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An Overview of Structural Integrity Technology

Peter M. Palermo, Member, Naval Ship Engineering Center, Hyattsville, Md.

ABSTRACT

Economic considerations have been a prime factor in fostering mechanization and automation in almost all fields of endeavor. This automation has enhanced capabilities to the point that new technological breakthroughs are becoming the rule rather than the exception. Accordingly, new technologies require even greater mechanization in order to retain viability. The same is true for ship structures. Our ability to efficiently design and fabricate new ship types having expanded operational capabilities will require increased mechanization in fabrication and an integrated approach to design and construction. This approach which is really an integration of existing technologies, thus providing a scientific basis for what has traditionally been termed "good design practice," has been labeled structural integrity technology. It is not really new and its conscious application to even conventional hulls can provide economic advantages.

An overview of past application of structural integrity starting in the mid-1940's is presented, and the requirements and capability in major technology areas are briefly reviewed. Detailed presentations in the major technology areas are avoided, but are provided in the companion papers in Session IX of the Hull Structures Symposium.

INTRODUCTION

Changing climates, both economic and political, have traditionally imposed new mission requirements on both our commercial and military fleets. Today's competitive market is no different and it is highly probable that before the end of the century novel ship types utilizing more exotic material systems will be required for unique purposes. Consideration of the structural aspects of these novel hulls must be premised on our present experience and technology, but not necessarily on our present procedures. Inherent in considerations of these novel high performance ships is the cost to acquire and to maintain. Just as diesel ships were more expensive than sailing ships, novel hulls will probably be more expensive than conventional hulls. However, proper application of structural design, material utilization and fabrication technology can be applied to keep costs within reasonable bounds and thus retain economic viability whether for commercial or military needs. Proper application of these technologies can also have economic advantages for conventional designs. This merger of technologies has been termed Structural Integrity approach to design.

Commercial and naval ship design practice has encompassed a structural integrity concept for many years. The concept's visibility has been lacking primarily because other unique considerations such as ballistic requirements and service ruggedness requirements have usually resulted in hull designs that are not controlled by normal seaway loadings. Structural integrity and the associated certification requirements have been specified in both the submarine and the aerospace community, and the advent of high performance surface ships of higher strength, less forgiving materials requires delineation of such concepts for surface ships.

Too often the ship structural designer is accused of being interested solely in strength properties of the hull materials. Past experience in bridge, pipeline, aircraft, rocket case, and ship hull failures provides sufficient evidence that the structural designer must be concerned with much more than simple strength properties. The history of Liberty ship and T-2 tanker failures in the 1940's impressed upon the designer the need for additional material properties prior to design application. Concurrently, structural material specialists have imposed upon material manufacturers new specification requirements that improved chemical compositions for welding, fabrication, and toughness; adapted production processing techniques for better toughness and mechanical properties; and, made chemical properties more compatible with the service environment.

The above actions only solved part of the problem and the structural designers continued their efforts to ensure structural integrity. Structural designs were categorized into two convenient groupings: safe-life and fail-safe. Safe-life implies that cracks will not develop during the life of the structure; fail-safe implies that if a flaw does grow, it will be detected during scheduled inspections or that sufficient load path redundancy is available to preclude catastrophic failure. As a result, naval ships are designed for safe-life, but the hull is straked for fail-safe concepts. This approach may appear incongruous but upon inspection it survives the test of reasonableness. Any fabricated structure will contain flaws and poor fabrication will enhance the possibility of flaw growth; thus, even though details are sized to minimize stress concentration, incipient flaws can propagate. In order to preclude catastrophic flaw propagation, fail-safe crack arrestors are employed.

Complex structures such as ships contain a number of highly stressed details. For most ship applications the forgiving nature of the hull material, coupled with conscious efforts to attenuate stress concentration effects in the design and fabrication, is sufficient to preclude critical flaw growth. However, for high performance craft or for those ships utilizing high strength structural materials, it is necessary to scrupulously analyze the state of stress and the material characteristics in developing the design of details. Further, in such cases it is necessary for the designer to be aware of the fabrication methods in order to ensure that his "optimum-detail" can be fabricated within the tolerances used in the analysis. Thus, structural integrity requirements lead to a methodology of a structural "systems analysis" approach to design and require consideration of the following primary items:

- basic material properties
- flaw sensitivity
- loading spectrum
- design and analysis
- fabrication
- life-cycle maintenance

These considerations are mandatory first steps in any design. Though all six do not have to be rigorously addressed in any one design, they should all be consciously considered. The engineering designs which dictate the degrees to which structural integrity requirements must be applied can be broadly bounded within the following limits:

- Elaborate - mission requirements dictate the use of high strength, exotic materials, therefore a high flaw sensitivity exists.
- Routine - mission requirements permit the use of the more conventional materials and therefore more tolerance to flaws is inherent.

For the normal hull materials used in surface ships, TABLE I presents a matrix indicating relative degree of application of structural integrity principles. It is beyond the scope of this paper to address the matrix items in detail, but a brief description of the influence of each is provided in the following sections. It should be noted that material properties and flaw growth characteristics should be available prior to starting a design and for this reason they precede the design considerations section.

