markings. There were numerous origins, arrests and branches of the fracture, particularly in the bottom of the hull. Although there was no clearly defined point of initiation, the general pattern of chevron markings in the deck and side shell plating indicated that the source was in the bottom. A number of T2 tankers had broken previously by brittle fracture from a similar location.

The estimated total tensile stress in the bottom of the hull derived from the static bending moments produced by the distribution of ballast and deadweight, and considerations of wave loading, was about 130 $N/mm^2$. The lowest yield stress, determined by tensile tests on pieces prepared from the 40 plates involved in the break, was 225 $N/mm^2$. The thicknesses of the plating ranged from 20 mm for the side shell to 30 mm for the deck, keel and shearstrake. Of 14 plates forming the bilge and bottom of the hull at the location of the fracture only two had Charpy (V-notch) impact energies below 25 J at the casualty temperature, and these were above 17 J. A number of plates in the side shell and bottom had notch tensile test transition temperatures below the casualty temperature. In general, the main fracture in these was brittle with fine chevron markings. Now Wells (1956) had determined by notched and welded wide plate tests of a ship plate, 26 mm thick, that the temperature below which low stress brittle fracture was probable corresponded to a Charpy impact energy of about 10 J. He also observed that fractures were ductile at temperatures above the notch tensile transition temperature. The brittle fracture of the tanker hull was inconsistent with these findings. The likely cause of the difference was a condition at the time of the ship casualty that lowered appreciably the transition temperatures of the affected steels. Impact loading produces a significant lowering of the ductile–brittle transition temperature of steel. It is concluded that one or more blows of explosive violence produced catastrophic rupture of the hull. Viewed in retrospect, the strakes of tough steel failed to arrest the high velocity brittle fracture because the combination of toughness and length were insufficient to provide for the reduction in velocity essential to full arrest at the level of applied stress.

Where the steel and weld zones of an 'as-welded' structure are notch brittle at the operating temperature, brittle fracture under low static stress as demonstrated by Wells (1956) had been responsible for many failures in service. The case of the T2 tanker *Schnectady*, which broke amidships while lying alongside a quay, is a well known example. Another interesting case concerned a cargo ship of about 1560 gross tonnage, and 86 m long. She sustained grounding damage to the port side bottom plating at no. 2 hold. The vessel was repaired in a floating dock during the winter in Stockholm. Part of the repairs consisted of the removal of a steel plate from the 'A' strake, fairing it and rewelding it into the hull. An internal water test of the repair was made early one morning when the air temperature was −10 °C. The surveyor who was examining the external surface of the repaired area thought he saw a drop of water on one of the new longitudinal welds. He rapped the spot with a hammer. There was a 'terrible bang' and the plate fractured across and diagonally from the site of the small leak, which came from a small transverse crack in the weld. The steel plate and weld metal were notch brittle at −10 °C. This showed the sensitivity of notch brittle welded construction to brittle fracture. It also illustrated the danger of hammer testing a weldment during proof loading and as specified in codes of practice published in the 1950s.

Hodgson & Boyd (1958) accepted that the very large and complex weldment represented by a ship's hull must contain some flaws in the vast lengths of butt and fillet welds. If catastrophic fractures were to be avoided, a special grade of steel had to be incorporated in the structure that had a notch toughness capable of reducing to a low level the risk of brittle fracture in the more highly stressed regions of the hull. The specified minimum Charpy impact energy of this steel, now referred to as grade D, was 47 J at 0 °C. This level was determined by consideration of the properties of steel plates that had arrested brittle fractures in ships' hulls during service. A superior grade E steel was specified with a minimum Charpy impact energy of 60 J at −10 °C for strakes that were to act as crack arresters in the event of a brittle fracture initiating in the lower stressed region of the hull structure that had been fabricated from ordinary ship steel (grade A). Where higher tensile ship steels were proposed, the specified minimum Charpy energy of each grade of special steel was increased as a function of the sum of the specified minimum yield stress and tensile strength (N.D.A.C.S.S. 1970). In general, the special grades of steel were used for the construction of decks, shearstrakes, bilges, bottoms and keels of ships when the thicknesses exceeded about 19 mm. These steels have performed well in service. They have reduced greatly the incidence of brittle fractures and have effected crack arrests as shown by the following examples.

