FRACTURE CONTROL PLAN FOR WELDED SHIP HULLS

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ABSTRACT

The present work describes a fracture control plan that optimizes different design parameters in order to establish efficient and safe performance of ship hulls relative to cost considerations (including material, design, fabrication, operation, testing and maintenance) following fail-safe philosophy.

For ship hull materials the toughness requirement necessary to ensure general elastic-plastic performance is:

$(K_{Id}/\sigma_{yd}) \geqslant 0.6$ at - 18°C

and at the minimum service temperature of 0 °C, $(K_{Id}/\sigma_{yd}) \approx 0.9$.

It is recommended to use 5/8 inch dynamic tear (DT) test specimens and use its results to predict the dynamic toughness values for ship hull steels and weldments.

INTRODUCTION

Real structures contain flaws or cracks that can originate due to variety of reasons. Defects due to welding, the effects of stress corrosion or even the presence of microcracks due to irreversable ship of bands in grains exposed to an external surface. The major concern is the propagation of these cracks during service. It is now generally accepted (1) that the primary parameters involved in brittle fracture design are the size, shape and location of the worst possible crack or defect, the magnitude of applied tensile stresses and the fracture toughness of the material.

If fracture initiates in a welded structure, there usually a contineous path for crack extension. However, in rivited or bolted structures. There is no contineous path for crack extension. Thus there is a large difference in the possible

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fracture behaviour for welded structures, compared with either rivited or bolted structures.

The interaction of material properties such as the fracture toughness, with the design stress and defect size controls the conditions for fracture in a component. For example, for a cracked plate:

$$K = K_c = \sigma \sqrt{\pi a} \qquad (1)$$

where K is the stress intensity
K_c is the fracture toughness
Design stress
a allowable flow size

This relationship may be used in one of several ways as to design against a component failure or to set guidelines for fracture control design problem.

The present paper describes a fracture control plan that optimizes different design parameters in order to establish efficient and safe performance against brittle and fatigue failure for welded ship hulls, relative to cost considerations following fail-safe philosophy.

SERVICE CONDITIONS FOR SHIP HULLS

Strain measurements on actual ships have indicated that ship hulls are subjected to a variable amplitude loading during service and that the maximum vertical wave-bending-stress is about 10 Ksi for slender cargo lines and about 14 Ksi for bigger ships such as tankers and bulk carriers (2,3). The maximum gross stress level in ship hulls was selected on the basis of these measurements to be 14 Ksi. Such gross stress level is less than one-half the yield stress for most ship hull steels but the local stress at stress concentrations can reach the yield stress level considering locations around notches and residual stress effects.

The actual loading rates for ship hulls are not known, therefore a concervative assumption is used which consider that ships are loaded under impact conditions. Since ship hulls are welded single load path structures, such concervative assumption is justified.

Ships operate at temperatures less than 0 °C only about 3% of the time (4). Therefore a design service temperature of 0 °C for welded ship hulls appears realistic.

REQUIRED PERFORMANCE CHARACTERISTICS

Brittle fracture occur because of particular combinations of material toughness, crack size, and tensile stress. This basic principal is combined with the fact that the stress level of a ship hull can reach yield stress magnitude and that discontinuities can be present in the welded hulls, the naval architect is faced with three possible solutions to prevent catastrophic brittle fracture:

1. Develop multiple load paths within the hull so that failure in one part of the cross section does not lead to total failure of the ship. This does not appear to be feasible for welded steel ship hulls.

2. Use extreemly notch-tough steels so that no brittle fracture can initiate or propagate. Such method appear to be economically unfeasible.

3. Provide fail-safe design using steels with intermediate 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 required fracture-control plan for welded ship hulls is to optimize the above possible performance criteria with cost to prevent brittle fracture or fatigue failure in welded ship hulls.

GENERAL LEVELS OF MATERIAL BEHAVIOUR

1. Elastic-Plain-Strain Behaviour

$$\frac{K_{Id}}{\sigma_{yd}} < \sqrt{\frac{t}{2.5}}$$

where: K_{Id} is dynamic fracture toughness of the material

σ_{yd} is dynamic yield strength

t plate thickness

In this case the material exhibit elastic-plain strain behaviour and generally fracture occur in a brittle manner. These materials are not usually used for most structural applications because of the high level of constraint at the crack tip and the small critical crack size at the design stress level.

