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SOME OBSERVATIONS ON THE BRITTLE FRACTURE PROBLEM

by

G. M. Boyd

SHIP STRUCTURE COMMITTEE

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ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U. S. COAST GUARD HEADQUARTERS
WASHINGTON 25, D. C.

July 31, 1959

Dear Sir:

Mr. G. M. Boyd of Lloyd's Register of Shipping, London, England, recently participated in a meeting of the Committee on Ship Steel of the National Academy of Sciences-National Research Council, one of the principal advisory committees to the Ship Structure Committee. The purpose of his visit was to describe recent interpretations of service failure data by Lloyd's Register of Shipping and to discuss recent work on brittle fracture mechanics in both Great Britain and the United States.

The enclosed report, entitled "Some Observations on the Brittle Fracture Problem," was prepared by Mr. Boyd to summarize his remarks for the Committee on Ship Steel. This report is being distributed by the Ship Structure Committee because it represents an important current approach to this problem.

Please send any comments on this report addressed to the Secretary, Ship Structure Committee.

Sincerely yours,

E. H. Thiele
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

Serial No. SSC-125

Special Report

on

SOME OBSERVATIONS ON THE BRITTLE FRACTURE PROBLEM

by

G. M. Boyd

Lloyd's Register of Shipping
London, England

Washington, D. C.
National Academy of Sciences-National Research Council
July 31, 1959

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INTRODUCTION

The problem of brittle fracture in structural steel has been vigorously attacked by powerful research efforts in many countries over the past sixteen years or so, but remains in some respects intractable. The main difficulty seems to lie in defining the problem itself, and in isolating the essential features. The investigations have been characterised by conflicts of ideas on these essentials, and on their interpretation, possibly because the problem has brought together into one forum, as it were, several branches of scientific and technical endeavour which in the past have functioned, to a large extent, independently. This has led to misunderstandings due to differences in terminology and other difficulties due to conflicts of interest.

In such circumstances it is often desirable to re-examine fundamentals, and the present notes are an attempt to do this. Such re-examinations often entail the repetition of "obvious" facts, and while this may appear tedious, it is essential to the process.

MODES OF FRACTURE

The first fundamental observation that has emerged is that the crystals of mild steel are capable of two distinct modes of fracture, i.e. shear and cleavage. There are other modes, which need not concern us here. In the shear mode, the individual crystal deforms and elongates, eventually fracturing by reduction of its cross section to near zero (Fig.1). In the cleavage mode, the crystal splits across on an atomic plane, without permanent deformation, leaving a mirror-like surface on the plane of fracture (Fig.2).

An intermediate mode is possible, in which the crystal elongates and deforms to some extent before fracturing by cleavage.

The relevant distinction between the two modes is illustrated diagrammatically in Fig. 3. In the shear mode, the load-extension curve rises gradually to a maximum and falls gradually to near zero (Fig.3a), while in the cleavage mode the graph is elastic up to the point of fracture,

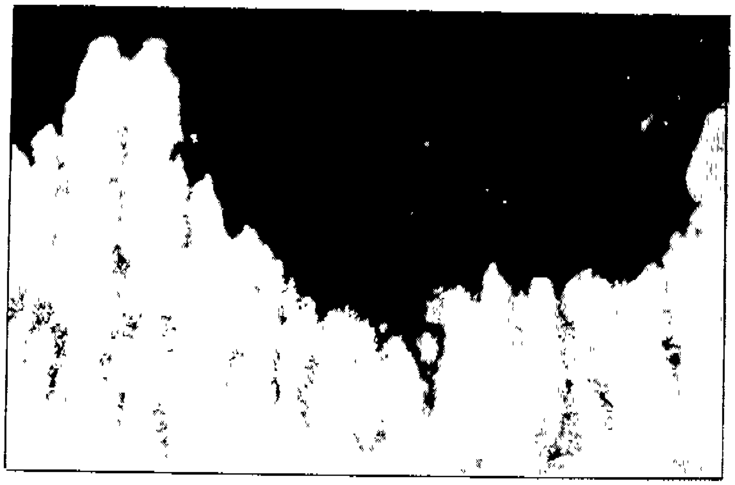

Fig. 1. Fibrous (Shear) Mode of Fracture. (X 500)

Fig. 2. Cleavage Mode of Fracture. (X 700)

from which point it drops suddenly to zero (Fig. 3b). In general it can be said that for identical crystals, the energy absorbed, as represented by the area under the curves in Fig. 3, is very much greater in the shear mode than in the cleavage mode. Cleavage is closely associated with brittleness, and the main object of the investigation is to avoid it.

The conditions which determine which mode will occur or prevail are manifold and complex. The difficulties in studying the many influential factors are very great, particularly when the crystals are imbedded in an aggregate with random orientations. This is the domain of metal physics.[1] It is sufficient here to record that the two modes can occur, and that the chances of an individual crystal fracturing by cleavage are favoured by low temperature, high rates of strain, and triaxiality of stress. In this context stress must be understood to mean that affecting each individual crystal, which may be very different from the stresses calculated by engineering methods.