In 1970, a large fast cargo ship, 22490 gross tonnage, 200 m long, encountered heavy seas and sustained a brittle fracture 8.5 m long across the port side of the upper deck between nos 5 and 6 hatchways. The deck was alleged to have been constructed of grade D steel plate,

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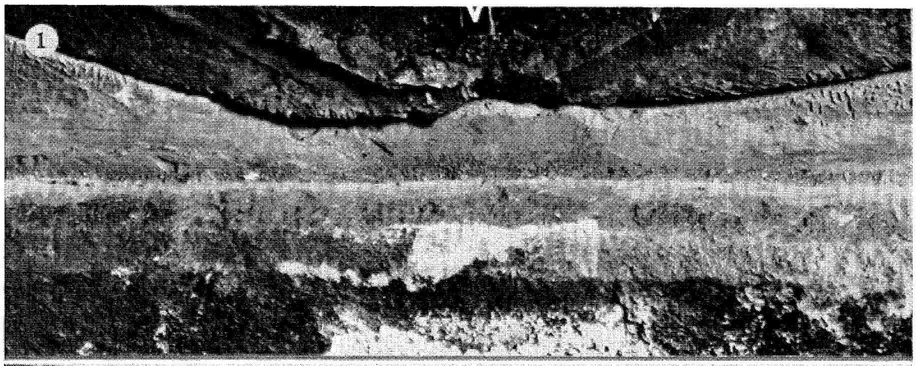
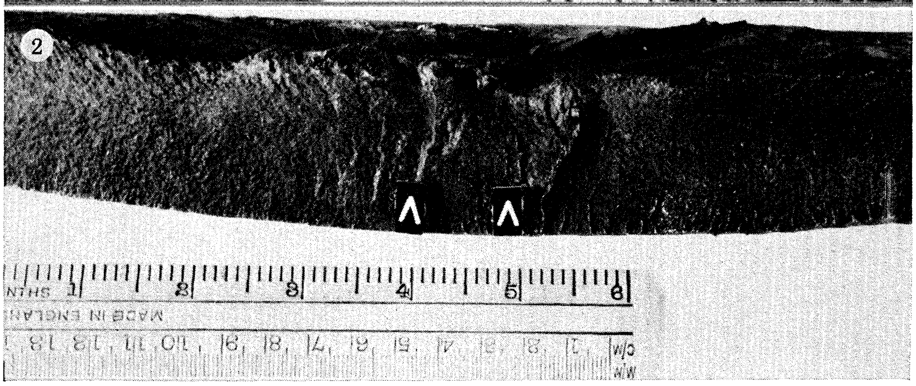
## Description of plate 1

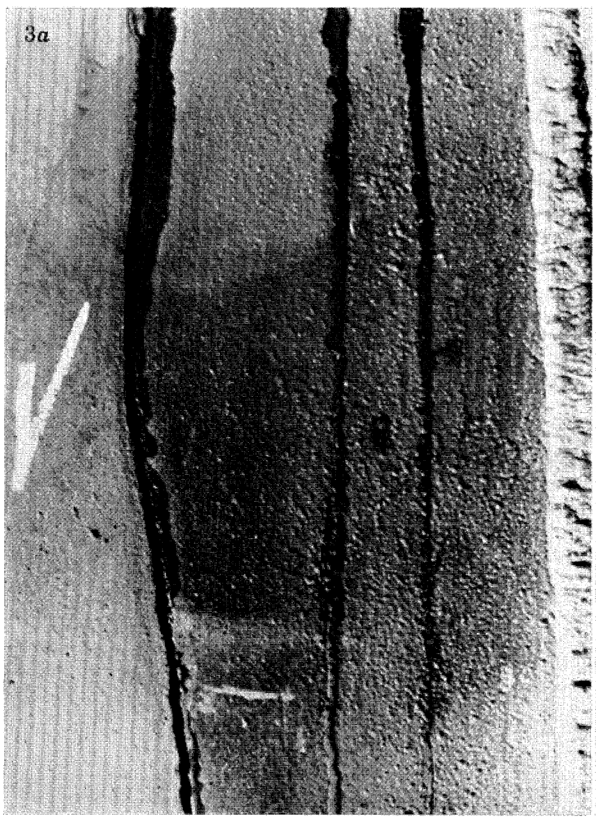
Figure 1. A major brittle fracture occurred in the deck of a cargo ship. This fracture started in a crevice between two close pitched fillet welded attachments to the deck plate. These were a thick plate type doubler and a tubular steel stanchion.

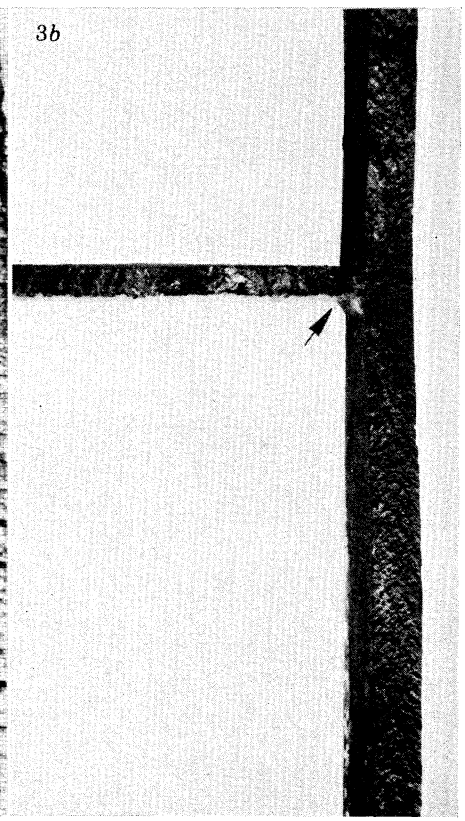
Figure 2. The surface of the fracture shown in figure 1. Local bending stress, superimposed on the tensile stress in the deck, initiated the fracture.

