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Fracture Mechanics, Fracture Criteria and Fracture Control for Welded Steel Ship Hulls

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ABSTRACT

This paper describes a comprehensive toughness criteria for welded ship hulls that can be used for shipbuilding steels of all strength levels. Because of the fact that stress concentrations are always present in large complex welded structures such as ships, high local stresses as well as discontinuities or flaws will be present in welded ship hulls. Therefore, primary emphasis in the proposed fracture-control guidelines is placed on the use of steels with moderate levels of notch-toughness and on the use of properly designed crack arresters. However, the importance of proper design and fabrication should be emphasized.

In general, concepts of fracture mechanics are used to develop the material toughness level that is required for fail-safe operation of welded ship hulls. This toughness level is estimated to be K_{ID}/σ_{yD} level of 0.9 at 32°F (0°C), where K_{ID} is the critical material toughness under conditions of dynamic loading and σ_{yD} is the yield strength of the material under the same dynamic loading. The assumption that ships are loaded dynamically is made because little information on loading rates existed at the time of this study and ships are basically single-load path structures. Hence the assumption of dynamic loading is conservative and needs to be studied further, in view of the excellent service history of welded steel ships.

Because the desired level of toughness cannot be measured directly using current fracture mechanics tests, the requirements are established in terms of the NDT (nil-ductility transition) temperature and DT (dynamic tear) test values for base metal, weld metal, and heat-affected-zone materials used in primary load-carrying members.

Although the criteria presented in this paper are primarily material specifications, the importance of proper design (avoiding details that lead to stress concentrations) and proper fabrication (good quality welding and inspection) is emphasized.

In general, the results of this investigation have developed conservative material-toughness requirements for ship steels of all strength levels which, in combination with properly designed crack arresters, should result in rational fracture-control guidelines that will minimize the probability of brittle fractures in welded ship hulls consistent with economic realities.

GENERAL PROBLEM OF BRITTLE FRACTURE IN SHIPS

Although welded ship failures have occurred since the early 1900's, it was not until the large number of World War II ship failures that the problem was fully appreciated[1])*. Of the approximately 5,000 merchant ships built during World War II, over 1,000 had developed cracks of considerable size by 1946. Between 1942 and 1952, more than 200 ships had sustained fractures classified as serious, and at least nine T-2 tankers and seven Liberty ships had broken completely in two as a result of brittle fractures. The majority of fractures in the Liberty ships started at square hatch corners or square cutouts at the top of the sheerstrake. Design changes involving rounding and strengthening of the hatch corners, removing square cutouts in the sheerstrake, and adding riveted crack arresters in various locations led to immediate reductions in the incidence of failures[2]). Most of the fractures in the T-2 tankers originated in defects in bottom shell butt welds. The use of crack arresters and improved workmanship reduced the incidence of failures in these vessels.

Studies indicated that in addition to design faults, steel quality also was a primary factor that contributed to brittle fracture in welded ship hulls[3]). Therefore, in 1947, the American Bureau of Shipping introduced restrictions on the chemical composition of steels and in 1949, Lloyds Register stated that "when the main structure of a ship is intended to be wholly or partially welded, the committee may require parts of primary structural importance to be steel, the properties and process of manufacture of which have been specially approved for this purpose[4])."

In spite of design improvements, the increased use of crack arresters, improvements in quality of workmanship, and restrictions on the chemical composition of ship steels during the later 1940's, brittle fractures still occurred in ships in the early 1950's[5]). Between 1951 and 1953, two comparatively new all-welded cargo ships and a transversely framed welded tanker broke in two. In the winter of 1954, a longitudinally framed welded tanker constructed of improved steel quality using up-to-date concepts of good design and welding quality broke in two[6]).

During the 1950's, seven Classification Societies responsible for the classification of ships (American Bureau of Shipping, Bureau Veritas, Germanischer Lloyd, Lloyd's Register of Shipping, Nipon Kaiji Kyokai, Det Norske Veritas, and Registro Italianno Navale) held numerous meetings and in 1959 published the Unified Requirements for Ship Steels[4]). These requirements specified various manufacturing methods, chemical composition, or Charpy V-Notch impact requirements for five grades of steel.

Since the late 1950's (although the actual number has been low) brittle fractures have still occurred in ships as indicated by Boyd's description of ten such failures between 1960 and 1965 and a number of unpublished reports of brittle fractures in welded ships since 1965[7]), as well as the brittle fracture that occurred in the Ingram Barge in 1972.

Therefore, although it has been approximately 30 years since the problem of brittle fracture in welded ship hulls was first recognized as a significant problem for the ship-building industry, brittle fractures still occur in ships. While it is true that during this time considerable research has led to various changes in design, fabrication, and materials so that the incidence of brittle fractures in welded ship hulls has been reduced markedly[8]), nonetheless, brittle fractures continue to occur in welded ship hulls fabricated with ordinary-strength steels. With the use of higher-strength steels, there is a definite concern that brittle fractures may occur in these steels also.

* See References

Currently there are no specific fracture-control guidelines or overall toughness criteria available for the practicing naval architect to specify in designing welded steel ship hulls of all strength levels. Therefore, the purpose of this paper is to provide rational fracture-control guidelines consistent with economic realities which, when implemented, will minimize the probability of brittle fractures in welded ship hulls. Although the fact is rarely stated, the basis of structural design in all large complex welded structures is an attempt to optimize the desired performance requirements relative to cost considerations (materials, design, fabrication) so that the probability of failure (and its economic consequences) is low.

For reasons developed in the following sections, the guidelines are primarily material oriented. This does not relieve the naval architect of responsibility for good ship design, but recognizes the fundamental importance of using good quality structural steels in large complex welded structures.

GENERAL PROBLEM OF BRITTLE FRACTURE IN WELDED STRUCTURES

An overwhelming amount of research on brittle fracture in welded steel structures has shown that numerous factors (e.g., service temperature, material toughness, design, welding, residual stresses, fatigue, constraint, etc.) can contribute to brittle fractures in large welded structures such as ship hulls[5-16]). However, the recent development of fracture mechanics[16-20]) has shown that there are three primary factors that control the susceptibility of a structure to brittle fracture. These three primary factors are:

1) <u>Material Toughness</u> (K_c, K_{Ic}, K_{ID})

Material toughness can be defined as the ability to deform plastically in the presence of a notch and can be described in terms of the static critical stress-intensity factor under conditions of plane stress (K_c) or plane strain (K_{Ic}). K_{ID} is a widely accepted measure of the critical material toughness under conditions of maximum constraint (plane strain) and impact-loading. In addition to metallurgical factors such as composition and heat treatment, the notch toughness of a steel also depends on the application temperature, loading rate, and constraint (state-of-stress) ahead of the notch as discussed in the Appendix.

2) Flaw Size (a)

Brittle fractures initiate from flaws or discontinuities of various kinds. These discontinuities can vary from extremely small cracks within a weld arc strike, (as was the case in the brittle fracture of a T-2 tanker during World War II) to much larger weld or fatigue cracks. Complex welded structures are not fabricated without discontinuities (porosity, lack of fusion, toe cracks, mismatch, etc.), although good fabrication practice and inspection can minimize the original size and number of flaws. Thus, these discontinuities will be present in all welded ship hull structures even after all inspections and weld repairs are finished. Furthermore, even though only "small" flaws may be present initially, fatigue stressing can cause them to enlarge, possibly to a critical size.

3) Stress Level (σ)

Tensile stresses, (nominal, residual, or both) are necessary for brittle fractures to occur. The stresses in ship hulls are difficult to analyze because ships are complex structures, because of the complexity of the dynamic loading, and because of the stress concentrations present throughout a ship which increase the local stress levels. The probability of critical regions in a welded ship hull being subjected to dynamic yield stress loading (σ_{yD}) is fairly high, particularly in regions of stress concentrations where residual stresses from welding may be present.

All three of these factors must be present for a brittle fracture to occur in structures. All other factors such as temperature, loading rate, residual stresses, etc. merely affect the above three primary factors.

Engineers have known these facts for many years and have reduced the susceptibility of structures to brittle fractures by applying these concepts to their structures qualitatively. That is, good design (lower stress levels by minimizing discontinuities) and fabrication practices (decreased flaw size because of proper welding control), as well as the use of materials with good notch-toughness levels (e.g., as measured with a Charpy V-notch impact test) will and have minimized the probability of brittle fractures in structures. However, the engineer has not had specified design guidelines to evaluate the relative performance and economic tradeoffs between design, fabrication and materials in a quantitative manner.

The recent development of fracture mechanics as an applied science has shown that all three of the above factors can be interrelated to predict (or to design against) the susceptibility of a welded structure to brittle fracture. Fracture mechanics is a method of characterizing fracture behavior in terms of structural parameters familiar to the engineer, namely, stress and flaw size. Fracture mechanics is based on stress analysis and thus does not depend on the use of empirical correlations to translate laboratory results into practical design information. Fracture mechanics is based on the fact that the stress distribution ahead of a sharp crack can be characterized in terms of a single parameter K_I, the stress-intensity factor, having units of ksi$\sqrt{\text{inch}}$ (MN/$m^{3/2}$). Various specimen geometries have been analyzed, and theoretical expressions for K_I in terms of applied stress and flaw size have been developed. Three examples are presented in Figure 1. In all cases, K_I is a function of the nominal stress and the square root of the flaw size. By knowing the critical value of K_I at failure, K_c, for a given steel of a particular thickness and at a specific temperature and loading rate, the designer can determine flaw sizes that can be tolerated in structural members for a given design stress level. Conversely, he can determine the design stress level that can be safely used for a flaw size that may be present in a structure.

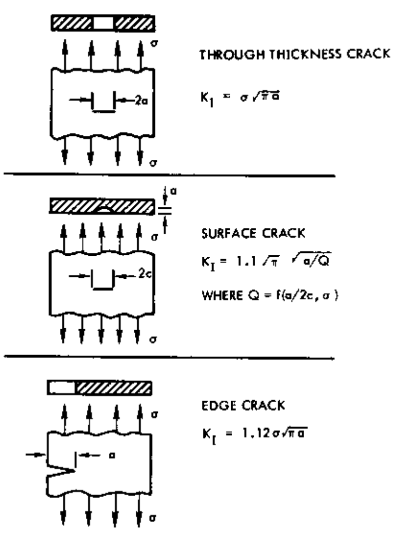

FIG. 1. K_I Values for Various Crack Geometries

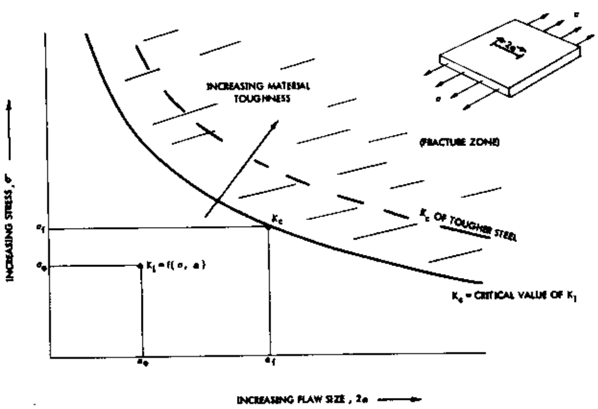

FIG. 2. Schematic Relation Between Stress, Flaw Size, and Material Toughness

This general relation is presented in Figure 2 which shows the relationship between material toughness (K_c), nominal stress (σ), and flaw size (a). If a particular combination of stress and flaw size in a structure (K_I) reaches the K_c level, fracture can occur. Thus there are many combinations of stress and flaw size (e.g. σ_f and a_f) that may cause fracture in a structure that is fabricated from a steel having a particular value of K_c at a particular service temperature, loading rate, and plate thickness. Conversely, there are many combinations of stress and flaw size (e.g., σ_o and a_o) that will not cause failure of a particular steel. A brief development and numerical example of the concepts of fracture mechanics is presented in the Appendix.

At this point, it should be emphasized that (fortunately) the K_c levles for most steels used in ship hulls are so high that they cannot be measured directly using existing ASTM standardized test methods. Thus, although concepts of fracture mechanics can be used to develop fracture-control guidelines and desirable toughness levels, the state of the art is such that actual K_c values cannot be measured for most ship hull steels at service temperatures. As will be described later, this fact dictates that auxiliary test methods must be used to insure that ship hull materials perform satisfactorily under service conditions.

DEVELOPMENT OF SPECIFIC FRACTURE-CONTROL CRITERIA FOR WELDED STEEL SHIP HULLS

General

In the previous chapter, concepts of fracture mechanics were introduced as the best method for developing fracture-control guidelines for welded steel structures. In this chapter, fracture-mechanics concepts are used to develop specific criteria to prevent catastrophic fractures in welded steel ship hulls. Concepts of fracture mechanics are emphasized rather than linear elastic fracture mechanics used in existing ASTM test methods because steels for ship hulls should have higher toughness levels than can currently be measured using ASTM specification test methods.

Service Conditions

A review of current practice of designing ship hulls indicates that the actual loadings are not well known[21,22]). Therefore, general rules of proportioning the cross section of ships have been developed, primarily on the basis of experience. Recent developments in analytical techniques and actual measurements of ship loadings have led to improvements in the understanding of the structural behavior of ships[23]). However, the design of ship hulls is primarily an empirical proportioning based on satisfactory past experience rather than a systematic analytical design and therefore calculated design stresses for specific sea states are rarely found.

Strain measurements on actual ships have indicated that the maximum veritical wave-bending-stress excursion (peak-to-trough) ever measured was about 24 ksi (165 MN/m^2). Also the maximum bending stress for slender cargo liners is about 10 ksi (69 MN/m^2) and for bigger ships such as tankers and bulk carriers, about 14 ksi (97 MN/m^2) [22,24]). Therefore, 14 ksi (97 MN/m^2) appears to be a reasonable maximum nominal stress level in ship hulls. Although this stress is less than one-half the yield stress of most ship hull steels, the local stress at stress concentrations reaches the yield strength level, particularly when the additional effects of residual stress are considered. Furthermore, because of the particular nature of ship hull loadings and the number of brittle fractures that have occurred in service, it is reasonable (and conservative) to assume that ships can be loaded under impact conditions, i.e., the loads can be applied rapidly enough so that the dynamic yield stress is reached. As discussed in the Appendix, the dynamic yield stress under impact loading is approximately 20 ksi (138 MN/m^2) higher than the static yield stress as measured in standard tension tests. The actual loading rate for ship hulls is probably between the limits of "static" loading (strain rate approximately $10^{-5} sec^{-1}$) and dynamic or impact loading (strain rate approximately $10 sec^{-1}$). However, in view of the general service behavior of ships, and the lack of information on specific loading rates, the conservative assumption that ships are loaded dynamically is made.

It should be emphasized that the material toughness requirements developed in this report would be changed significantly if an "intermediate" loading rate were assumed for ship hull structures rather than a dynamic loading rate. For purposes of comparison, bridge structures are assumed to be loaded at an intermediate loading rate and their material toughness requirements are less stringent than those developed in this paper.

Studies have shown that ships operate at temperatures less than 32°F (0°F) only about 3% of the time, Figure 3[25]. Therefore, a design service temperature of 32°F (0°C) for welded steel ship hulls appears realistic. For special applications, such as icebreakers, the design service temperature should be lower.

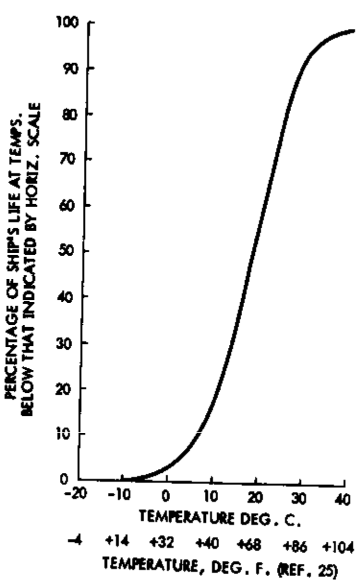

FIG. 3. Distribution of Service Temperature for Ships (Ref. 25).

Therefore, from a fracture-control standpoint, the probability is high that critical regions in welded ship hulls can be subjected to impact loadings at 32°F (0°C) such that the dynamic yield stress of the material can be reached. Thus, the use of dynamic fracture parameters, K_{ID}/σ_{yD} (see Appendix), rather than static fracture parameters, K_{Ic}/σ_{ys}, is justified, although it should be emphasized that this is a conservative assumption, particularly in view of the excellent service experience of welded steel ships.

Required Performance Characteristics

Previously, it has been shown that brittle fractures occur because of particular combinations of material toughness, flaw size, and tensile stresses. If this basic principle is combined with the realistic fact that the stress level in critical parts of a ship hull will reach yield stress magnitude and that flaws or discontinuities will be present in the hull, the naval architect is faced with three possible solutions to prevent catastrophic brittle fractures in ships[26]:

1) Develop multiple-load paths within the hull so that failure of any one part of the cross section does not lead to total failure of the ship. Although this solution is satisfactory for other types of welded structures such as stringer-type bridges with concrete decks, it does not appear to be feasible for monolithic welded steel ship hulls-

2) Use extremely notch-tough steels so that no brittle fractures can initiate or propagate, even at very high stress levels. Although this solution would eliminate the problem of brittle fracture in welded steel ship hulls, it is economically unfeasible because such extreme levels of notch toughness actually are not required. Furthermore, even notch-tough materials can fail if the loading is severe enough.

2) Provide a fail-safe design using steels with moderate levels of notch-toughness in combination with properly designed crack-arresters, so that even if a crack initiates, it will be arrested before catastrophic failure occurs.

The fundamental problem in a realistic fracture-control plan for welded ship hulls is to optimize the above possible performance criteria with cost considerations so that the probability of complete structural failure due to brittle fracture in welded ship hulls is very low. In that sense, the toughness criterion proposed in this report is an attempt to optimize satisfactory performance with reasonable cost, following a fail-safe philosophy.

Thus, the third solution, namely the use of steels and weldments with moderate levels of notch toughness combined with properly designed crack arresters, is recommended as a fracture criterion for welded ship hulls.

In line with this general fracture-control plan, the following items are noted.

1) As has been well documented during the past 30 years, the definite possibility of brittle fracture in welded ship hulls exists because welded ship hulls are complex structures that can be subjected to local loading of yield point magnitude at temperature as low as 32°F (0°C). The assumption of dynamic loading is made to be conservative and because ships are generally single-load path structures. That is, if a fracture initiates, it will continue to propagate unless arrested, because the structure is continuous around the hull.

