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Fracture Characteristics of Ship Steel under Extremely High Loading Rates

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ABSTRACT

This paper surveys the fracture-resistance response of ship steels to extremely high loading rates. These loading conditions are viewed principally as very short loading times resulting in high loading rates at the tips of weld imperfections, geometrical stress concentrations, or cracks that may be present in the structure. Although the focus of the survey is on the material response to these extremely high loading conditions, it is not possible to divorce the influence of the original design (design details and/or criteria) and the method of fabrication from these considerations. In particular, the design of the ship and the loading distribution within the ship will have a dominant influence on the redistribution of stresses, and therefore, on the ability to arrest a crack once it starts to propagate unstably.

The effect of extremely high loading rates on crack initiation and propagation and arrest of cracks is examined. The problem is complicated by the fact that the fracture resistance of steels is significantly influenced by loading rate as well as by temperature. Thus the resistance to initiation and propagation/arrest of cracks for steels that exhibit a fracture-toughness-transition behavior is examined in the three regions of fracture behavior: (1) low-toughness brittle or cleavage fracture, (2) transitional or mixed-mode brittle-ductile fracture, and (3) upper-shelf or fully ductile fracture. To emphasize the differences in fracture-resistance behavior in these regions, design philosophies for applications other than ships are discussed.

INTRODUCTION

The fracture behavior of steels used in ships and other structures is governed primarily by (1) the service conditions, namely the rate of loading and the ambient temperature; (2) the mechanical properties of the steel; (3) the design and fabrication of the structure; and (4) the operating conditions. The service conditions affect the mechanical properties because the mechanical properties of various steel grades respond differently to the rate of loading and to temperature. The design and fabrication, including redundance of members and local geometries (stress concentrations) of structural details, determine the magnitude and distribution of localized stresses and the response of the structure to externally applied loads. The procedures used to load a ship contribute to the operating conditions. Thus, all these factors must be considered in the development of a fracture-control plan of a structural component and in assessment of the effect of extremely high loading rates on fracture control. However, because the primary effect of changing loading rate is to change the mechanical properties of steel, the major emphasis of this paper will deal with rate effects on strength and fracture characteristics of steels.

Before it is possible to start a discussion of the effects of extremely high loading rates on the mechanical properties and fracture resistance of ship steels, nonextreme loading rates for normal operating conditions must be defined. As listed in Table I, stresses and strains in ships on gently rolling seas may fluctuate from a maximum to a minimum in the time period of a minute or in minutes. However, as

Table I

Conditions for Various Rates of Loading

"Type" of Loading	Laboratory-Test Example	Service Example	Approximate Nominal Straining Rate, in./in./second	Approximate Time of Loading, seconds
Static	Tension test. Static K_{Ic} test.	Hull loading during calm seas.	1×10^{-5}	100
Intermediate	K_{Ic} test at fastest rate of loading in Universal Testing machine.	Hull loading during slamming conditions on rough seas.	1×10^{-3}	1
Extremely High	Charpy V-notch Test. Dynamic Tear Test. Nil-Ductility-Temperature Test.	Local damaged areas during a collision. Explosive loading of structure.	10	0.1×10^{-3}

shown from studies of the S. S. Wolverine State,(1,2) during slamming conditions these loading times are of the order of one second. Thus, normal operating conditions of ships must comprehend these short loading times and will be referred to in this review as an intermediate loading rate because the loading times are shorter than static loading times (minutes) but longer than impact loading times (a millisecond or less). Hence, in terms of load rise times, extremely high loading rates may be considered comparable to impact loading times and may result from collision or explosive loadings.[1] In most cases the extremely short loading times will be confined to very local areas of a ship. The massiveness and flexibility of large structures such as ships will dampen stress waves of short duration, and hence, not transmit them to other major areas of the structure. Only in lightweight stiff structures would one expect the natural frequency of the member to be high enough to transmit short-duration large-amplitude impulse loads over significant distances and result in extremely high loading rates of significant magnitude over major portions of a ship.

Once an appropriate loading rate has been established for a specific ship detail, determination of the fracture behavior of the steel may be complicated by the inconsistencies in loading rates for the various mechanical property tests. For example, the strength properties of steels are generally specified and obtained at static loading rates (tension tests), whereas most toughness tests are determined under impact conditions (Charpy V-notch or CVN and nil-ductility-temperature or NDT tests), Table I. The differences in loading rates between these tests are approximately six orders of magnitude.(3) Because of the rate and temperature sensitivity of structural grades of steels (including steels for ordinary and higher-strength hull construction), care must be taken when estimating or describing fracture characteristics of steels to be consistent in determining and designating the mechanical properties at the same loading rate and temperature.