Figure 3. The origin of a major brittle fracture which occurred in the side shell of a 250000 d.w.t. tanker. It originated during storm loading, from lack of penetration in a butt weld of a longitudinal that was also fillet welded to the plating of the side shell.




FIGURES 1–3. For description see opposite.

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38 mm thick. Figure 1, plate 1, shows the origin of fracture. Brittle fracture had initiated from a small surface crack in a groove between two adjacent fillet welds that attached a vertical stanchion and a heavy steel doubler to the deck. These two attachments increased the effective thickness of the deck at the origin of fracture, and formed a severe stress concentration. As shown in figure 2, plate 1, the fracture occurred under a high local bending stress (arising from loads imposed on the attachments) superimposed on the service tensile stress in the deck. Tests on the steel of the associated deck plate showed that it was a rogue that was notch brittle at the casualty temperature. The brittle fracture was arrested at the inboard end in plate of true grade D steel. It was stopped at the gunwale by grade E steel plate. Both plates had tensile strengths of 433 $N/mm^2$, the Charpy impact energies at the casualty temperature being 84 J and 92 J respectively. The design detail at the origin of fracture was open to criticism. At that time it was a common feature of welded construction. Soon afterwards I discovered at least five cases in which brittle fractures of pressure vessels had started from a similar type of weld detail. Steps were therefore taken to prevent the further use of such detail by suitable amendments to design codes for welded pressure vessels and structures.

The second case concerned a single-screw, all-welded steel tanker (v.l.c.c.), 250000 d.w.t., 350 m long. In the winter of 1972, she left Norway in ballast, and turned southward into the Atlantic. She encountered a severe storm from the southwest with high seas. When she approached the Azores the weather abated and the mate was able to go on deck to check the general condition of the hull and equipment. He saw a short fracture at the edge of the deck on the starboard side. When he looked over the side he observed that this fracture was the end of a brittle fracture some 20 m long that extended down the side shell to just above the waterline. The air temperature during the period of the storm ranged from +3 to +10 °C.

The vessel was of modern design with continuous butt welded longitudinals. Those of the side shell were rolled steel angle sections having deep webs and thick flanges. The deck was fabricated from grade DH steel plate, 25 mm thick. Grade EH plate 25 mm thick formed the radiused gunwale, while the side shell was of grade A steel of similar thickness. The brittle fracture originated from gross lack of penetration, sharpened by fatigue crack propagation, in a butt weld in no. 5 longitudinal of no. 3 starboard wing tank. The fracture propagated into the side shell plating which was notch brittle at the temperature prevailing during the storm (Charpy impact energy of 13 J at +10 °C) (figure 3). In the upward direction the brittle racture was arrested initially by the grade EH plate of the gunwale. Under further pounding of the hull by the sea, the fracture reinitiated as a branch into and through a butt weld in the gunwale, and was stopped finally about 1 m into the deck by grade DH steel plate. Both special quality plates that arrested the fracture were tough, as evidenced by Charpy impact energies of at least 100 J. At the lower end, the brittle fracture curved towards the bow and stopped in grade A plate. This fracture was initiated under impact loading. It could have been reduced in severity by the use of special quality, notch tough plate for the side shell. However, the defect in the butt weld in the longitudinal could and should have been detected and rectified at the time of construction. Such action offers a superior solution.

Ship casualties have shown the vital importance of crack arresters made from wide strakes or tough grades of steel. The design of such arresters is still empirical, but has proved effective in arresting long brittle fractures in thicknesses up to 38 mm and for tensile stresses up to about 140 $N/mm^2$. Hahn *et al.* (1978) have reviewed the state of the art in the application of theory to the design of crack arresters. The conclusion is clear that for large welded constructions of structural steels, the designer has not yet been provided with a reliable method of calculating the widths of arresters capable of stopping long fast running fractures. He has not the means of specifying the required toughnesses of the steels, nor a production test to ensure that the manufacture meets the required standards.