2) Because of current limitations in fabrication practice and inspection at shipyards, a large probability exists that large undetected flaws (e.g., equal to ½ the plate thickness) will be present at some time during the life of welded ship hulls. Even "with" improvements in control of welding quality during fabrication, some discontinuities will still be present prior to the service life of the structure and fatigue may cause these discontinuities to grow in size during the life of the structure. Thus, it is assumed that flaws are present in all welded ship hulls.

3) The naval architect generally does not have absolute control over the fabrication of a welded ship hull. Thus, he should establish material and design controls during the design process that are adequate to prevent the occurrence of brittle fractures in welded ship hulls. Although the designer tries to avoid details that act as stress raisers, this is an impossible task in large complex welded structures. Hence, the emphasis in this fracture-control plan is on the choice of proper materials (toughness specifications for steels and weldments) and design (proper use of crack arresters), even though quality fabrication and inspection of welds are extremely important.

4) Although specifying solely the metallurgy and manufacturing process, including composition, deoxidization practice, heat treatment, etc., has been one method of controlling the level of notch toughness in a steel, the only method of measuring the actual toughness of a steel is a toughness test. A direct measure of toughness would appear to be better for the user because he is ultimately concerned with the performance of the steel or weldment, and this performance can best be determined by a notch-toughness test. Also a specification based on a notch-toughness test would appear to be more equitable for steelmakers in that it leaves them some latitude to adopt the process best suited to their particular operation in satisfying the toughness requirement. However, a toughness test does have the disadvantage in that a test value pertains to only one location in a plate whereas proper processing control should pertain to the entire plate. However, because this may not always be true, a toughness test is no less effective as an indication of the service performance of the entire plate.

5) Because of the difficulties in conducting a toughness test on a composite weldment, notch-toughness specimens should be taken from each of the following regions: base metal, weld metal, and heat-affected zone. While there is no "one" heat-affected-zone, an average measure of toughness can be obtained by notching the test specimen so that the tip of the notch is approximately at the center of the heat-affected-zone region. Existing ABS Rules[27]) specify that five sets of impact specimens be taken during welding Procedure Qualification Testing for weldments used for very low-temperature service. The notches for the specimens are located at the centerline of the weld, on the fusion line, and in the heat-affected-zone, 0.039-in (1 mm), 0.118-in (3 mm), and 0.197-in (5 mm) from the fusion line. For weld qualification tests it may be desirable to follow this practice, although this practice may be quite expensive for normal quality control.

The specific requirements to implement these fail-safe fracture-control guidelines consist of 1) establishing a satisfactory level of notch toughness in the steels and weldments, and 2) developing of properly designed crack arresters. These requirements are presented in detail in SSC Report 244. It should be re-emphasized that improper fabrication can still lead to structural failure regardless of the level of notch-toughness. Thus good quality welding and inspection practices must be followed.

MATERIALS PERFORMANCE CHARACTERISTICS

General

In general, the primary load-carrying members of steel ship structures are the plate members within the center .4L of the hull that comprise the upper deck, bottom shell, side plating, and longitudinal bulkheads. Because these members are the primary load-carrying members, material toughness requirements should be specified for them. Although stiffeners can also be primary load-carrying members, they are not connected to each other and thus failure of one stiffener should not lead to failure of adjacent stiffeners. Therefore, they need not be subject to the proposed criteria.

Stresses in a ship hull vary from extreme levels in the upper deck and bottom shell to essentially zero at the neutral axis as indicated in Fig. 4, which illustrates an idealized stress distribution in the section. As shown schematically in Fig. 2, the critical crack size for a given material is influenced by the nominal tensile stress level. Because stresses in the main-stress regions (Fig. 4) can reach critical levels, the materials performance characteristics of the primary load-carrying plate members in these areas should be specified by a toughness requirement. Stresses in the secondary-stress region are somewhat lower, and for primary load-carrying plate members in this area, a less-stringent toughness requirement is needed.

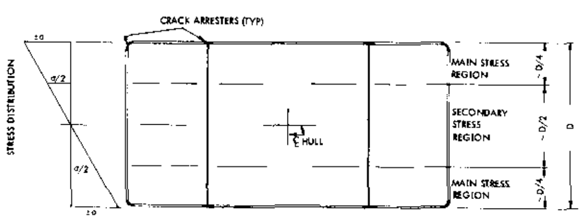

FIG. 4. Schematic Cross-Section Showing Primary Load-Carrying Members in Main-and Secondary Stress Regions

Development of Toughness Requirement for Main-stress Regions

Traditionally, the fracture characteristics of low- and intermediate strength steels have been described in terms of the transition from brittle to ductile behavior as measured by impact tests. This transition in fracture behavior can be related schematically to various fracture states as shown in Fig. 5. Plane-strain behavior refers to fracture under elastic stresses with little or no shear-lip development and is essentially brittle. Plastic behavior refers to ductile failure under general yielding conditions with very large shear-lip development. The transition between these two extremes is the elastic-plastic region which is also referred to as the mixed-mode region.

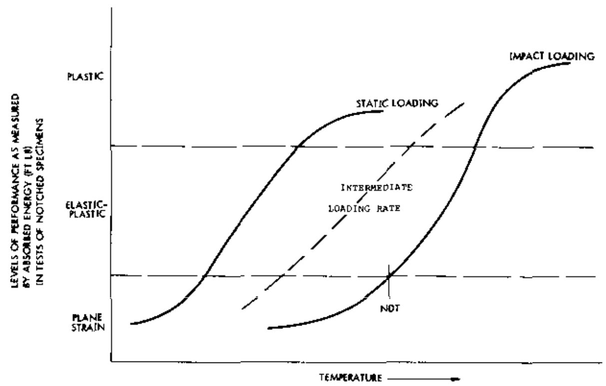

FIG. 5. Schematic Showing Relation Between Notch-Toughness Test Results and Levels of Structural Performance for Various Loading Rates.

For static loading, the transition region occurs at lower temperatures than for impact (or dynamic) loading, depending on the yield strength of the steel. Thus, for structures subjected to static loading, the static transition curve should be used to predict the level of performance at the service temperature.

For structures subjected to some intermediate loading rate, an intermediate loading rate transition curve should be used to predict the level of performance at the service temperature. Because the actual loading rates for ship hulls are not well defined, and to be conservative, the impact loading curve (Fig. 5) is used to predict the service performance of ship hull steels. As noted on Fig. 5, the nil-ductility transition (NDT) temperature generally defines the upper limit of plane-strain under conditions of impact loading.

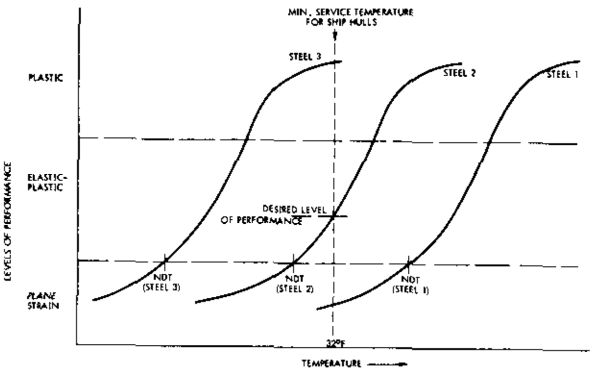

FIG. 6. Schematic Showing Relation Between Level of Performance as Measured by Impact Tests and NDT for 3 Arbitrary Steels.

A fundamental question to be resolved regarding a fracture criterion for welded ship hull steels is: "What level of material performance should be required for satisfactory performance in a ship hull subjected to dynamic loading?" That is, as shown schematically in Fig. 6 for impact loading, one of the following three general levels of material performance must be established at the service temperature for the steels that are primary load-carrying members:

1) Plane-strain behavior - Use steel (1) - Fig. 6
2) Elastic-plastic behavior - Use steel (2) - Fig. 6
3) Fully plastic behavior - Use steel (3) - Fig. 6

Although fully plastic behavior would be a very desirable level of performance for ship hull steels, it may not be necessary, or even economically feasible. A reasonable level of elastic-plastic behavior (steel 2 - Fig. 6) should be satisfactory to prevent initiation of most brittle fractures. (If fractures do initiate, they should not lead to catastrophic failure of a ship as long as properly designed crack arresters are used.) Specifying that the NDT temperature of all steels and weldments used in primary load-carrying members in the center 0.4L of ships be equal to or less than 0°F (-18°C) (32°F (18°C) below the minimum service temperature) should establish the required performance level, if the materials follow the general behavior of steel 2 in Fig. 6.

Thus, the recommended primary material specification in an overall fracture-control plan for welded steel ship hulls is that all steels and weldments used in primary load-carrying plate members in the main stress regions of ships have a maximum NDT of 0°F (-18°C) as measured by ASTM Test Method E-208-69[28].

Although necessary, this primary NDT requirement alone is not sufficient, since an additional toughness requirement is necessary to insure that the resistance to fracture of the steels and weldments whose NDT is 0°F (-18°C) (or lower) is actually satisfactory at 32°F (0°C). That is, this additional requirement is necessary to guarantee that materials follow the general performance level shown in Fig. 6, rather than exhibit a low-energy shear behavior. Fig. 7 shows the relationship of low-energy performance to normal behavior and very-high level behavior (HY-80 type behavior for military applications).

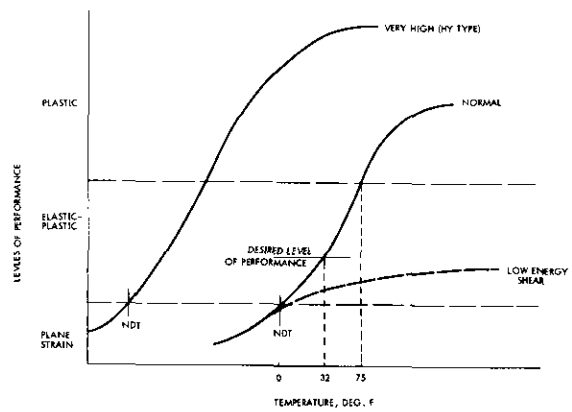

FIG. 7. Schematic Showing Relation Between Normal-, High-, Low-Energy Shear Levels of Performance as Measured by Impact Tests.

Low-energy shear behavior usually does not occur in low-strength steels but is sometimes found in high-strength steels, i.e., steels having yield strengths approaching 100 ksi. Thus the additional toughness requirement is necessary to eliminate the possibility of low-energy shear failures, primarily in the higher-strength steels.

In terms of fracture-mechanics concepts, the critical dynamic toughness, K_{ID}, is approximately equal to $0.6\sigma_{yD}$ at NDT, where σ_{yD} is the dynamic yield strength of the material. Thus for the ship hull materials that satisfy the criterion that NDT be equal to or less than 0°F (-18°C),

$$\frac{K_{ID}}{\sigma_{yD}} \simeq 0.6 \text{ at } 0°F\ (-18°C)$$

At the minimum service temperature of 32°F (0°C)

$$\frac{K_{ID}}{\sigma_{yD}} \text{ is estimated to be about } 0.9$$

because of the rapid increase in K_{ID} with temperature in the transition temperature region. Although the value of 0.9 cannot be established theoretically, experimental results for various steels[29]), including ABS-C and ASTM A517 steels, Figures 8 and 9, indicate that this is a realistic value.

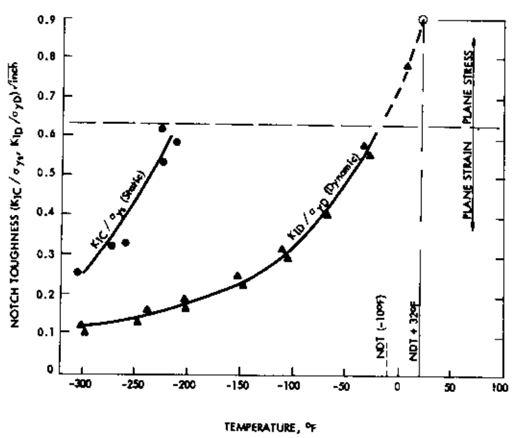

FIG. 8. Crack-Toughness Performance for ABS-C Steel

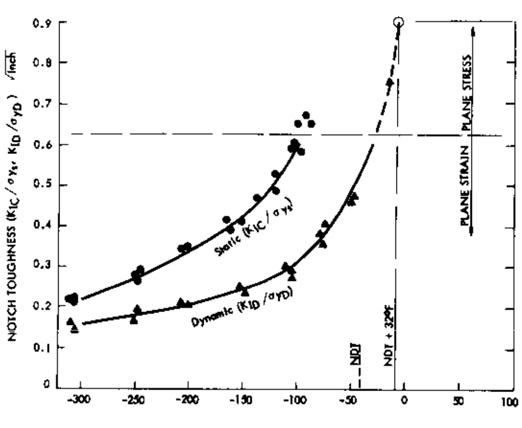

FIG. 9. Crack-Toughness Performance for A517-F Steel

It should be emphasized that although concepts of fracture mechanics have been used to develop an auxiliary toughness requirement that $K_{ID}/\sigma_{yD} \geq 0.9$ for 1-inch-thick (25.4 mm) plates), materials satisfying this criterion will exhibit elastic-plastic, non-plane-strain behavior. Therefore, this toughness level cannot be measured using existing state-of-the-art fracture-mechanics tests as specified by ASTM[30]). That is, for 1-inch-thick (25.4 mm) plates, the upper limit of dynamic plane-strain behavior is

$$1.0 = 2.5 \left(\frac{K_{ID}}{\sigma_{yD}}\right)^2$$

or $K_{ID}/\sigma_{yD} = 0.63$. Thus NDT (where $K_{ID}/\sigma_{yD} \geq 0.6$) is the upper limit of dynamic plane-strain behavior for 1-inch-thick (25.4 mm) plates.

At 32°F (0°C), K_{ID}/σ_{yD} is specified in this criterion to be 0.9, which is beyond the limits of dynamic plane-strain behavior for 1-inch-thick (25.4 mm) plates.

For 2-inch-thick (50.8 mm) plates,

$$2.0 = 2.5 \left(\frac{K_{ID}}{\sigma_{yD}}\right)^2$$

or $K_{ID}/\sigma_{yD} = 0.89$ is the limit of dynamic plane-strain behavior. Thus, a 2-inch-thick (50.8 mm) plate, loaded dynamically to the full yield stress of a material in the presence of a sharp flaw at 32°F (0°C) would be at the limit of dynamic plane-strain behavior. Because the probability of all these factors occuring simultaneously is minimal, the requirement that $K_{ID}/\sigma_{yD} \geq 0.9$ appears to be satisfactory for all thicknesses of plate 2 inches (50.8 mm) or less. However, the required toughness levels for plates thicker than 2 inches (50.8 mm) should be increased.

Using concepts of fracture mechanics, as well as engineering experience, the following observations can be made regarding the level of performance at 32 F°(0°C) for steels and weldments that satisfy the primary toughness requirement of NDT $\leq$ 0°F (-18°C) and the auxiliary toughness requirement that $K_{ID}/\sigma_{yD} \geq 0.9$ at 32°F (0°C):

1) The start of the transition from brittle to ductile behavior will begin below the minimum service temperature of 32°F (0°C). Therefore, at the minimum service temperature, the materials will exhibit some level of elastic-plastic non-plane-strain be-

havior in the presence of a sharp crack under dynamic loading.

2) Although not specified in the proposed toughness requirement, the materials will exhibit some percentage of fibrous fracture appearance at 32°F (0°C). Service experience has shown that fracture appearance is an effective indicator of the resistance to brittle fracture. Thus, this criterion is consistent with service experience of ship hulls.

3) Although precise stress-flaw size calculations cannot be made for material exhibiting elastic-plastic behavior, estimates of critical crack sizes for 40 ksi (276 MN/m^2) yield strength steels can be made as follows:

   a) For a $K_{ID} \simeq 0.9\sigma_{yD}$ and a nominal stress of 14 ksi (97 MN/m^2) the critical crack size at 32°F (0°C) is estimated to be 8-10 inches (203-254 mm) as shown in Fig. 10.

   b) For one of the largest stress ranges (peak to trough) ever recorded ships, i.e., about 24 ksi (165 MN/m^2), the critical crack size is estimated to be 3 inches (76 mm).

   c) For the worst possible cases of dynamic loading of yield point magnitude, the dynamic critical crack size is estimated to be 1/2 inch (12.7 mm).

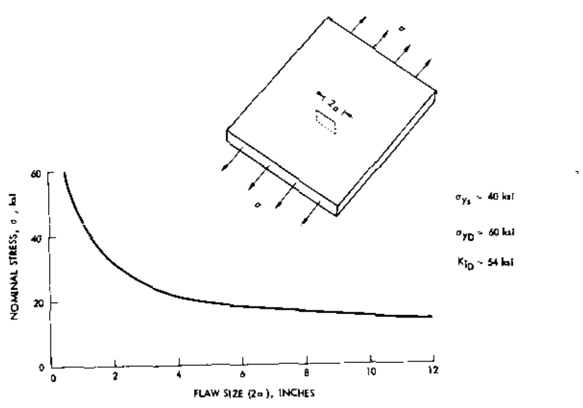

FIG. 10. Estimate of Stress-Flaw Size Relation for ABS Steel with $K_{ID}/\sigma_{yD} \simeq 0.9$.

Ideally, the auxiliary toughness requirement that $K_{ID}/\sigma_{yD} \geq 0.9$ at 32°F (0°C) should be established by conducting a K_{ID} test at 32°F (0°C). Unfortunately, no inexpensive standard K_{ID} test specimen exists. Furthermore, research test procedures to obtain K_{ID} values directly are currently too complex for use in specifications. Thus some other test specimen must be used to insure that $K_{ID}/\sigma_{yD} \geq 0.9$ at 32°F (0°C).

The test specimen should be loaded dynamically, easy to use, standardized, and the results should be readily interpretable. In addition, the specimen should have a sharp notch to closely approximate the sharp crack conditions that exist in large complex welded structures such as welded ship hulls. Finally, the test specimen should be as large as practical because of the effect of constraint on the fracture behavior of structural steels.

After careful consideration of which of the various fracture test specimens (e.g., CVN, pre-cracked CVN, Crack-Opening Displacement-COD, DT, and K_{ID}) would be most applicable to the particular requirement for welded ship hulls, the 5/8-inch (15.9 mm) thick dynamic tear (DT) test specimen[31]) is recommended as the auxiliary test specimens.