MATERIAL / ITEM	STEELS					TITANIUM	COMPOSITES	ALUMINUM
	ABS/MS	HTS	HY 80	HY 100	> HY 100			
LOADING SPECTRUM	X	X	X	X	X	X	X	X
MATERIAL CHARACTERISTICS	X	X	X	X	X	X	X	X
FLAW GROWTH ANALYSIS				R	S	S	S	S
DESIGN & ANALYSIS	R*	R	R	R	S	S	S	R/S
FABRICATION CONTROLS			R	R	S	S	S	S
SPECIAL MAINTENANCE REQUIREMENTS					X	X	X	X

X Necessary
R Routine, generally simplified requirements
S Sophisticated techniques

STRUCTURAL INTEGRITY REQUIREMENTS
TABLE I

MATERIAL TOUGHNESS CONSIDERATIONS

The primary structural material used in U. S. Navy ships is steel, although aluminum has been used in superstructures and in the hulls of some smaller ships. Glass Reinforced Plastic (GRP) has been used for hulls of specific smaller craft and possesses an attractive potential particularly in designs where wood has been the usual hull material, and the more exotic materials, such as titanium, have desirable properties for unique applications. Copper-Nickel, because of its excellent anti-fouling properties, offers considerable advantages for specific underwater hull applications. TABLE II is a matrix of materials used or proposed for use as a function of ship type.

SHIP HULL TYPE	STEELS			ALUMINUM	TITANIUM	COMPOSITES		WOOD	FERRO CEMENT
	MS HTS	HY80 HY100	HY130 HY180			GRP	FRC		
MONO HULL SHIPS									
LARGE MONOHULLS	X	X	P						
HIGH SPEED MONOHULLS	X	X	P	X		X			
AUXILIARIES		P				P		X	P
MULTI-HULL SHIPS	X	P		P					
HIGH PERFORMANCE SHIP									
HYDROFOILS HULL		P	P	X	P	P	P		
HYDROFOILS STRUT		X	X	X	X	P	P		
HYDROFOILS FOIL		P	X	X	P	P	P		
AIR CUSHION VEHICLES			P	X	P	X	P		
SURFACE EFFECT SHIPS	X	P	X	X	P	X	P	X	X

LEGEND X APPLIED P POTENTIAL

TABLE II
POTENTIAL APPLICATION OF MATERIALS TO
SHIP STRUCTURES

Generally it has been the practice to select structural material for ships from an approved list of "tough materials" in order to ensure adequate tolerance to flaws. Though the base material may be inherently tough, other measures are also utilized in order to preclude any possibility of catastrophic failure. The primary such measure is the use of high strength, very tough steel plating at the sheer strake and at the turn of the bilge, in order to arrest any rapidly propagating cracks.

Of utmost importance in any material application is the fabricability of the material system which includes the weldment or other specified joining technique. In this regard it cannot be too strongly stated that the weldment (base metal, heat-affected zone (HAZ), and weld metal) could be, and often is, the Achilles heel of a material system. Therefore, material application in design must be premised on fabricated properties. It is mandatory that adequate structural/material tests of details be evaluated to adequately define the necessary properties.

Metal Systems

All of the structural metal systems have varying tolerances to flaws and are in reality transitioning from high fracture tolerance to very low fracture tolerance over a relatively narrow band of yield strengths. At the low end of the yield strength range, the high-to-low fracture tolerance of the alloys is based on transition temperature effects and at the other end primarily on strength level. In general, for most metal systems, as temperature decreases the tolerance to flaws also decreases, and as yield strength increases the tolerance to flaws decreases. For this latter reason alone, it can be costly to choose a material solely on the basis of nominal strength level.

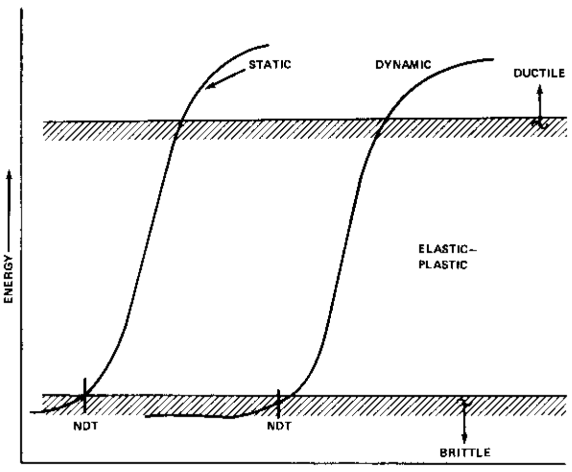
The structural metals in the presence of a flaw, a tensile stress field, and the proper temperature conditions can fracture in one of three modes:

- o brittle - low energy fracture tearing under nominal elastic stresses
- o elastic-plastic - mixed mode failure requiring higher nominal elastic stresses and/or larger flaws
- o ductile - plastic stress conditions necessary for fracture

It is most desirable to utilize materials that will fracture in a ductile mode, but with proper engineering analysis high elastic-plastic materials can be safely used.

The fracture performance of the material is also affected by the loading rate. Under static loading, the metals are less sensitive to flaws than they are under dynamic loadings; however, because naval ships are expected to withstand the rigors of combat, it is the usual procedure to assess the material toughness under dynamic testing. The absorbed energy of a low strength structural steel under both types of loading is shown in Figure 1. Of major significance in Figure 1 is the point designated NDT (Nil Ductility Transition). The NDT temperature defines that temperature below which the material will always fracture in a brittle mode. Therefore, it is mandatory for thicker sections that the NDT temperature be lower than the minimum temperature that the ship is expected to see in service.