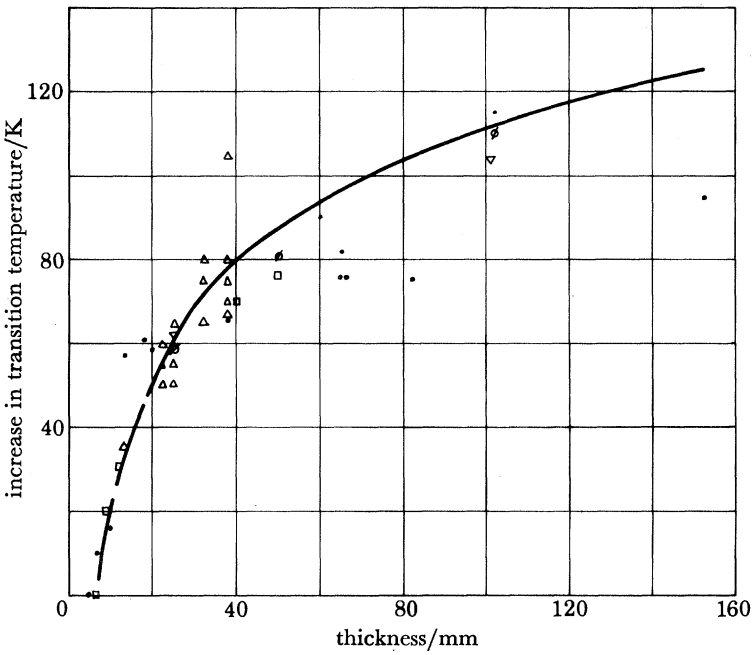


FIGURE 4. The increase in the brittle–ductile transition temperature of steel with increase in section thickness is independent of the type of test and the basis of the assessment. (References: ø, ▽, Witt *et al.* (1971); ●, Cotton *et al.* (1976); △, Lessels *et al.* (1971); □, Woodley *et al.* (1974).)

Of the tests that have been proposed to determine the crack arrest capabilities of steel, the Robertson isothermal wide plate test (ISO) (1968) in its original form or with modifications, provided valuable data on the relative merits of different steels and the effect of plate thicknesses and applied stress. Lessells & Leggett (1971) determined on a wide variety of structural steels the influences of plate thickness and the magnitude of applied tensile stress on the ISO arrest temperature. It was observed that at constant tensile stress, the ISO arrest temperature increased by about 40 K with increase of plate thickness from 13 to 38 mm. A similar increase in the arrest temperature may be expected over the range of thickness from 38 to 100 mm (figure 4). With constant plate thickness the arrest temperature increased almost linearly with the applied tensile stress transverse to the crack path. Over the range of stress from 125 to 250 N/mm$^2$, the increase amounted to between 2 and 3 K per 15 N/mm$^2$. No precise correlation was found between a reference ISO temperature and either a Charpy impact property or the drop weight n.d.t. However, for a plate thickness of up to 22 mm and a tensile stress of 125 N/mm$^2$, a minimum of 75% crystallinity in Charpy impact tests on steel appeared to provide crack arrest.

The apparent superiority of thin plate to arrest a brittle fracture has been queried on the evidence of some service failures at low temperatures. With increasing competition for refrigerated cargoes, the trend in the early 1970s was to lower the hold temperatures to −20 to −25 °C.

In one ship the 'tween decks were fabricated from plates 8.6 mm and 10 mm thick that had Charpy impact properties in excess of 45 J (with less than 75% crystallinity in the fracture) at the hold temperature of $-22$ °C. At least five brittle fractures happened and extended from the hatch coaming to within a short distance of the side shell (lengths of fractures between 6 and 7 m). Each fracture originated and propagated initially up to 0.5 m, in a butt weld which was notch brittle at the hold temperature. The thin and apparently tough parent plate was unable to arrest further brittle fracture at the low temperature even though the tensile stress in the deck was below 140 N/mm$^2$.

Lessells & Leggett (1971) demonstrated that the Robertson ISO temperature for the arrest of a fracture in a tough steel may not be valid if the brittle fracture is initiated in a notch brittle plate welded to it. The arrest temperature increased significantly for the dual test plate. Thus the arrest temperature alone is of limited value because the propagation and arrest of a brittle fracture are governed by the stress field, crack velocity, crack length and fracture toughnesses of the steel. These parameters have been studied principally in Japan with respect to the arrest of long fractures. Kanazawa *et al.* (1977) reviewed progress in the researches. It was established that criteria that satisfied the arrest of a short crack did not hold for the case of a long fracture. Based on the results of numerous fracture tests on steel plates up to 2.4 m in width, corrections were proposed to the crack length and stress intensity factor, $K$, appropriate to arrest. Preliminary consideration was given to an alternative concept based on total energy or recoverable kinetic energy. This approach did not appear to offer an advantage. The real issue is that crack opening exerts a control but as yet it has not received due consideration.