Although many types of materials are used in ship structures, the present discussion will be restricted to wrought structural steels having room-temperature static yield strengths less than about 110 ksi or 758 MPa (ABS grades). Accordingly, the materials discussed all exhibit a fracture-transition behavior, from ductile tearing to cleavage fracture, with decreasing temperature. An increase in the loading rate will manifest itself as an embrittling effect by elevating the yield strength and decreasing the plastic-zone size at stress concentrations in regions of changes in cross

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[1] In the <u>immediate</u> vicinity of an explosive charge, the loading rates may be of shorter times than those obtained from impact loading.

section, at imperfections or actual cracks in the base metal, or, more often, in welds. As demonstrated in laboratory tests, a structure containing a stress concentration will also exhibit a transition in fracture behavior at different temperatures, depending on the rate at which the load is applied, Figure 1. An increase in the loading rate causes the fracture-transition behavior to occur at high temperatures.

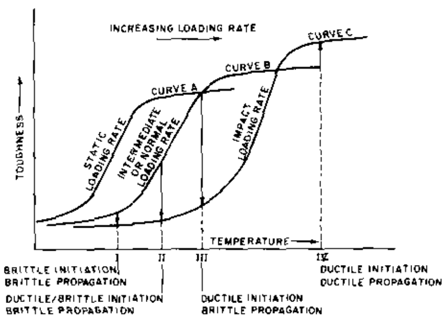

Fig. 1 Schematic Representation of Various Types of Initiation and Propagation Fracture-Toughness Behavior for Normal Loading Rates.

As previously mentioned, the fracture characteristics of ships are not determined by just the material characteristics but, just as importantly, by the design, fabrication, and operating procedures of the ship. For example, as shown in the failure of the Ingrahm barge,(4) incorrect ballasting can result in the overloading of a deck plate and failure in an area of a structural detail having high triaxial stresses: in this case a King Post. Any material, if subjected to sufficiently high stresses, will fail. Furthermore, although the present discussion focuses on the materials aspect of the problem, it will be obvious to the reader that design plays as important or greater a role in the arrest of a crack than does the material behavior.

In the following discussion, the fracture characterization of ship steels will be examined according to the relationship between the temperature of the structural member and the relative position of the fracture-toughness transition curve of the material of the member subjected to that temperature, Figure 1. Although the schematic drawing of Figure 1 shows different modes of fracture occurring at different temperatures, it is understood that, at one temperature, any particular fracture mode may occur, depending on the selection of the steel and its specific transition-temperature behavior. In this discussion, the intermediate loading rate for normal operating conditions and fracture characteristics will first be examined, followed by discussions of anticipated fracture behaviors at extremely high loading rates. The fracture characteristics of ship steels will be examined for intermediate and extreme loading rates according to the type of fracture behavior observed for the three principal regions of a fracture-transition curve: (1) lower-shelf behavior characterized by a fracture surface having a brittle cleavage appearance and the structural response of a linear-elastic fracture behavior; (2) transition-temperature behavior characterized by a ductile/brittle, ductile-dimple/cleavage mixed-mode elastic-plastic fracture behavior; and (3) upper-shelf behavior characterized by a fully ductile dimple and shear fracture mode with significant through-thickness-contraction plastic-fracture behavior.

BRITTLE-FRACTURE BEHAVIOR

The viewpoint taken in the present discussion is that a crack initiates at one straining or loading rate and propagates at a higher strain rate. Thus the fracture-transition curve corresponding to the crack-initiation event is different from that corresponding to the fracture-transition curve used to describe the material response for a propagating crack. The fracture characteristics of a propagating (running) crack correspond to the fracture behavior of the steel under impact loading times.(5) Therefore, if a fracture initiates under extremely high loading rates, both the initiation and propagation events are assumed to correspond to the curve on the far right in Figure 1. On the other hand, if a crack initiates as a truly brittle fracture at an intermediate loading rate, Temperature I in Figure 1, it propagates in a similar brittle low-energy-fracture manner. If the loading rate at Temperature I is a static loading condition, the fracture-initiation behavior would be elastic-plastic.

For brittle-fracture initiation and subsequent brittle propagation, the fracture toughness of the steel is similar. As the crack starts to extend in a brittle manner under constant or increasing tensile load, the force driving the crack will increase, be overdriven, and will generally branch into multiple fractures.(6) This behavior may be illustrated best by using the fracture mechanics methodology for describing fracture. The stress intensity, K_I, for the crack-tip stress field is of the form

$$K_I = C \sigma \sqrt{\pi a} \tag{1}$$

where

- C = a constant dependent on the geometry of the member,
- σ = the gross or remote field stress, and
- a = the half-crack length.