2. Plane Stress(elastic-plastic) Behaviour

$$\frac{K_{Id}}{\sigma_{yd}} < \alpha\sqrt{t}$$

where α ranges from 2 to 3.

Structural materials whose toughness levels are such that they are in the above range generally exhibit elastic-plastic fractures with varying amounts of yielding prior to fracture. The tolerable flow size at fracture can be fairly large. Fracture is usually preceded by the formation of large plastic zones ahead of the crack.

3. General Yielding (Plastic)

$$\frac{K_{Id}}{\sigma_{yd}} > \alpha\sqrt{t}$$

where α ranges from 2 to 3.

Structural materials falling in this region usually exhibit duatile plastic fractures preceded by large deformations. Fig. (1) shows the general levels of performance for typical structural steels as measured by charpy vee Notch(CVN) and Ductile Tear (DT) tests.

EFFECT OF LOADING RATE

Structural steels generally show loading rate effects and as a result the notch toughness of these steels becomes dependent on the loading rate. A specific example of ABS class C structure steel commonly used in ship building (5) is given in figure (2).

The results in this figure show that if the actual structure is loaded statically then the elastic plastic level of performance is obtained at all service temperatures above-220°F. However if the structure is loaded dynamically the same level of performance (elastic-plastic) will be obtained only at service temperatures above - 20°F.

SUGGESTED ELASTIC-PLASTIC PERFORMANCE

For most structural applications, as bridges, ships, pressure vessels, off shore drilling rigs,...etc, certain level of elastic-plastic behaviour should be selected at service temperature and loading rate to develop a satisfactory criteria for design against fracture. The fracture criteria selection should be based on careful study of the particular requirements for a particular structure. Various factors include the service conditions as loading, temperature, loading rate, consequences of failure and economy should be considered. The establishment of the proper fracture criteria for a given application should be the basis of material selection, structural design, fabrication procedures and inspection requirements. In welded ship hulls, it is assumed that the nominal stress approaches the dynamic yeild stress at some critical locations. The maximum available flow size (a) is related to the dynamic notch toughness (K_{Id}) and the dynamic yield strength (σ_{yd}) as:

$$a = A \left(\frac{K_{Id}}{\sigma_{yd}}\right)^2 \qquad (1)$$

where A is constant (1)

The flow size becomes proportional to $(K_{Id}/\sigma_{yd})^2$ where both dynamic toughness and dynamic yield strength should be measured at the service temperature. Thus (K_{Id}/σ_{yd}) becomes a good index for measuring relative toughness of structural material and weldments in ship hulls. It is always desirable to select material that can tolerate large flows without fracture (high (K_{Id}/σ_{yd}) ratio), i.e. elastic plastic behaviour.

DEVELOPMENT OF TOUGHNESS REQUIREMENT FOR MAIN-STRESS REGIONS IN WELDED SHIP HULLS.

The primary load carring members of steel ship structures are the plate members within the center of the hull that comprise the upper deck, bottom shell, side plating and longitudinal bulk heads. Because these are primary load carring members, material toughness requirements should be specified for them. Although stiffners can also be primary load-carring members, they are not connected to each other and failure of one stiffner should not lead to failure of adjacent stiffners. Stress in ship hull vary from extreme levels in the upper deck and bottom shell to zero at the neutral axis as shown in figure 3. In the main stress regions, stresses can reach critical levels and should be specified by a toughness requirement.

As discussed above, the fracture characteristics can be represented interms of transition from brittle to ductile behaviour as measured by impact tests and can be related to either plane strain behaviour or plane stress(plastic) behaviour with a transition region in between. A reasonable level of elastic-plastic behaviour should be satisfactory for ship hull steel and weldments to prevent initiation and propagation of brittle fracture or fatigue with the use of crack arrestors to ensure fail safe philosophy. A schematic representation shows the material selection for ship hull steels is presented in fig. (4).