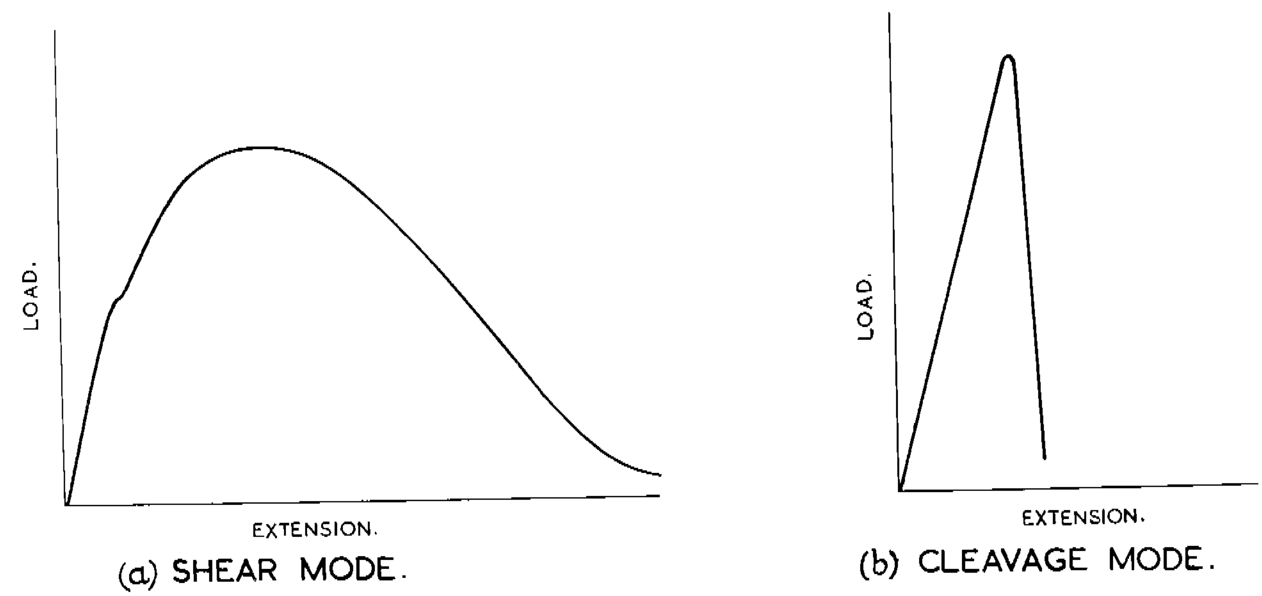

Fig. 3. Load-Extension Curves Illustrating Relevant Distinction between Shear and Cleavage Fracture Behavior.

KINDS OF FRACTURE

The second fundamental observation that has emerged is that there are two distinct kinds of fracture which concern us, namely, the stable kind and the unstable kind. The former, stable, kind is associated with ductility, which in this context is merely a convenient term to denote that the fracture is of the gradual, or controllable kind associated with ductile materials. The second, unstable kind is associated with brittleness, which again is merely a convenient term, denoting the sudden, uncontrollable kind of fracturing. The latter kind is anathema to engineers, and its occurrence is the root of our problem.

The fundamental conditions governing stability and instability in fracturing may be stated as follows:

Consider an isotropic elastic body of any form, loaded at the boundaries in any manner, provided that a tension field exists in some region within the body. Suppose that within the tension field, a slot or crack is progressing, and let A be some convenient measure of the extent of this crack. We will further suppose that during the extension of the crack, no plastic deformation occurs except in the immediate vicinity of the "front" of the crack, i.e. at the parts where it is actually extending.

Then denoting by P the elastic strain energy contained in the body at the instant when the crack commences, i.e. when $A = 0$, and denoting by F any external energy supplied by displacement of the loads during the progress of the crack, we may write, for the energy at any instant,

$$E = P + F - U \qquad \ldots\ldots(1)$$

where U is the elastic energy released by the presence of the crack. This differs from the energy P contained initially in the body by the amount,

$$P - (P + F - U) = - F + U \qquad \ldots\ldots(2)$$

This difference is accounted for by conversion to two other forms, i.e. (1) the kinetic energy of the moving parts, denoted by K, and (2) the work done against the resistance offered by the material, including any plastic flow necessary for the extension of the crack, denoted by W. We may therefore write

$$- F + U = W + K \qquad \ldots\ldots(3)$$

$$\text{or} \qquad K = U - W - F$$

With this information we may now examine whether the system is stable or not. If a small extension of the crack increases the "free" kinetic energy K, then the system is unstable. In order to investigate this, we differentiate Eq. 3 with respect to the extent of the crack and find

$$\frac{dK}{dA} = \frac{dU}{dA} - \frac{dW}{dA} - \frac{dF}{dA} \qquad \ldots\ldots(4)$$

If K is increasing (unstable condition), dK/dA must be positive, and we conclude that for instability,

$$\frac{dU}{dA} > \frac{dW}{dA} + \frac{dF}{dA} \qquad \ldots\ldots(5)$$

$$\text{or} \quad \frac{dW}{dA} < \frac{dU}{dA} - \frac{dF}{dA}$$

This is a very general statement of the condition for instability, and is not limited, for instance, to a flat plate, nor to "fixed grip" conditions. In this form it is of little practical value, being merely a truism based on the principle of conservation of energy and on the ordinary criteria for the stability of mechanical systems generally. In order to apply it to actual cases we must evaluate the three terms of Eq. 5 and this is where the main difficulties arise. We are forced to make certain assumptions, chosen so as to agree with experimental evidence, and such evidence is very scanty at present.

Some of the methods suggested for evaluating the three terms have been discussed in Ref. 2 and need not be repeated here, but some general remarks are appropriate. In general, each of the three terms will be a function of A, and probably also of the time-rate of increase of A, i.e. of dA/dt. Some strong indications of this have been given in the literature.[2, 3] In general also, the functions will be different at different parts of the crack front, and will depend upon the properties of the material. This renders the solution very difficult, but ultimately the nature of these functions will have to be established before a full understanding of the fracture phenomenon can be achieved.