Alternately, the crack driving force, G_I, is expressed as

$$G_I = K_I^2/E = C^2 \sigma^2 \pi a/E \tag{2}$$

where E is the elastic modulus.

If the stress level, σ, reaches a critical value in the presence of a crack, 2a, such that the stress intensity equals the critical-stress intensity or plane-strain fracture toughness, K_{IC}, of the steel, the crack will extend as an unstable fracture. Because the fracture speeds of brittle cracks are in excess of 1000 feet per second (305 m/s), there will be insufficient time for the load to be transferred to other structural members. As seen from Equation 2, the brittle crack will be overdriven during propagation if σ is constant while the crack length, a, increases. Hence the crack will branch to form additional fracture surfaces to dissipate the additional fracture energy.(6)

Ship steels are selected such that brittle fracture would seldom occur under normal operating conditions. As shown for Temperature I in Figure 1, if brittle-fracture initiation does occur at an intermediate loading rate, an extreme loading rate of 3 to 4 orders of magnitude shorter loading time would also result in brittle-fracture initiation similar to that obtained at the intermediate rate. The principal difference in behavior that would be expected between the two loading rates would be additional crack branch during propagation for extremely high loading rates.

If a brittle-fracture initiation occurs in any particular steel plate and the load on the member remains constant, brittle propagation will occur, crack-tip stresses will not decrease, and the crack will be overdriven. Therefore, it is not possible to stop or arrest the crack by utilizing the material properties of the plate in which the crack initiated. Because the stresses may not decrease during propagation, the crack(s) can only be arrested if the stress field through the transfer of loads to other members is reduced or if the crack runs through thicker sections or into materials of significantly greater ductility (than the steel in which the crack initiated). Rolfe, Rhea, and Kuzmanovic(7) have presented an excellent summary of the structural details of existing ships and of proposed changes in these details for improving crack-arresting-performance characteristics. Previous design procedures have utilized steels with low transition temperatures as in-plane arrestors, Figure 2, in critical areas such as sheerstrakes and lower turns of the bilge.

As shown by Equations 1 and 2, long cracks can only be arrested by materials of very high dynamic toughness. Even with the progress in understanding and the quantitative assessment of fracture control in structures, material properties alone cannot be relied on to arrest running cracks. The use of out-of-plane members, such as stiffeners, is a much more effective means of arresting cracks. The intensity of the crack-tip stress field of propagating cracks will be significantly reduced if the crack propagates to the stiffening member and the stresses around the crack are transferred to the stiffening member.

MIXED-MODE OR FRACTURE-TRANSITION BEHAVIOR

Normal Operating Conditions of Intermediate Loading Rates

Current American Bureau of Shipping (ABS) rules for setting toughness requirements for ship steels can, in many cases, be shown to be

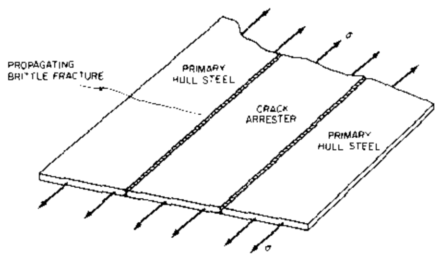

Fig. 2A Typical Geometry of In-Plane Crack Arrester

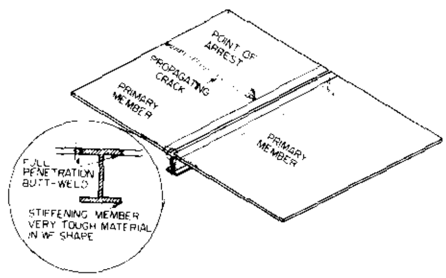

Fig. 2B Schematic showing Out-Of-Plane Crack Arrester

Fig. 2 Types of Crack-Arrester Systems (Reference No. 7).

representative of a design philosophy for prevention of crack initiation (the beginning of unstable crack extension) at intermediate loading rates.(4) As indicated in Table I, slamming conditions having loading times of the order of a second are representative of intermediate loading rates. Specifications have been established which, in essence, require that the steel have a sufficiently low transition temperature to give mixed-mode or an elastic-plastic fracture (transition temperature) behavior at the service conditions, as shown by Temperature II in Figure 1. That is, the crack initiates in an elastic-plastic manner and, because of the high rate of crack growth, would be expected to propagate in a brittle manner.

