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

Experience in the Petroleum Industries [and Discussion]

H. C. Cotton, T. G. F. Gray and B. J. L. Darlaston

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Experience in the petroleum industries

By H. C. Cotton
British Petroleum Limited, Britannia House, Moor Lane, London EC2Y 9BU, U.K.

[Plate 1]

The petroleum industry engages in the design, construction and operation of huge steel constructions of almost every type.

The design temperature of vertical cylindrical storage tanks ranges from −196 to +80 °C: they are often sufficiently large to hold far more than 100 000 t of product in a single container.

Pipelines, often larger than 48 in (122 cm) in diameter are used to transport crude oil and gas at high pressure over distances of hundreds of miles often in arctic climates.

Offshore platforms are designed for service in the deep sea: in the North Sea the depth of water may exceed 200 m and waves of 30 m are encountered.

Fracture mechanics, notably crack opening displacement (c.o.d.), are used extensively in selecting materials and welding procedures for such constructions, but *J*-integral and linear elastic methods (l.e.f.m.) are used also when these alternatives seem appropriate.

The selection of steel grades is greatly facilitated by the use of fracture mechanics techniques but weld metal deposits provide special problems for which solutions are still sought.

Introduction

The vast production of the petroleum industries and the remoteness of the source of its raw materials from the place of use necessitates that huge containers be made available for storage and transport. These may take the form of tanker ships, storage tanks (Cotton & Denham 1968) and pressure vessels. Transportation of crude oil and gas from its source to locations convenient for its refining and treatment entails also the use of large-diameter pipelines (Cotton 1975, 1978).

Crude hydrocarbons are frequently contaminated, notably with CO_2, H_2S and chlorides, and with water. These undesirable impurities may cause the liquids and gases to become aggressively corrosive to the walls of the container. The poisoning action of H_2S and certain other compounds results often in hydrogen's entering the steel and inhibiting its notch ductility thereby (Moore & Warga 1976).

The sources of crude hydrocarbons from deep within the Earth are invariably warm, but the ambient temperatures at these fields vary from about −50 °C to +50 °C depending upon their location. In cold climates the notch ductility of nominally ductile ferritic steels is severely impaired at the ambient temperature (Cotton *et al.* 1976). However such steels may, in warm climates, suffer also from stress corrosion effects that are frequently intensified by increase in temperature within the climatic ambient range.

The storage of gas, because of its low density and large volume, often necessitates that it be liquefied. Liquefaction can be achieved by pressurizing, but more often cooling to very low temperatures is applied. This allows hydrocarbon gases to be stored in huge containers (100 000 m^3) at little more than atmospheric pressure. Under some circumstances the containers may thus be exposed to the combined effects of stress corrosion and low temperature.