The theoretical position is not, however, entirely hopeless. There are some plausible assumptions that can be made which greatly simplify the evaluation. The first of these is that brittle (unstable) fractures progress under "fixed grip" conditions. This means that during the progress of the fracture, the points of application of the loads do not move, so that no external energy is supplied, and $dF/dA = 0$. This immediately reduces the number of terms to be evaluated from three to two, an enormous simplification. This assumption is justified by observation, and seems to arise from the great rapidity with which brittle fractures progress, at least in steel.

A second important assumption that seems justifiable is that soon after its commencement the fracturing settles down to a "steady state." This assumption, originally made for the mechanism close to the active front of the fracture[4] was extended to the study of fracturing of a wide flat plate of uniform thickness.[2] There is at present little direct experimental evidence to justify the "steady state" assumption, but its adoption has led to descriptions which bear a satisfactory resemblance to actual experience.

If both assumptions, i.e. "fixed grip" and "steady state" are adopted, the term dF/dA disappears, and the other three terms in Eq. 4 tend to constant values. This would mean that if the ultimate constant value of dW/dA is always greater than that of dU/dA, unstable fracturing cannot occur.

There remains, however, the difficulty of determining these ultimate values, and little progress has yet been made in this direction. The thought is, however, extremely attractive, and appears to justify experimental work specifically directed to the verification of the "steady state" assumption.

Briefly recapitulating the foregoing, we note that there are two fundamental modes of fracture, shear and cleavage, of which the latter is undesirable and to be avoided. There are also two kinds of fracturing, stable and unstable, of which the latter is undesirable and to be avoided.

It is important here to avoid confusion between modes and kinds. It is easy, and unfortunately common, to confuse shear with stability and cleavage with instability, but such confusions can seriously retard progress. Both shear and cleavage can occur in either a stable or an unstable fracture. There are materials, including some types of steel, in which cleavage cannot occur within the range of ambient temperatures, and yet unstable fracturing can occur in these materials. Unstable fracturing can occur in noncrystalline materials, which are of course incapable of cleavage.

At this point we may revert to Fig. 3 to note that the shear mode is essentially a stable mode, while the cleavage mode is essentially unstable. The converse, however, is not necessarily true, as we have seen.

We may now consider how the undesirable features, cleavage and instability can be recognized, and what can be done to avoid them.

It is fortunate that cleavage can easily be recognized in actual fractures, by examination of the surface texture. Crystals that have broken by cleavage have, when new, a glistening "crystalline" appearance, in contrast to the matt, silky appearance of those which have fractured in the shear mode.

It is not always so easy to recognize instability, but there are several characteristic symptoms, which assist diagnosis. Unstable fractures, as we have seen, occur under the influence of the elastic energy stored in the body, without necessarily any increase in the external loads. They have therefore the features of spontaneity and suddenness. They are usually accompanied by a loud bang, or report, caused by the sudden release of energy. The surfaces of unstable fractures are usually perpendicular to the direction of stress, and are marked with the familiar chevron pattern, the mechanism of which is discussed in Ref. 4.

The distinction between stable and unstable fracturing can be readily recognized if a load deflection diagram can be drawn, as illustrated schematically in Fig. 4.

If, from the point B at which fracturing commences, we draw a sloping line BE, the slope of which is a reflection of the elastic line appropriate to the specimen or structure to which the diagram relates, then the area of the triangle BCE will represent the stored elastic energy at the moment when fracture commences. If, as the test is continued and the fracture extends, the load deflection curve continues in such a way that its slope is never steeper than that of the line BE, the fracturing will be stable, and external energy represented by the area BEF must be supplied. If, however, the slope of the diagram is steeper than that of BE, the fracturing will be unstable, and elastic energy represented by the area BDE will be released. It is this released energy which causes the "loud bang."