Achievement of a low NDT temperature is only part of the basic requirement. The next requirement is to have adequate toughness at the lowest operating temperature in order to ensure ductile or at least high elastic-plastic fracture response. This is achieved by requiring a high ratio of the stress intensity required to drive a flaw, to



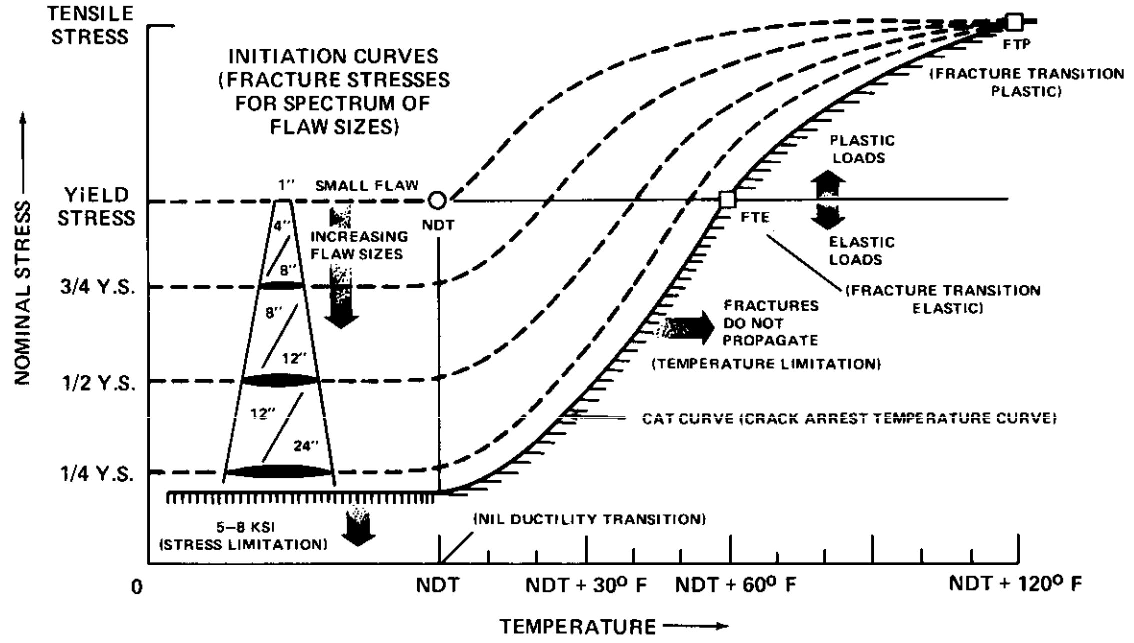
ENERGY – TEMPERATURE TRANSITION CURVE REPRESENTATIVE OF LOW YIELD STRENGTH STEELS

Fig. 1

the yield strength of the material at the minimum operating temperature.

Another way to consider toughness is to consider the effect of temperature increase on fracture mode. It has been demonstrated that, for sections up to 3 inches in thickness, predominately ductile behavior will occur if tests are conducted at a temperature of 70° F above NDT*. This new point is called FTE (Fracture Transition Elastic), and it represents the temperature at which the fracture mode transitions from predominately low temperature plane strain to predominately high temperature plane stress. Finally, a region of full ductility (complete plane stress) is achieved and this temperature is designated FTP (Fracture Transition Plastic). The FTP is on the order of 70° F in excess of the FTE, and it is usually referred to as the shelf temperature because there is no further increase in fracture toughness above it. The above discussion can be graphically illustrated for most ship steels by a Fracture Arrest Curve such as Figure 2. For example, in referring to Figure 2, at the NDT temperature a 24 inch long defect will propagate in a brittle manner at a stress level of one-fourth the yield strength. If, however, the temperature is increased by 40° F, the stress level for failure for the same size defect is raised to three-fourths the yield strength. At the NDT temperature for a stress level of three-fourths the yield strength, a defect of about 8 inches long can be tolerated; but at NDT + 40° F, a 24 inch long defect can be tolerated.

In the United States, fracture characteristics of metals are generally obtained from Charpy V Notch tests (CV) and from Dynamic Tear (DT) tests. Because the DT test, by its very nature, requires large crack extension, it is



GENERALIZED FRACTURE ANALYSIS DIAGRAM AS REFERENCED BY NDT TEMPERATURE

Fig. 2

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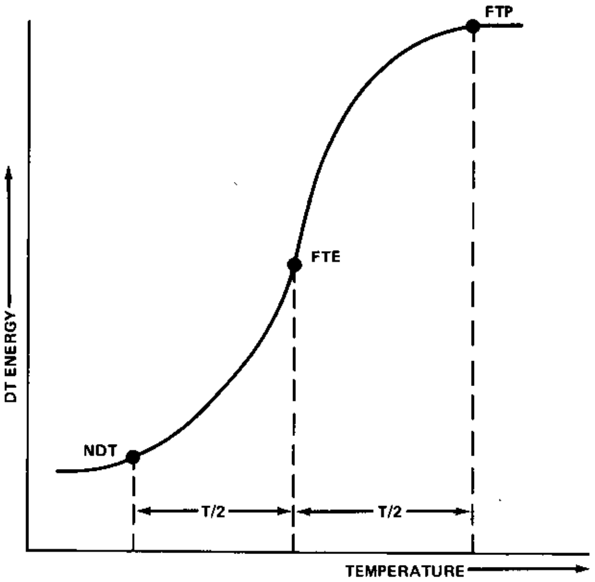
* For 12 inch thick sections, the FTE temperature is approximately 140° F above the NDT temperature.