This concept is illustrated in the following example of an ABS grade D steel intended for use in a vessel to carry liquified gases (ABS Section 24) operating at or above 0°F (-18°C):

The ABS rule 24.55.3 requires that notch-toughness tests be conducted 10°F (5.5°C) below the minimum service temperature. Thus for steels to be used at 0°F (-18°C) and above (ABS rule 24.59.5), the steel must exhibit a minimum CVN toughness in any single transverse specimen of 13.5 foot pounds (18.3 J) at -10°F (-23.5°C). Barsom has shown(8) that the corresponding dynamic critical-stress-intensity factor, $K_{IC(0.1)}$[2], can be estimated as

$$K_{IC(0.1)} = \sqrt{5E\ (CVN)} \qquad (3)$$

where

$K_{IC(0.1)}$ = dynamic critical-stress-intensity factor, psi $\sqrt{in.}$ obtained at a loading time of about 0.1 millisec, E = Elastic Modulus, 30×10^6 psi or 2.07×10^5 MPa,

CVN = CVN energy absorbed, ft-lb, in the lower portion of the transition-temperature curve where CVN is in ft-lb and < 1/2 yield strength is in ksi.

Thus the 13.5-foot-pound requirement corresponds to a dynamic fracture toughness of 45 ksi $\sqrt{in.}$ (49.5 MPa $\sqrt{m}$). If the actual loading rate in the ship were extremely high (impact), then this level of toughness could lead to brittle fracture initiation at the minimum service temperature because brittle plane-strain fracture behavior is expected in plate thicknesses, t, according to the equation(10)

$$t \geq 2.5 \left(\frac{K_{IC(x)}{}^2}{\sigma_{yd}}\right) = 2.5 \left(\frac{45}{75}\right)^2 =$$

$$0.9 \text{ inches } (23 \text{ mm}) \qquad (4)$$

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2 The number 0.1, in parenthesis, refers to the estimated rise time of the test in millisec,9) taken here to be about 0.1 millisec for impact loading.

where

σ_{yd} = dynamic yield strength,[3] ksi, determined at the loading time corresponding to $K_{IC(x)}$.

As is evident from the excellent service history of ship steels, the normal operating conditions of ships are not impact because few brittle fractures have occurred in these steels at or above this temperature. The fracture behavior corresponding to the actual operating rates of loading in ships is established by shifting the fracture-toughness curve determined by impact loading of Charpy specimens to the temperatures corresponding to intermediate loading rates, Figure 3. This temperature shift can be estimated according to the equation[8)]

$$\Delta T = \frac{2}{3}\,(215 - 1.5\,\sigma_{ys}) \qquad (5)$$

where

σ_{ys} is the static room-temperature yield strength, ksi.

In the present example, this steel which exhibited a dynamic fracture toughness of 45 ksi $\sqrt{\text{in.}}$ at -10°F would be expected to exhibit the same fracture toughness of 45 ksi $\sqrt{\text{in.}}$ at an intermediate loading rate and a temperature of about -110°F (-79°C). Furthermore, this steel would behave in a very ductile manner at intermediate loading rates at -10°F. Brittle plane-strain fracture behavior would not be

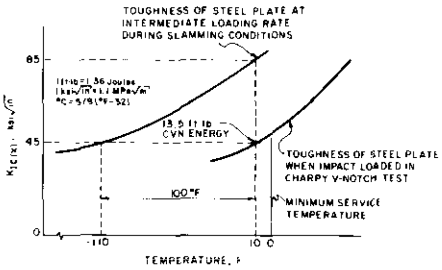

Fig. 3 Example of Toughness Behavior of Steel Plate Exhibiting 13.5 ft-lb at -10°F.

expected[4] for intermediate loading rates at -10°F except for thicknesses greater than 3.2 inches (81 mm).

A crack propagating in a steel plate meeting ABS rules may do so in a brittle manner, Temperature II in Figure 1. Recent research on crack-arrest measurements suggests that crack-arrest toughness values for Temperature II may be slightly higher than those obtained at the same

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[3] In this example it is assumed that an ABS Grade D steel is being considered for this vessel. Although the minimum allowable yield strength is 34 ksi (234 MPa), for purposes of discussion this value is rounded up to 40 ksi (276 MPa). Thus the dynamic yield strength of 75 ksi (517 MPa) was estimated to be the static room-temperature value of 40 ksi plus an elevation of 5 ksi (34 MPa) because the temperature was -10°F plus an elevation of 30 ksi (207 MPa) for impact loading (about 6 orders of magnitude increase in loading rate over static conditions).[1)]