The depletion on land of the reserves of many minerals essential to man has forced him to explore and exploit the seabed for further supplies. At present crude oil and petroleum gases are in demand. For drilling and production from marginal fields and certain support functions, special forms of floating structures have been developed such as semi-submersibles and jack-up barges. The loss of the *Sea Gem*, a jack-up barge, which collapsed, capsized and sank in December 1965 with the loss of 19 lives, focused attention on the vital importance of proper considerations of fatigue and fracture toughness at the design stage (H.M.S.O. 1967). The support structures of mobile drilling units are such that crack arresters cannot be utilized for the avoidance of catastrophic brittle fracture. Moreover, the complexity of the welded steel construction is such that there is a risk of fatigue cracking during the service life notwithstanding careful consideration in design. It is necessary to provide redundancy where possible, and to use notch tough steel to prevent brittle fracture.

Periodical in-service inspection is also essential to safety. In effect there is a difference in approach to fracture safety between a ship's structure and that of a mobile. In the former the objective is to restrict the length of a brittle fracture by the use of crack arresters. The objective in the latter types of structures is to prevent the initiation of a brittle fracture, and the recommendations given in the U.K. Department of Energy guidance on the design and construction of offshore installations (H.M.S.O. 1977) are based on this philosophy. The same attitude is adopted to the design of the structures of drilling and production steel platforms fixed to the seabed.

The four structures for the exploitation of crude oil from the Forties Field in the northern North Sea were of traditional framed, welded tubular steel construction. Since these were the first platforms to be placed in deep treacherous northern waters, special consideration was given to the materials of construction. In anticipation of problems with lamellar tearing during the welding of brace members to main (chord) members, B.P. Ltd decided to use a special grade of steel that had been developed to avoid such faults (Cotton 1979). The steel, of C–Mn type, was made to a modification of BSS 4360, grade 50D, in that the sulphur content was kept below 0.010%, vacuum degassing was employed and the plates were supplied in the normalized condition. It was found that this quality of steel plate provided virtual freedom from lamellar tearing and also a very high level of fracture toughness (Smedley 1975).

B.P. Ltd also investigated the fracture toughness of weld metals and heat-affected zones produced by different welding processes and consumables. Crack opening displacement (c.o.d.) tests and tensile tests on welded wide plates containing fatigue crack notches were adopted for the investigation (Cotton 1979). The selection of consumables and welding parameters was based on optimum toughness displayed in the tests. For thick sections and complex construction, post-weld heat treatment was adopted as an additional safeguard. In the construction it was felt that a problem might arise with single sided butt welds between braces and brace stubs of prefabricated tubular connections. Because of the large diameters, and expected problems of fit-up at the erection site, some root misalignment and associated root defects were inevitable. A series of c.o.d. and wide plate tests were made to provide guidance on the defect tolerance at the roots of the butt welds at temperatures of −10 and −20 °C. By using the welding procedure and consumables approved for production, it was found that the fracture toughness of the weld metal was such that root defects (mismatch and lack of penetration sharpened by fatigue crack propagation) could be tolerated even though they were grossly in excess of specification requirements.

The approach to fracture-safe construction adopted for these platforms has been applied to later constructions in the North Sea and other waters. Some relaxation was permitted in the thickness above which post-weld heat treatment had to be employed (H.M.S.O. 1977). On occasions, oil companies have stipulated in contract specifications minimum c.o.d. requirements of welds. This has caused some hardship because there is no National Standard relevant to production weldments, and most fabricators lack the know-how to meet c.o.d. values of 0.15 mm or greater.

## 4. Pressure vessels and storage tanks

The Code Authorities responsible for pressure vessels accepted that resistance to the initiation of a fast fracture was necessary in the interests of safety. The relatively high design stress of two-thirds of the yield stress of the steel, and the significant level of stress often maintained during fracture because of the pressure–volume relation of a stored fluid, cast doubt on the effectiveness of any steel to halt a running fracture. Of principal concern was the increase in stress at the crack tip arising from instability produced by the internal pressure on the unsupported regions of the shell on either side of the fracture. In the U.K. the notched and welded wide plate tensile test was regarded as the best method of evaluating resistance to the initiation of major fracture. For standard grades of steel the temperatures above which at least 0.5% general plastic strain occurred before major fracture were determined with respect to plate thickness, Charpy impact energy of the steel and condition (as welded or post-weld heat treated). A marked thickness effect was observed, the magnitude being similar to those established by other types of notched tests (figure 4). Post-weld heat treatment was found to impart substantial resistance to brittle fracture. Acceptance criteria were proposed for the two principal conditions of supply. These related the minimum design metal temperature to the shell thickness and the temperature at which a standard Charpy impact energy had to be obtained for the materials of construction (Cotton *et al.* 1968). (See BS 5500, 1976 spec., for unfired fusion welded pressure vessels: appendix D1.)