considered to be a more accurate measure of toughness than the Charpy test and is receiving greater acceptance within the Navy community. Accordingly, it seems proper to discuss the relationship between DT energy and crack arrest properties. This relationship for structural steels is shown graphically in Figure 3. As indicated in Figure 3, crack arrest for elastic stresses (FTE) occurs at about the midpoint of the transition region of the DT curve. Again, relating to Figure 2, the portion of the curve NDT-FTE in both Figures 2 and 3 is comparable. Therefore, we can relate a DT energy requirement from Figure 3 to a load-flaw size comparison of Figure 2. These relationships are significant because through their use we can specify high-NDT relatively low priced steels in ship hulls with considerable confidence. But more important, the adequacy of such steels in Navy ships has been amply verified over the years by the proven lack of brittle fracture in any naval ship constructed of medium steel.



RELATIONSHIP OF DT TEST TO FRACTURE ARREST FOR STRUCTURAL STEELS

Fig. 3

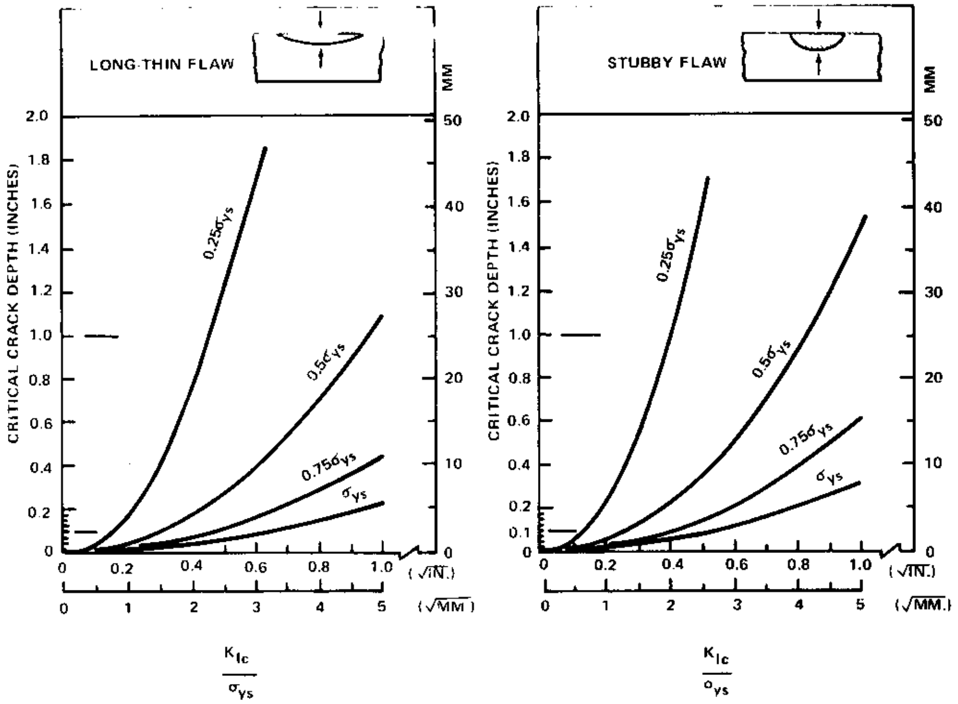
As indicated earlier, material flaw tolerance is either temperature-transitional or strength-transitional. The preceding discussions briefly outlined the considerations for temperature-transitional materials. The following paragraphs will briefly discuss the strength-transitional materials.

The strength-transitional materials are those steels with yield strengths in excess of 80,000 psi, the aluminums, and the titaniums. In general, they are employed as basic hull materials in only those designs requiring maximum efficiency of hull weight. In such cases typical hull stresses can be expected to be a much higher percentage of the allowable values than would be expected in the lower strength conventional hulls. As will be discussed in more detail later, the concern for relatively large-size surface flaws with the lower strength, temperature-transitional material, is now transferred to short (less than an inch long) flaws in the much higher strength materials.

Fracture mechanics principles can be used to provide engineering parameters for evaluating material requirements for adequate toughness. The primary parameter in the fracture mechanics approach is the stress intensity factor K_I, units Ksi $\sqrt{in.}$ K_I, can have various subscripts denoting different failure conditions, but in all cases it is a function of stress level and square root of flaw size. Therefore, knowing the critical stress intensity at failure, K_{I_c}, designs can be premised on critical flaw size for a given design stress or on design stress for an assumed flaw size. This relationship between flaw size and stress level is shown in Figure 4. It is obvious from Figure 4 that there are many combinations of stress levels and flaw sizes that will cause failure in specific metals.