[4] This estimate of plane-strain behavior is based on Equation 4 and a $K_{IC(100)}$ estimate of 85 ksi $\sqrt{\text{in.}}$ (93.8 MPa $\sqrt{\text{in.}}$) for intermediate loading rates at -10F. The value of 85 ksi $\sqrt{\text{in.}}$ is based on the sum of the toughness value of 45 at -110°F plus an increase of 40 ksi $\sqrt{\text{in.}}$ (44 MPa $\sqrt{\text{in.}}$) estimated from the K_{IR} curve of ASME[11)] that suggests an increase of about 40 ksi $\sqrt{\text{in.}}$ in K_{IC} for a 100°F (55°C) increase in temperature above the NDT temperature, Figure 4. The estimate of the increase in fracture toughness with increasing temperature is only an approximation because different steels will exhibit different K_{IR} curves. The curve used for the ASME code was developed as a conservative estimate for A533 Class I and A508 steels. Examination of available data in the literature suggests that for K_{IC} values up to about 100 ksi $\sqrt{\text{in.}}$ (110 MPa $\sqrt{\text{m}}$), high-strength steels may exhibit a somewhat steeper curve, whereas very-low strength steels have somewhat shallower K_{IR} curves. Above K_{IC} values of 100 ksi $\sqrt{\text{in.}}$, this procedure maybe very conservative.

temperature by impact loading in crack-initiation-test specimens.(12) Therefore, crack-arrest values may be conservatively estimated from crack-initiation data. This difference has been attributed to a somewhat artificially low initiation-toughness value for crack initiation caused by the smooth nature of the original fatigue crack in a laboratory-test specimen. Macroscopic-observations of the fracture surfaces of arrested brittle cracks show a roughened surface, and even ligaments between fracture faces, in the vicinity of the arrested crack tip.[5]

Extremely High Loading Rates

If the steel described in the present example were subjected to extremely high loading rates, the fracture-initiation event would be a brittle fracture. The extreme rate of loading would be comparable to impact loading rates resulting in a $K_{IC(0.1)}$ of about 45 ksi $\sqrt{in.}$ To assure a ductile-fracture initiation for impact loading times, it is necessary to either require CVN toughness levels greater than those currently specified, Temperature II, Figure 1, or reduce the specification testing temperature. Rolfe, et al.(7) have proposed "Fracture-Control Guidelines for Welded Steel Ship Hulls," based on impact loading rates. These guidelines focused attention on the use of the dynamic-tear-test specimen for measuring fracture toughness. Subsequently, Hawthorne and Loss(13) showed that, on the basis of these assumptions of impact loading, most steels previously and currently used in ships would be expected to fail in a brittle manner. Recently, Sovak, Caldwell, and Shoemaker(2) showed that, if the guidelines of Rolfe, et. al. were adjusted for intermediate loading rates, the guidelines would be similar to the ABS rules using Charpy-specimen testing and would be more consistent with the history of the ship industry. These analyses indicate that, if the same degree of safety ensured with the current CVN requirements for a 40 ksi yield-strength steel for normal operating conditions (intermediate loading rates) is maintained for extreme loading rates, then the required CVN toughness should be 100°F below the current test-temperature requirement. Similarly, on the basis of Equation 5, the CVN test temperature should be decreased 65°F (36°C) for an 80 ksi (552 MPa) yield-strength steel subjected to extreme impact loading.

One of the salient features of the Rolfe, et al. guidelines is the recognition that toughness requirements, whether for normal or extremely high loading rates, must be adjusted according to the yield strength of the steel. Such adjustments are made by requiring greater toughness values for high-strength steels or by decreasing the testing temperature. This requirement is illustrated by the following:

As described in the previous example, assume that the shape of the toughness-temperature curve of a steel is the same at all strain rates and the same as the K_{IR} curve. The NDT temperature corresponds to plane-strain fracture in a 1-inch-thick (25.4 mm) plate for impact loading.(3) Hence, the K_{IR} curve for impact loading passes through NDT at a $K_{IC(0.1)}$ of 40 ksi $\sqrt{in.}$ for a steel having a static yield strength of 40 ksi (example previously described), Figure 4. For intermediate loading rates, plane-strain behavior would be predicted by shifting the impact curve 100°F lower in temperature. On the other hand, the use of Equation 4 for a steel having a static yield strength of 80 ksi (dynamic yield strength of 110 ksi requires a concommitently higher $K_{IC(0.1)}$ value at NDT of 70 ksi $\sqrt{in.}$ (77 MPa $\sqrt{m}$), Figure 4. The toughness curve for the intermediate loading rate of the 80 ksi yield-strength steel is shifted about 65°F to the left, Equation 5. Also shown in Figure 4 are the toughness levels for plane-strain fracture

[5] A point of clarity regarding fracture appearance is perhaps in order. The major portion of the fracture surface observed after the fracture of a plate is the propagation event and not the initiation event. Ship steels are selected principally on the basis of designing against fracture initiation. The ductility exhibited by the steel at the loading rate of the initiation event is only evident at the very tip of the original crack or imperfection. Once the cracks starts to run the fracture may be flat and brittle cleavage in appearance and is not indicative of the original ductile-fracture-nitiation event.