A review of brittle fractures of pressure vessels disclosed that they had either not conformed to the toughness criteria or failed during hydrostatic pressure test from sizable cracks in the shells and in regions of stress concentration (Kihara *et al.* 1968; Smith *et al.* 1968). Burdekin & Dawes (1971) proposed the application of elastic and yielding fracture mechanics to the design of pressure vessels. For normal pressure vessel practice, leak before break and tolerance to defects in zones of the shell subjected to plastic strain are essential to safe operation. They related the critical size of crack that could be tolerated in the shell of a vessel to the applied strain and the minimum crack opening displacement of the steel. The technique has proved invaluable for the assessment of the significance of defects discovered by non-destructive testing of vessels either at the final stages of construction or during periodical in-service inspections. Where vessels are subjected to cyclic loading during service, estimates of fatigue crack propagation based on linear elastic fracture mechanics have been used in conjunction with the Burdekin & Dawes procedure. Unfortunately, little effort has been made to develop their procedures. In general, welded seams have posed the main problem. C.o.d. tests on weld metals can vary so widely that estimated sizes of critical cracks based on minimum c.o.d. values are often ridiculously small.

Most welded pressure vessels that represent a major hazard in the event of rupture of the shell in service are relatively thick and are supplied in the post-weld heat treated condition. The specified Charpy impact tests are usually made at or below the operating temperature. Most purchasers of such vessels impose notch toughness requirements for welds and parent metals that are in excess of Code requirements. The practice is intended to increase defect tolerance.

Pressure vessels are used for the storage of some gases at ambient temperature. However, the bulk storage of many gases in liquid form at low temperatures is more economical and attractive. Because of the low vapour pressures the containers are classed as tanks. These tanks are usually made of steels that are notch tough at the operating temperatures. Nevertheless in Germany at the end of the 1940s, circumstances dictated that welded vessels for the storage of liquid oxygen had to be made of aluminium-treated fine-grained steel, and supplied in the post-weld heat treated condition. With strict control of operation these vessels proved satisfactory in service.

Large single-walled tanks for the storage of liquid propane gas at $-45$ °C, fabricated from C–Mn steel, are of as-welded construction but incorporate prefabricated sections with nozzle attachments that have been post-weld heat treated. The practice is similar to that for oil storage tanks. The specified minimum notch toughnesses of plates and welds are prescribed on similar bases to those for pressure vessels (BS 4741, 1971), or must meet defined Charpy impact energy requirements at or just below the minimum design metal temperature (marine and U.S. land practice).

Tanks for the storage of liquid propane gas on land are usually of free-standing, cylindrical type. The diameter and height of modern tanks are about 43 and 30 m respectively. The maximum design stress permitted by the Code is the lesser of 260 N/mm$^2$ or two-thirds of the specified minimum yield stress of the steel plate. For tanks having twelve courses of plates, the nominal stresses in the upper four or five courses are relatively low and the thickness is restricted to 8 mm, the lowest nominal shell thickness allowed by the Code. The bottom course is about 20 mm thick.

The foreword to the Code states that the toughness requirements are based on the results of notched and welded wide plate tests (Woodley *et al.* 1964) that take account of the effect of section thickness. It states further that these requirements should provide tolerance to a through-thickness defect up to 10 mm long located in locally embrittled as-welded material subject to a tensile strain of approximately four times the yield point strain. Thus thinner plate and associated welds are checked for compliance with a minimum Charpy impact energy at a higher temperature than thicker plates and welds. For example, 8 mm thick steel plate to BSS 4360 grade 43 could be required to display a minimum Charpy impact energy of 27 J at −20 °C for a design metal temperature of −45 °C. Only the relatively thick plates and welds of the bottom course would be tested at or below the design metal temperature.

Within the last 2 years, three brittle fractures have occurred in thinner parts of tanks of this type. One caused disruption of the tank when it was full of liquid propane. In some respects the mode of fracture of this tank resembled that of a cylindrical oil storage tank, 42.7 m diameter and 16.5 m high, which sustained a vertical brittle fracture in the shell during a full-head water test at Fawley in 1952 (*British Welding Journal* 1955). The accidents to the liquid propane gas tanks have given rise to a loss of confidence in the Code requirements. The basis of design is such that the initiation of fast fracture will lead to uncontrollable brittle fracture. There is now serious doubt about the capabilities of materials of construction, complying with the specified minimum requirements of providing security for all conditions likely to be encountered in low temperature service. This applies particularly to materials of thin sections. Is there justification for the application of theory supported by limited laboratory testing to the formulation of minimum requirements for the security of very large weldments that pose a major hazard in the event of rupture during service? The industry cannot take chances. Some liquid propane gas tanks designed to the Code have been modified to incorporate an inner shell. A few users have adopted 9% Ni steel tanks for such service while for some time other users have selected C–Mn steel plate, and welding processes and consumables that offer optimum toughness at −50 °C. In the latter case, the quality of steel plate has been similar to that used for offshore structures, i.e. very low sulphur and phosphorus; carbon equivalent below 0.43%; vacuum degassed; normalized. Such steel can have high toughness at −50 °C and can offer a high probability of the arrest of any fracture that might originate in a weld zone. In effect the trend is towards greatly increased security including superior proof testing before service. This is the correct approach and was accepted many years ago for pipelines.