At the minimum service temperature of 0 °C, the fracture performance of steel B is elastic plastic (fig.4), steel C is plane strain and steel A is plastic. Steel B then is selected for welded ship hull application and suitable welding procedures should be employed to achieve same fracture levels for all weldments. Steel A will not be used for this application because of its high cost while steel C will be usafe. In terms of fracture mechanics parameters, the dynamic toughness K_{Id} is approximately equal to 0.6 σ_{yd} at the NDT (nil ductility transition) temperature where fracture behaviour shift from plane strain to elastic-plastic region (5).

$$\frac{K_{Id}}{\sigma_{yd}} \geq 0.6 \quad \text{at N.D.T.}$$

and that the NDT temperature should be less than - 18 °C. The estimated crack toughness performance (K_{Id}/σ_{yd}) will be equal to 0.9 at 0 °C due to the rapid increase in K_{Id} with temperature in the transition region. Experimental results for ABS-C ship building steel is represented in Fig.2. For crack toughness of 0.9 and nominal stress level of 14 Ksi, the critical crack size is estimated to be about 8 inches as shown in fig.5. For the worst possible case if dynamic loading reaches the yield level, the critical crack size is estimated to be 0.5 inch.

CRACK ARRESTERS

Crack arresters are usually considered in the design of structures to ensure safe operation and prevent catastropic failure of the structures (fail-safe philosophy). Such cracks can originate in the structure during service either by brittle fracture , fatigue or stress corrosion. Both types of welded in plane and out of plane crack arresters are suitable for ship hull construction. The welded in-plane crack arresters is used in welded ship hulls as integral load carring components in conjunction with the primary hull structure as shown in fig.6.

The arresters are usually made of steel with much higher level of notch toughness than the basic metal used in hull structure. The width of the crack arrester should be designed in away to be able to stop the propagating crack. Out of plane crack arresters (fig.7) may also be practical because of their configuration as they work as stiffening members in ship structure.

MATERIAL EVALUATION AND TESTING

The toughness requirement discussed above should be established by conducting K_{Id} test (5) at 0 °C. Such test is expensive and some other test specimen could be used to ensure that $K_{Id}/\sigma_{yd} \approx 0.9$ at 0 °C. Test specimen should be loaded dynamically, easy to use, have a sharp notch to approximate closely the sharp crack condition that exist in large complex welded structures as welded ship hulls. The specimen should also be large to include the effect of constraint. The 5/8 inch thick dynamic tear (DT) test specimen (6) is recommended for this application as it satisfies the above mentioned requirements. Fig. (8) shows the results of DT tests for ABS-C steel.

A review of the available experimental test results (5) indicate that at NDT, where $\left(K_{Id} / \sigma_{yd}\right) \approx 0.6$, the amount of absorbed energy for 5/8 in. thick specimens is 100 ft. Ib. The minimum absorbed energy for the 5/8" DT specimen can be approximated by 0.9/0.6 times 100 or equal to 150 ft. Ib that satisfies $\left(K_{Id} / \sigma_{yd}\right) = 0.9$ at the service temperature of 0 °C. Therefore the accepted steel for WSH application should meet the 150 ft. Ib 5/8" DT specimen criterain at 0 °C. Then K_{Id} could be estimated which reflet the fracture behaviour of the steel and could also be used in the design against fracture. Fig.8 also give the relationship between results of 5/8" DT tests and CVN values which can be used to relate between results of both testing procedures. The above mentioned toughness requirements should be applied on the material and weldments in the main stress regions of welded ship hulls.

Due to the practical situation of manufacturing and inspection in ship yards a relatively large defects could be present in welded ship hulls. Such defects may be tolerated at the begining of the service as they are smaller than the critical flow size but with time during service pre-existing flaws may graw by fatigue and the possibility of brittle fracture in the ship hulls appears again once the final crack reaches the critical size. In this case the rate of fatigue crack propagation in the ship hulls should be determined and suitable fracture mechanics analysis is needed to predict the residual life.

One of the present authors(7) hence developed an elastic-plastic fracture mechanics model to predict crack propagation in welded details. In this model the crack length as a function of load cycles was predicted successfully as shown in fig.(9) for several types of welded geometries subjected to various stress levels. A similar analysis can also be followed to determine fatigue crack propagation lives in welded hull structures considering variable amplitude type loading and environmental conditions. Such analysis determines the increase in crack size with time. Once a crack reaches the critical size,brittle fracture will occur. The fatigue analysis also help in scaduling inspection and maintenance programms for welded ship hull structures.