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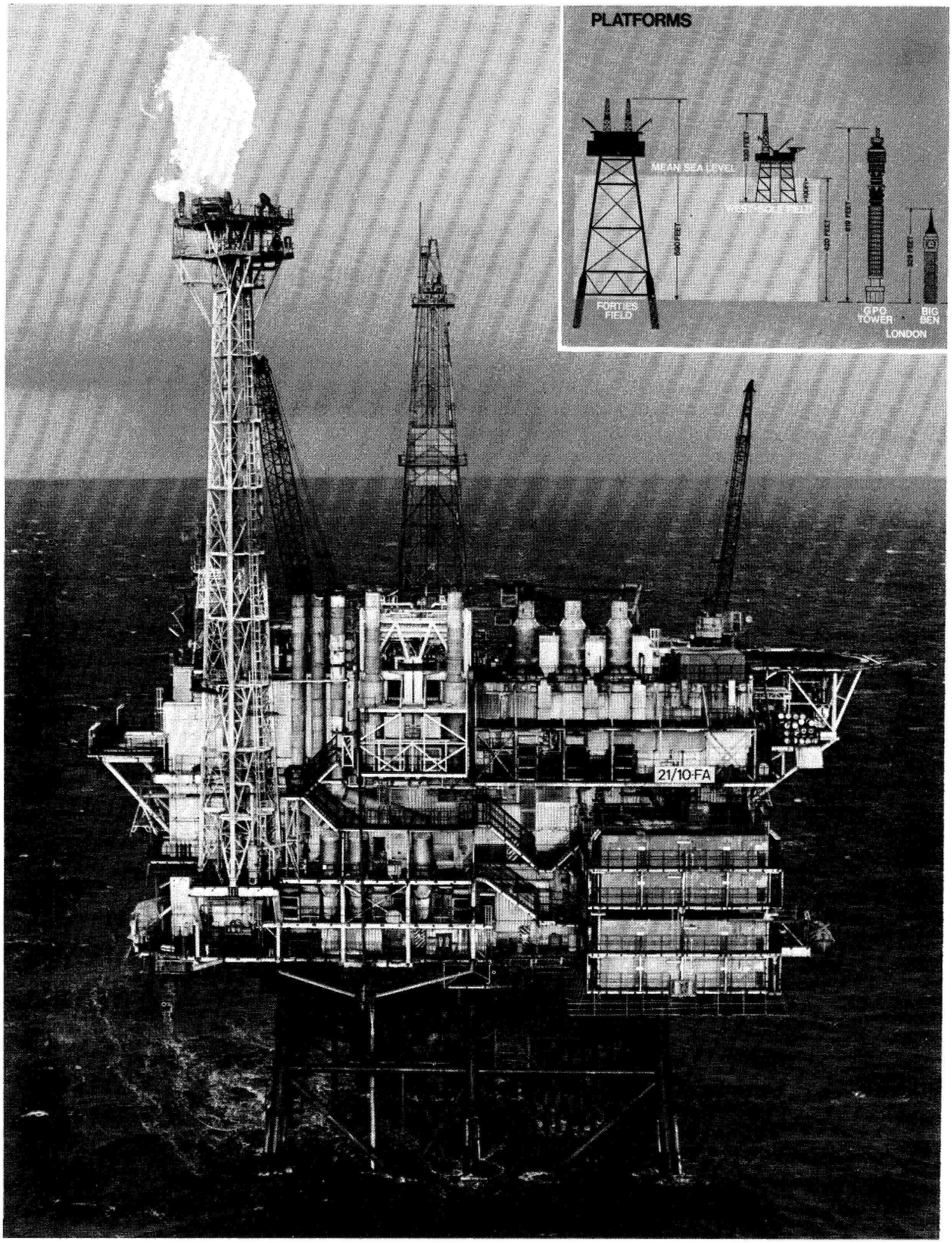

Figure 1. Production platform FA in BP's Forties oilfield in the North Sea.

The petroleum industry is faced with low-stress fracture risks in both arctic and tropical climates. This risk may be present in its drilling operations, during crude oil and gas production, in transportation through pipelines and by tanker ship, during storage, refining, gas liquefaction and, to a lesser extent, during distribution. In recent years, faced with a sustained demand for hydrocarbons at a time when supplies are dwindling, exploration and production has moved into areas hitherto regarded as too difficult or costly. Sites such as the North Slope of Alaska and the deep waters at the edge of the continental shelf of the North Sea are examples (figure 1). Problems with the cold of the Arctic necessitated a re-evaluation of materials selection and design techniques that had been long used in the past and hitherto regarded as safe. Assessment of the notch ductility of thick welded connections, particularly between chord and brace of offshore structures (figure 2, plate 1), presents problems even in temperate climates. These difficulties have still not been solved economically (Cotton 1979).

The petroleum industry, as a whole, is beset with numerous problems for which it would seem that the application of fracture mechanics techniques would provide appropriate solutions. However, inferior empirical methods based mainly upon Charpy V are most commonly applied in solving problems relating to low-stress fracture other than that induced by cyclic stress.

The causes of this reluctance to adopt mathematical techniques in respect of notch ductility, in lieu of experimentally derived methods such as Charpy V, are several. They relate partly to a general failure to explain fracture mechanics principles in suitably simple and convincing terms. They can be attributed to the complexity and cost of the testing methods themselves (Cotton *et al.* 1971); to the absence of accepted minimum property data for conventional and widely used materials and welding technique necessitating excessive testing. Most of all, there is the lack of consensus as to how fracture mechanics should be applied to a particular problem and to the difficulties of establishing realistic stresses for given loadings in complex constructions within the available time (Wordworth & Smedley 1978).

In short, the use of fracture mechanics at the design stage is currently more likely to compound a problem than to solve it. The time taken to conduct the experiments necessary to back up a fracture mechanics design approach is long and therefore costly. The information derived from crack opening displacement (c.o.d.) tests in welded connections is difficult to evaluate. As a result, the use of fracture mechanics in the petroleum industries is more often applied to investigations into failures than used for design and fabrication purposes. Under such relatively rare and unhappy circumstances time is less pressing (Cmnd 3409 1967).