## 5. The future

From the foregoing consideration, the development of tough steels by the steelmakers has provided the means of solving most of the problems of brittle fracture of C–Mn steel weldments. Some fabricators and users have been slow to respond even though the additional cost has been small in comparison with the total cost of the installation or the financial losses incurred by a major accident. This attitude has also reduced greatly the incentive of the steelmaker to invest in further research and development.

While there have been developments in welding consumables and process, these have not matched the efforts of the steelmakers. Future research must concentrate on solutions to the serious deficiencies of weld zones. It will require theoretical studies and experimental tests towards a better understanding of the determination of defect tolerance and the translation of the results into reliable production testing and acceptance criteria. Additional research must focus on factors that could be detrimental to the resistance of weld zones to the initiation of fast fracture. These include the effects of cold work, strain ageing, corrosion and stress corrosion cracking, stress concentration and impact loading. Pending the results of such research, special consideration should be given to the notch toughness of weldments of thin sections for service at low temperatures.

In general, Codes of Practice are intended to define requirements that will ensure safe design and construction. The authorities responsible for these Codes must take speedy and effective action to revise the requirements when deficiencies have led to hazards in operation. They must also make provision for improvements in material quality and fabrication practice that have an impact on the security of structures and plants. With reference to liquid natural gas and liquid propane gas storage tanks, the standards for carriage at sea have been appreciably more severe than for storage on land. The difference is not attributable solely to the more severe loadings in the former application. It therefore appears that closer collaboration between land and marine authorities could also be beneficial to the integrity of welded constructions, as well as to the direction of future research and development.

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FIGURE 1. A major brittle fracture occurred in the deck of a cargo ship. This fracture started in a crevice between two close pitched fillet welded attachments to the deck plate. These were a thick plate type doubler and a tubular steel stanchion.

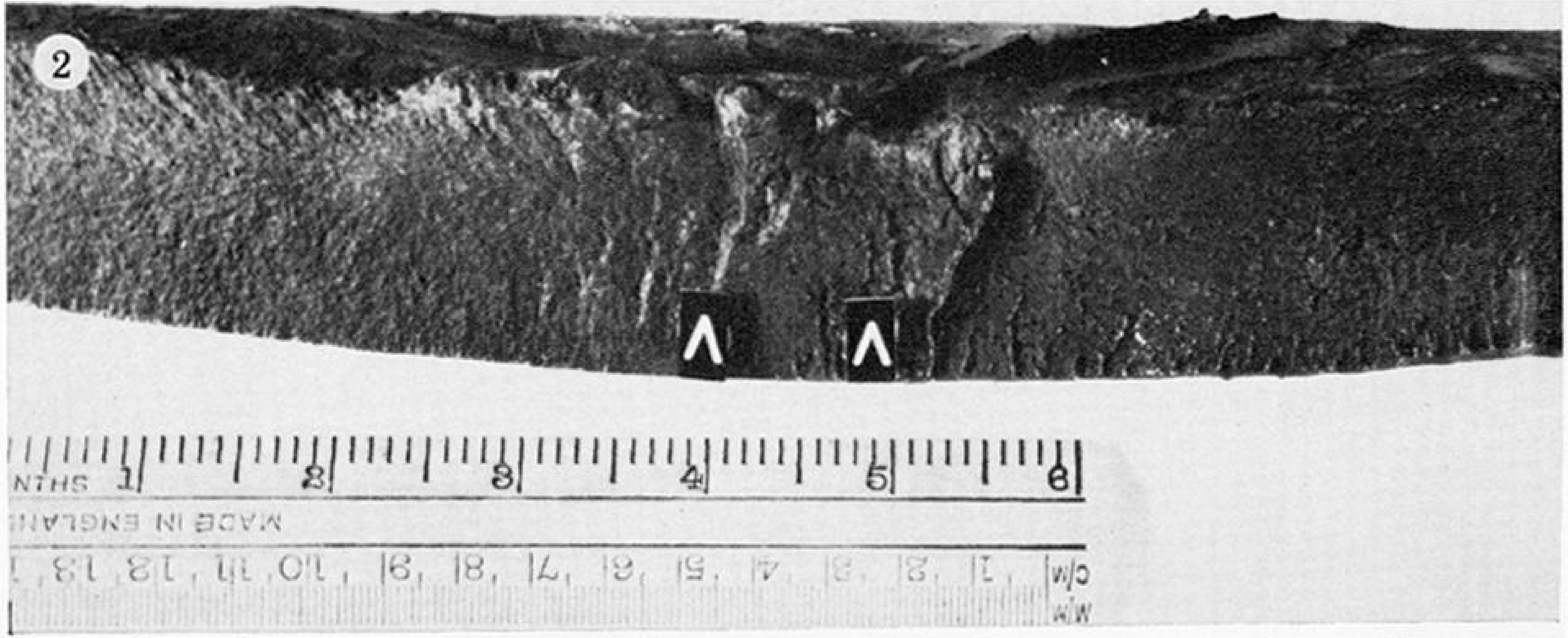


FIGURE 2. The surface of the fracture shown in figure 1. Local bending stress, superimposed on the tensile stress in the deck, initiated the fracture.