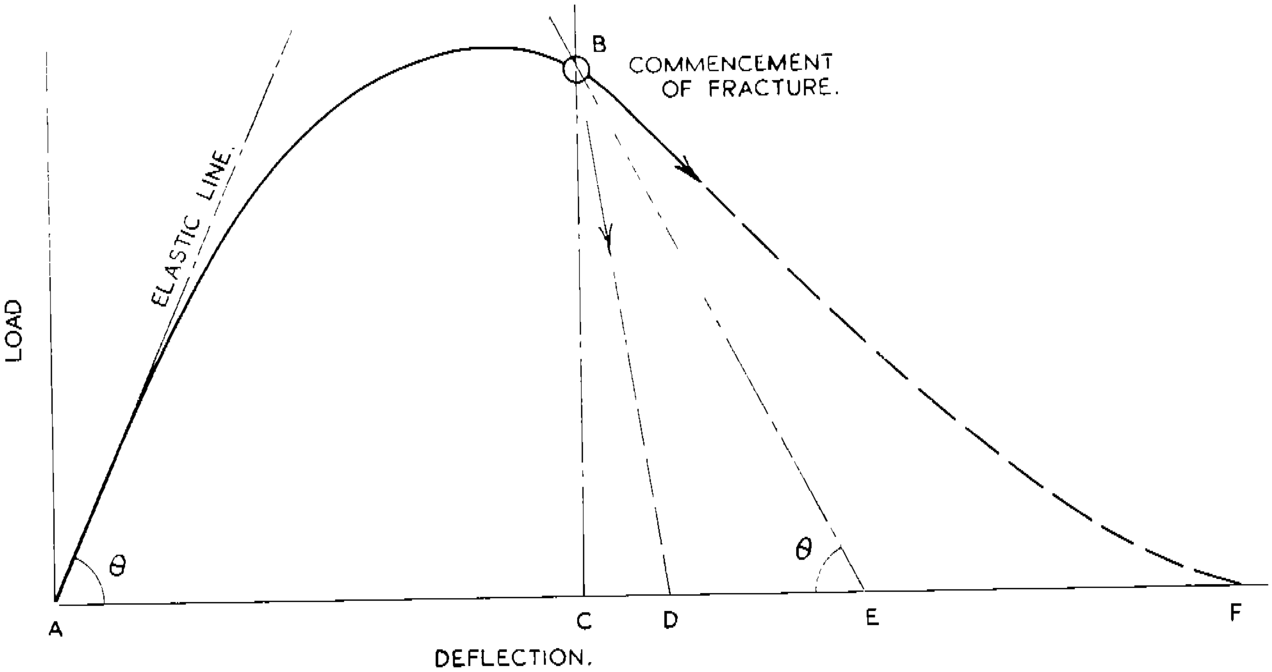

Fig. 4. A Schematic Load-Deflection Curve Indicating the Distinction between Stable and Unstable Fracturing. If the Curve Continues to the Right of the Reflected Elastic Line, BE, such as along BF, the Fracture will be of a Stable Kind, but if the Curve Continues to the Left of BE, the Fracture will be Unstable.

The area BCF (for stable fracture) or BCD (for unstable fracture) represents the energy absorbed in actual fracturing, i.e., the work done in overcoming the resistance offered by the material to the propagation of fracture.

This area is usually greater than BCE for stable fracturing, and less than BCE for unstable fracturing, but this is not the essential feature, since the fracture may commence in a stable manner and later become unstable, or vice versa. The essential feature is the slope of the load extension diagram at any stage.

It is not difficult to see, in reference to Fig. 4, that the area BCE may be large enough to accommodate a considerable percentage of crystals fracturing by shear, and conversely that the area BCF may not be diminished to the point of instability even if a considerable proportion of the crystals fracture by cleavage. Indeed, in actual experience, mixed shear and cleavage have been observed in fractures of both the stable and unstable kinds.

Recapitulating, we can recognize the undesirable mode, cleavage, by examination of the texture of the fracture surface, and we can recognize the undesirable <u>kind</u> by examination of the load-extension diagram, beyond the point at which fracture commences.

INITIATION OF UNSTABLE FRACTURING

Dr. Tipper[5] has pointed out that unstable (brittle) fracturing in steel occurs in an intermittent manner. Within the solid material, in advance of the main fracture front, groups of crystals fracture by cleavage, forming internal disc-shaped cracks, which rapidly expand and coalesce with the main fracture.[4] Near the point of coalescence, the "bridges" of solid material may break down by shear, resulting in a "mixed" fracture. This may be regarded as the third of the fundamental observations.

This behaviour may be understood, in terms of stresses, as follows. Even at the root of the sharpest notch, the principal stress normal to the surface must be zero, and the other two principal stresses must be different from each other. This gives rise to a stress condition which favours shear fracture and is inimical to cleavage. However, within the solid material, beyond the root of the notch, the conditions are such that all three principal stresses are nearly equal, i.e., a triaxial stress state which favours cleavage and inhibits shear. If the stress level in this triaxial region is above the critical value necessary for cleavage, an internal crack of the kind observed by Dr. Tipper will occur. At this point, however, the stress level must be considerably lower than the main principal stress at the surface of the notch root.

It is difficult to understand how a sufficiently high stress can arise in the triaxial region to cause cleavage while the surface is still in a yielding condition, unless the yield point is raised very considerably. Orowan[6, 7] has pointed out three factors that can raise the yield point, i.e. work hardening, elastic superstressing, and high rate of strain. All these factors probably operate in a rapid unstable fracture, but at the origin, only the first two can be operative. Orowan has estimated that these two can raise the yield point by a factor of three, which is probably enough to account for the observed discrepancy, and other factors may also operate near the origin, such as local embrittlement and impact.[2]

At this point it seems appropriate to dwell on the vexing question of the distinction between initiation and propagation, which has aroused considerable controversy. We consider first the sequence of events, with the aid of Fig. 5. In this diagram, the upper part represents the edge of a wide plate, in which there is a slot, or notch from which a fracture starts and progresses. The lower part of the diagram is a schematic plotting versus crack length of the strain energy released per unit crack length dU/dc and of the work done per unit crack length dW/dc.

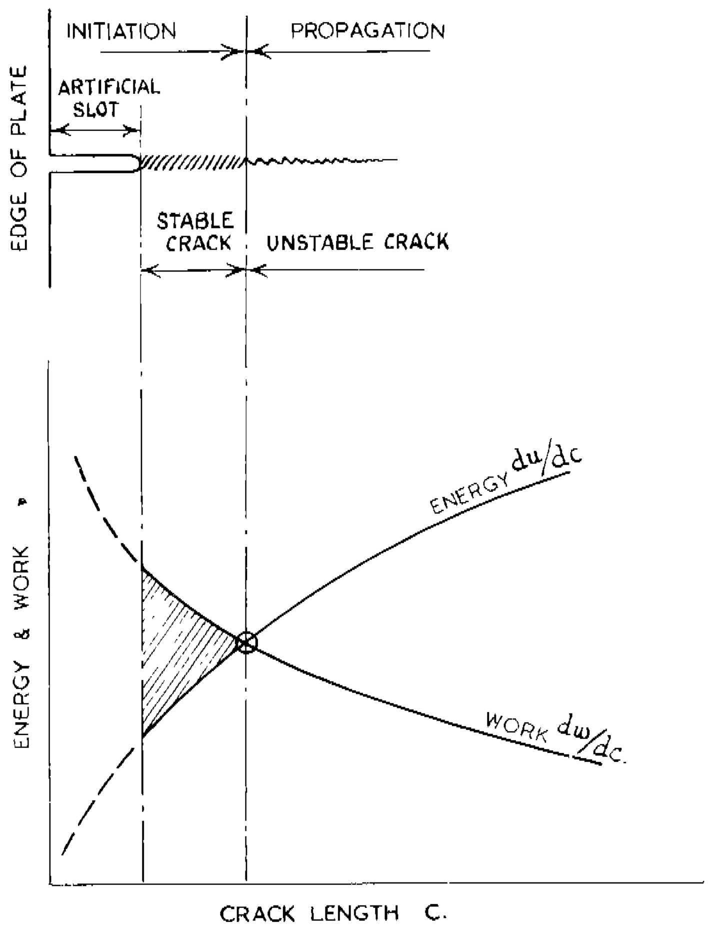

Fig. 5. Schematic Diagrams to Determine the Initiation and Propagation Stages of Fracture.