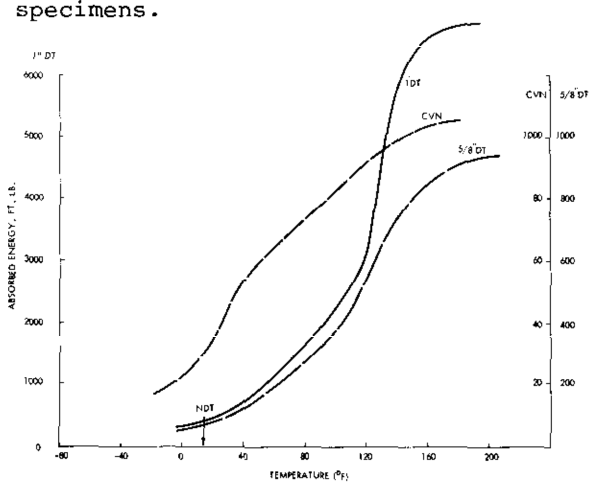

FIG. 11. Relation Between NDT, CVN, and DT Test Results for ABS-B Steel.

For the ship hull steel application, the DT test specimen currently satisfies all of the above requirements better than any other test specimen. The DT test is an impact test (high-loading rate) that has a sharp pressed notch with residual tensile stresses (thus the strain concentration is larger than for machined notches). The beginning of the elastic-plastic transition occurs at NDT as shown in Figures 11, 12, and 13 for representative ABS-B, ABS-C, and A517 steels, respectively. Thus the DT test specimen results can be easily related to the NDT values for ship steels.

If the loading rates for ships were shown conclusively to be intermediate or slow, and if less conservatism were desired, then the DT test might not be the test that most closely models the structural behavior of ship hull steels. However, for the assumption of dynamic loading in the presence of a sharp crack it does model the behavior better than any other specimen.

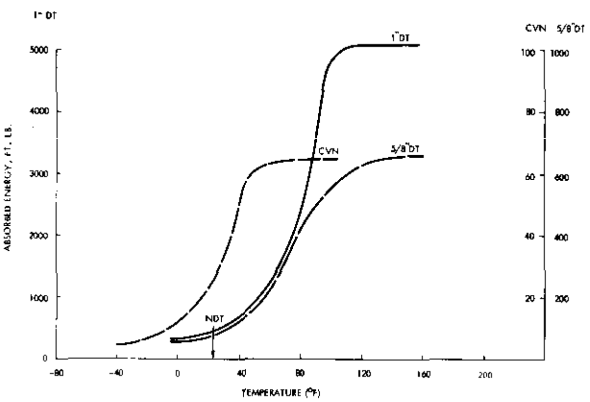

FIG. 12. Relation Between NDT, CVN, and DT Test Results for ABS-C Steel.

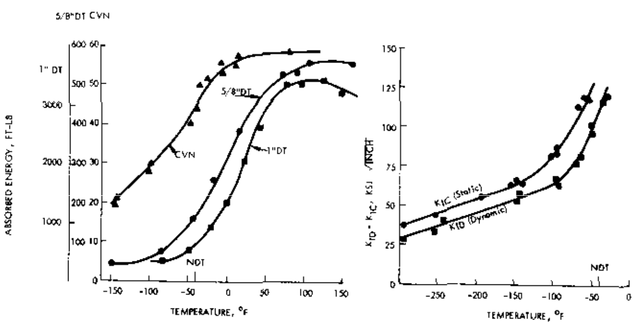

FIG. 13. Relation Between NDT, CVN, DT, K_{Ic}, and K_{ID} for A517 steels.

If the loading rates for ships were shown conclusively to be intermediate or slow, and if less conservatism were desired, then the DT test might not be the test that most closely models the structural behavior of ship hull steels. However, for the assumption of dynamic loading in the presence of a sharp crack, it does model the behavior better than any other specimen.

For the plate thicknesses normally used in ship hull construction (less than 2-inches (50.8 mm) thick), thickness has a second-order effect on the toughness behavior in the transition temperature region compared with the first-order effects of loading rate and notch acuity. Increasing the loading rate of notched steel specimens raises the transition temperature as shown in Fig. 8 and 9 [32]). Increasing the notch acuity (from that in a machined CVN specimen to that in a pressed-notch DT specimen) also raises the beginning of the transition temperature range as shown in Fig. 11-13 and 26-29. The second-order effect of thickness (namely the very small change in transition behavior between 5/8 (15.9 mm) and 1 inch (25.4 mm) thick DT specimens) is shown in Figs. 11, 12, and 13. There are larger changes in transition temperature for much thicker plates (e.g.,3- to 12-inch (76 to 305 mm) thick plates used in thick-walled pressure vessels) but for the ship hull application (plates less than 2-inches (50.8 mm) thick), the effects of specimen thickness are second order and can be ignored.

Therefore, although it would be technically more desirable to use full-thickness DT specimens to specify the behavior of ship steels, only the 5/8-inch (15.9 mm) thick DT specimen is being recommended because the practical aspects of testing the 5/8-inch (15.9 mm) thick DT specimen far outweigh the disadvantage of having to use a less than full-plate thickness test specimen. The 5/8-inch (15.9 mm) DT specimen has recently been standardized (MIL Standard 1601[31])--also see Appendix C) and can be conducted in existing NDT type falling-weight test machines or in relatively small pendulum type machines.

For above reasons, the DT test is recommended as the auxiliary test specimen to be used to insure that elastic-plastic behavior is actually being obtained in steels and weldments for welded ship hulls even though CVN impact test results currently are widely used as reference values for predicting the behavior of ship steels. Because of the wide-spread use of CVN test results, particularly in quality control, CVN values that are equivalent to DT test values are presented in Appendix E.

After having selected the DT test specimen as the auxiliary test specimen, the next step is to establish the DT value at 32°F (0°C) that will insure a K_{ID}/σ_{yD} ratio of 0.9 so that the desired level of elastic-plastic behavior is obtained for all steels and weldments. Because there are no direct theoretical solutions to establish the DT values corresponding to $K_{ID}/\sigma_{yD} = 0.9$, empirical considerations are used.

A review of available experimental test results indicates that at NDT, where $K_{ID}/\sigma_{yD} = 0.6$, the amount of absorbed energy for 5/8-inch (15.9 mm) thick DT specimens is approximately absorbed energy for the DT specimens can be approximated by (0.9/0.6) times 100, or equal to 150 ft lb (203J). The general relation between K_I and energy in the elastic region would indicate that this ratio should be squared. However, in the elastic-plastic region, where the absorbed energy is increasing very rapidly with temperature, a linear relation may be more realistic. The value of 150 ft lb (203J) is relatively small and, therefore, it is recommended that the DT test be conducted at 75°F (24°C) (room temperature) rather than 32°F (0°C) because it may be difficult to measure a significant change in resistance to fracture between 0°F (-18°C) (limit of plane-strain behavior) and 32°F (0°C) (a moderate level of elastic-plastic behavior). Although from a technical viewpoint it would be preferable to conduct the DT test at both 32°F (0°C) and 75°F (24°C), the practical considerations of the specification suggest that the DT test be conducted at +75°F (24°C) (room temperature).

If the test is conducted at 75°F (24°C), the minimum K_{ID}/σ_{yD} ratio should be 1.5 on the basis of a non-linear extrapolation from 0.9 at 32°F (0°C)as shown in Fig. 14. Thus, the minimum DT value should be (1.5/0.9) times 150, or equal to 250 ft lb (339J). Fig. 14 also shows a schematic representation of the lower-bound specification curve of required values (NDT = 0°F (-18 °C) and $K_{ID}/\sigma_{yD} \simeq 1.5$ at 75°F (24°C) - actually 250 ft lbs (339J) in a DT test) and the minimum desired values of $K_{ID}/\sigma_{yD} = 0.9$ at 32°F (0°C) compared with possible curves for ship steels that either do or do not meet the criterion. This figure shows that by meeting both of the toughness requirements at 0°F(-18°C) and 75°F (24°C) the desired behavior at 32°F (0°C) ($K_{ID}/\sigma_{yD} \geq 0.9$) should be met.

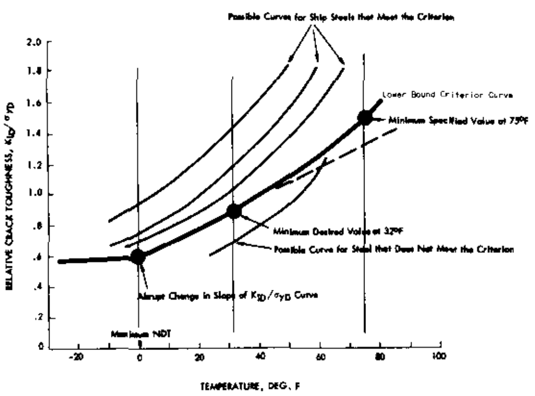

FIG. 14. Schematic Showing the Relation Between Proposed Toughness Criterion for Members in the Main-Stress Region and Behavior of Actual Ship Steels.

Assuming that the dynamic yield strength is approximately 20 ksi (138 MN/m^2) higher than the static yield strength of a steel (Appendix), the required DT values at 75°F (24°C) $K_{ID}/\sigma_{yD} \geq 1.5$) can be proportioned for strength level as shown in Table 1. This adjustment is necessary to insure that high strength steels have the same relative toughness levels as lower strength steels.

Thus, the recommended auxiliary material specification in an overall fracture-control plan for welded steel ship hulls is that all steels and weldments used in primary load-carrying plate members in the main-stress regions of ships exhibit the levels of absorbed energy in a 5/8-inch (15.9 mm) dynamic tear (DT) specimen as presented in Table 1.

The values presented in Table 1 should be the minimum values of specimens oriented in the same direction as the primary stress level (notch oriented perpendicular to the direction of primary stress). In most cases, the specimens will be longitudinal to the rolling direction. However, if the transverse stress level becomes significant, then the test specimens should be oriented in the transverse direction.

It should be emphasized that the values presented in Table 1 are not fully plastic "shelf-level" values, but rather, are values that should insure the desired level of elastic-plastic behavior.

Development of Toughness Criterion for Secondary-Stress Regions

The toughness criteria developed thus far in this section are applicable to areas of maximum stress levels which include critical members in the main-stress regions of the hull. Stiffeners and web frames probably do not need the same level of toughness as the main plating because of their discontinuous nature. Primary load-carrying members within the secondary-stress region (central D/2 portion-Fig. 4) will now be considered.

In this vicinity, nominal stresses can usually be expected to be less than one-half the maximum normal hull stress in the deck. Because low stresses (5 to 8 ksi (34 to 55 MN/m^2)) have been known to initiate brittle fractures in steels at temperatures less than NDT[5]), and flaws are present in ships, it accordingly follows that a moderate notch-toughness criterion is required even in secondary-stress regions of primary load-carrying members.

TABLE 1

Dynamic Tear (DT) Requirements at +75°F (24°C) for Steels and Weldments in Main-Stress Regions for Primary Load-Carrying Members* of Ship Hulls

Actual Static Yield σ_{ys}		Assumed Dynamic Yield Strength σ_{yD}		Proportionality factor for Strength Level	Absorbed Energy Requirements** for 5/8-inch (15.9 mm) thick specimens	
ksi	MN/m^2	ksi	MN/m^2		ft-lb	J
40	276	60	414	(60/60)	250	339
50	345	70	483	(70/60)	290	393
60	414	80	552	(80/60)	335	454
70	483	90	621	(90/60)	375	508
80	552	100	689	(100/60)	415	563
90	621	110	758	(110/60)	460	624
100	689	120	827	(120/60)	500	678

* These members must also meet the requirement of NDT $\leq$ 0°F (-18°C)

** Dynamic elastic-plastic behavior approximating $K_{ID}/\sigma_{yD} = 1.5$

Because the same size flaws can exist throughout the entire hull section, the toughness criterion for the secondary stress regions should result in the same required stress-intensity factor (K_{ID}) for both primary-and-secondary-stress regions. Thus, for the main-stress region, $K_{ID} \sim \sigma\sqrt{a_{cr}}$ and for the secondary-stress region, $K_{ID} \sim \sigma/2\sqrt{a_{cr}}$. A comparison of these relations shows that the required K_{ID} for the secondary-stress region is one-half that of the main-stress region. Accordingly, the required K_{ID}/σ_{yD} ratio is equal to 0.45 (K_{ID}/σ_{yD} is 0.9 for the main-stress regions). However, a history of welded steel fractures indicates that a design for this particular level of toughness (<NDT) would not be desirable because fractures have initiated from very small flaws when service temperatures are lower than NDT, even when the applied stresses were quite low[5]).

Thus, even though a tolerable flaw size can be numerically computed for a K_{ID}/σ_{yD} ratio of 0.45, it would be very small (≃0.1 inch (2.5 mm)), and a minimum service temperature coincident with NDT (K_{ID}/σ_{yD} = 0.6) appears to be the lowest realistic design-toughness level. A graphical representation of this design-toughness level is presented in Figure 15.

A review of several hull cross sections indicates that primary load-carrying members in the secondary-stress regions usually have nominal-section thicknesses less than or equal to one inch (25.4 mm)[33]). This is due to the fact that the steel in these members is seldom a higher grade than ABS Grade B, which is restricted by ABS rules[25]) to a one-inch (25.4 mm) thickness for this application. Thus a one-inch (25.4 mm) section thickness would appear to be the maximum thickness used. As mentioned previously, NDT essentially represents the upper limit of plane-strain behavior for this thickness.

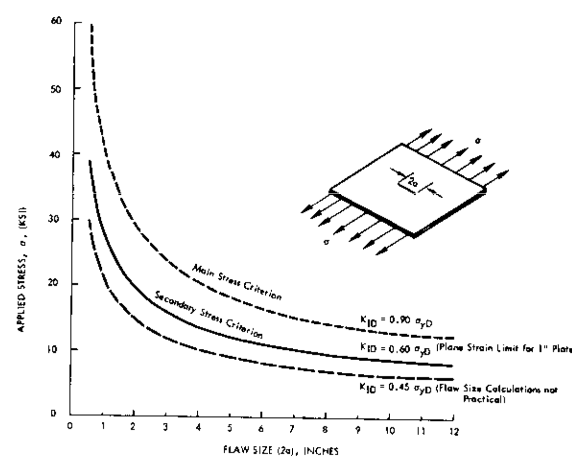

FIG. 15. Schematic Comparison of Main-Stress and Secondary-Stress Criterion

Because the material-toughness requirement of K_{ID}/σ_{yD} = 0.6 at the minimum service temperature (32°F(0°C)) is coincident with the NDT temperature, it can be conveniently established by using the NDT test. Such a marginal toughness level does not require an auxiliary test to evaluate transition behavior. However, past experience with the NDT testing procedure indicates that a margin of at least 10°F (6°C) be allowed, particularly for a specification that is based solely on NDT. For all practical purposes, an NDT temperature of 20°F (-7°C) should be sufficient to assure that $K_{ID}/\sigma_{yD} = 0.6$ at 32°F (0°C).

Thus, it is recommended that all steels and weldments used in primary load-carrying plate members in the secondary-stress regions must satisfy a less stringent material-toughness requirement of NDT $\leq$ 20°F (-7°C).

As stated previously, the above material specifications for either the main-stress regions or the secondary-stress regions will not guarantee the complete absence of brittle fractures in welded ship hulls. Therefore, a fail-safe philosophy that incorporates properly designed crack arresters fabricated from steels with very high levels of notch toughness should be used in conjunction with the above material requirements. However, these material-toughness requirements should result in rational fracture-control guidelines that will minimize the probability of brittle fractures in welded ship hulls consistent with economic realities.

ACKNOWLEDGMENT

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APPENDIX
INTRODUCTION TO CONCEPTS OF FRACTURE MECHANICS

Fracture Mechanics is a method of characterizing fracture or fatigue behavior in terms of structural parameters familiar to the engineer, namely, stress and flaw size. Fracture mechanics is based on stress analysis and thus does not depend on the use of empirical correlations to translate laboratory results into practical design information as long as the engineer can properly analyze the stresses in a specific structural application and knows the size of the flaws present in the structure. Therefore, the development of fracture mechanics offers considerable promise in solving the problem of designing to prevent brittle fractures in large complex welded structures, as well as to characterize flaw growth by such mechanisms as fatigue,stress corrosion or corrosion fatigue.

Fracture mechanics can be subdivided into two general categories, namely linear-elastic and general-yielding fracture mechanics. Although linear-elastic fracture mechanics techniques are reasonably well established (compared with general yielding fracture mechanics, parameters such as COD, J integral and R curve) most structural materials, including ship steels, do not behave elastically to fracture and thus linear-elastic fracture mechanics techniques are not widely used for most structural materials However, all existing toughness specifications, including the ones recommended in this paper are based on the principles of linear elastic fracture mechanics rather than a direct application of linear elastic fracture mechanics. This is actually a very desirable situation because the designer wants his materials to exhibit general yielding behavior rather than linear elastic (brittle) behavior. However, as a result, direct applications of linear elastic fracture mechanics are limited, and the designer must rely on the use of auxiliary test methods for specification purposes because general-yielding fracture mechanics concepts are not yet well-defined. In fact, there are no standardized general yielding fracture mechanics test methods available to the designer, although the British have a tentative test method for COD measurements.

Thus, as described in the main sections of this paper, auxiliary test methods, i.e., NDT and DT test specimens had to be used to specify the desired material properties, based on concepts of linear elastic fracture mechanics.

The fundamental princple of linear elastic fracture mechanics is that the stress field ahead of a sharp crack can be characterized in terms of a single parameter K_I, the stress intensity factor, having units of ksi$\sqrt{\text{inch}}$ MN/$m^{3/2}$). The equations that describe the elastic-stress field in the vicinity of a crack tip in a body subjected to tensile stresses normal to the plane of the crack are presented in Figure A-1. These stress-field equations show that the distribution of the elastic-stress field in the vicinity of the crack tip is invarient in all structural components that are subjected to deformations of this type (designated as Mode I because the applied stress is normal to the crack surface). Furthermore, the magnitude of the elastic-stress field can be described by a single parameter, K_I. Consequently, the applied stress, the crack shape and size, and the structural configuration associated with structural components subjected to this type of deformation affect the value of the stress-intensity factor (K_I) but do not alter the stress-field distribution ahead of the crack. Thus this analysis can be used for different structural configurations as shown in Figure A-2. Other crack geometries have been analyzed for different structural configurations and are published elsewhere. In all cases, K_I is a function of the nominal stress and the square root of flaw size.