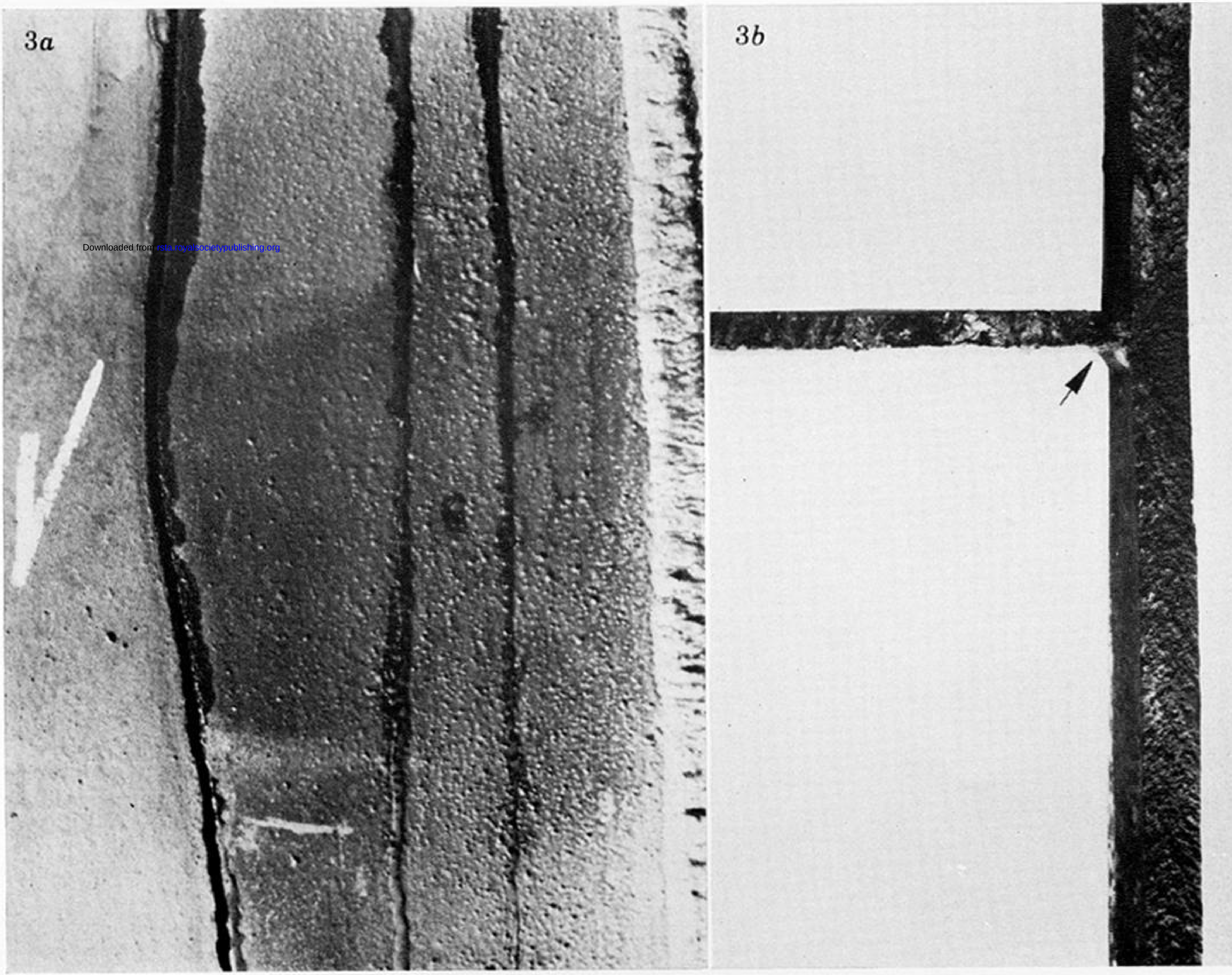







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FIGURE 3. The origin of a major brittle fracture which occurred in the side shell of a 250000 d.w.t. tanker. It originated during storm loading, from lack of penetration in a butt weld of a longitudinal that was also fillet welded to the plating of the side shell.