As the tension across the notch is increased, the notch will open up, and a stable crack will form and extend slowly, while dU/dc increases. At some crack length, dU/dc may become greater than dW/dc, and if so, an unstable crack will ensue. If this does not occur, the crack will continue to extend in a stable manner. We note that during the extension of the stable crack, external energy, represented by the shaded area in the diagram, must be supplied, and we may agree to call this the "initiation energy" and to regard it as a barrier which must be surmounted before instability can occur.

On this basis, we must regard the events prior to instability as the "initiation stage." Correspondingly we must regard the events subsequent to the onset of instability as the "propagation stage." It is not so easy to define "propagation energy" in these terms, since after the instability point there is indeed a surplus of energy. We might, however, think of the area under dW/dc curve as "propagation energy" in the sense that it represents the resistance to the propagation of the unstable fracture. This, however, is not very helpful, since it is, by definition, insufficient to prevent propagation.

From this discussion we can see that the terms "resistance to initiation" and "resistance to propagation" cannot denote precise concepts. It may be as a result of this lack of precision that the controversy has been inconclusive.

SELECTION OF A TEST

Reviewing what has been said, it can be seen that while the fundamentals can be fairly well understood, the relevant quantities such as stresses, strains, energies and so on, cannot yet be evaluated satisfactorily. In particular, there does not seem to be any reliable method for measuring dU/dA or dW/dA, yet these are the quantities which govern the onset of brittle fracture.

In these circumstances, the engineer has no other recourse than to resort to empirical methods. These, however, must be soundly based, and related to the known fundamental facts, as well as to experience in the field.

The first essential for an empirical approach is to devise a test by which the susceptibility of a material to unstable fracturing can be assessed. The quest for such a test has absorbed a great deal of effort, and generated enormous controversy, due partly to confusions of the kind mentioned in the introduction, and partly to conflicts of interest.

In choosing, or devising, such a test, there seem to be two basic requirements. Firstly, the test must take account of the fundamental facts that have been discussed, and secondly, it must enable judgments to be made which will reduce the risk of brittle fractures in service. A third feature, of relatively less importance, is that it should preferably be easy to carry out under day-to-day test house conditions. Another feature, the importance of which is often under-estimated, is that it should be acceptable to a sufficiently large body of technical opinion, and to the many vested interests concerned. It is to be remembered also that any test consists of two distinct parts, namely, the physical nature of the test, and the criterion by which its results are to be interpreted.

Taking all these conditions into account, it is probable that the Charpy V-notch impact test is the best practical compromise available today. It is well known, widely accepted, comparatively easy to carry out, and its high rate of straining is comparable with that which probably occurs in the unstable fractures observed in service. The test has several unsatisfactory features, but these seem to be outweighed, and therefore it is desirable to consider what criterion should be used in judging its results.

Remembering the two modes of fracture, shear and cleavage, and the two kinds, stable and unstable, and accepting that cleavage and instability are the undesirable characteristics, we may consider how they can be recognized in this test. There are two possible ways in which this can be done. In the first place, cleavage can be recognized by an examination of the fractured surface, and in the second place, the character of the load-deflection diagram can, at least theoretically, be studied in the manner discussed earlier.

If a load-deflection diagram is plotted for a notched bend test, such as the Charpy test, its characteristics are found to be as indicated diagrammatically in Fig. 6, which will be recognized as similar to Figs. 3 and 4. Such diagrams have actually been produced for fast[8] and slow[9] notched bend tests.