CONCLUSION

1. For ship hull steels and weldments the toughness requirement necessary to ensure general elastic-plastic performance is $(K_{Id}/\sigma_{yd}) \approx 0.6$ at - 18 °C and at minimum service temperature 0°C , $(K_{Id}/\sigma_{yd}) \approx 0.9$.

2. 5/8 inch dynamic tear test specimens is recommended to predict K_{Id} for ship hull steels and weldments.

3. Beside these toughness requirement, the use of suitable crack arresters is also recommended to ensure fail safe performance.

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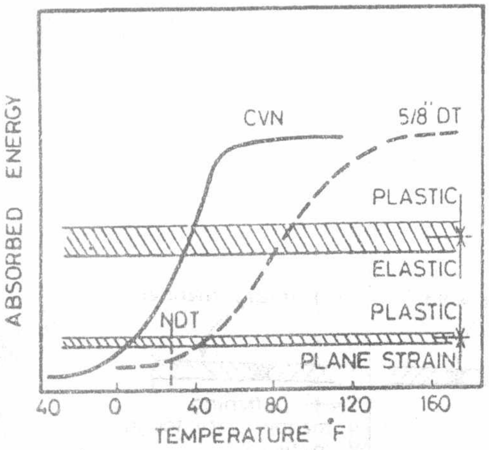

Fig.1. Relation among plane strain,elastic-plastic and plastic levels.

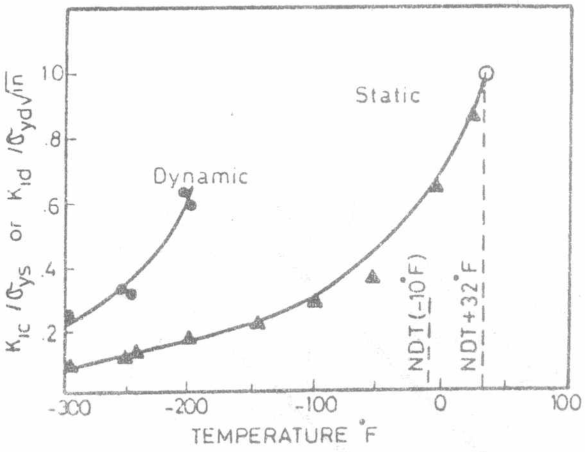

Fig.2. Crack-toughness performance for ABS-C steel.

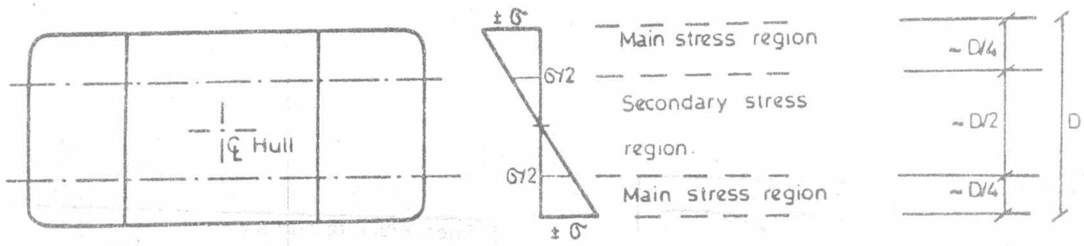

Fig.3. Schematic cross section showing primary load carring members in main and secondary-stress regions (5).

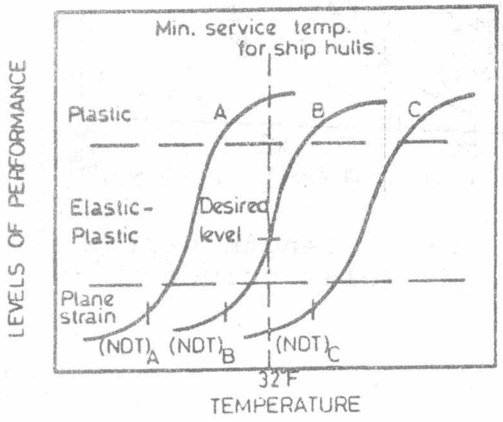

Fig.4. Schematic representation showing level of performance for three arbitary steels.