The record of the petroleum industry in handling volatile, flammable and, under some circumstances, explosive materials is good. However, from time to time events occur that call attention to the inadequacy of the empirical rules currently defined in national and international codes and standards. These events indicate that the limits of the parametric envelope within which established techniques are safe are uncertain. As a result, engineers and others when straying outside well proven areas of application are beginning to resort to the use of fracture mechanics to supplement conventional design requirements. The data produced by such sorties has been most illuminating.

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Linear elastic fracture mechanics

The detailed design of most of the hardware used in the petroleum industry is insufficiently precise to allow for materials to be used in the linear elastic fracture mechanics (l.e.f.m.) régime. Even when stresses are precisely known, manufacturing tolerances for welded fabrications are usually large enough to entail significant shakedown during first loading. Techniques available for practical non-destructive testing within the time allowable are insufficiently precise to allow for accurate measurement of the imperfections that are frequently present. The welding methods employed preclude fabrication to the very high standards of freedom from imperfections required, without extensive repair work. Working in the l.e.f.m. range is too costly and is inappropriate for the general type of construction used by the petroleum industry.

General yielding fracture mechanics (g.y.f.m.)

The lack of precision inherent in current design, construction and inspection practices leads to the necessity of assuming significant strain, at least during first loading, at design and weld discontinuities. The c.o.d. test is applied by some workers in the petroleum industries to evaluate the tolerance of base metal and welded seams to these localized stresses. But it is by no means common practice to do so (Cotton 1976).

Currently the application of c.o.d. to petroleum industry hardware is restricted almost entirely to ferritic materials: the range of temperature of interest being 50 to −110 °C. For temperatures below −110 °C, 9 % nickel steel, austenitic stainless steel and non-ferrous metals are used. The few c.o.d. tests that have been made on such base materials and their welded joints indicate that low stress fracture initiation at the temperatures at which these nominally ductile materials are used in the petroleum industry is not a problem. The same cannot always be said of ferritic steel fabrications.

Fracture initiation and arrest

It would seem appropriate at this stage to compare the requirements for fracture propagation, K_{Id}, with those of fracture initiation (K_{Ic}, c.o.d., etc.). But, in the context of current practice in the petroleum industry, to do so would be quite unrealistic and misleading. Empirically derived tests are used almost to the exclusion of fracture mechanics to design for fracture arrest.

Designing against fracture initiation in welded connections, especially those that have not been stress-relieved, is complicated and rarely if ever certain. Locally embrittled zones in welds and their heat-affected zones are difficult to detect (figure 3). Although the probability of their presence may be low, their complete absence can never be guaranteed. The presence of imperfections at locations where the stress is low can be regarded as more tolerable than their occurrence at points of high stress intensification (hot spots). Non-destructive testing is therefore concentrated at hot spots in an effort to detect flaws in excess of the maximum allowable size. These dimensions can be calculated from c.o.d. test results (B.S.I. 1974). Such procedures can, however, be very costly and time-consuming if accurate results are required. Furthermore, it is never quite safe to rely upon the absence of imperfections greater in size than the calculated dimensions, as the possibility of fracture initiating from some unexpected cause – sabotage, for example – cannot be entirely discounted. A safe procedure is to provide materials capable of

FIGURE 2. Defective welded connection between leg and brace to an offshore platform.

(*Facing p.* 182)

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arresting a running fast fracture, however initiated. This philosophy forms the basis of many materials selection procedures used in the oil industry. However, fracture mechanics (K_{Id}, etc.) is rarely if ever used for this purpose.

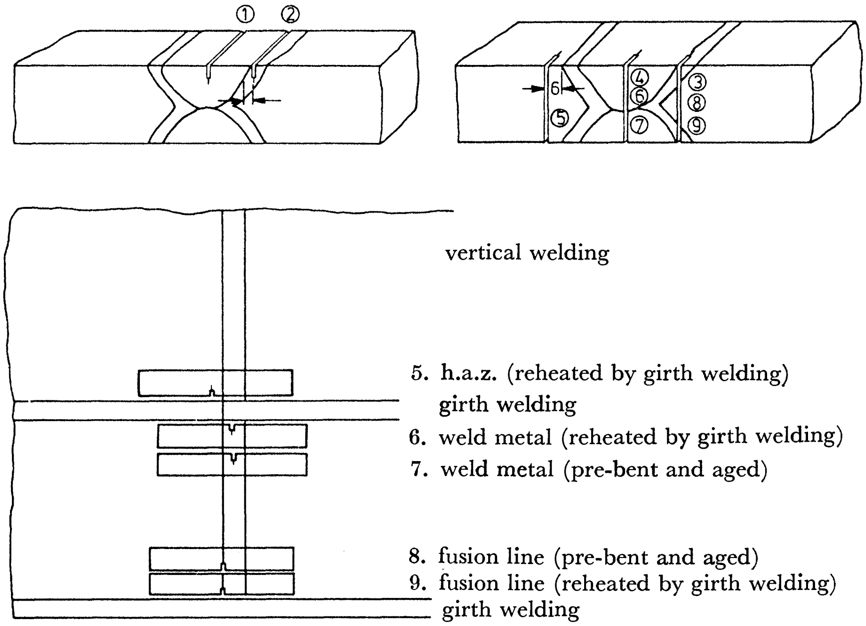

Figure 3. Examples of locations worthy of attention in searching for embrittled areas in welded connections.