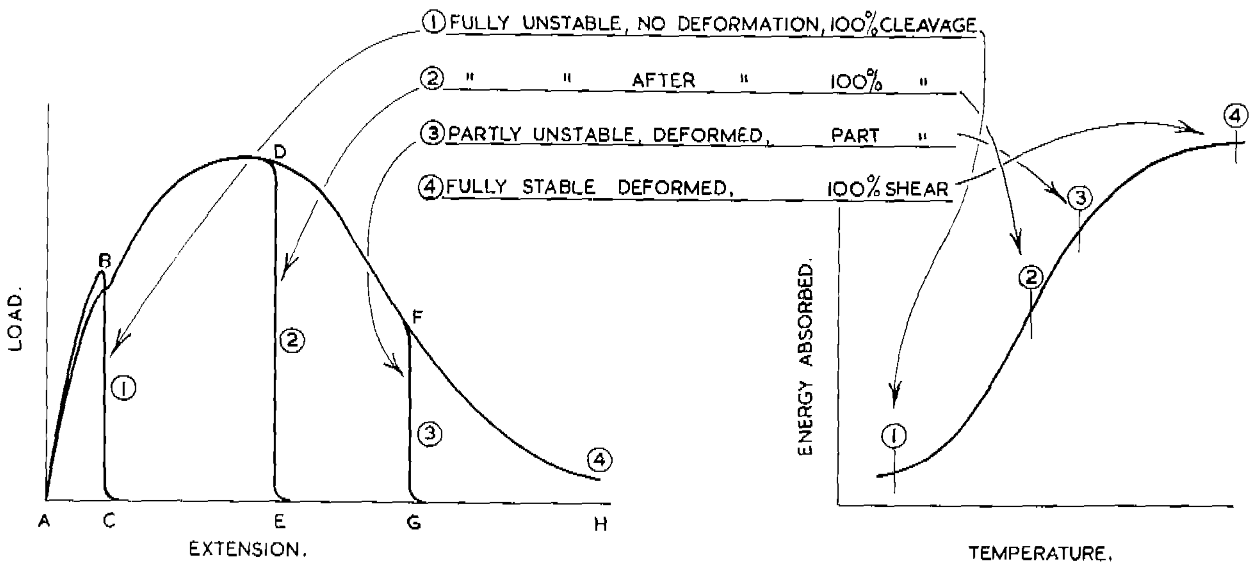

Fig. 6. Schematic Diagrams Representing Successive Charpy Tests on the Same Material at Different Temperatures.

This diagram (Fig. 6) may be taken as representing, in schematic form, successive Charpy tests on the same material at different temperatures. It will be seen that the general shape of the envelope curve is constant, apart from minor deviations that need not concern us here, but the vertical parts BC, DE, etc. occur at different stages, depending on the temperature, being nearer to the origin at the lower temperatures. These vertical parts are indicative of instability, or brittleness, and are reflected in the character of the fracture by the percentage of crystallinity.

Naturally, the nearer the vertical part is to the origin, the greater is the "brittleness," and it is therefore natural that such proximity to the origin should be a factor in judging the results.

In practice it is not feasible to record load-deflection diagrams for the Charpy test, but the total energy absorption, represented by the area under the load-deflection diagram can be measured. In general this area gives very little information regarding the shape of the curve, but it is easy to see that the greater the energy the more probable it is that the fracture was a stable one, or at least that instability had occurred at a later stage. This inference, however, can only be reliable if we have some information regarding the shape of the envelope curve for the steel considered, or alternatively if we know the energy absorptions for the same steel at a sufficient number of temperatures covering the range from fully stable to fully unstable.

It was thought until quite recently that for a given type of steel there was a simple relationship between energy absorption and crystallinity, whereby the latter could reasonably be inferred from the former. However, a study of a wide variety of steels has shown that this relationship, if it exists, is very unsatisfactory.