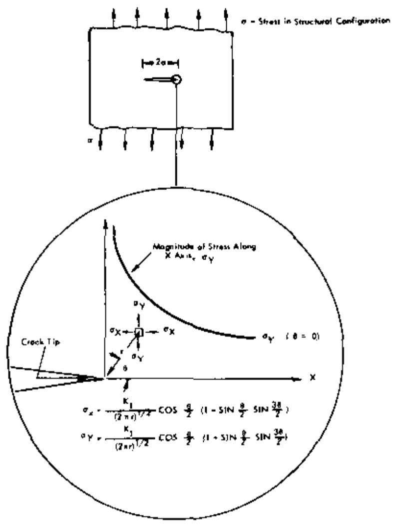

FIG. A-1. Elastic-Stress-Field Distribution Ahead of a Crack

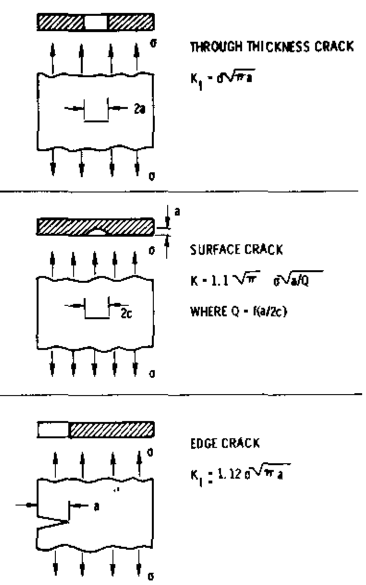

FIG. A-2. K_I Values for Various Crack Geometries

The material properties that are a measure of the fracture resistance likewise have units of ksi√inch (MN/m$^{3/2}$) but depend on the particular material, loading rate, and constraint as follows:

K_c = Critical stress-intensity factor for static loading and plane-stress conditions of variable constraint. Thus, this value depends on specimen thickness.

K_{Ic} = Critical stress-intensity factor for static loading and plane-strain conditions of maximum constraint. Thus, this value is a minimum value for thick plates.

K_{ID} = Critical stress-intensity factor for dynamic (impact) loading and plain-strain conditions of maximum constraint.

Each of these values are also a function of temperature for those steels exhibiting a transition from brittle to ductile behavior. For a given temperature, generally $K_{ID}<K_{Ic}<K_c$.

By knowing the critical value of K_I at failure (K_c, K_{Ic}, or K_{ID}) for a given steel of a particular thickness and at a specific temperature and loading rate, the designer can determine flaw sizes that can be tolerated in structural members for a given design stress level. Conversely, he can determine the design stress level that can be safely used for a flaw size that may be present in a structure.

As a general example, consider the equation relating K_I to the applied stress and flaw size for a through-thickness crack in a wide plate, that is $K_I = \sigma\sqrt{\pi a}$. Assume that laboratory test results show that for a particular structural steel with a yield strength of 80 ksi (552 MN/m^2) the K_c is 60 ksi√inch (66 MN/m$^{3/2}$) at the service temperature, loading rate, and plate thickness used. Also assume that the design stress is 20 ksi (138 MN/m^2). Substituting K_I=K_c=60 ksi√inch (66 MN/m$^{3/2}$) into the appropriate equation in Figure A-3, 2a=5.7 inches (145 mm). Thus for these conditions the tolerable flaw size would be about 5.7 inches (145 mm). For a design stress of 45 ksi (310 MN/m^2), the same material could only tolerate a flaw size, 2a, of about 1.1 inches (27.9 mm). If residual stresses such as may be due to welding are present so that the total stress in the vicinity of a crack is 80 ksi (552 MN/m^2), the tolerable flaw size is reduced considerably. Note from Figure A-3 that if a tougher steel is used, for example, one with a K_c of 120 ksi√inch (132 MN/m$^{3/2}$) the tolerable flaw sizes at all stress levels are significantly increased. If the toughness of a steel is sufficiently high, brittle fractures will not occur and failures under tensile loading can occur only by general plastic yielding, similar to the failure of a tension test-specimen. Fortunately, most ship steels have this high level of toughness.

A useful analogy for the designer is the relation between applied load (P), nominal stress (σ), and yield stress (σ_Y) in an unflawed structural member, and between applied load (P), stress intensity (K_I), and critical stress intensity for fracture (K_c, K_{Ic}, or K_{ID}) in a structural member with a flaw. In an unflawed structural member, as the load is increased, the nominal stress increases until an instability (yielding at σ_Y) occurs. As the load is increased in a structural member with a flaw (or as the size of the flaw grows by fatigue), the stress intensity, K_I, increases until an instability (fracture at K_c, K_{Ic}, K_{ID}) occurs. Thus the K_I level in a structure should always be kept below the appropriate K_c value in the same manner that the nominal design stress (σ) is kept below the yield strength (σ_Y).

Another analogy that may be useful in understanding the fundamental aspects of fracture mechanics is the comparison with the Euler column instability. The stress level required to cause instability in a column (buckling) decreases as the L/r ratio increases. Similarly, the stress level required to cause instability (fracture) in a flawed tension member decreases as the flaw size (a) increases. As the stress level in either case approaches the yield strength, both the Euler analysis and the K_c analysis are invalidated because of yielding. To prevent buckling, the actual stress and (L/r) values must be below the Euler curve. To prevent fracture, the actual stress and flaw size, a, must be below the K_c line shown in Figure A-3. Obviously, using a material with a high level of notch toughness (e.g. a K_c level of 120 ksi√inch (132 MN/m$^{3/2}$) compared with 60 ksi√inch (66 MN/m$^{3/2}$) in Figure A-3) will increase the possible combinations of design stress and flaw size that a structure can tolerate without fracturing.

The critical stress-intensity at fracture (K_c, K_{Ic}, or K_{ID} depending on plate thickness) of a particular material for a given temperature and loading rate is related to the nominal stress and flaw size as follows:

$$K_c,\ K_{Ic},\ \text{or}\ K_{ID} = C\,\sigma\sqrt{a}$$

where K_c, K_{Ic}, or K_{ID} = material toughness, ksi√inch ($MN/m^{3/2}$) at a particular temperature, loading rate, and plate thickness

C = constant, function of crack geometry

σ = nominal stress ksi (MN/m^2)

a = flaw size, inches (mm)

Thus, the maximum flaw size a structural member can tolerate at a particular stress level is:

$$a = \left(\frac{K_c,\ K_{Ic},\ \text{or}\ K_{ID}}{C\sigma}\right)^2$$

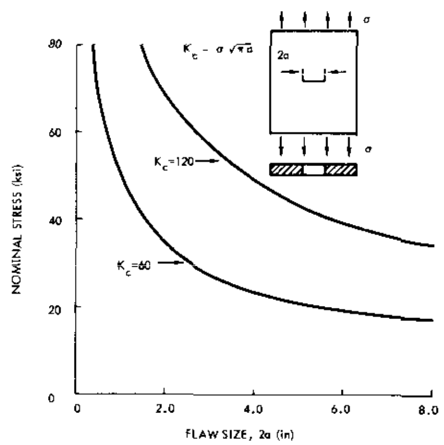

FIG. A-3. Stress-Flaw Size Relation for Through Thickness Crack

By knowing the particular relation between K_c, K_{Ic}, or K_{ID}, σ, and flaw size, a, for a given structure (the most widely used relations are shown in Figure A-2) the engineer can analyze the safety of a structure against fracture in the following manner:

1) Obtain the values of K_c, K_{Ic}, or K_{ID} and σ_y at the service temperature and loading rate for the materials being used in the structure. Note that for a complete analysis of welded structures, values for the base metal, weld metal and heat-affected zone should be obtained. As noted in the main report, most ship steels have toughness values greater than can be measured by existing ASTM test methods and thus auxiliary test methods must be used to estimate K_{ID} values. Although this is a very desirable condition because it means most ship steels are not brittle at service temperatures, the determination of the critical toughness values is quite difficult.

2) Select the type of flaw that will most likely exist in the member being analyzed and the corresponding K_I equation. Figure A-2 shows the fracture mechanics models that describe the most common types of flaws occurring in structural members. Complex shape flaws can often be approximated by one of these models. Additional equations to analyze other crack geometries are given in reference 16 of the text.

3) Plot the stress-flaw-size relation using the appropriate K_I expression.

An example of this relation between stress, flaw size, and material toughness is presented in Figure A-3. The results of this stress-flaw size curve can be used to establish design stress levels and inspection requirements. The following important conclusions should be noted:

1) In regions of high residual stress, where the actual stress can equal the yield stress over a small region, the critical crack size has to be computed for σ_y instead of the design stress, σ. If the material (steel and weld metal) is sufficiently tough, the critical crack size at full yield stress loading should be satisfactor. Under fatigue loading, the residual stresses should decrease and the critical crack becomes the value at the design stress. Note that the "critical crack size" in a structure is a function of the stress level and *is not a single value for a particular material.*

2) If the level of toughness of the material is sufficiently high, any crack which does initiate from a weld in the presence of residual stresses should arrest quickly as soon as the crack propagates out of the region of high residual stress. However, the initial flaw size for any subsequent fatigue crack growth will be fairly large.

3) For design stress levels, check the calculated critical crack size. If it is larger than the plate thickness, crack growth (by fatigue) should lead to relaxation of the constraint ahead of the crack, i.e., plane-stress behavior. For this case, the K_c (critical plane-stress stress-intensity factor) will be greater than K_{Ic} or K_{ID} which is an additional degree of conservatism.

4) For steels with low-toughness values and high design stress levels, e.g., design stress of 60 ksi (414 MN/m^2) and a K_c of 60 ksi inch (66 $MN/m^{3/2}$), Figure A-3, the steel could still be used if the design stress is reduced significantly. However, use of structural steels with low-toughness levels requires precise levels of total inspection of the structure and is not considered "feasible for ships".

EFFECT OF TEMPERATURE, LOADING RATE, AND THICKNESS ON K_c, K_{Ic}, or K_{ID}

General

In principle, the application of fracture mechanics in analysis of flawed members is straightforward, as shown in the previous examples. In reality, however, the application of fracture mechanics to analyze flawed members depends on the engineer having specific information in the following areas:

1) Stress Analysis of Cracks

The stress-intensity factor, K_I, has been established for various crack geometries, and can be approximated for other geometries. Thus the application of fracture mechanics generally is not hampered by the availability of stress-intensity factors for various shape cracks. The most commonly used stress-intensity factors were shown in Figure A-2.

2) Actual Flaw Sizes

The actual flaw size in a structure is very difficult to determine. Such factors as quality of inspection, skill of the inspector, available equipment, etc., make the determination of actual flaw sizes in a structure extremely difficult. From an engineering viewpoint, the designer must assume that the largest possible reasonable size flaw can be present in regions of maximum stress unless he has specific knowledge to the contrary.

3) Crack-Toughness Values for Particular Materials

As is well known, the inherent crack toughness of most structural steels decreases with decreasing temperature and/or increasing loading rate. In addition the notch toughness also decreases with increasing plate thicknesses up to the limiting value of plane strain, K_{Ic} of K_{ID}. Thus, before the engineer can predict the fracture behavior of a particular structural member, using concepts of fracture mechanics, he must know the K_c value for the particular service temperature and loading rate, as well as member thickness. Very little quantitative information on the crack toughness of ship steels currently exists, although that which does exist indicates that the toughness levels of these steels are higher than can be measured using existing ASTM Standardized Test Methods. Thus auxiliary test methods are necessary to estimate the crack-toughness levels of ship steels.

Thickness Effects

Ahead of a sharp crack, the lateral constraint is such that through-thickness stresses are present. Because these stresses must be zero at each surface of a plate, the through-thickness stresses are less for thin plates compared with thick plates. For very thick plates, a triaxial state-of-stress occurs which reduces the apparent ductility of the steel and the notch toughness is reduced. This decrease in notch toughness is controlled by the thickness of the plate, even though the inherent metallurgical properties of the material are unchanged. Thus the notch toughness (K_c) decreases for thick plates compared with thinner plates of the same material. This behavior is shown in Figure A-4, for a high strength maraging steel. For thicknesses greater than some value related to the toughness and strength of individual steels, maximum constraint occurs and plane strain (K_{Ic}) behavior results. Conversely, as the thickness of the plate is decreased (even though the inherent metallurgical characteristics of the steel are not changed), the notch-toughness increases and plane-stress (K_c) behavior exists.

Figure A-5 shows the shear lips on the surface of fracture test specimens having different plate thicknesses. The percentage of shear lips as compared with the total fracture surface is a qualitative indication of notch toughness. A small percentage of shear lips as compared with the total fracture surface is a qualitative indication of notch toughness. A small percentage of shear lip area indicates a relative brittle behavior. A comparison of the fracture surfaces in Figure A-5 shows that thinner plates are more resistant to brittle fracture than thick plates. *This fact is not new to* engineers, but the fact that a quantitative fracture mechanics analysis of the phenomena *can now be made* is *new.*

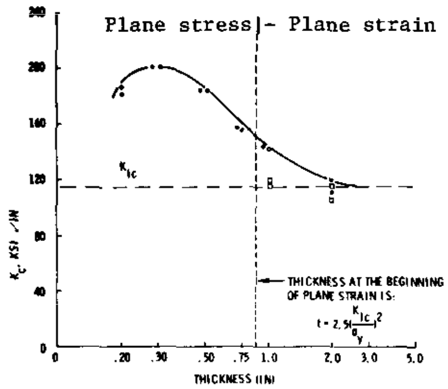

FIG. A-4. Effect of Thickness on K_c Behavior

Temperature and Loading Rate

In general, the *crack* toughness of most steels decreases with decreasing temperature and increasing loading rate. *Loading rate refers* to the time it takes to reach maximum load and for most structures can vary from very slow (essentially static for K_{Ic}) to dynamic (usually impact loading rates for K_{ID}). Examples of this type behavior for two ship steels, ABS-C and A517, were presented in Figures 8 and 13. Note that the same general behavior exists for the K_{Ic}, CVN, and DT test results (Figure 13) but that the rapid increase in values occurs at different temperatures because the tests are conducted at different loading rates. The actual loading rates for most structures are generally between the limits of "static" *loading (strain rate* approximately 10^{-5} sec^{-1}) and dynamic or impact (strain rate approximately *10* sec^{-1}). *If* specific information on the loading rates of actual structures can be obtained, an intermediate loading rate (Figure 5) can be used to analyze the fracture behavior. However, intermediate loading-rate tests are extremely expensive to conduct.

The salient features of the results presented in Figures 8, 13, and A-4 may be summarized as follows:

1) Increasing test temperature increases the K_c, K_{Ic}, or K_{ID} value at a particular loading rate for most structural steels.

2) Increasing the loading rate decreases the critical K_c or K_{Ic} value to a K_{ID} value at a particular temperature for most

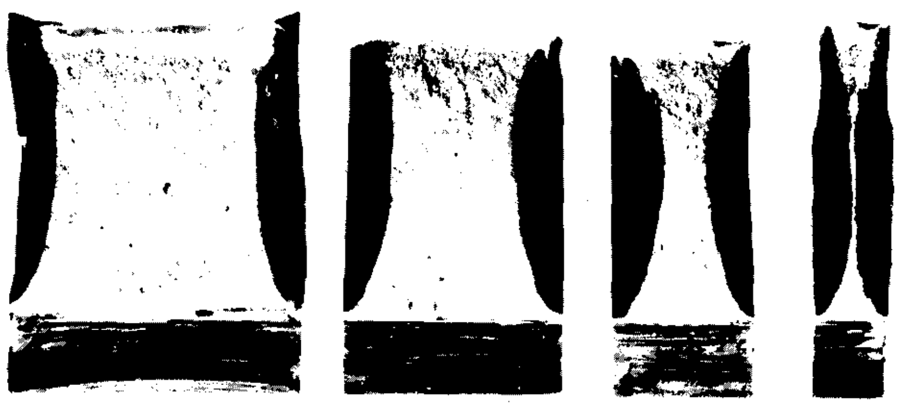

FIG. A-5. Effect of Specimen Thickness (2-, 1 1/2-, 1-, and 1/2- inches) on Toughness as Determined by Size of Shear Lips structural steels.

3) Increasing the thickness of the plate of steel being investigated decreases the K_c value to a lower bound K_{Ic} value, Figure A-4.

STATIC VERSUS DYNAMIC CONDITIONS

Current methods of design and fabrication are such that engineers expect structures to be able to tolerate yield stress loading in tension without failing. The maximum allowable flaw size in a member can be related to the notch toughness and yield strength as follows:

$$a = \left(\frac{K_c,\ K_{Ic},\ \text{or}\ K_{ID}}{C\sigma_y}\right)^2$$

For conditions of maximum constraint (plane strain), such as would occur in thick plates or in regions of high constraint, the flaw size becomes proportional to $(K_{Ic}/\sigma_y)^2$, where both K_{Ic} and σ_y should be measured at the service temperature and loading rate of the structure.

Thus the K_{Ic}/σ_y ratio (or K_{ID}/σ_{yD}) becomes a good index for measuring the relative toughness of structural material. Because for most structural applications it is desirable that the structure tolerate large flaws without fracturing, the use of materials with high K_{Ic}/σ_y ratios is a desirable condition.

The question becomes, how high must the K_{Ic}/σ_y ratio for a structural material be to insure satisfactory performance in complex welded structures such as ships, where complete initial inspection for cracks and continuous monitoring of crack growth throughout the life of a structure are not always possible, practical, or economical.

No simple answer exists because the engineer must take into account such factors as the design life of the structures, consequences of a failure in a structural member, redundancy of load path, probability of overloads and fabrication and material cost. However, as described in the main report, fracture mechanics can provide an engineering approach to rationally evaluate this question. Basic assumptions are that flaws do exist in structures, yield stress loading is probably in some critical parts of a structure, and plane-strain conditions can exist (although the use of thin plates tends to minimize the possibility of plane-strain behavior). Therefore, the K_{Ic}/σ_y ratio for materials used in particular structure is one of the primary controlling parameters that defines the relative safety of a structure against brittle fracture.

If a structure is loaded "slowly" ($\sim10^{-4}$ in/in/second), the K_{Ic}/σ_{ys} ratio is the controlling toughness parameter. If, however, the structure is loaded "rapidly" ($\sim10^{1}$ in/in/second or impact loading), the K_{ID}/σ_{yD} ratio is the controlling parameter. Definitions and test conditions for each of these ratios is as follows:

1) K_{Ic} - critical plane-strain stress-intensity factor under conditions of static loading as described in ASTM Test Method E-399 - Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials.

2) σ_{ys} - Static tensile yield strength obtained in "slow" tension test as described in ASTM Test Method E-8 - Standard Methods of Tension Testing of Metallic Materials.

3) K_{ID} - Critical plane-strain stress-intensity factor as measured by "dynamic" or "impact" tests. The test specimen is similar to a K_{Ic} test specimen, but is loaded rapidly. There is no standardized test procedure but the general test method is described elsewhere.