Fracture safe design procedures

The fracture safe design procedures (f.s.d.p.) proposed 20 years ago by Pellini still provide the best and most readily understandable explanation of fracture initiation and arrest in carbon–manganese steels (Pellini & Puzak 1973). Unfortunately, Pellini was never permitted to complete this vital work. The basic procedure in use today has not changed since the publication of the report so long ago.

The procedure centred around the establishment of a so-called 'nil ductility temperature' (n.d.t.). This was defined firstly as a flat fracture in the explosion bulge test and subsequently in terms of limited shear in a drop weight tear test (d.w.t.t.). The design of the specimen and the type of notch (fatigue cracked, saw cut, TIG embrittled, hard weld bead, etc.) have been varied over the years. Currently the standard notch is pressed (A.S.T.M. 1969). Some workers envisage the drop weight test as merely a full size Charpy specimen. By making temperature adjustments to allow for size effects, Charpy V absorbed energy and observations of percentage shear in the broken specimen are used to supplement or to substitute for d.w.t.t. data.

Attempts to separate initiation energy absorption effects from tear energy in the simple d.w.t.t. have so far been unsuccessful. Crude attempts to separate these considerations by comparing the energy absorbed by the pressed notch test piece with that absorbed in the embrittled notch test piece exemplify the poor technology that exists in the field. The suggestion that the type of initiating notch used should be different for steels with more than 50 ft lbf (*ca.* 68 J) C.V than for steels with a smaller absorbed energy is clearly confusing and will lead to further imponderables (Eiber 1979).

It is claimed that the d.w.t.t. works reasonably well in predicting fracture propagation behaviour in low ductility steels. Be that as it may, the design of the d.w.t.t. specimen has not yet been defined adequately. Pressed-notch d.w.t.t. transition temperatures do not correlate with the behaviour of, for example, cracks in higher toughness CMn steel line pipe (Wilkowski 1979). Presumably the same applies to similar steels when used in oil or gas storage tanks and to a lesser extent in pressure vessels. An unequivocal and reliable definition of 'nil ductility temperature' is required.

There have been many full-scale experiments reported that were aimed at developing a pseudo-fracture mechanics approach, which could be applied to propagating fracture in pipelines. Such tests are extremely costly and provide only limited information. In addition, they tend to preserve an unjustifiable mystique in respect of the fundamental relevance of the Charpy V test. The correlation between the Charpy V test and the d.w.t.t. is poor or non-existent unless numerous 'corrections' are made to the results (Maxey 1979). Bulging effects and the effect of forces acting upon opening pipes and cylinders during fracture propagation are difficult to quantify, especially for buried pipes and for those in deep water. Correlations between C.V and observed fracture behaviour appear to be very limited and casual. Practically all the rules used to design for fracture arrest or to limit propagation rely upon empirically derived data (Wilkowski 1979).

Fracture mechanics is rarely if ever used by the petroleum industry as an aid in designing for fast fracture arrest. This area of materials behaviour requires urgent attention. In the absence of reliable fundamental data engineers are turning away from the use of the relatively cheap CMn steels to expensive austenitic or 9% Ni steels even for duty at −50 °C. We do not know how to design accurately and economically when faced with the problem of providing for fracture arrest.

Fracture initiation

The resistance of a material to the extension of a flaw at nominally static rates of strain is an important consideration in testing and operating petroleum industry equipment. This follows from the previous discussion wherein the techniques used to design for fracture arrest are identified as being experimentally derived, subject to frequent variation, and uncertain. In the absence of certainty in providing for fracture arrest, an understanding of the mechanism whereby a crack remains stable under a given load, or where it grows through the wall and then becomes stable giving rise only to a leak, is important in providing safe constructions. This is of vital importance when considering the safety of large vessels with a capacity of as much as 200000 m^3 containing flammable hydrocarbons. Liquefied gases are stored similarly and their volatile nature indicates a need for special prudence. Ammonia and chlorine are stored also in large tanks at low temperatures. The reliability in service of such vessels must be beyond question. High-pressure pipelines, especially those traversing built-up areas, must also be designed and constructed to demanding safety requirements. The probability of crack extension depends, *inter alia*, upon the notch ductility under the ambient conditions and the rate and intensity of loading that prevails (Burdekin & Dawes 1971). It is in this connection that fracture mechanics has been most widely used by the petroleum industry.