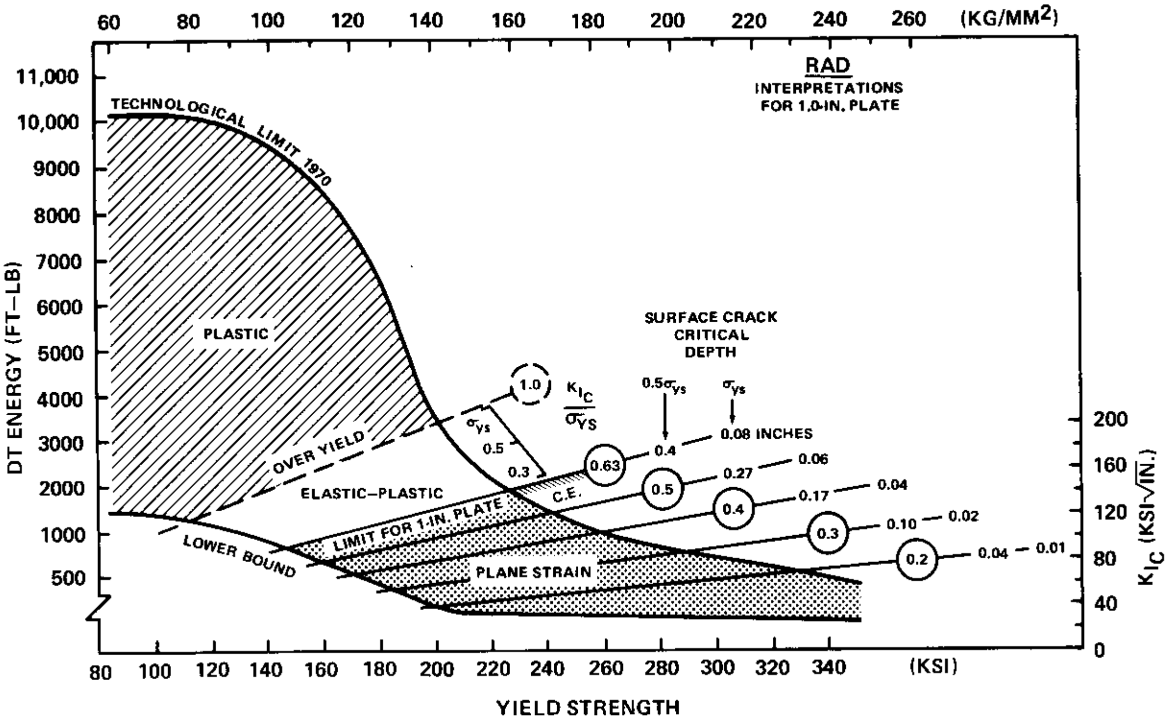
Figure 4 represents the limiting cases for surface flaws expected in service. The use of the curves is limited to those metals where linear elastic fracture principles can be applied, i.e., section thickness, B, must be equal to or greater than 2.5 $(K_{I_c}/\sigma_y)^2$. This defines the limit of brittle behavior. The boundary between plastic and elastic-plastic has been conservatively estimated to be defined by the expressions $B \geq (K_{ID}/\sigma_{yd})^2$ (where subscript D refers to dynamic properties). Though the above expressions and the curves of Figure 4 are only applicable when flaw depth is less than 0.6 thickness, they have been applied as conservative estimates for through-thickness cracks.

It is possible to graphically depict the fracture resistance of strength-transitional material over the fracture range by applying fracture mechanics principles in conjunction with DT test results. Figure 5, relating yield strength, K_{I_c} and DT energy, is commonly referred to as a Ratio Analysis Diagram (RAD). The radial lines developed on the basis of a one-inch section denote the limit of flaw size and stress level for ratios of K_{I_c}/σ_y. The technological optimum limit line represents the envelope of highest level of fracture resistance measured by DT tests over the entire yield strength range or by K_{I_c} tests in the plane strain range; the lower bound represents the lowest values of fracture resistance for the poorest production material. The ratio lines are developed from the curves of



GRAPHICAL FRACTURE MECHANICS PLOT OF SURFACE CRACK FOR TWO FLAW SHAPES.