Fig. 7 shows the relationship found between energy and percentage

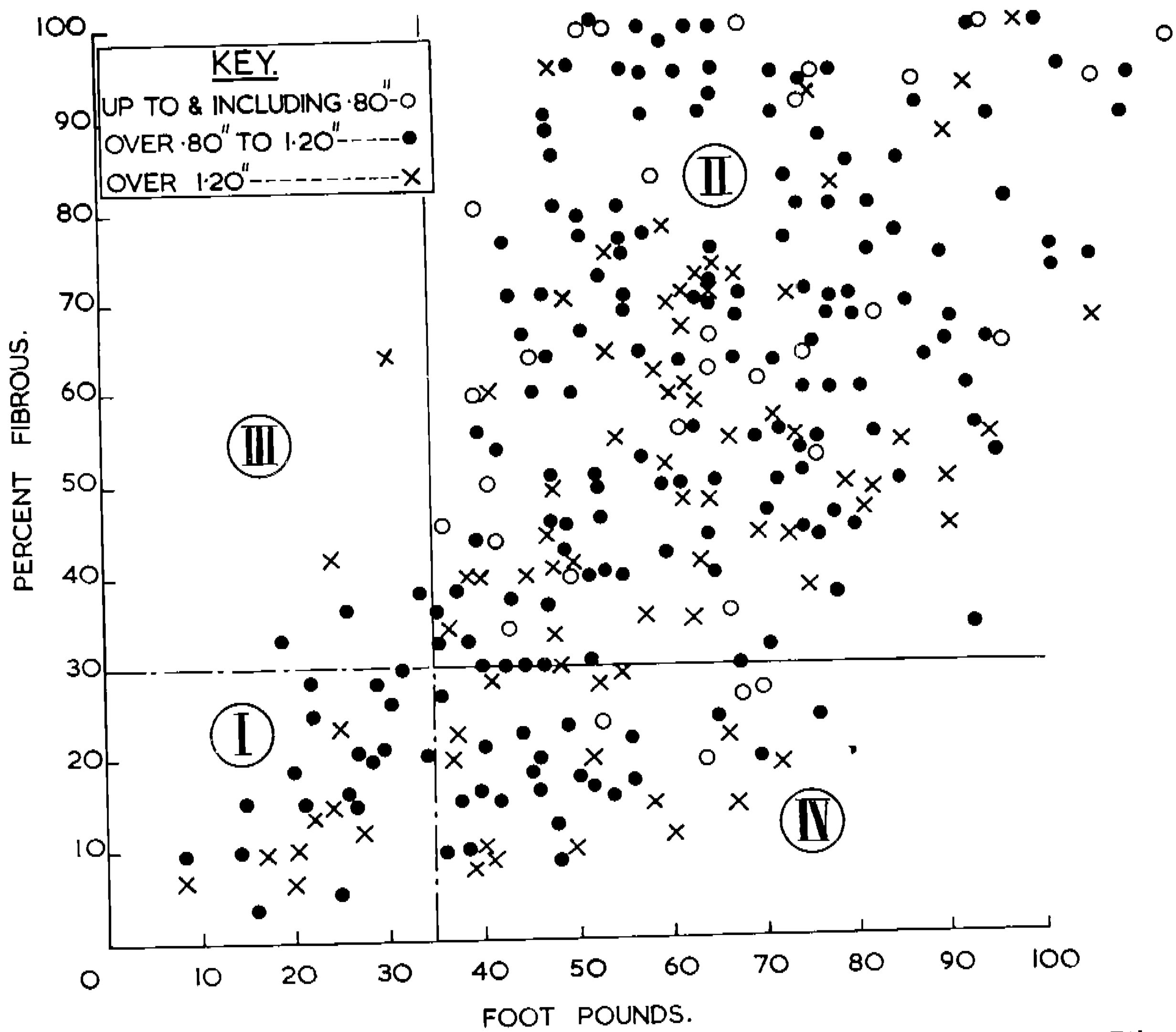

Fig. 7. A Graph Showing the Relationship between Energy and Percentage Fibrous in the Charpy Test at 0°C for a Large Number of Samples of Ship Steel that had the Same Requirements for Tensile Strength.

fibrous in the Charpy test at 0°C for a large number of samples of ship steel, all meeting the same requirements for tensile strength. It can be seen that the relationship is very poor. This might have been expected from what has been said in relation to Fig. 6 bearing in mind the considerable variations to be expected in the envelope curves for different steels, even when they are of similar static tensile strengths.

In these circumstances, it is clear that if we are to adopt the Charpy V-notch test, without making load-deflection diagrams, we have two alternative methods of interpretation, i.e.,

(1) We can observe the energy absorptions over a sufficient range of temperature, and infer from the shape of the resulting curve the temperature at which an undesirable degree of instability becomes apparent, or

(2) We can observe the percentage of crystallinity at the lowest temperature to be expected in normal service, and limit this to a certain maximum. Clearly, with this alternative it is desirable to observe the energy absorption at the chosen temperature, and to limit this to a certain minimum.

Of these two alternatives, the second requires the least number of tests, and a minimum of temperature control. Neither alternative is entirely satisfactory, because in the first place the test itself is probably not truly representative of the conditions to be expected in actual structures, and in the second place, neither of the alternatives provides a direct measure of instability. The percentage of crystallinity is probably the nearest approach to such a measure, since it indicates the extent to which cleavage enters into the process of fracturing in this test at the chosen temperature.

EMPIRICAL MEASURES

On the basis of reasoning similar to that outlined here, combined with exhaustive studies of data from service experience, Lloyd's Register of Shipping recently amended its Rules for Ship Steel to include, for certain applications, a Charpy V-notch test at 0°C with a minimum energy 35 ft-lbs and a maximum of 70% crystallinity.

The bulk of the service data on which this decision was based has been published,[10] and is summarized in Fig. 8. In this plotting, the upper two

TESTS ON CASUALTY MATERIAL.