The concept of c.o.d., whereby a paddle rotating in an opening crack was found to correlate well with the notch root contraction in the loaded specimen, was enticing in its simplicity. However, the application of such tests to steel samples of heterogeneous microstructure such as weldments, coupled with the adoption of clip gauges in lieu of paddles, focused attention upon the phenomenon of 'pop in' (figure 4) (BS 5762 1979).

The desirability of using natural cracks in lieu of the jewellers' saw cut, as in the original design of the test-piece, led to fatigue cracking, which in turn introduced the problem of achieving smooth crack fronts in samples of welded joints, especially those that had not been stress-relieved. Precompression was applied to relieve residual stress effects by the application

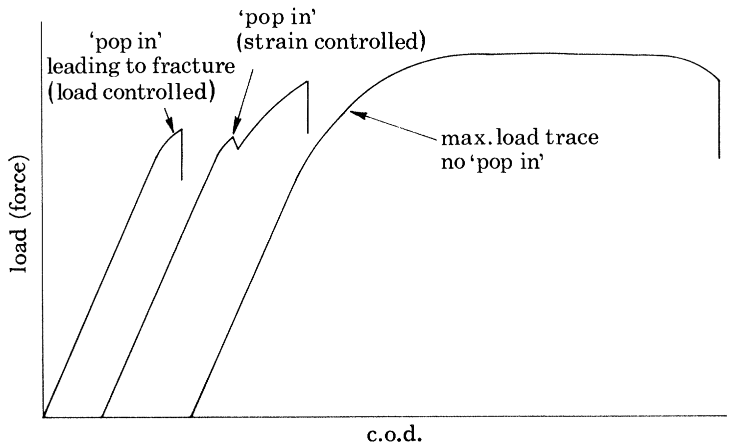

FIGURE 4. Schematic representation of typical force–c.o.d. curves.

of controlled strain (Dawes 1971). The c.o.d. test as applied to welded joints is now very complex. In the presence of mixed metallurgical structures, or when the fatigue crack front is uneven or badly shaped, the phenomenon of 'pop in' is observed. The behaviour of the crack after 'pop in' depends to some extent upon the compliance of the test machine itself. In load-controlled machines, 'pop in', except at very low values of c.o.d., leads usually to fracture of the specimen. The critical value of c.o.d. depends, it seems, upon the causes of 'pop in'. An increase in specimen thickness results, because of the increased triaxiality at the centre of the deep notch, in 'pop in' at lower values of c.o.d. for a given microstructure (Kamath *et al.* 1978). The critical value of c.o.d. is thus dependent on specimen shape. But the relevance of the standard c.o.d. test specimen to real-life weldments in the petroleum industry is doubtful. The test method currently in use seems to be exceedingly severe. Joints made by welding methods and consumables that for years have been used with apparent success appear to be unexpectedly intolerant of imperfections during first loading. The validity of such conclusions is being questioned.

In practical terms, the difficulties currently encountered in providing adequate resistance to fracture initiation appear often to be solvable by simple actions such as changing the weld procedure or the type of welding consumable. However, significant difficulties are experienced in achieving sufficiently large values of crack opening displacement to meet present requirements in through-notched c.o.d. specimens of welded joints made in positions other than the flat. This is specially so when testing samples over about 40 mm in thickness and when testing at −10 °C or less. At lower temperatures the critical thickness diminishes so that at −50 °C the weld metals in even 12 mm thick CMn steel, weldments occasionally begin to present very low values.

'Pop in' events seem to be associated with first loading. Many petroleum industry constructions designed to contain fluids are subjected to hydrostatic proof overloads before being brought into service. Often the service temperature is considerably lower than the proof test temperature. If consensus could be obtained on how to design for such situations it would be helpful. For those constructions that cannot currently be proof-overload tested, the 'pop in' event can hardly be ignored if it leads to fracture in load controlled tests. This conclusion is extremely costly in the context of large offshore platforms.