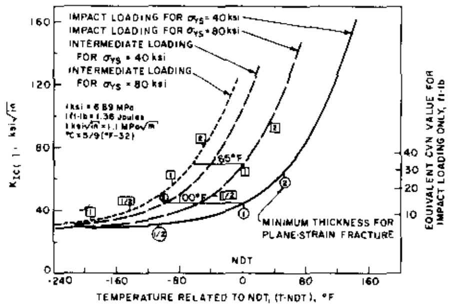

Fig. 4 Estimates of Fracture Toughness for Normal and Extremely High Loading Rates for Two Steels Based Upon ASME K_{IR} Reference Curve.

in 1/2-, 1-, and 2-inch-thick (12.7-, 25.4-, and 50.8 mm) plate. Steels having these estimated toughness values, but of thinner section, would be expected to behave in a more ductile manner than that previously calculated because of non-plane-strain-fracture behavior.

Brittle-fracture-behavior estimates for static, intermediate, and impact loading rates are summarized in Table II for steels having 40, 60 and 80 ksi or 276, 414, and 552 MPa static yield strengths. Equivalent CVN energy levels for dynamic loading, plotted by using Equation 3, are also shown. To maintain the same factor of safety established by current ABS rules for normal loading rates, the data in Table II and Figure 4 suggest that toughness requirements for extremely high loading rates would require that the specification temperature be decreased by as much as 100°F for a steel of 40 ksi. Steels having a yield strength of 80 ksi, used for extreme loading rates, would require reductions in specification-testing temperature by as much as 65°F below those specified for intermediate loading rates, and the toughness level would have to be increased (33 ft-lb or 45 J for 80 ksi steels versus 13 ft-lb for 40 ksi steels). These higher toughness levels would correspond to Temperature III on the toughness curve for impact loading in Figure 1.

Current research of crack-arrest behavior suggests that the crack-arrest values for mixed-mode propagating fractures may be somewhat lower than the fracture-toughness values for crack initiation under impact loading.(12) It is not clear at this point that these differences are significant. Thus, a good method to estimate the determination of mixed-mode crack-arrest behavior is to use the conditions for initiating cracks under extreme (impact) loading rates.

FULLY DUCTILE FRACTURE BEHAVIOR

Quantitative assessment is much more difficult for ductile-crack initiation than for brittle-fracture initiation. For fully ductile shear-fracture initiation, the toughness or resistance to initial crack extension (resistance or R-curves) may be dependent on the crack length, plate thickness, and specimen geometry.(14) Unique material-toughness K_{IC} values for a given temperature and loading rate are no longer applicable. Furthermore, depending on the structural component, the crack-size, and the material ductility, the crack extension event may depend on the flow strength of the steel rather than the toughness. Full-scale tests of large-diameter pipe containing longitudinal cracks have shown that the critical crack length becomes independent of toughness above some yield-strength-to-toughness ratio.(15)

Very little is known about the effects of loading rate on the fully ductile fracture behavior of steels. The increase in toughness observed in the energy absorption of the upper CVN shelf, Temperature IV in Figure 1, is generally attributed to the increase in yield strength from static to dynamic loading. However, little information is available regarding rate effects on K_C (plane stress) values. K_C values of 150 to 200 ksi $\sqrt{in.}$ (165 to 220 MPa $\sqrt{m}$) or greater have been measured, with attendant zones at the crack tip approaching a foot in diameter.

Examples of the application of steels in which fully ductile fracture is utilized include (1) large-diameter gas-transmission line pipe, (2) military applications in which explosive (shock wave) loading rates may be encountered, and (3) very heavy section pressure vessels for critical applications, such as the containment vessel for nuclear reactors.