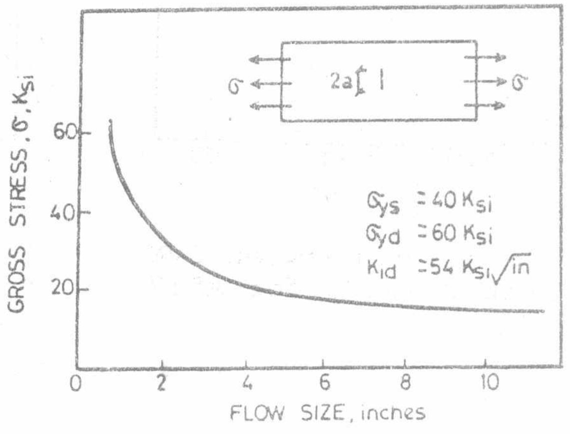

Fig.5. Stress-flow size relation for ABS steel with $K_{ID}/\sigma_{yd} \approx 0.9$.

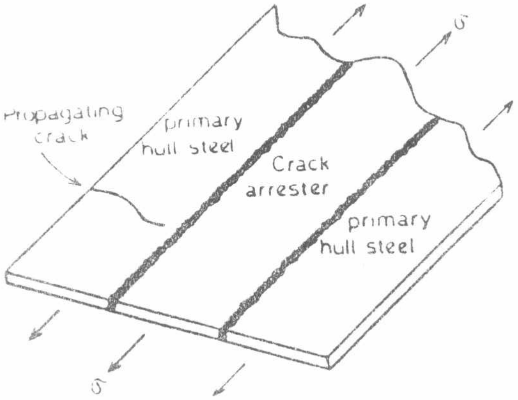

Fig.6. Geometry for in-plane crack arrester.

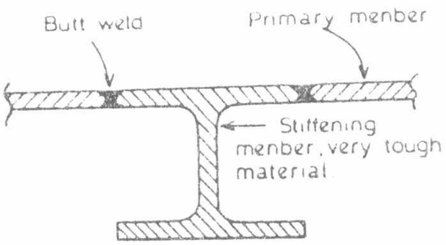

Fig.7. Geometry for out-of-plane crack arrester.

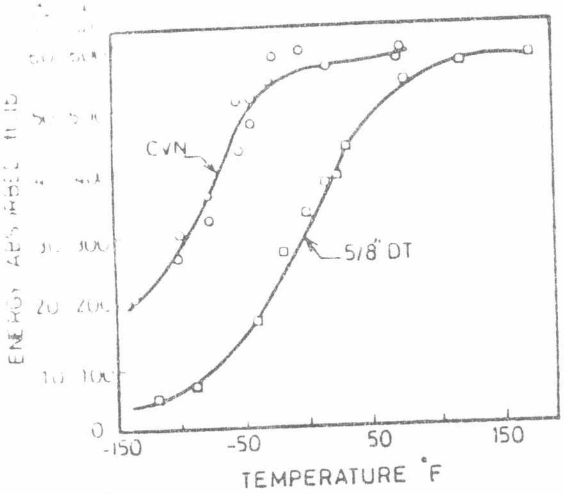

Fig.8. Relation between CVN and DT Test results for A517 Steel.

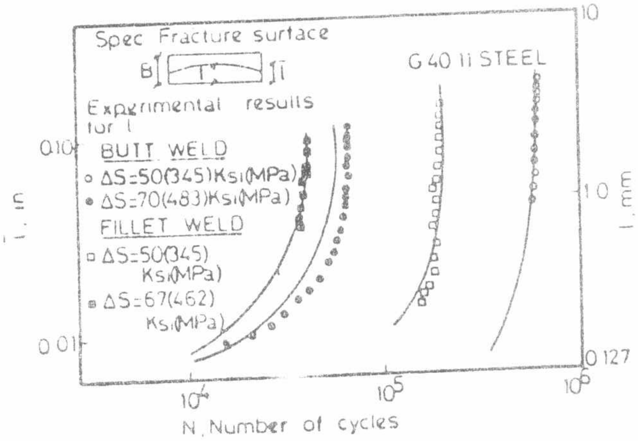

Fig.9. Crack length versus number of cycles curves.