Post-weld heat treatment in the stress-relieving range of temperature has a dramatic effect upon the occurrence of 'pop in' in thick (50 mm) through-notched c.o.d. test pieces (Harrison 1976). This improvement has been attributed variously to reduction in residual stress, to over-ageing of strain-age damaged weld metal, to tempering effects, hydrogen diffusion, etc. Fracture mechanics thus provides a most useful tool for the examination of these effects and for the improvement of welding and stress-relieving procedures. Its usefulness as an acceptance test defined in absolute terms for contractual purposes is less certain.

Conclusion

General yielding fracture mechanics (g.y.f.m.) provides a means whereby investigations into the effects of changes in welding and fabrication procedures in general upon the notch ductility of a welded joint can be conducted in a highly discriminating manner. Within the last few years much information about the significance of imperfections in welded joints has been assembled as a result of c.o.d. testing. These data are now sufficiently extensive to allow them to be used in rewriting acceptance standards for welded connections. This is being done in the petroleum industry. The c.o.d. test as currently applied is considered to be highly conservative. As a result, welding procedures that seem to have worked well in the past are frequently rejected on the grounds of poor or indifferent c.o.d. It is believed that the present practice in interpreting results is excessively prudent.

The standard test-piece, by its very nature, shows little comparability with the type of cracking normally experienced in real welds. Placing the fatigue crack in the centre of the weld and normal to its surface exposes the crack front to the worst combination of metallurgical and mechanical effects that could possibly occur in practice.

'Pop in' occurs at locations where brittle zones coincide with the crack front. The coincidence of one of these zones with the fatigue crack front depends upon probability (Johnston 1978). These brittle zones may be very small or few and far between. In such an event the probability of their occurrence at the exact point of the crack front is probably small also. The wide scatter observed in c.o.d. testing thick weldments seems to provide some support for this contention.

These brittle, or relatively brittle, zones result mainly from localized differences in microstructure and to strain–age damage effects. This can be attributed to small differences in welding technique, electrode manipulation, restraint, interpass temperature, etc. These variables are ever present in practical welding applications, especially in manual welding in difficult positions of welding. As already mentioned, the physical dimensions of these zones of doubtful notch ductility are often small and their distribution discontinuous or even widely spaced. If this is so, the statistical chance that a real weld crack front would coincide with a zone of critical brittleness seems also to be small. Indeed, the very brittleness of the zone would imply that other than for hot cracks, the original crack growth would be less likely to come to rest at just that location.

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The c.o.d. test has come to be accepted by welding engineers and metallurgists alike as providing valuable information. This information can be used in developing optimum welding procedures and this is being done in the petroleum industry. What is still in dispute is the necessity of recognizing lower bound c.o.d. values as critical for a given welding procedure. This question is particularly relevant when the location of the crack in the c.o.d. specimen and the constraint offered by the standard test-pieces bears little comparison with the practical case under consideration.

Permission to publish this paper has been given by the British Petroleum Company Limited.

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Discussion

T. G. F. Gray (*Department of Mechanics of Materials, University of Strathclyde, Glasgow, U.K.*). Professor Cotton drew attention to uncertainties associated with the use of Charpy energy absorption data for the selection of materials to be used in low temperature storage vessels, as recommended by certain British Standards. He showed that for weld metals particularly there is poor correlation between impact energy and more 'respectable' measures of toughness such as critical c.o.d. This is worrying, as fabricators use these Standards rather freely.

As a self-acknowledged disciple of Wells and Burdekin, I wonder whether Professor Cotton has considered the effect of weld metal yield strength on Charpy energy. Wells has shown that within a given mode of fracture, and neglecting rate effects, any relation that may exist between c.o.d. and energy absorption should depend linearly on yield strength. As the yield strengths of weld metals tend to be high, variable and direction-dependent, one wonders whether any lack of correlation is due to this factor. In addition, Wells showed that transposition points in fracture behaviour or 'mode shifts' depend on the square of yield strength and this may also be worthy of consideration by those responsible for revising the low-temperature fracture assessment clauses of relevant standards.

H. C. Cotton. I do not believe that correlations between Charpy V and c.o.d. exist for weld metals unless the whole of the weld metal is in a very brittle state. By very brittle I mean, perhaps, rather less than 20 J C.V. The correlations to which Dr Gray refers and the work of Wells in this respect were, I believe, in respect of homogeneous base metal. C.o.d. is an initiation test, whereas the Charpy V test consists of two components: initiation and propagation. For this reason I expect that correlations, if they exist at all, between c.o.d. and C.V for weld metal will only be found when the energy absorbed in propagating the running crack through the breaking C.V specimen is very low.