4) σ_{yD} - Dynamic tensile yield strength obtained in "rapid" tension test at loading rates comparable to those obtained in K_{ID} tests. Although extremely difficult to obtain, a good engineering approximation based on experimental results of structural steels is:

$$\sigma_{yD} = \sigma_{ys} + 20\ \text{ksi}$$

As discussed in the main report, the toughness of ship hull steels was analyzed using K_{ID}/σ_{yD} values, because ships can be subjected to dynamic loadings. If ships are loaded at somewhat lower loading rates, the use of K_{ID}/σ_{yD} parameters to establish required toughness levels is conservative.

Discussion

J. R. Cheshire, Member

Professor Rolfe's interesting paper generally endorses the practices used by Lloyd's Register of Shipping since the early 1950's for the avoidance of failures in a brittle manner of welded ships' hulls. These include the use of steels with moderate levels of notch toughness, the use of crack arrestor strakes, careful consideration of design and adequate control of workmanship.

In contrast with the practices of some other Classification Societies, we have always believed that it was essential to prove the notch toughness of ship steels by suitable acceptance tests and that, with the exception of grade A steel, it was not satisfactory to rely only on specifying chemical composition, deoxidation practice and heat treatment. Charpy V-notch impact tests are used for acceptance purposes and, in spite of the many criticisms made of this type of test and the difficulties in correlation with other, more sophisticated forms of fracture toughness tests, service experience indicates the KCV tests are quite adequate for quality control purposes at steelworks.

Professor Rolfe suggests that variations of plate thickness within the range used in hull construction have a second order effect on toughness behaviour and that the effects of loading rate and notch acuity are more significant. This is not in accordance with the practices generally adopted for hull construction and conflicts with the results of substantial research programmes carried out in the U.K., notably by the Welding Institute, which indicate that plate thickness is one of the important primary factors in toughness behaviour.

For the main stress regions of ships' hulls, L.R. present practice for plate material is as follows:-

Thickness	Grade	Notch Toughness
$\leq$ 20.5 mm	A	No impact tests, $\frac{MN}{C} \geq 2.5$ KCV of 27J at +20°C or better is expected
20.5 to 25.5 mm	B	KCV 27J at 0°C
$>$25.5 mm	D	KCV 47J at 0°C

There has been very limited service experience of thicker grade D steel and at present consideration is being given to a requirement for the use of grade E steel plates (27J at -40°C) for main stress regions over, say, 35mm thick.

It would appear from the table in Appendix E of paper SSC/244 that grade B steel would suffice to meet Professor Rolfe's proposed criteria $\frac{K_{ID}}{\sigma_{YD}} \geq 0.9$ at 0°C but we would hesitate to allow the use of this grade of steel in thicknesses over 25mm in main stress regions.

Regarding the proposal for NDT - 18°C, this would exclude the use of both grade A and grade B steels as such a criteria could only be consistently met by grade E steel and by certain types of grade D steel, i.e. when made using fine-grain practice and supplied in the normalised or controlled rolled conditions.

LCDR A. E. Henn, USCG, Visitor

I would like to compliment the author on his development of what I believe are rational fracture control guidelines. His combination of fracture mechanics, fracture criteria, and fracture control provides another important bridge between the areas of research and application in the field of engineering.

I have three comments, the first rather general while the other two are somewhat more specific in nature.

As I see it, the author has recommended that the following be included in the rational fracture control guidelines for welded steel hulls:

a. All steels and weldments used in the primary load carrying plate members in the main stress regions have levels of absorbed energy in a 5/8-inch dynamic tear specimen of 250 ft-lbs or greater at 75°F (24°C);

b. All steels and weldments used in the primary load carrying plate members in the secondary stress regions must have a NDT of equal to or less than 20°F (-7°C); and

c. Crack arresters made from steels with a very high notch toughness.

This appears to be the first complete set of fracture control guidelines for welded steel hulls that is based on fracture mechanics. I feel the guidelines have been developed in a manner which is consistent with the approaches used by other segments of industry. These guidelines, which exceed Coast Guard requirements, provide the methodology to apply the results of research in fracture mechanics to the design of welded steel hulls. Using the methodology, a designer can make his own fracture control evaluations of a welded steel hull or variations in the design of a hull. As with any new set of guidelines, it behooves us to consider carefully the assumptions and resulting criteria. I believe that the assumptions concerning the loading rate and design temperature of welded steel hulls are two areas which will need further consideration.

The second comment deals with the design service temperature. A design service temperature of 32°F (0°C) may be reasonable for general cargo and tank vessels. However, I agree with the author that for special applications, such as ice breakers and certain vessels carrying cryogenic cargoes, special consideration should be given to the service temperature. As an example, the Coast Guard specifies the following ambient design temperatures for the contiguous hull structure of new liquefied gas carriers that have a cargo containment system requiring a secondary barrier:

Lower 48 States	
Air (at 5 knots):	0°F (-18°C)
Sea Water :	32°F (0°C)

Alaska	
Air (at 5 knots):	-20°F(-29°C)
Sea Water :	+28°F (-2°C)

Also, the Coast Guard requires crack arresters in the deck stringer, sheer strake, and bilge strake. The minimum acceptable grades are Grade E steel for the deck stringer and the sheer strake and Grades D or E for the bilge strake.

My third and final comment pertains to the toughness test of a composite weldment. For a designer to use the guidelines in evaluating the primary load carrying plate members in the main stress region, he needs to know the absorbed energy in a 5/8 - inch dynamic tear specimen at a specified temperature for each steel and weldment selected. For most steels and weldments this information is probably not readily accessible to the designer. There is another consideration. The dynamic tear test is a tentatively accepted ASTM standard for the base plate and weld metal. Although, the test is not being used to evaluate the toughness of the heat-affected zone of weldments, it appears the test could be used for that purpose. This would require a test program to verify the suitability of the dynamic tear specimen for evaluating the toughness of the heat-affected zone and to standardize the testing procedure. With regard to the testing procedure, the author has suggested that the tip of the notch of the dynamic tear specimen be placed in the center of the heat-affected zone. This should result in some average toughness value for the heat-affected zone. However, to determine the area of the heat-affected zone which has undergone the greatest reduction in toughness due to welding, it seems that at least two dynamic tears speciments will be needed at two or more locations (i.e. 2mm, 5mm and 8mm from the fusion line).

This concludes my comments. Again I would like to compliment the author on his excellent paper and express my thanks for an opportunity to offer comments.

Eugene A. Lange, Visitor

This paper presents a much needed analysis for the control of fracture in ships. It is becoming more and more embarrassing to write or talk on fracture mechanics technology and use as illustrations the two broken tankers, one a T-2 that broke in 1943 and one a barge type that broke in 1972, and call the illustration, "Thirty years of Engineering Progress." The economics of ship construction may have justified the minimal corrective measures with respect to fracture in ships that have been taken during the past 30 years, but as Dr. Rolfe points out, the measures taken in design refinement have not been sufficient to preclude catastrophic fractures. The big question is how much will it cost to have a more fracture resistant steel in the critical regions of a ship. The economic factors will change as improved steels are made more available at a nominal premium. However, even with a premium of 10% on the price of the steel that is to be used in the 20% of a ship that is considered critical, the overall cost of the materials for the ship should not increase more than 1% or 2%, a small increment in cost to preclude fracture.

Dr. Rolfe's justification for the use of dynamic criteria should be expanded upon. Certainly, the static fracture toughness properties of the conventional steels used for ships, bridges, pressure vessels, etc., control the performance of most structures in service. However, if a local condition develops and a small crack pops in, then the dynamic properties of the steel control the performance of the structure even though the nominal loads are static or pseudostatic.

Dr. Rolfe points out that the criteria for the fracture resistance of steels for bridges are based upon an "intermediate loading rate", and while most bridges stay up, some do have costly fractures that would not have been precluded even with the current criterion, Ref. 1. In Ref. 1, Mr. Harry Czyzewski reported on a fracture that occurred in 1971 that led to repair costs of $5 million for a bridge in Portland, Oregon, and the redesign of three others. That amount of money would have paid the premium on the steel in the critical members of quite a few bridges. In the report, Ref. 1, he pointed out that the new requirements for the replacement steel was a Charpy V-notch value of 15 ft-lb (20.4 J) to be met at 40°F (4.4°C) which is intended to preclude fracture down to 0°F (-18°C). However, the data cited for the steel in the girder that failed at 35°F (1.6°C) were in ft-lb (J); 31 (42.3), 33.2 (45.2), 15.5 (21.1), 24 (32.6), 16.5 (22.4) at 40°F (4.4°C). It is apparent that steel that was involved in the fractured girders would have passed the new criterion, obviously a fracture toughness criterion based upon an intermediate loading rate does not reliably protect a welded steel structure from catastrophic fracture. Therefore, a dynamic fracture toughness criterion is not considered "conservative" if the performance of the steel in a structure must be certified. The importance of a dynamic criterion was first documented in the analysis of the massive amount of service data on WW II ships.

One of the earliest reports on the use of the Drop-Weight NDT test in the analysis of WW II ship fractures was by Puzak, Babecki, and Pellini in 1958, Ref. 2. Over the years this analysis has been refined and Pellini published an updated version that introduced linear elastic fracture mechanics to the analysis in 1973, Ref. 3. Mr. Pellini points out that ship fractures initiated and totaled the ship when the fracture resistance of the steel was less than 0.5 K_{ID}/σ_{yd} (< NDT temperature), but only partial fractures occurred when there was a high probability that the crack would run into a plate having a fracture resistance above 0.9 K_{ID}/σ_{yd}. It would thus appear that Dr. Rolfe's proposed criterion is based upon service experience.

In order to have steel plates meet the proposed Rolfe criterion, a recent study by Hawthorne and Loss has shown that conventional ship steels would have to be given a normalized heat treatment, Ref. 4. There are other techniques for refining the grain size of steels to decrease the temperature of the transition region, such as microalloying plus controlled rolling. These metallurgical techniques have been used recently to develop steels for arctic pipeline use. If it proves economical to use these steels for ship construction, this could significantly expand the flexibility of ship design because the new steels have higher yield strength, good weldability, and improved fracture toughness characteristics.

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3. Pellini, W. S., "Analytical Design Procedures for Metals of Elastic-Plastic and Plastic Fracture Properties," Welding Research Council Bulletin No. 186, August 1973.
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I. L. Stern, Visitor

The author is to be complimented on a paper which presents a logical approach toward the analysis of fracture characteristics of hull steels. The value of the work is indicated by the fact that the SSC-244 report, from which the paper is derived, has led to several additional ongoing SSC projects intended to amplify and pursue the subject. However, to fully appreciate the paper, consideration should be given to its content from the broad shipbuilding aspect, in addition to the materials aspect emphasized therein. Since a detailed analysis along these lines would represent another paper, I will confine my remarks to brief comment of some pertinent points of such consideration.

In regard to the discussion of the general problem of brittle fracture in ships, greater emphasis should be given to the excellent service history of welded steel ships rather than isolated instances of service failures, which have been long since corrected by appropriate modifications in design or material specifications. In addition, while the importance of design and fabrication aspects is mentioned, the great influence that these items have on the overall performance of a ship in regard to brittle fracture is not given proper emphasis.

For example, in illustrating that brittle fractures are still occurring in ships, Boyd is referenced as a reporter of ten brittle fracture failures between 1960 and 1965. However, Boyd (1) in 1970 reports the following service experience for the years 1949 - 1963:

(1) Brittle Fracture in Steel Structures - G. M. Boyd 1970, Butterworth & Co., London

	Tankers	Dry Cargo
Average No. in Commission (over 2500 ton)	2,431	8,404
Aggregate years of service	36,467	126,070
No. broken in two	15	5
Pre-War built	7	-
War built (40-45)	4	4
Post War built	4*	1

* (1-1946; 1-1948; 2-1949; 1-1952)

The record for dry cargo ships would not suggest a need for concern of a fracture problem with hull steels in use in 1963; the problem should be of even lesser concern today, in view of the fact that since 1963 steels of superior notch toughness such as ABS Grades E and CS have been made available to provide for locations where the need for toughness is of particular concern. The somewhat higher frequency of fractures noted for tankers in the above table indicates the importance of design and service in assessment of overall fracture considerations. It is well to note that the latest fracture reported by Boyd for the tankers occurred in 1952, 11 years before the end of the reporting period, and that since that time, improvements through modifications of the compositions of ship steels have been effected. The introduction of these improved steels has reduced the frequency of nuisance cracks appreciably. With current materials and technology the rare occurrence of a fracture is more likely to be attributable to a design detail or from improper fabrication, rather than a basic material deficiency; the solution of the problem is usually effected by a modification of design or fabrication practice.

The paper recommends that the use of a Dynamic Tear (DT) criterion in addition to the Drop Weight (DWT) test and indicates the former is necessary for eliminating the possibility of low-energy shear. However, as is noted in the paper, low-energy shear does not occur in low-strength steels but is sometimes found in steels approximating yield strengths of 100,000 psi or higher. The necessity of imposing the DT requirement on the ordinary and higher strength hull steels, 51,000 Y.S. and lower is not apparent, especially since the absence of low-energy shear in these steels has been well documented.

In the paper, the author recognizes that a realistic fracture control plan must take economic considerations into account, and consequently develops a plan which provides for steels with moderate levels of notch toughness. With the proposed criteria, possibility of brittle fracture is minimized but not eliminated; the use of very tough steels which would eliminate brittle fracture is indicated as economically unfeasible. The unanswered question remaining is the quantitative estimate of the reduced possibility of catastrophic failures that would be effected by use of the proposed material guide lines, and/or crack arrestor systems.

The paper indicates that since dynamic loading has been assumed, the proposed criteria are on the conservative side and that the service history of welded steel ships has been excellent. It also states that the proposed criteria could be relaxed if slower loading rates are assumed. Further exploration of this point would clarify the relationship of the proposed standards to current hull steel requirements. Such exploration may possibly lead to the conclusion that the proposed criteria are representative of a conservative limit; the hull steel grades of the World War II steels may well represent the limiting boundary for the lowest toughness levels which could provide satisfactory service with close attention to deisgn detail, and hull steels in current use may well represent the optimum compromise. Further clarification of this aspect might be expected upon the completion of the SSC programs derived from the subject paper, which are concerned with loading rate effects and assessment of the suitability of the proposed requirements.

An overall comment pertinent to the subject paper, as well as other related papers concerned with brittle fracture of ship steels is the failure to give appropriate emphasis and consideration to the fact that in all but very exceptional circumstances, a fracture in a ship plate is arrested within the structure during service, and is repaired at the appropriate opportunity, well before a catastrophic failure occurs. In many cases these cracks may be several feet long, far in excess of the critical crack lengths estimated on the basis of fracture mechanics. Analysis of the conditions and reasons why catastrophic failures do not occur in these instances and further development of theory which would explain the mechanics by which relatively long cracks are arrested, could provide a new insight into the relationships of the fracture mechanics principles described in the paper to actual service performance.

In general, if the assumptions and theory upon which the proposed criteria are based were valid, we should be experiencing a far greater frequency of catastrophic ship failures. The fact is that a catastrophic brittle ship failure is of such rarity that, if it occurs, often leads to headlines and investigations. In most instances, design, fabrication, or service factors have been more influential than material. In view of this fact, the author's indication that the proposed criteria are on the conservative side appears valid; the key question is the degree to which the proposed theory should be modified and proposed criteria relaxed to reflect service performance. If this relationship could be established, then the approach described herein should be particularly useful in determining suitability for intended service for new hull steels or applications for which adequate service experience for determining suitability is not available.

In regard to the above, it would be logical to establish as a base line of acceptability, the ordinary and higher strength (to 51,000 psi yield) steels which are currently used and specified internationally by all Ship Classifica-Societies. The extensive background of research with these steels and the prolonged satisfactory service experience demonstrated under the wide variety of conditions encountered in international shipping, attest to their suitability. When used in applications and ship locations specified by applicable Classification Society Rules, these steels are designed to provide a level of reliability which has earned international acceptance. If those concerned, such as regulatory bodies, Classification Societies, ship operators or underwriters thought otherwise, then modification of currently accepted steel requirements would have been made.

Reconsideration of the assumptions of the fracture mechanics analysis upon which the criteria are based, which would take into account the above, could indicate the extent to which the criteria in the paper are conservative and lead to modified requirements which are more representative of service experience.

R. H. Sterne, Jr., Visitor

Dr. Rolfe's initial effort is to be commended as it contributes to the extension of fracture mechanics into the realm of ship steels.

Several assumptions made in the paper certainly biased the conclusions toward the conservative side, as the author states clearly. These are:

(1) Assuming Dynamic Loading
(2) Assuming that a K_{ID}/y.s. ratio of 0.9

at 32°F is necessary to avoid brittle failure At the same time, questions are raised that point the way for future research these include:

(1) Acutal loading rates experienced in a variety of sea states by a representative group of ships.

(2) Analysis of the loading rates, in high stress areas, as they apply to the fracture mechanics approach used by the author.

(3) The need to establish the effect of loading rate on the fracture toughness of a variety of ship hull steels, ranging from the ordinary strength to the higher strength (H Grades) and particularly the highest strength quenched and temper grades gaining increasing use in ships, of the 60-100 KSI yield strength rnage.

(4) The need to assess the fracture toughness of the previously noted steels in the welded form, including a variety of welding processes and techniques.

It would be remiss for this reviewer to make the previous suggestions for future research without noting that the ship structure committee is presently embarking upon two programs to investigate both loading rate effects on steel and to extend Dr. Rolfe's fracture mechanics work to a broader range of steel grades, including, I believe, weldments.

The economic effect of applying the author's conclusions to actual ship designs is one area of concern to this reviewer, and needs to be examined further.

Finally, we must be careful to review Dr. Rolfe's criteria in light of the success which has been experienced in the application of ABS and other Classification Societies' rules. The work performed and described is an initial and important step in gaining a better understanding of how fracture mechanics can be used to improve the fracture safe design of ships.

P. R. Christopher, Visitor

Professor Rolfe states on P. 11 that thickness has a second-order effect on toughness behavior in the transition temperature region compared with the first-order effects of loading rate and notch acuity. From the D. W. T. graphs shown in Figure 11, Figure 12 and Figure 13, it might be supposed that the thickness effect is small although the temperature scale used, perhaps, disguises the fact that there is some definite increase in transition temperature which might be crucial in a given steel for a particular application. Certainly guidance notes for offshore steel properties in the U. K. make a distinction between plates above and below 1" thickness. Indeed it is recommended that above 1-1/2" thickness stress relieving should be applied to important structure.