Fig. 4



RAD FOR STEELS

Fig. 5

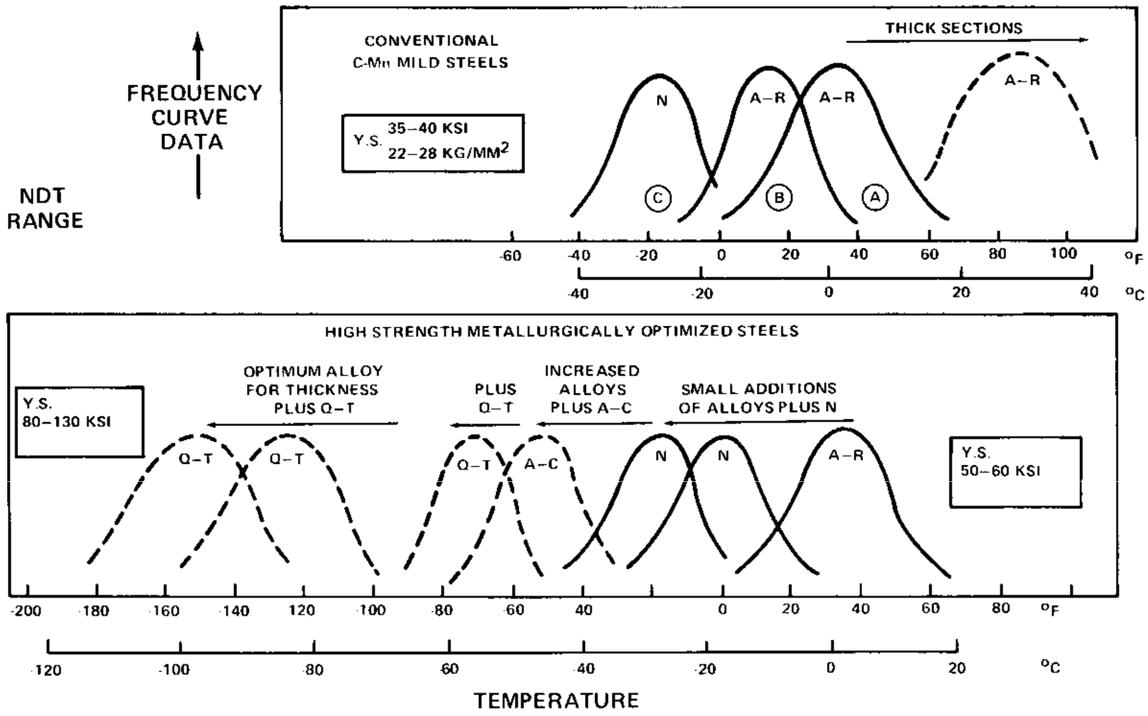


ILLUSTRATION OF THE RANGE OF NDT TEMPERATURES AVAILABLE FOR STEELS. DIFFERENCES ARE CONTROLLED BY CHEMISTRY AND HEAT TREATMENT.

Fig. 6

Figure 4 and as such in Figure 5, critical long thin surface flaw sizes for half yield and for yield strength loading are shown on each line. In the elastic-plastic region conservative stress levels for through-cracks are shown.

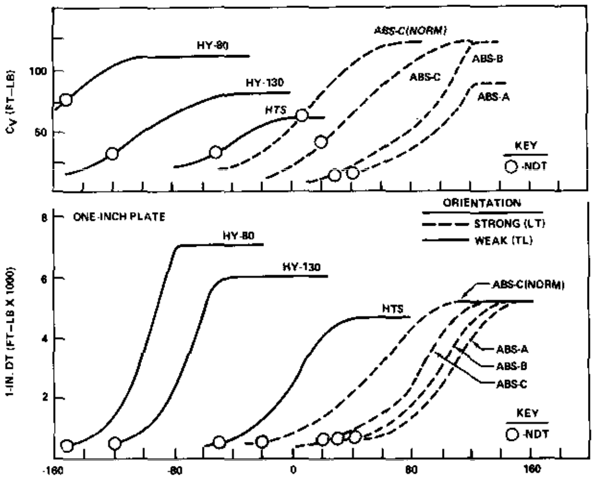
As indicated in Figure 5, below the plane strain limit line brittle (low energy tearing) fracture will occur; above the general yield plane stress limit ductile fracture will occur; and between the two mixed-mode (elastic-plastic) fracture will occur.

In summary, in order to preclude fast fracture under normal service conditions, the metal systems should have low NDT temperatures and a sufficiently high dynamic tear energy at the lowest operating temperature to safely tolerate a realistic size flaw without catastrophic brittle failure.

Steel

Strength and toughness properties of steel are enhanced by heat treatment, alloying, and specialized melting and rolling practices. For the temperature-transitional materials (i.e., American Bureau of Shipping, grades A, B, C steels) design application is associated with selecting a material with an NDT sufficiently below minimum operating temperature and of sufficient toughness at operating temperature; however, care must be exercised in selecting a representative NDT temperature because of the statistical distribution of properties. As shown in Figure 6, the NDT can be lowered from the as-rolled (AR) value by normalizing (N), alloying, accelerated cooling (A-C), and quench and tempering (Q-t). All of these add cost, but they do improve the metal performance. This additional cost is insignificant compared to the fabrication excellence and surveillance inspection program costs that would be necessary to live with the brittle plane-strain type materials.

Typical toughness-temperature curves for ship building steels used by the U. S. Navy are shown in Figure 7. For U. S. Navy ships the Class A medium steels are used only in thicknesses less than 1/2 inch; the Class B in thicknesses from 1/2 inch to 1 inch; the Class C (normalized) in thicknesses greater than 1 inch; HTS (normalized) in thicknesses greater than 1/2 inch; HY-80 basically for high toughness crack arrest material; HY-80/HY-100 for combat ruggedness and very high stressed areas in highly efficient designs, and HY-130 for unique applications in highly efficient areas (foil and strut systems). Figure 7 summarizes all of the foregoing