B. J. L. Darlaston (*Berkeley Nuclear Laboratories, Central Electricity Generating Board, Berkeley, Gloucestershire, U.K.*). The British Standard 4741 relating to low-temperature storage tanks is in the process of being amended with respect to the section on notch ductility and brittle fracture. I have two questions:

1. Will the amendment be similar to the procedures of BS 5500 with respect to Charpy V test results, and will the allowable values be correlated with wide-plate test results?
2. What are the practical implications of the proposed amendments? For example, are they likely to be more restrictive because of the inherent scatter and also low impact values obtained from weld metal tests?

I should like to comment that the practice of carrying out a test at ambient temperature and then assuming that the result provides guidance to behaviour at -60 °C is not, in my view, very satisfactory.

H. C. Cotton. No one can predict what form amendments to British Standards will take. I am not certain that much amendment to the requirements for notch ductility in plates is called for. The second question seems to relate to weld metal notch ductility. I entirely agree that neither the C.V nor the c.o.d. properties of welds at one temperature can or should be inferred from their performance at another, although I have some sympathy with this practice in selecting parent metals such as plate. It is my view that the requirement for notch ductility for weld metals for low-temperature storage tanks should be significantly more restrictive. This is especially important when such vertical cylindrical containers are not given a full height water test before being brought into service.

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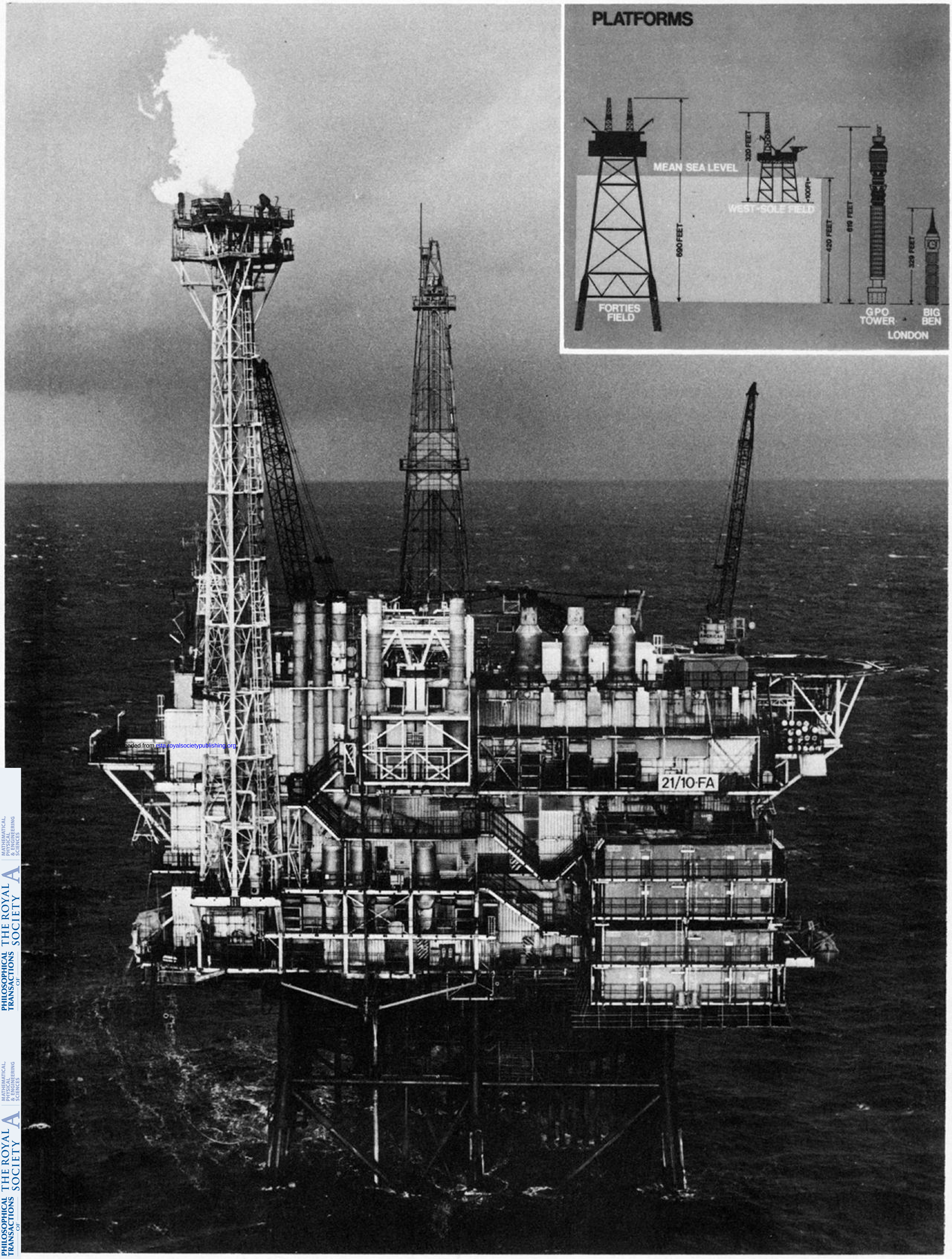

FIGURE 1. Production platform FA in BP's Forties oilfield in the North Sea.