Certainly the statement that for plates less than 2" thickness, the effects of specimen thickness can be ignored seems wrong. This raises the important question, in relation to any test, of the scatter that might be expected in results obtained from plate to plate, and within a plate and whether or not this is greater within the transition range. The results given for the DWT tests in Figure 11 - 13, for instance, may not be a true average particularly since, in the transition range, there may be more than one arrest and restart of fracture. It also raises the question as to what strain rate is representative of a particular application and whether or not impact tests are really necessary since servo-hydraulic machines may well be capable of simulating the strain rates applied in many service applications.

I make these remarks because it is important to be quite clear on this question of thickness in the 0 - 4" range since it is just this range which interests us most in offshore applications. Surely it was when thickness began to exceed about 1" that brittle fracture started to be a worry?

With respect to ship fractures I think the 1972 failure which Professor Rolfe described is very important. Even though it may be an isolated case I think that there may be much to be learned from it.

I was very interested in Professor Rolfe's idea of using an "I" beam as a crack arrester, the top face being butt welded into the plating. One wonders if he has carried out any investigations of this idea: it is not clear why the crack should not pass through the top face leaving the structure held together by a rather flimsy stringer.

Author's Closure

First, I would like to thank the various discussors for their comments. Structural research is of little value to the profession unless it leads to improvements in the overall understanding of the behavior and design of ship hull structures and certainly an intermediate step in this process is the interchange of ideas and discussions such as the foregoing ones.

Mr. Cheshire of Lloyd's Register of Shipping is correct in pointing out the usefulness of the Charpy V-notch impact test in quality control. The Charpy test has served engineers quite well and will be with us for some time.

The dynamic fracture criteria described in the paper is such that existing ABS-steels probably will just meet them most of the time. However, to meet them consistently on a guaranteed minimum basis of performance, it would probably be necessary to modify processing practices (e.g., use normalized steel plates). With the general trend to probabilistic analysis and design, specification of materials on a probabilistic basis of material properties rather than guaranteed minimums may be very feasible and might result in a more realistic use of the dynamic criterion.

Plate thickness is important in defining constraint. However, compared with the shift in transition behavior due to loading rate (up to 160°F), the shift in transition temperature between 1-in. and 2-in. thick specimens is secondary, i.e., on the order of 30-40°F.

As LCDR Henn, USGG correctly notes, the proposed fracture criteria do exceed existing Coast Guard requirements. Furthermore he is correct in stating that fracture mechanics provides a methodology to make fracture criterion more or less severe than that described in the paper, based on service conditions other than those described in the paper. I agree that the loading rate assumption is crucial and that additional information is needed.

Regarding the need for crack arrestors, an interesting design is the use of WF shapes rather than plates. Structural shapes of steels with good notch toughness could have excellent properties because of the directional working during rolling. Also the mechanical constraint of the WF section should provide considerable arrest capability. I agree with Commander Henn's statement that additional work on toughness tests of weldments is needed and certainly the experience with the Charpy V-notch impact test should not be discarded lightly.

Mr. Lange of the Naval Research Laboratory (NRL) questions our engineering progress during the past 30 pears. I believe that the shipbuilding industry has indeed made considerable progress since the early ship failures that occurred in World War II. Our understanding is better, the safety and reliability is much better, and the frequency of failures is considerably less. Much of the success in this progress is indeed due to the long-standing contributions that the Naval Research Laboratory, led by Bill Pellini, has made in the field of notch toughness testing of structural steels. Considerable improvements have been made in design, fabrication, and materials since the World War II ships and the recent brittle fracture of the barge that occurred in 1972 apparently was primarily a problem in operations, rather than these other factors.

The concept of a small crack pop-in leading to a dynamic stress field in statically loaded structures has long been a point of considerable debate among engineers. Perhaps it is easier to think of larger stiffeners, gusset plates, or other secondary members failing under overload, leading to a large dynamic stress field rather than the sudden pop-in of a small microcrack leading to a dynamic stress field. Possible failure of a secondary member leading to a dynamic stress field emphasizes the point that design of secondary members or stiffeners is not "just a detail," but rather is a very important part of the overall design of the structure and can be as important as the design of the primary load-carrying members. Because of the importance of details in a fracture-resistant design, there appears to be a definite need for a "cataloguing" of the relative severity of typical ship details, in the same manner that the bridge industry has done for bridge details.

Reference was made to the use of an intermediate loading rate in the development of the AASHTO material toughness specifications for bridge steels and that these specifications, adapted in 1973, would not have prevented the fracture that occurred in the Fremont Bridge in Oregon. A complete analysis of that fracture is beyond the scope of this discussion. However, it should be noted that if the steel had been tested in the same orientation as it was loaded in the structure, namely the transverse direction, the test results would not have met the AASHTO requirements. The transverse CVN impact property values were: 8.8, 12.5, 10.0, 6.5, and 6.5 ft. lbs. and thus did not meet the 15 ft. lb. requirement. At the same temperature, the longitudinal values, which were not in the primary loading direction, were 31, 33.2, 15.5, 24, and 16.5 ft. lbs. As is often the case, other factors besides material toughness were involved in this fracture. Specifically, the particularly severe stress concentration, and the use of very thick plates that were rolled longitudinally, cut transversely, and then loaded transversely definitely contributed to this fracture.

The $K_{ID}/\sigma_{yd} \gtrsim 0.9$ ratio proposed as a dynamic criterion for welded ship hull steels agrees with the NRL yield criterion (Y.C.) and is a conservative dynamic criterion to provide a specific level of dynamic toughness. Designers, fabricators, and operators also have a responsibility for the safety and reliability of structures. A realistic concern is that if material requirements become too conservative, designers will not pay proper attention to these other factors, which are also very important in a total Fracture Control Plan.

Mr. I. L. Stern of the American Bureau of Shipping is correct in his statement that existing experience for ship hulls is excellent and this fact should be emphasized. Materials, design, fabrication, inspection, and operation are all important in the overall safety and reliability of ship hull structures. The reason that more emphasis is usually given to the role of notch toughness of materials as a factor affecting brittle fracture rather than the role of design, fabrication, inspection, and operation is that few designers appear to be really interested in the importance of structural details. Thus some toughness level is desired to compensate for possible fabrication or design errors. This is not always the most economical or even the most desirable solution but is one that is widely used. A large need is to "catalog" the severity of typical details -- similar to the way AISC has cataloged bridge details so that the severity of certain details is established.

In response to another question by Mr. I.L. Stern, I would agree that low-energy shear is really not a problem with low-strength steels and that while desirable for completeness of the criterion, the DT requirement may not be necessary for low-strength steels.

As indicated in the paper, the theoretical crack size, a_{cr}, for low-stress levels can be several feet long, in fact, in some cases semi-infinite. A fracture mechanics analysis is somewhat meaningless in this case, in the same manner that an Euler buckling analysis that results in a critical buckling stress much larger (for very small ℓ/r) than the yield strength is meaningless. In both cases, other modes of failure control the behavior but the concepts of both these analyses are used to insure that failures do not occur by these particular modes of failure.

I would also agree that if all structures were loaded dynamically, we might be experiencing a far greater frequency of catastrophic ship failures than we are. The same statement could be made for bridges, leading to the conclusion that the loading rate shift may well explain why many ships and bridges perform very satisfactorily at temperatures below their dynamic NDT temperature.

Mr. R. H. Sterne of Lukens Steel raises a question regarding the assumption of a dynamic loading rate. Certainly, as a starting point, dynamic loading should be assumed until a better understanding of the implications of this assumption are understood, and this was what was done in the Ship Structure Committee (SSC) research. However, in view of the excellent service experience of ship steels, the need for this assumption certainly has a right to be questioned, although all structural steels should have some minimum (moderate) level of notch toughness. Additional work is necessary to determine what the optimum trade-off between safe, reliable material behavior and economics actually is.

As Mr. Sterne has noted, the Ship Structure Committee is conducting research on:

a. loading rates for ship steels and
b. a study of the adequacy of the dynamic criterion.

One additional program which should be recommended to the SSC is a study and cataloguing of the severity of typical design details, both from a fracture as well as a fatigue viewpoint. If the designer had some indication during the design stage of just how deleterious certain details are, they could be eliminated. AISC has done this for various bridge details and the allowable fatigue stress range is decreased as the severity of the detail is increased.

Mr. Christopher of the Naval Construction Research Establishment of the United Kingdom points out that thickness is important and I agree with his statement. However, it is not as significant as the loading rate shift for thickness up to 2-inches. For thicknesses greater than 2-inches, I agree that constraint becomes increasingly more important. Scatter in material properties certainly is a fact of life that must be dealt with. The general move toward probabilistic design may provide a better solution to this situation than the present use of guaranteed minimum values.

Once again, I would like to thank the reviewers for their interest as shown by their pertinent discussions. Thank you.

Discussion

J. R. Cheshire, Member

Professor Rolfe's interesting paper generally endorses the practices used by Lloyd's Register of Shipping since the early 1950's for the avoidance of failures in a brittle manner of welded ships' hulls. These include the use of steels with moderate levels of notch toughness, the use of crack arrestor strakes, careful consideration of design and adequate control of workmanship.

In contrast with the practices of some other Classification Societies, we have always believed that it was essential to prove the notch toughness of ship steels by suitable acceptance tests and that, with the exception of grade A steel, it was not satisfactory to rely only on specifying chemical composition, deoxidation practice and heat treatment. Charpy V-notch impact tests are used for acceptance purposes and, in spite of the many criticisms made of this type of test and the difficulties in correlation with other, more sophisticated forms of fracture toughness tests, service experience indicates the KCV tests are quite adequate for quality control purposes at steelworks.

Professor Rolfe suggests that variations of plate thickness within the range used in hull construction have a second order effect on toughness behaviour and that the effects of loading rate and notch acuity are more significant. This is not in accordance with the practices generally adopted for hull construction and conflicts with the results of substantial research programmes carried out in the U.K., notably by the Welding Institute, which indicate that plate thickness is one of the important primary factors in toughness behaviour.

For the main stress regions of ships' hulls, L.R. present practice for plate material is as follows:-

Thickness	Grade	Notch Toughness
$\leq$ 20.5 mm	A	No impact tests, $\frac{MN}{C} \geq 2.5$ KCV of 27J at +20°C or better is expected
20.5 to 25.5 mm	B	KCV 27J at 0°C
> 25.5 mm	D	KCV 47J at 0°C

There has been very limited service experience of thicker grade D steel and at present consideration is being given to a requirement for the use of grade E steel plates (27J at -40°C) for main stress regions over, say, 35mm thick.

It would appear from the table in Appendix E of paper SSC/244 that grade B steel would suffice to meet Professor Rolfe's proposed cri- criteria $\frac{K_{ID}}{\sigma_{YD}} \geq 0.9$ at 0°C but we would hesitate to allow the use of this grade of steel in thicknesses over 25mm in main stress regions.

Regarding the proposal for NDT - 18°C, this would exclude the use of both grade A and grade B steels as such a criteria could only be consistently met by grade E steel and by certain types of grade D steel, i.e. when made using fine-grain practice and supplied in the normalised or controlled rolled conditions.

LCDR A. E. Henn, USCG, Visitor

I would like to compliment the author on his development of what I believe are rational fracture control guidelines. His combination of fracture mechanics, fracture criteria, and fracture control provides another important bridge between the areas of research and application in the field of engineering.

I have three comments, the first rather general while the other two are somewhat more specific in nature.

As I see it, the author has recommended that the following be included in the rational fracture control guidelines for welded steel hulls:

a. All steels and weldments used in the primary load carrying plate members in the main stress regions have levels of absorbed energy in a 5/8-inch dynamic tear specimen of 250 ft-lbs or greater at 75°F (24°C);

b. All steels and weldments used in the primary load carrying plate members in the secondary stress regions must have a NDT of equal to or less than 20°F (-7°C); and

c. Crack arresters made from steels with a very high notch toughness.

This appears to be the first complete set of fracture control guidelines for welded steel hulls that is based on fracture mechanics. I feel the guidelines have been developed in a manner which is consistent with the approaches used by other segments of industry. These guidelines, which exceed Coast Guard requirements, provide the methodology to apply the results of research in fracture mechanics to the design of welded steel hulls. Using the methodology, a designer can make his own fracture control evaluations of a welded steel hull or variations in the design of a hull. As with any new set of guidelines, it behooves us to consider carefully the assumptions and resulting criteria. I believe that the assumptions concerning the loading rate and design temperature of welded steel hulls are two areas which will need further consideration.

The second comment deals with the design service temperature. A design service temperature of 32°F (0°C) may be reasonable for general cargo and tank vessels. However, I agree with the author that for special applications, such as ice breakers and certain vessels carrying cryogenic cargoes, special consideration should be given to the service temperature. As an example, the Coast Guard specifies the following ambient design temperatures for the contiguous hull structure of new liquefied gas carriers that have a cargo containment system requiring a secondary barrier:

Lower 48 States	
Air (at 5 knots):	0°F (-18°C)
Sea Water :	32°F (0°C)

Alaska	
Air (at 5 knots):	-20°F(-29°C)
Sea Water :	+28°F (-2°C)

Also, the Coast Guard requires crack arresters in the deck stringer, sheer strake, and bilge strake. The minimum acceptable grades are Grade E steel for the deck stringer and the sheer strake and Grades D or E for the bilge strake.

My third and final comment pertains to the toughness test of a composite weldment. For a designer to use the guidelines in evaluating the primary load carrying plate members in the main stress region, he needs to know the absorbed energy in a 5/8 - inch dynamic tear specimen at a specified temperature for each steel and weldment selected. For most steels and weldments this information is probably not readily accessible to the designer. There is another consideration. The dynamic tear test is a tentatively accepted ASTM standard for the base plate and weld metal. Although, the test is not being used to evaluate the toughness of the heat-affected zone of weldments, it appears the test could be used for that purpose. This would require a test program to verify the suitability of the dynamic tear specimen for evaluating the toughness of the heat-affected zone and to standardize the testing procedure. With regard to the testing procedure, the author has suggested that the tip of the notch of the dynamic tear specimen be placed in the center of the heat-affected zone. This should result in some average toughness value for the heat-affected zone. However, to determine the area of the heat-affected zone which has undergone the greatest reduction in toughness due to welding, it seems that at least two dynamic tears speciments will be needed at two or more locations (i.e. 2mm, 5mm and 8mm from the fusion line).

This concludes my comments. Again I would like to compliment the author on his excellent paper and express my thanks for an opportunity to offer comments.

Eugene A. Lange, Visitor

This paper presents a much needed analysis for the control of fracture in ships. It is becoming more and more embarrassing to write or talk on fracture mechanics technology and use as illustrations the two broken tankers, one a T-2 that broke in 1943 and one a barge type that broke in 1972, and call the illustration, "Thirty years oi Engineering Progress." The economics of ship construction may have justified the minimal corrective measures with respect to fracture in ships that have been taken during the past 30 years, but as Dr. Rolfe points out, the measures taken in design refinement have not been sufficient to preclude catastrophic fractures. The big question is how much will it cost to have a more fracture resistant steel in the critical regions of a ship. The economic factors will change as improved steels are made more available at a nominal premium. However, even with a premium of 10% on the price of the steel that is to be used in the 20% of a ship that is considered critical, the overall cost of the materials for the ship should not increase more than 1% or 2%, a small increment in cost to preclude fracture.

Dr. Rolfe's justification for the use of dynamic criteria should be expanded upon. Certainly, the static fracture toughness properties of the conventional steels used for ships, bridges, pressure vessels, etc., control the performance of most structures in service. However, if a local condition develops and a small crack pops in, then the dynamic properties of the steel control the performance of the structure even though the nominal loads are static or pseudostatic.

Dr. Rolfe points out that the criteria for the fracture resistance of steels for bridges are based upon an "intermediate loading rate", and while most bridges stay up, some do have costly fractures that would not have been precluded even with the current criterion, Ref. 1. In Ref. 1, Mr. Harry Czyzewski reported on a fracture that occurred in 1971 that led to repair costs of $5 million for a bridge in Portland, Oregon, and the redesign of three others. That amount of money would have paid the premium on the steel in the critical members of quite a few bridges. In the report, Ref. 1, he pointed out that the new requirements for the replacement steel was a Charpy V-notch value of 15 ft-lb (20.4 J) to be met at 40°F (4.4°C) which is intended to preclude fracture down to 0°F (-18°C). However, the data cited for the steel in the girder that failed at 35°F (1.6°C) were in ft-lb (J); 31 (42.3), 33.2 (45.2), 15.5 (21.1), 24 (32.6), 16.5 (22.4) at 40°F (4.4°C). It is apparent that steel that was involved in the fractured girders would have passed the new criterion, obviously a fracture toughness criterion based upon an intermediate loading rate does not reliably protect a welded steel structure from catastrophic fracture. Therefore, a dynamic fracture toughness criterion is not considered "conservative" if the performance of the steel in a structure must be certified. The importance of a dynamic criterion was first documented in the analysis of the massive amount of service data on WW II ships.

One of the earliest reports on the use of the Drop-Weight NDT test in the analysis of WW II ship fractures was by Puzak, Babecki, and Pellini in 1958, Ref. 2. Over the years this analysis has been refined and Pellini published an updated version that introduced linear elastic fracture mechanics to the analysis in 1973, Ref. 3. Mr. Pellini points out that ship fractures initiated and totaled the ship when the fracture resistance of the steel was less than 0.5 K_{ID}/σ_{yd} (< NDT temperature), but only partial fractures occurred when there was a high probability that the crack would run into a plate having a fracture resistance above 0.9 K_{ID}/σ_{yd}. It would thus appear that Dr. Rolfe's proposed criterion is based upon service experience.

In order to have steel plates meet the proposed Rolfe criterion, a recent study by Hawthorne and Loss has shown that conventional ship steels would have to be given a normalized heat treatment, Ref. 4. There are other techniques for refining the grain size of steels to decrease the temperature of the transition region, such as microalloying plus controlled rolling. These metallurgical techniques have been used recently to develop steels for arctic pipeline use. If it proves economical to use these steels for ship construction, this could significantly expand the flexibility of ship design because the new steels have higher yield strength, good weldability, and improved fracture toughness characteristics.

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I. L. Stern, Visitor

The author is to be complimented on a paper which presents a logical approach toward the analysis of fracture characteristics of hull steels. The value of the work is indicated by the fact that the SSC-244 report, from which the paper is derived, has led to several additional ongoing SSC projects intended to amplify and pursue the subject. However, to fully appreciate the paper, consideration should be given to its content from the broad shipbuilding aspect, in addition to the materials aspect emphasized therein. Since a detailed analysis along these lines would represent another paper, I will confine my remarks to brief comment of some pertinent points of such consideration.