COMPARISON OF CHARPY–V AND DYNAMIC TEAR ENERGY FOR VARIOUS HULL STEELS

Fig. 7

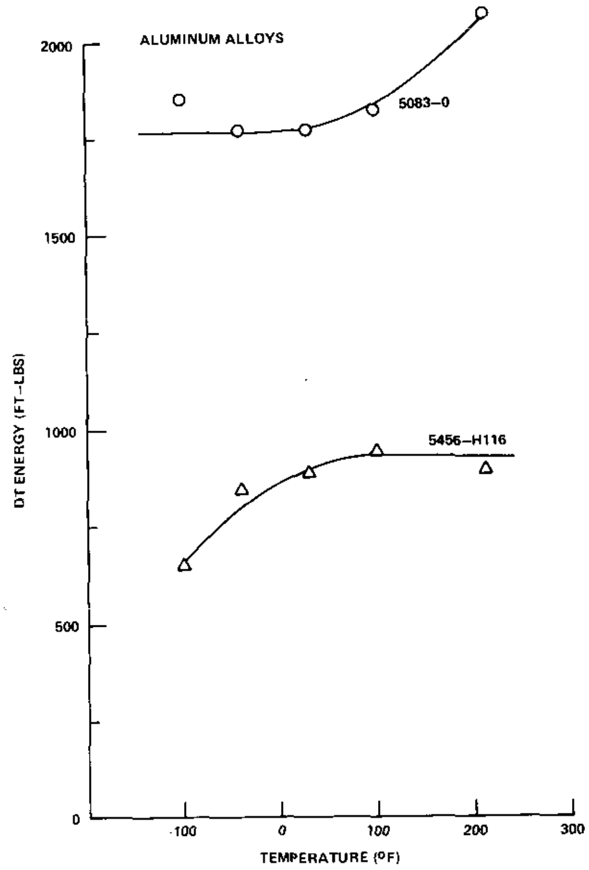
thoughts because it dramatically depicts the increase in toughness, and/or decrease in NDT temperature of the various materials, from the Class A materials used in less critical areas through to the more highly stressed materials.

Aluminum Alloys

Aluminum alloys in the 5000 series are used for welded marine applications because of their high strength-to-density ratio, and good oxidation, corrosion, and non-magnetic characteristics. The high strength 7000 and 2000 series aluminum alloys are not used because of their poor corrosion resistance, poor weldability and low fracture resistance. The 6061-T6 alloy has been precluded from Navy usage because of base metal heat-affected zone softening during welding. In general, large-scale usage of aluminum alloys in the hulls of large ships is precluded due to low modulus, low resistance to thermal effects, and high cost. However, aluminum alloys offer significant advantages from a weight standpoint in selected areas of large ships and as a hull material in high speed smaller ships. Figure 8 shows the typical dynamic tear energy plot for the 5000 series aluminum alloys and a typical RAD plot is given in Figure 9. It should be noted in Figure 8 that the 5456 alloy has a degradation of toughness properties at temperatures below 100° F, but the 5083 alloy appears insensitive to temperature effects below 100° F.

Miscellaneous Alloys

The titanium alloys have superior strength-to-density ratios coupled with excellent corrosion, erosion, cavitation, and non-magnetic properties. many of the titanium alloys have a wide range of strength level and fracture resistance as a result of heat treatment, processing, and chemistry-factor variations. Fabrication cost and fabrication requirements are such that large-scale application of the material in hull systems is presently not feasible; however, selected usage of the material is feasible. Figure 10 is a typical dynamic tear energy plot for a titanium alloy, and a typical RAD is presented in Figure 11.