Table II

Estimates of Maximum Critical-Stress-Intensity Factors for Various Yield Strengths, Loading Rates, and Plate Thicknesses

Yield Strength, ksi*			**Temperature Shift, °F		***Maximum Critical-Stress-Intensity Factor ksi $\sqrt{in.}$ for Various Plate Thicknesses											
					t = 1/2 in.				t = 1 in.				t = 2 in.			
σ_{static}	$\sigma_{inter.}$	σ_{impact}	2/3 ΔT	ΔT	K_{IC}	$K_{IC(100)}$	$K_{IC(0.1)}$	+(CVN ft-lb)	K_{IC}	$K_{IC(100)}$	$K_{IC(0.1)}$	(CVN ft-lb)	K_{IC}	$K_{IC(100)}$	$K_{IC(0.1)}$	(CVN ft-lb)
40	50	70	104	155	18	22	31	(6.5)	25	32	44	(13)	36	45	63	(26)
60	70	90	84	125	27	31	40	(11)	38	44	57	(22)	54	63	80	(43)
80	90	110	64	95	36	40	49	(16)	51	57	70	(33)	72	80	98	(64)

* Assume $\Delta\sigma_{ys}$ = 5 ksi/order magnitude increase in loading rate.

** $\Delta T = 215 - 1.5\ \sigma_{static}$

*** $t > 2.5 \left(\frac{K_{Ix}}{\sigma_{Ix}}\right)^2$ where x is at same loading rate.

+ $K_{IC(0.1)} = \sqrt{5E\ (CVN)}$.

Note:

1 ksi = 6.89 MPa

°C = 5/9 (°F - 32)

1 ksi $\sqrt{in.}$ = 1.1 MPa $\sqrt{m}$

1 ft - lb = 1.36 J

Most of the applications of fully ductile fracture behavior of steels used in ships would be for containment vessels of cryogenic materials. If these steels are utilized at temperatures such that fully ductile fracture propagation occurs, the propagating-fracture speed will be significantly slower than that of a brittle fracture. The slow crack velocity should allow more time for loads to be redistributed to other members (if the structure is redundant) and limit the amount of crack extension. However, as shown in full-scale tests of running shear fractures in line pipe,(16) if the driving force is maintained, then a fully ductile fracture can also propagate very long distances. The use of mechanical crack arrestors is the best way to redistribute the load to secondary members and thereby reduce the crack-driving force.(17)

MATERIALS SELECTION FOR EXTREMELY HIGH LOADING RATES

As previously described, designing against extremely high loading rates will generally require selecting of steels with lower transition temperatures than those of steels used for normal operating conditions. It should be recognized that the transition temperatures for plates of the same steel grade in the as-rolled condition are quite variable. One of the principal causes of this variation is the differences in rolling practice (temperature range for hot work) that can result in important changes in grain size and microstructure. It is believed that fully killed (Si or Si-Al deoxidized) steels generally exhibit somewhat lower (improved) transition temperatures compared with silicon semikilled steels.(8) Additionally, innovations have been made in control rolling of high-strength low-alloy steel plate for obtaining low transition temperatures. One of the primary applications of this technology has been the production of plate for arctic grade line pipe,(19) Figure 5. However, this time-temperature controlled-rolling process is generally limited to plate thickness of about one inch (because of high rolling-mill loads) and to considerations of production schedules involving time delays in plate rolling. Normalizing or quenching and tempering will generally result in the most significant reduction in the transition temperature of ordinary and high-strength ship steels. Because of the numerous steelmaking and processing variables that affect toughness or transition temperature, it is best for the designer to specify the appropriate toughness level necessary and not the processing method, for example, deoxidation practice. The steel supplier

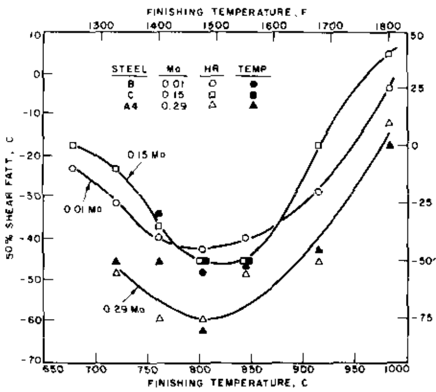

Fig. 5 Effect of Finishing Temperature and Molybdenum Content on the CVN 50% Shear FATT of Hot-Rolled and of Tempered Plates of Low-Carbon Mn-Mo-Cb Line-Pipe Steels (Reference 19).

can then determine the best processing method which will vary for different steel producing facilities) to obtain the desired mechanical properties.