In regard to the discussion of the general problem of brittle fracture in ships, greater emphasis should be given to the excellent service history of welded steel ships rather than isolated instances of service failures, which have been long since corrected by appropriate modifications in design or material specifications. In addition, while the importance of design and fabrication aspects is mentioned, the great influence that these items have on the overall performance of a ship in regard to brittle fracture is not given proper emphasis.

For example, in illustrating that brittle fractures are still occurring in ships, Boyd is referenced as a reporter of ten brittle fracture failures between 1960 and 1965. However, Boyd (1) in 1970 reports the following service experience for the years 1949 - 1963:

(1) Brittle Fracture in Steel Structures - G. M. Boyd 1970, Butterworth & Co., London

	Tankers	Dry Cargo
Average No. in Commission (over 2500 ton)	2,431	8,404
Aggregate years of service	36,467	126,070
No. broken in two	15	5
Pre-War built	7	-
War built (40-45)	4	4
Post War built	4*	1

* (1-1946; 1-1948; 2-1949; 1-1952)

The record for dry cargo ships would not suggest a need for concern of a fracture problem with hull steels in use in 1963; the problem should be of even lesser concern today, in view of the fact that since 1963 steels of superior notch toughness such as ABS Grades E and CS have been made available to provide for locations where the need for toughness is of particular concern. The somewhat higher frequency of fractures noted for tankers in the above table indicates the importance of design and service in assessment of overall fracture considerations. It is well to note that the latest fracture reported by Boyd for the tankers occurred in 1952, 11 years before the end of the reporting period, and that since that time, improvements through modifications of the compositions of ship steels have been effected. The introduction of these improved steels has reduced the frequency of nuisance cracks appreciably. With current materials and technology the rare occurrence of a fracture is more likely to be attributable to a design detail or from improper fabrication, rather than a basic material deficiency; the solution of the problem is usually effected by a modification of design or fabrication practice.

The paper recommends that the use of a Dynamic Tear (DT) criterion in addition to the Drop Weight (DWT) test and indicates the former is necessary for eliminating the possibility of low-energy shear. However, as is noted in the paper, low-energy shear does not occur in low-strength steels but is sometimes found in steels approximating yield strengths of 100,000 psi or higher. The necessity of imposing the DT requirement on the ordinary and higher strength hull steels, 51,000 Y.S. and lower is not apparent, especially since the absence of low-energy shear in these steels has been well documented.

In the paper, the author recognizes that a realistic fracture control plan must take economic considerations into account, and consequently develops a plan which provides for steels with moderate levels of notch toughness. With the proposed criteria, possibility of brittle fracture is minimized but not eliminated; the use of very tough steels which would eliminate brittle fracture is indicated as economically unfeasible. The unanswered question remaining is the quantitative estimate of the reduced possibility of catastrophic failures that would be effected by use of the proposed material guide lines, and/or crack arrestor systems.

The paper indicates that since dynamic loading has been assumed, the proposed criteria are on the conservative side and that the service history of welded steel ships has been excellent. It also states that the proposed criteria could be relaxed if slower loading rates are assumed. Further exploration of this point would clarify the relationship of the proposed standards to current hull steel requirements. Such exploration may possibly lead to the conclusion that the proposed criteria are representative of a conservative limit; the hull steel grades of the World War II steels may well represent the limiting boundary for the lowest toughness levels which could provide satisfactory service with close attention to deisgn detail, and hull steels in current use may well represent the optimum compromise. Further clarification of this aspect might be expected upon the completion of the SSC programs derived from the subject paper, which are concerned with loading rate effects and assessment of the suitability of the proposed requirements.

An overall comment pertinent to the subject paper, as well as other related papers concerned with brittle fracture of ship steels is the failure to give appropriate emphasis and consideration to the fact that in all but very exceptional circumstances, a fracture in a ship plate is arrested within the structure during service, and is repaired at the appropriate opportunity, well before a catastrophic failure occurs. In many cases these cracks may be several feet long, far in excess of the critical crack lengths estimated on the basis of fracture mechanics. Analysis of the conditions and reasons why catastrophic failures do not occur in these instances and further development of theory which would explain the mechanics by which relatively long cracks are arrested, could provide a new insight into the relationships of the fracture mechanics principles described in the paper to actual service performance.

In general, if the assumptions and theory upon which the proposed criteria are based were valid, we should be experiencing a far greater frequency of catastrophic ship failures. The fact is that a catastrophic brittle ship failure is of such rarity that, if it occurs, often leads to headlines and investigations. In most instances, design, fabrication, or service factors have been more influential than material. In view of this fact, the author's indication that the proposed criteria are on the conservative side appears valid; the key question is the degree to which the proposed theory should be modified and proposed criteria relaxed to reflect service performance. If this relationship could be established, then the approach described herein should be particularly useful in determining suitability for intended service for new hull steels or applications for which adequate service experience for determining suitability is not available.

In regard to the above, it would be logical to establish as a base line of acceptability, the ordinary and higher strength (to 51,000 psi yield) steels which are currently used and specified internationally by all Ship Classifica-Societies. The extensive background of research with these steels and the prolonged satisfactory service experience demonstrated under the wide variety of conditions encountered in international shipping, attest to their suitability. When used in applications and ship locations specified by applicable Classification Society Rules, these steels are designed to provide a level of reliability which has earned international acceptance. If those concerned, such as regulatory bodies, Classification Societies, ship operators or underwriters thought otherwise, then modification of currently accepted steel requirements would have been made.

Reconsideration of the assumptions of the fracture mechanics analysis upon which the criteria are based, which would take into account the above, could indicate the extent to which the criteria in the paper are conservative and lead to modified requirements which are more representative of service experience.

R. H. Sterne, Jr., Visitor

Dr. Rolfe's initial effort is to be commended as it contributes to the extension of fracture mechanics into the realm of ship steels.

Several assumptions made in the paper certainly biased the conclusions toward the conservative side, as the author states clearly. These are:

(1) Assuming Dynamic Loading

(2) Assuming that a K_{ID}/y.s. ratio of 0.9 at 32°F is necessary to avoid brittle failure

At the same time, questions are raised that point the way for future research these include:

(1) Acutal loading rates experienced in a variety of sea states by a representative group of ships.

(2) Analysis of the loading rates, in high stress areas, as they apply to the fracture mechanics approach used by the author.

(3) The need to establish the effect of loading rate on the fracture toughness of a variety of ship hull steels, ranging from the ordinary strength to the higher strength (H Grades) and particularly the highest strength quenched and temper grades gaining increasing use in ships, of the 60-100 KSI yield strength rnage.

(4) The need to assess the fracture toughness of the previously noted steels in the welded form, including a variety of welding processes and techniques.

It would be remiss for this reviewer to make the previous suggestions for future research without noting that the ship structure committee is presently embarking upon two programs to investigate both loading rate effects on steel and to extend Dr. Rolfe's fracture mechanics work to a broader range of steel grades, including, I believe, weldments.

The economic effect of applying the author's conclusions to actual ship designs is one area of concern to this reviewer, and needs to be examined further.

Finally, we must be careful to review Dr. Rolfe's criteria in light of the success which has been experienced in the application of ABS and other Classification Societies' rules. The work performed and described is an initial and important step in gaining a better understanding of how fracture mechanics can be used to improve the fracture safe design of ships.

P. R. Christopher, Visitor

Professor Rolfe states on P. 11 that thickness has a second-order effect on toughness behavior in the transition temperature region compared with the first-order effects of loading rate and notch acuity. From the D. W. T. graphs shown in Figure 11, Figure 12 and Figure 13, it might be supposed that the thickness effect is small although the temperature scale used, perhaps, disguises the fact that there is some definite increase in transition temperature which might be crucial in a given steel for a particular application. Certainly guidance notes for offshore steel properties in the U. K. make a distinction between plates above and below 1" thickness. Indeed it is recommended that above 1-1/2" thickness stress relieving should be applied to important structure.

Certainly the statement that for plates less than 2" thickness, the effects of specimen thickness can be ignored seems wrong. This raises the important question, in relation to any test, of the scatter that might be expected in results obtained from plate to plate, and within a plate and whether or not this is greater within the transition range. The results given for the DWT tests in Figure 11 - 13, for instance, may not be a true average particularly since, in the transition range, there may be more than one arrest and restart of fracture. It also raises the question as to what strain rate is representative of a particular application and whether or not impact tests are really necessary since servo-hydraulic machines may well be capable of simulating the strain rates applied in many service applications.

I make these remarks because it is important to be quite clear on this question of thickness in the 0 - 4" range since it is just this range which interests us most in offshore applications. Surely it was when thickness began to exceed about 1" that brittle fracture started to be a worry?

With respect to ship fractures I think the 1972 failure which Professor Rolfe described is very important. Even though it may be an isolated case I think that there may be much to be learned from it.

I was very interested in Professor Rolfe's idea of using an "I" beam as a crack arrester, the top face being butt welded into the plating. One wonders if he has carried out any investigations of this idea: it is not clear why the crack should not pass through the top face leaving the structure held together by a rather flimsy stringer.

Author's Closure

First, I would like to thank the various discussors for their comments. Structural research is of little value to the profession unless it leads to improvements in the overall understanding of the behavior and design of ship hull structures and certainly an intermediate step in this process is the interchange of ideas and discussions such as the foregoing ones.

Mr. Cheshire of Lloyd's Register of Shipping is correct in pointing out the usefulness of the Charpy V-notch impact test in quality control. The Charpy test has served engineers quite well and will be with us for some time.

The dynamic fracture criteria described in the paper is such that existing ABS-steels probably will just meet them most of the time. However, to meet them consistently on a guaranteed minimum basis of performance, it would probably be necessary to modify processing practices (e.g., use normalized steel plates). With the general trend to probabilistic analysis and design, specification of materials on a probabilistic basis of material properties rather than guaranteed minimums may be very feasible and might result in a more realistic use of the dynamic criterion.

Plate thickness is important in defining constraint. However, compared with the shift in transition behavior due to loading rate (up to 160°F), the shift in transition temperature between 1-in. and 2-in. thick specimens is secondary, i.e., on the order of 30-40°F.

As LCDR Henn, USGG correctly notes, the proposed fracture criteria do exceed existing Coast Guard requirements. Furthermore he is correct in stating that fracture mechanics provides a methodology to make fracture criterion more or less severe than that described in the paper, based on service conditions other than those described in the paper. I agree that the loading rate assumption is crucial and that additional information is needed.

Regarding the need for crack arrestors, an interesting design is the use of WF shapes rather than plates. Structural shapes of steels with good notch toughness could have excellent properties because of the directional working during rolling. Also the mechanical constraint of the WF section should provide considerable arrest capability. I agree with Commander Henn's statement that additional work on toughness tests of weldments is needed and certainly the experience with the Charpy V-notch impact test should not be discarded lightly.

Mr. Lange of the Naval Research Laboratory (NRL) questions our engineering progress during the past 30 pears. I believe that the shipbuilding industry has indeed made considerable progress since the early ship failures that occurred in World War II. Our understanding is better, the safety and reliability is much better, and the frequency of failures is considerably less. Much of the success in this progress is indeed due to the long-standing contributions that the Naval Research Laboratory, led by Bill Pellini, has made in the field of notch toughness testing of structural steels. Considerable improvements have been made in design, fabrication, and materials since the World War II ships and the recent brittle fracture of the barge that occurred in 1972 apparently was primarily a problem in operations, rather than these other factors.

The concept of a small crack pop-in leading to a dynamic stress field in statically loaded structures has long been a point of considerable debate among engineers. Perhaps it is easier to think of larger stiffeners, gusset plates, or other secondary members failing under overload, leading to a large dynamic stress field rather than the sudden pop-in of a small microcrack leading to a dynamic stress field. Possible failure of a secondary member leading to a dynamic stress field emphasizes the point that design of secondary members or stiffeners is not "just a detail," but rather is a very important part of the overall design of the structure and can be as important as the design of the primary load-carrying members. Because of the importance of details in a fracture-resistant design, there appears to be a definite need for a "cataloguing" of the relative severity of typical ship details, in the same manner that the bridge industry has done for bridge details.

Reference was made to the use of an intermediate loading rate in the development of the AASHTO material toughness specifications for bridge steels and that these specifications, adapted in 1973, would not have prevented the fracture that occurred in the Fremont Bridge in Oregon. A complete analysis of that fracture is beyond the scope of this discussion. However, it should be noted that if the steel had been tested in the same orientation as it was loaded in the structure, namely the transverse direction, the test results would not have met the AASHTO requirements. The transverse CVN impact property values were: 8.8, 12.5, 10.0, 6.5, and 6.5 ft. lbs. and thus did not meet the 15 ft. lb. requirement. At the same temperature, the longitudinal values, which were not in the primary loading direction, were 31, 33.2, 15.5, 24, and 16.5 ft. lbs. As is often the case, other factors besides material toughness were involved in this fracture. Specifically, the particularly severe stress concentration, and the use of very thick plates that were rolled longitudinally, cut transversely, and then loaded transversely definitely contributed to this fracture.

The $K_{ID}/\sigma_{yd} \gtrsim 0.9$ ratio proposed as a dynamic criterion for welded ship hull steels agrees with the NRL yield criterion (Y.C.) and is a conservative dynamic criterion to provide a specific level of dynamic toughness. Designers, fabricators, and operators also have a responsibility for the safety and reliability of structures. A realistic concern is that if material requirements become too conservative, designers will not pay proper attention to these other factors, which are also very important in a total Fracture Control Plan.

Mr. I. L. Stern of the American Bureau of Shipping is correct in his statement that existing experience for ship hulls is excellent and this fact should be emphasized. Materials, design, fabrication, inspection, and operation are all important in the overall safety and reliability of ship hull structures. The reason that more emphasis is usually given to the role of notch toughness of materials as a factor affecting brittle fracture rather than the role of design, fabrication, inspection, and operation is that few designers appear to be really interested in the importance of structural details. Thus some toughness level is desired to compensate for possible fabrication or design errors. This is not always the most economical or even the most desirable solution but is one that is widely used. A large need is to "catalog" the severity of typical details -- similar to the way AISC has cataloged bridge details so that the severity of certain details is established.

In response to another question by Mr. I.L. Stern, I would agree that low-energy shear is really not a problem with low-strength steels and that while desirable for completeness of the criterion, the DT requirement may not be necessary for low-strength steels.

As indicated in the paper, the theoretical crack size, a_{cr}, for low-stress levels can be several feet long, in fact, in some cases semi-infinite. A fracture mechanics analysis is somewhat meaningless in this case, in the same manner that an Euler buckling analysis that results in a critical buckling stress much larger (for very small ℓ/r) than the yield strength is meaningless. In both cases, other modes of failure control the behavior but the concepts of both these analyses are used to insure that failures do not occur by these particular modes of failure.

I would also agree that if all structures were loaded dynamically, we might be experiencing a far greater frequency of catastrophic ship failures than we are. The same statement could be made for bridges, leading to the conclusion that the loading rate shift may well explain why many ships and bridges perform very satisfactorily at temperatures below their dynamic NDT temperature.

Mr. R. H. Sterne of Lukens Steel raises a question regarding the assumption of a dynamic loading rate. Certainly, as a starting point, dynamic loading should be assumed until a better understanding of the implications of this assumption are understood, and this was what was done in the Ship Structure Committee (SSC) research. However, in view of the excellent service experience of ship steels, the need for this assumption certainly has a right to be questioned, although all structural steels should have some minimum (moderate) level of notch toughness. Additional work is necessary to determine what the optimum trade-off between safe, reliable material behavior and economics actually is.

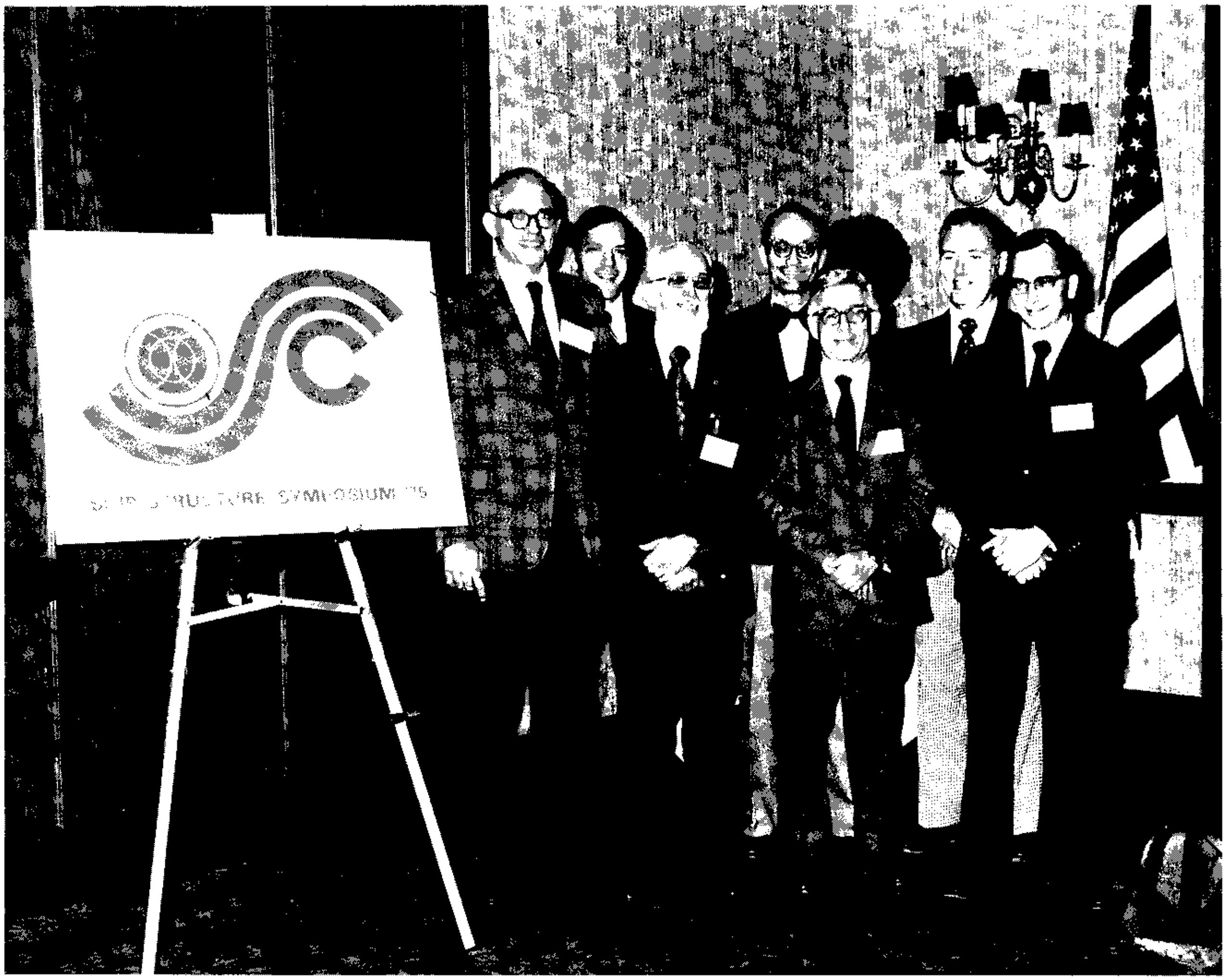
As Mr. Sterne has noted, the Ship Structure Committee is conducting research on:

a. loading rates for ship steels and
b. a study of the adequacy of the dynamic criterion.