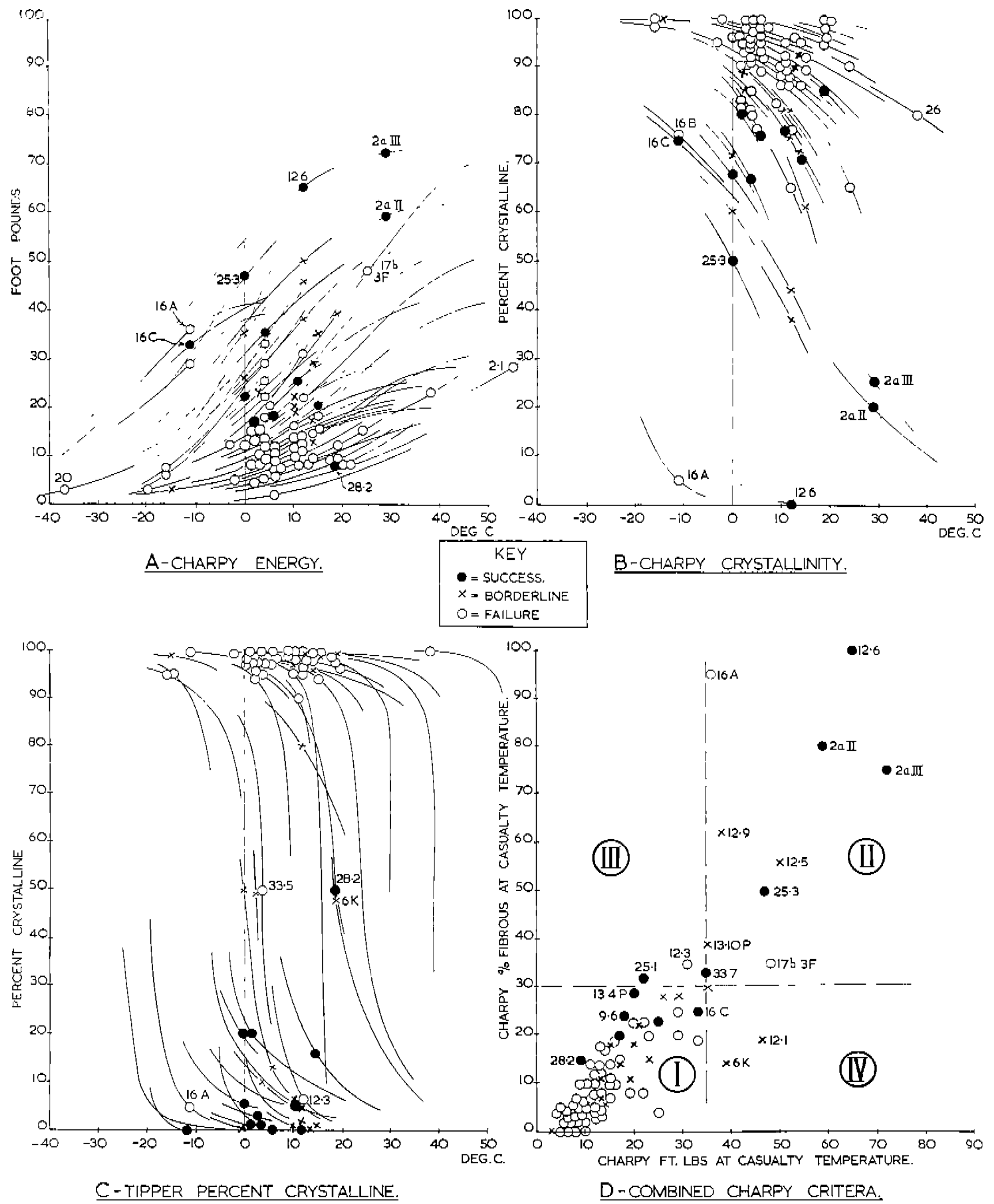

Fig. 8. Data from Various Tests on Ship Casualty Material.

diagrams, A & B, indicate respectively, the Charpy energy and crystallinity curves, versus temperature, for a considerable number of plates involved in service fractures. On each curve, a symbol is placed at the relevant casualty temperature, indicating the "category" assigned to each plate according to the following simple scheme:

"Success" plates (black circles) are those which fractured in a ductile (stable) manner, or in which a brittle (unstable) fracture originating outside the plate was arrested.

"Failure" plates (open circles) are those which were completely traversed by a brittle fracture.

"Borderline" plates (crosses) are those which cannot be classified in either of the above groups.

Considering the energy curves (Fig. 8A) it is difficult to choose an energy level at any temperature which would satisfactorily separate the "successes" from the "failures," bearing in mind the shapes of the curves. Considering the crystallinity curves (Fig. 8B) the position is a little better. If, for example, a maximum of 80% crystallinity at 0°C were applied, the separation would be fairly satisfactory.

It was considered, however, that both energy and crystallinity should be taken into account at a temperature of 0°C, which temperature was chosen partly for its significance in relation to service, and partly for its reproducibility under test house conditions.

With this in view, the data was replotted as shown in Fig. 8D from which it can be seen that if a minimum energy of 35 ft-lbs is combined with a maximum of 70% crystallinity (30% fibrous) the separation between "successes" and "failures" is fairly good. These requirements were then examined from the point of view of availability of acceptable steels. It was found (see Fig. 7) that an adequate percentage of available steels would comply, and the requirements were accordingly incorporated in the Rules, after the usual process of discussion in Committee.

In view of the fact that the significance of fracture appearance had not until then been widely appreciated, and that steelmakers had as yet little experience in the application of such a criterion under production conditions, it was agreed to suspend the crystallinity clause for a period during which further data will be accumulated.

OTHER FORMS OF TEST

Many different forms of tests have been suggested to enable the tendencies to brittleness to be estimated. Most of these rely, explicitly or implicitly, upon the detection of either cleavage, or instability as a function of temperature. In particular, the Navy Tear Test[11] investigates the energy absorption before and after fracture commences. The former is found to be practically constant over a wide temperature range, while the latter (post crack energy) undergoes a sharp transition, indicating that at some temperature instability supervenes. In the van der Veen slow notch bend test[9] instability is judged directly from the character of the fracture, or from a load-deflection diagram. This also applies to the Tipper notched tensile test[12] in which the main criterion is the percentage of crystallinity in the fracture, which undergoes a sharp transition when the temperature is lowered. This test was used quite extensively in studying the service fractures referred to,[10] with results which are plotted in Fig. 8C. It can be seen that this test clearly separates "successes" from "failures," with very few exceptions.

The Robertson test[13] studies the normal stress and temperature at which instability ceases, i.e. at the point where an unstable fracture is arrested. This test is also found to correlate fairly well with service experience[10] although the amount of available data is somewhat scanty.

The Pellini drop-weight nil-ductility transition temperature[14] is related to instability, and refers to the temperature at which "ductility" virtually disappears, and the fracture is completely unstable. This point is analogous to the vertical line BC in Fig. 6, which corresponds to the lower limb of the Charpy energy versus temperature curve. It has been shown[14, 15] that above this "NDT" temperature, the initiation of unstable fractures becomes progressively more difficult. Unfortunately, little data relating this criterion to service behaviour is available in the U. K., and the test was not used in the investigation of the cases reported in Ref. 10.

Closely related to the NDT transition is the 15 ft-lb transition temperature in the Charpy V-notch test. This criterion, which has been strongly advocated, is not strictly speaking a "transition" temperature, since the energy-temperature curve does not usually show any marked change at the 15 ft-lb level. It is, however, related to the lower limb of this curve, and may be taken to represent a temperature at which most steels would be prone to instability. The difficulty in accepting such a criterion is that it represents virtually the temperature at which the material is fully brittle, and of itself it gives no indication of how much higher the energy ought to be to ensure adequate safety. As Admiral Cowart put it in 1951:

> "There is a danger of brittle fracture in ship steel when, in a standard V-notch Charpy impact test the energy absorption is less than 15 ft-lb at a temperature of 60°F. It is not known, however, how much greater the notch toughness of the steel must be to remove the danger of brittle fracture.[16]

The position seems to be very similar today. It can be seen from Fig. 8A that it would be difficult to assign a 15 ft-lb transition which would satisfactorily separate "failures" from "successes."

While all these criteria have their merits and demerits, the main overriding factor affecting their adoption is that which has been mentioned, i.e., their acceptability to a wide enough body of opinion. This factor may, of course, be expected to change with the increasing accumulation of facts, so that the decisions taken at the present time may well require eventual amendments.

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