Several steel-processing procedures are available to improve the CVN upper-shelf energy-absorption values. Cross rolling of plate (there are restrictions on size) will result in an improvement in the transverse CVN upper-shelf value with a concomitant decrease in the longitudinal-shelf value, as compared with a straightaway-rolled plate. Also, some steel producing plants have the facilities for special melting practices to produce low-sulfur steels. Further benefits in upper-shelf toughness can be achieved with the use of rare-earth metals for control of the shape of sulfide inclusions during plate rolling. Generally the improvement in toughness obtained from these processes results in limited increases in CVN energy absorption in the lower portion of the transition-temperature range, with the most significant benefit being realized in an increase in the upper-shelf energy values. Little or no effect is generally seen in an actual shift in the transition-temperature behavior. Low-sulphur and sulfide-shape-control steel-making practices are also used to improve the through-thickness (z direction) ductility necessary for some applications of heavy sections or highly constrained structural details.(20) Results from a recent study(21) in which rare-earth additions were made to 0.10 and 0.20 percent carbon steels demonstrate these trends, Figure 6. These steelmaking practices have little or no effect on the transition temperature in the longitudinal and transverse orientations.

SUMMARY

The history of failures in ships demonstrates that design procedures, standards, and materials selection have generally been adequate for the service conditions. Analyses of these procedures and supporting research progams by the Ship Structures Committee have suggested that normal operating conditions for ships, including slamming conditions, correspond to loading times of the order of a second. Extremely high loading rates that might occur as a result of a collision or an explosion are of the order of a millisec or less. Present American Bureau of Shipping (ABS) rules principally focus on setting material specifications for designing against mixed-mode fracture initiation at intermediate loading rates. Arrest of a running fracture is best accomplished with mechanical crack arrestors (out-of-plane members).

To maintain the same margin of safety currently obtained with ABS rules for normal operating conditions, specifications for extremely high loading rates in structures would require specification temperatures for Charpy V-notch (CVN) testing to be decreased by as much as 100°F (55°C) for a 40 ksi (276 MPa) yield strength steel. Steels of 80 ksi (552 MPa) would require test temperatures about 65°F (36°C) lower than current values and concomitant increases in CVN energy-absorption levels. Several methods of steel processing are available to improve transition temperature and toughness behavior of steels. However, processes that improve through-thickness properties would not significantly improve the safety and reliability of ship steels at extremely high loading rates.

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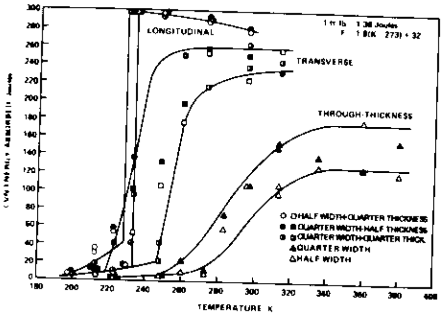

Fig. 6A-1 Charpy V-Notch Impact Energy Curves of Longitudinal, Transverse, and Through-Thickness Specimens of Steel 6 (0.10C, 0.013S, RE).

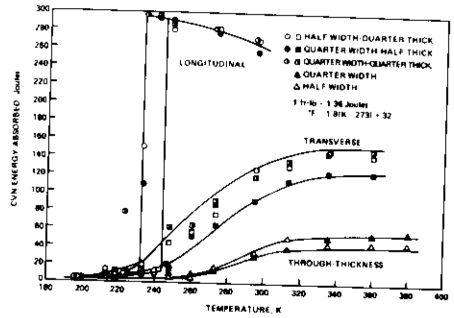

Fig. 6A-2 Charpy V-Notch Impact Energy Curves of Longitudinal, Transverse, and Through-Thickness Specimens of Steel 8 (0.11C, 0.013S).

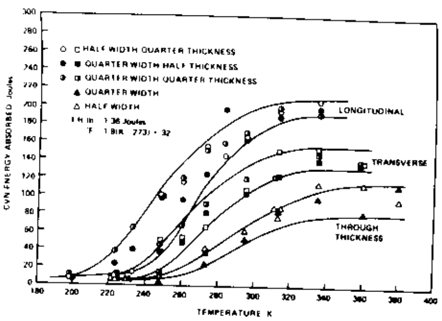

Fig. 6B-1 Charpy V-Notch Impact Energy Curves of Longitudinal, Transverse, and Through-Thickness Specimens of Steel 7 (0.20C, 0.013S, RE).

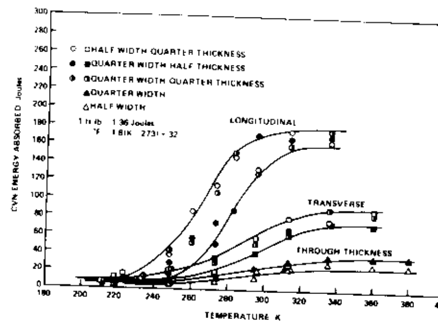

Fig. 6B-2 Charpy V-Notch Energy Curves of Longitudinal, Transverse, and Through-Thickness Specimens of Steel 9 (0.21C, 0.012S).

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