One additional program which should be recommended to the SSC is a study and cataloguing of the severity of typical design details, both from a fracture as well as a fatigue viewpoint. If the designer had some indication during the design stage of just how deleterious certain details are, they could be eliminated. AISC has done this for various bridge details and the allowable fatigue stress range is decreased as the severity of the detail is increased.

Mr. Christopher of the Naval Construction Research Establishment of the United Kingdom points out that thickness is important and I agree with his statement. However, it is not as significant as the loading rate shift for thickness up to 2-inches. For thicknesses greater than 2-inches, I agree that constraint becomes increasingly more important. Scatter in material properties certainly is a fact of life that must be dealt with. The general move toward probabilistic design may provide a better solution to this situation than the present use of guaranteed minimum values.

Once again, I would like to thank the reviewers for their interest as shown by their pertinent discussions. Thank you.



Third Day Session

From left: P. Palermo, J. Lisnyk, D. Wilson
T. Crooker, authors; J. Goldberg, presiding;
R. Manley, A. Dinsenbacher, authors.

Just how one-sided this OTA report actually is, becomes clear when one reads the comments of the members of the review panel. This panel, charged with reviewing the OTA study on tanker safety, was made up of university professors, consultants, members of the National Research Council, and representatives of the petroleum, salvage, and tanker industries. Three of the review panel members objected to the conclusions drawn with regard to double bottoms and suggested that both sides of the controversial issue be fully presented. One panel member even requested that if counter-arguments were not presented in the report, then his letter, which outlined some of these counter-arguments, should be added as a minority opnion. All of these requests for full and fair treatment of the issue were denied by OTA. In the face of such evidence, how can one even pretend that this study is competent and unbiased.

Let us now look at what the effect would be if this bill were to pass.

First, it is certain that requiring double bottoms would increase construction costs. As I stated earlier, estimates of the amount of the increase vary widely, from 2 to 13 percent. But there is no question that construction costs will rise. This cost increase will be reflected in required freight rates and will, in turn, be passed on to consumers of the petroleum products. Since everyone either uses oil and gas directly, or uses some product or service which uses oil and gas, every American would face price increases as a result of mandatory double bottoms.

Although this bill only requires double bottoms on U.S.-flag ships operating in U.S. waters, the Ports and Waterways Safety Act states that the same regulations must apply to foreign vessels operating in U.S. waters. Therefore, it seems that the increased cost of double bottoms would not disrupt the competitive balance between U.S. and foreign-flag vessels. However, the mandatory double-bottom requirement only applies to vessels constructed after a certain date.

Now, foreign fleets have made major expansions in the past decade with vessels that do not meet the new specifications. Under the proposed bill, they would not be subject to the new requirements. Neither would they be required to retrofit to meet the new requirements.

Conversely, this country's tanker fleet is in the beginning stages of its expansion. The new U.S. vessels would be much more expensive because they would be subject to the standards and be in competition with existing lower-cost foreign tankers. Thus our fleet would be put in a crippling competitive economic position. One expert suggested the "net result would probably be to bring the U.S. shipbuilding program to a halt because our U.S. market would continue to be served by foreign vessels contracted for and built before the relevant dates."

Finally, in light of all the evidence I have presented here tonight it seems totally unreasonable to me to require a technological innovation whose benefits are not generally accepted, and whose opponents have a great deal more experience with double bottoms than we do. And to impose a standard that can only hurt American interests, while providing no visible benefits to the marine environment or to the marine industry seems totally senseless to me.

I can only urge you tonight to join me in opposition to this bill. Judging from the support that the mandatory double-bottom amendment received last year from both Houses of Congress, it seems clear to me that the Members of Congress are not familiar with all the arguments regarding double bottoms. I ask that you help me in presenting the full story on double bottoms, and clarify this controversial, complex, and potentially harmful issue.

regulations will in effect enforce those international regulations adopted at the 1973 IMCO Convention. They will set discharge limits, specify required equipment, require segregated ballast tanks, and limit the size of cargo tanks.

In addition, the Coast Guard will go even further in a proposed regulation to be published this week. This proposed regulation will establish a formula for how the segregated ballast tanks should be distributed. This formula will not make double bottoms mandatory, but will allow a degree of flexibility in how the ballast tanks are arranged. This will allow for "J" wing tanks, "L" wing tanks, and other combinations of wing tanks, double bottoms and double sides. By allowing this flexibility in the distribution of ballast tanks, the Coast Guard has recognized two essential facts. One, defensive spaces can be effective in minimizing oil outflow in tanker accidents. And, two, groundings only account for one-fourth of the oil discharged in tanker accidents. Protection on the sides of the hull is also needed in case of collisions and rammings. The Coast Guard has wisely ascertained that double bottoms are not the panacea for oil pollution that proponents claim them to be -- U.S. Coast Guard, "Final Environmental Impact Statement." Regulations for Tank Vessels engaged in the carriage of oil in domestic trade.

In addition to the final regulations and the proposed regulations that will be issued by the Coast Guard this week, the Coast Guard is also pursuing a number of other courses of action to help mitigate oil pollution.

In a few months, the Coast Guard will extend these regulations governing U.S. vessels in U.S. waters to U.S. vessels operating in foreign waters, and to foreign vessels operating in U.S. waters.

The Coast Guard is also studying the need for construction requirements for inland tank barges.

They are also considering regulations dealing with vessel traffic management systems, and improved vessel controllability and maneuverability.

Finally, the Coast Guard is doing all it can to encourage ratification of the 1973 IMCO Convention by the maritime nations of the world.

You may be wondering why a Member of the House of Representatives is telling you about an issue that has twice been debated in distinguished forums, and twice been resolved. I have brought up the subject tonight because the issue is before us once again. Several distinguished Members of Congress will apparently settle for nothing short of mandatory full double bottoms.

Last year an amendment was added to the Energy Transportation Security Act that would require double bottoms on vessels operating in the inland waters of the west coast. This provision was passed by both the House of Representatives and the Senate, but was vetoed by President Ford.

Again, in January of this year, a separate piece of legislation was introduced that would make double bottoms mandatory for new U.S. tankers operating not only on the west coast, but in all U.S. waters. This bill is now under consideration by the Senate Commerce Committee.

The committee seems determined to have this legislation enacted. One of the courses of action the committee has taken, was to request a study of the entire issue of tanker safety by the congressional Office of Technology Assessment.

Now the Office of Technology Assessment, or OTA, was established in 1972 to provide competent, unbiased information concerning the physical, biological, economic, social, and political effects of advanced technological applications. The office is charged with providing early indications of the probable beneficial and adverse impacts of these applications of technology.

One can hardly say that the report that OTA issued in July of this year on tanker safety was a competent and unbiased study. The study draws conclusions favoring double bottoms after considering only a portion of the available information. It never really gives a strong argument for why double bottoms should be required. Instead, it refutes arguments from opponents of double bottoms and presents irrelevant information as though it supported their conclusion.

For instance, the study gives two tables showing the number of double-bottom tankers in operation and on order worldwide as if the mere fact that some shipbuilders are building double bottoms were proof that they were effective in reducing oil pollution.

Also, the study discusses at length the various cost estimates for double-bottom tankers and concluded that the actual increase in cost is less than feared by the shipbuilding industry. Does this in itself constitute an argument for requiring double bottoms?

When it comes to the effectiveness of double bottoms in mitigating oil discharges from tanker accidents, the OTA report is definitely short on evidence. It cites the Coast Guard study I mentioned earlier which claimed double bottoms to be 90 percent effective, but fails to fully consider how erroneous that estimate is and the fact that the original estimate was subsequently substantially reduced -- by the Coast Guard.

And yet, for all their lack of evidence and the speculative nature of their arguments, the OTA still finds it possible to state, and I quote, "from a technical standpoint, it is generally accepted that double bottoms will prevent most oil spillage which results from limited intensity hull ruptures due to groundings. This report supports the finding that double bottoms offer a significant degree of protection from oil pollution in the event of a grounding accident."

What this report fails to point out is that double bottoms will only protect against groundings, and will have no utility in the case of collisions or rammings. Since collisions and rammings occur even more frequently than groundings, and result in about the same amount of oil outflow, there is no reason to require full double bottoms and not allow for flexibility in how the defensive spaces are arranged.

Clearly, this report was never intended to be a competent and unbiased study, but was prepared merely to provide support to the Senate bill. This is a clear distortion of the purpose of the OTA.

last tank.

A final concern of this third group is over the cost of requiring double bottoms. Estimates of the added cost of fitting tankers with double bottoms range from 2 to 13 percent. As I stated earlier, the benefits accruing from this added cost are, at best, difficult to assess. But let us try to put these benefits into perspective.

As I stated in the beginning, the National Academy of Sciences has estimated that marine transportation accounted for one-third of the total flow of oil into the world's oceans. That is, 2 million out of approximately 6 million tons of oil. Now, not all of the oil pollution from marine transportation comes from tankers -- only about two-thirds. And of the oil pollution caused by tankers, only 15 percent is caused by tanker accidents; the rest is intentional from normal tanker operations. Now, of the 200,000 tons of oil flowing from tanker accidents, only one-fourth results from groundings. Most result from structural failures and collisions. So what have we arrived at? We have found that only 50,000 tons out of 6 million tons of oil pollution is caused by tanker groundings. That is less than one percent of all the oil flowing into the oceans from all sources. Less than 1 percent -- National Academy of Sciences, "Petroleum in the Marine Environment."

So if we could eliminate all oil pollution caused by tanker groundings, we would only reduce the total amount of oil flowing into the oceans by one percent. And it is clear that we could never hope to eliminate all oil pollution resulting from groundings. In fact, we cannot even be certain whether by requiring double bottoms we would reduce or would increase the total oil outflow.

It is clear to me at this point that it would be a mistake to require double bottoms on all oil tankers. There is simply not enough evidence to justify the claims made by advocates of the double bottoms. Nor is there enough evidence to justify banning the double-bottom tankers from the world's oceans. We must maintain a degree of flexibility and gather more evidence before setting up regulations.

In stating these views, I am supporting the actions of two impressive organizations: the Inter-Governmental Maritime Consultative Organization, or IMCO, and the United States Coast Guard. Both of these organizations have considered a number of measures designed to reduce oil pollution, including requiring double bottoms. Both, upon review of the evidence, decided not to impose the double-bottom requirement.

In October 1973 IMCO held the International Convention for the Prevention of Pollution from Ships, in London. Representatives from 79 maritime nations presented their views and reached an agreement on an international convention.

One of the American positions at the beginning of the conference was in favor of requiring segregated ballast by the use of double bottoms on all new tankers. However, other nations which had experience with double-bottom tankers were opposed to making double bottoms mandatory. At that time, in 1973, there were only 6 double-bottom oil tankers in crude oil trade operating and they were all registered under foreign flags. The question of mandatory double bottoms was twice put to a vote at the conference and was defeated soundly both times: 22 to 9 as a requirement for larger tankers, and 21 to 5 for the smaller tankers.

The conference did adopt a number of measures which will go far toward minimizing the amount of oil pollution in the oceans. The regulations agreed to, deal with three aspects of operational oil pollution from tankers.

First the convention sets discharge criteria, including the requirement that the amount of oil discharged in a ballast voyage of new oil tankers cannot exceed 1/30,000 of the amount of cargo carried. This standard is twice as strict as the old standard. In addition, specified areas which are considered to be particularly vulnerable to pollution by oil have been designated as "special areas." The main special areas are the Mediterranean Sea, the Red Sea, the Baltic Sea, the Black Sea, and the Persian Gulf area.

Second the convention sets standards which will govern the cleaning of oil cargo tanks. All tankers must be capable of operating with the method of retention on board in association with the "load-on-top" system. To effect this, all tankers must be fitted with appropriate equipment, which will include an oil discharge monitoring and control system, oily water separating equipment or filtering system, slop tanks, sludge tanks, piping and pumping arrangements.

Third, the convention sets construction standards. New oil tankers greater than 70,000 deadweight tons will be required to be fitted with segregated ballast tanks. These must be sufficient in capacity to provide adequate operating draft without a need to carry ballast water in oil cargo tanks. Also, subdivision and damage stability requirements have been set.

All of these actions will serve to greatly reduce the amount of oil flowing from normal tanker operation -- bilge discharge and tank cleaning and ballasting -- which constitute 80 percent of all the oil pollution caused by tankers.

The U.S. Coast Guard has also had a chance to set regulations designed to mitigate oil pollution. Under the Ports and Waterways Safety Act of 1972, the Coast Guard has broad authority to establish vessel traffic control systems and to set standards governing the design, construction, maintenance, and operation of oil-carrying vessels. In January 1973, the Coast Guard proposed regulations in compliance with the Act. Among the regulations was one requiring segregated ballast capability achieved in part by fitting in the cargo length a double bottom of a minimum height of one-fifteenth of the beam. This was the position that the United States was to take at the October IMCO convention.

However, subsequent to the IMCO Convention, and based in part on the evidence presented there, the Coast Guard decided not to make double bottoms mandatory.

The Coast Guard will be issuing final regulations this week regarding domestic tankers operating in domestic waters. The Coast Guard argue that in cases where both hulls are ruptured, containment of the cargo would be helped by the double bottoms, and the rate of discharge of the oil would be slower, thus allowing more time for response.

Finally, advocates of the double bottoms point to the fact that a smooth inner surface of the cargo tanks means there is less surface area and less clingage when the cargo is removed. This in turn means that there is less residue following unloading of a tanker; cargo tanks need to be cleaned less frequently; and oil pollution from tank cleaning operations is reduced -- U.S. Congress, Office of Technology Assessment, "Oil Transportation by Tankers: An Analysis of Marine Pollution and Safety Measures."

Now let us turn to the opponents of double bottoms. This faction argues that double-bottom tankers pose an even greater threat to the marine environment than single-bottom tankers. They contend that a minor grounding accident in a single-bottom tanker could turn into an accident of catastrophic proportions if the tanker had a double bottom. Their argument runs like this:

When a single-bottom tanker runs aground, it loses some of its cargo and becomes lighter. As a result, it rises slightly out of the water, thus automatically helping to free itself.

However, if the same tanker had a double bottom, then instead of losing cargo, water would rush into the empty ballast space between the two layers of steel, make the tanker heavier, and the vessel would sink deeper in the water.

Now, it is argued by opponents of double bottoms that by sinking deeper, the tanker settles more firmly aground and there is a greater chance of major damage, including the total breakup and loss of the ship.

This means that what might have been only a minor spill from a single-bottom tanker could become a major accident in a double-bottom tanker, involving the loss of the entire cargo and possibly the loss of lives.

Opponents of double bottoms also argue, as did the Norwegians at the 1973 IMCO conference, that there is a possibility that flammable vapors will accumulate in the spaces between the outer hull and the cargo tanks. This could result in disastrous explosions, also involving the loss of the entire cargo and the loss of lives.

The final argument made by opponents of double bottoms is that by placing empty ballast spaces below a loaded cargo tank, you raise the ship's center of gravity. A higher center of gravity, or course, means reduced stability and a greater chance of capsizing. This is a particularly important consideration in rough seas. Thus, requiring double bottoms could actually increase the number of tanker accidents. -- American Institute of Merchant Shipping, "Tanker Double Bottoms. Yes or No?"

Now between those who want to require and those who want to prohibit the use of double bottoms in tankers, stand those who demand flexibility in the regulations. This group is not convinced by the arguments of either side, and prefers to wait until more evidence is collected. This group recognizes that there are now only seven double bottom oil tankers in the crude oil trade in operation worldwide and that this hardly constitutes an adequate data base. Indeed, most of the arguments on both sides are based on speculation -- speculation about the safety of the ships and about their effectiveness. The arguments of this third group, therefore, stress the uncertainty surrounding the arguments of the first two groups.

Let us now look at the arguments presented by this third group: Those who see flexibility as the most effective way of reducing oil pollution.

First, they dispute the claims of double-bottom tanker advocates wtth regard to the effectiveness of double bottoms. Those who favor double bottoms frequently cite a published analysis of 30 grounding accidents.

In 27 of these, vertical damage was less than one-fifteenth of the vessel's beam. That means that in 90 percent of the groundings, the cargo tank would not have ruptured if there had been a double bottom of about 2 meters in depth. This seems to be a persuasive argument in favor of the effectiveness of double bottoms. However, there are two important factors which raise doubts about the validity of this argument.

For one, there is evidence that the inner layer of steel might still rupture, just from the integral structural connection between the two layers. An IMCO study found this to be the case in many groundings of double-bottom dry cargo vessels.

Also, this fails to take into account the possibility of greater damage occurring as the tanker sinks deeper in the water. Therefore, the actual effectiveness of double bottoms is undoubtedly less than the 90 percent figure cited in this Coast Guard study.

Indeed, this estimate has been reduced several times in subsequent studies. The Coast Guard did a second study and judged the effectiveness of double bottoms to be on the order of 73 percent. Later, the U.S. Department of Commerce Maritime Administration re-evaluated the Coast Guard's findings and estimated that only 35 percent of the oil discharged from groundings could have been avoided if the ships involved had had double bottoms.

Second, this group that demands flexibility in the arrangement of segregated ballast tanks, questions the arguments presented by those who oppose double bottoms. As stated above, opponents of double bottoms have argued that a firmly grounded double-bottom tanker could cause salvage problems and result in a greater outflow of oil. However, some advocates of double bottoms argue exactly the opposite, that a firmly grounded tanker makes salvage easier, and many salvage experts view double bottoms with favor.

Again, the differing views stem from a lack of experience with double-bottom tankers, and one cannot argue with certainty that double-bottom tankers are more dangerous and will increase pollution.

Those who seek flexibility in the regulations also dispute opponents' concern over explosive vapors accumulating in empty spaces. These spaces, they claim, can be inerted and monitored and made as safe as any empty bal-