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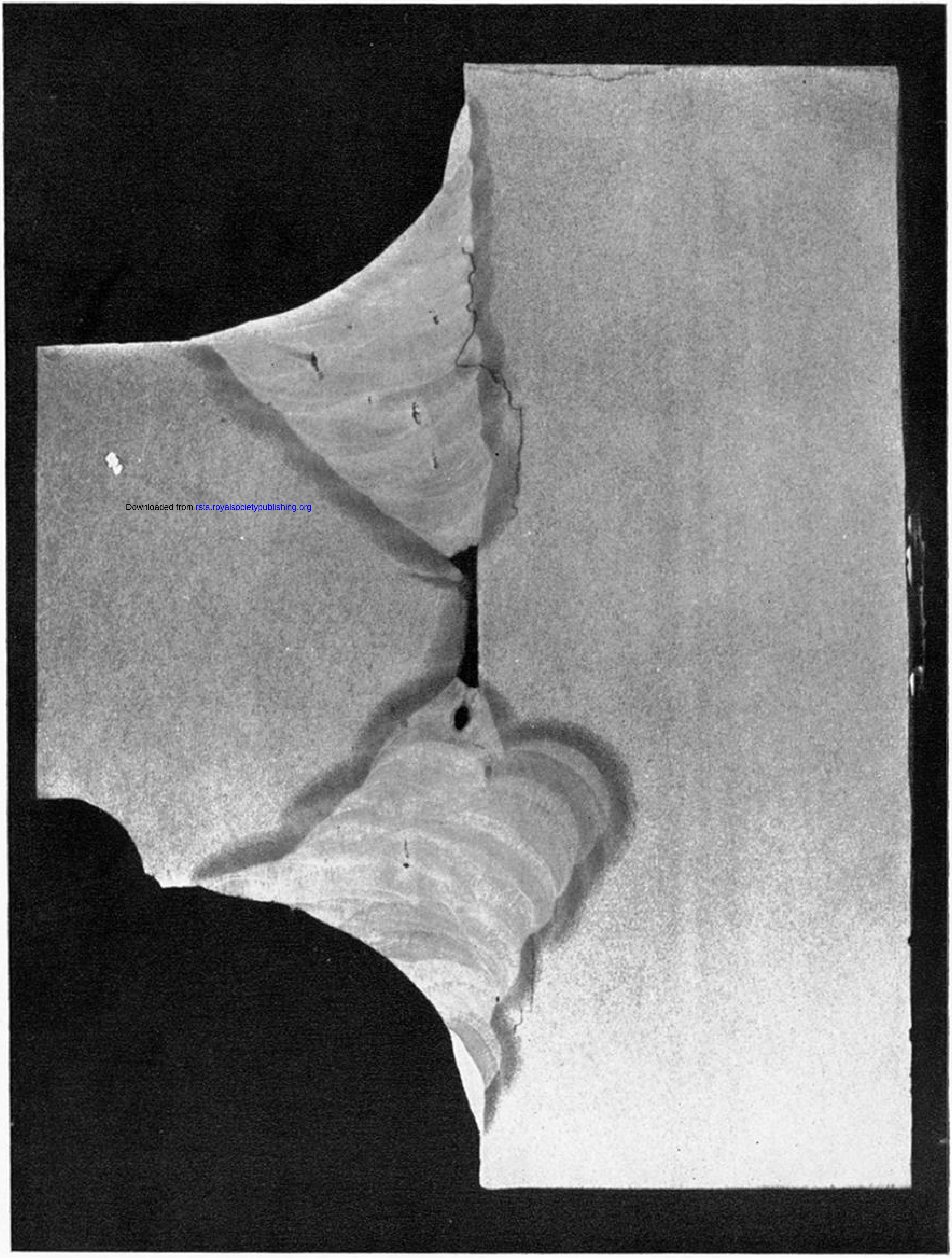

GURE 2. Defective welded connection between leg and brace to an offshore platform.