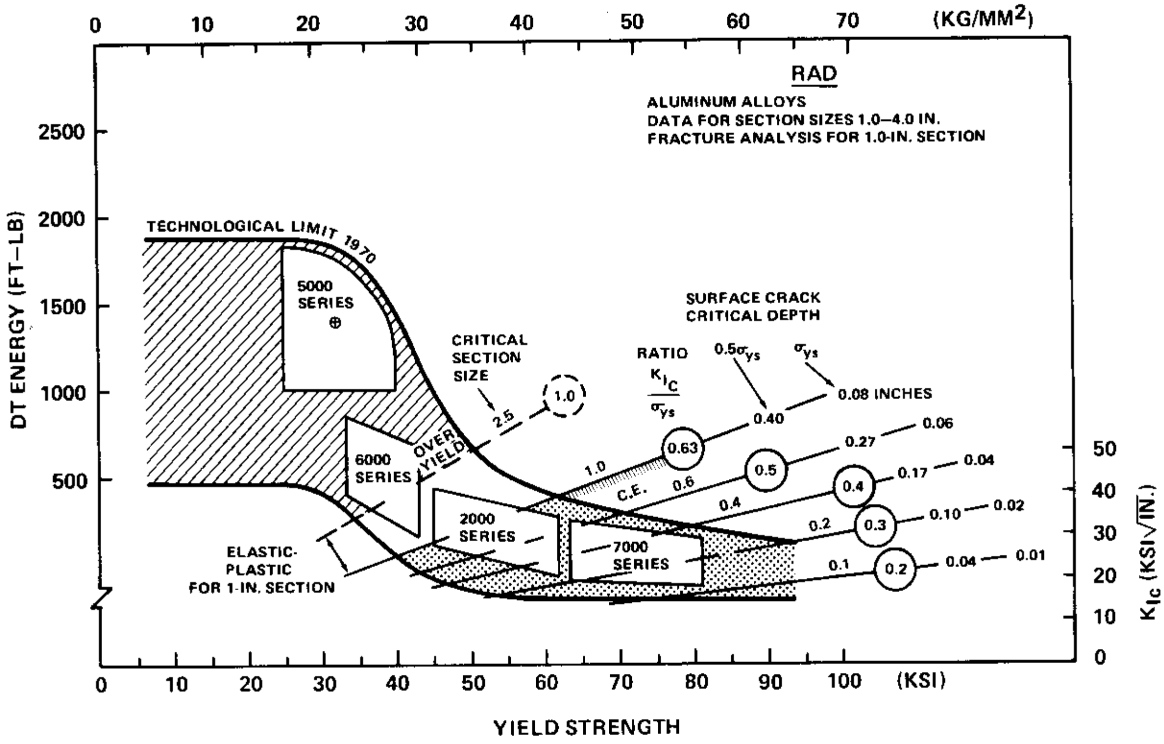


DYNAMIC TEAR ENERGY CURVES FOR TWO ALUMINUM ALLOYS

Fig. 8

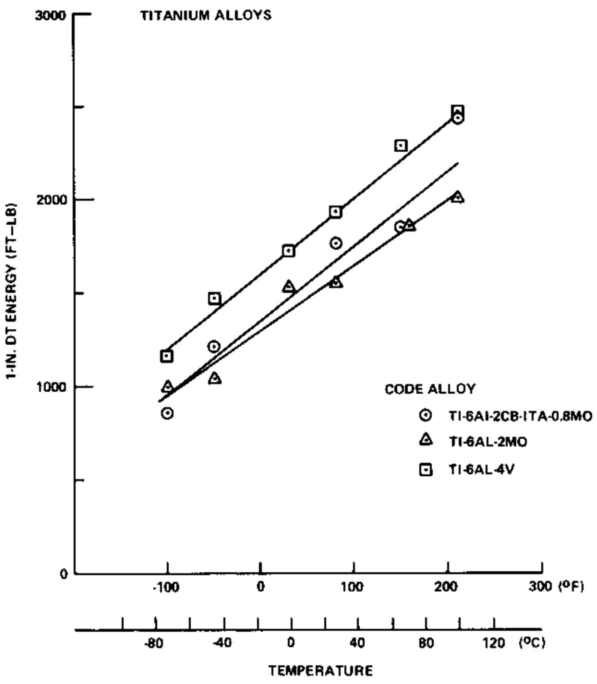
Composite Systems

The composites consist of metallic or non-metallic fibers enclosed in a plastic binder. Of primary significance in the application of composites is the fact that the material can be designed (layed up) in the most favorable orientation for the applied loads. This laying-up procedure is also one of the potential problems in adequate usage of the material because it carries



RAD FOR ALUMINUM ALLOYS AS PREPARED FOR TRADE-OFF ANALYSIS INVOLVING PLATE OF 1.0-IN. (25 MM) SECTION SIZE.

Fig. 9



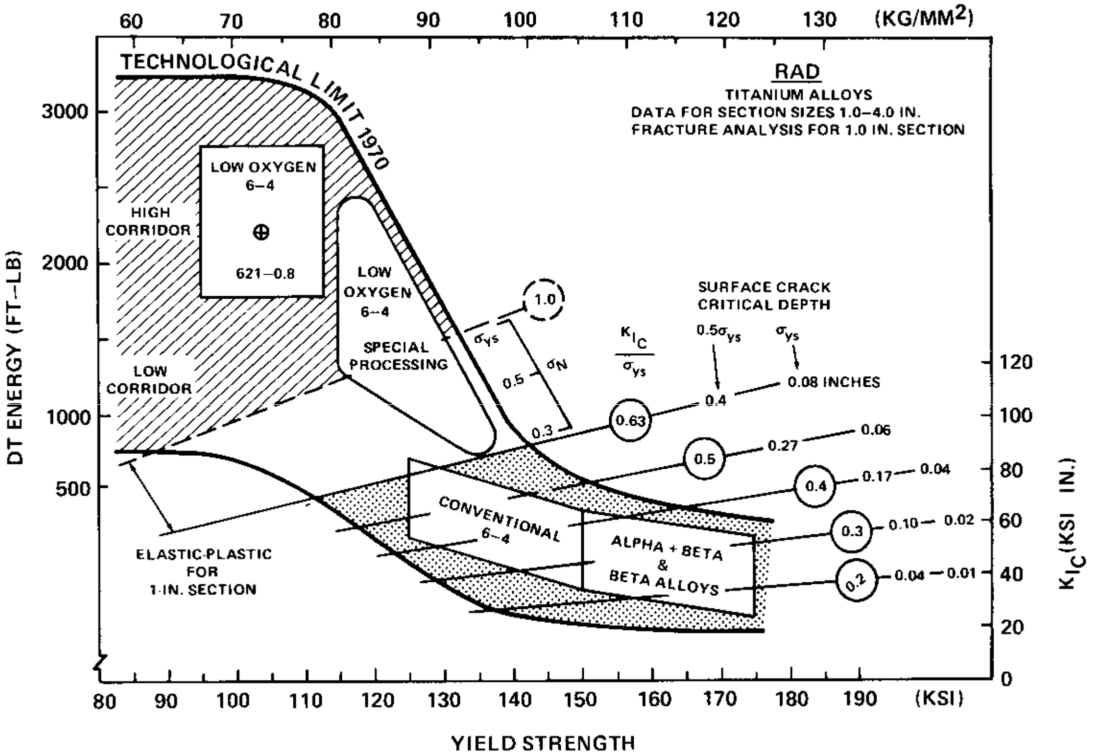
DYNAMIC TEAR ENERGY CURVES FOR TITANIUM ALLOYS

Fig. 10

with it an inherent large statistical variation in material properties. The inherent advantages of composites as a hull material are high strength-to-weight ratio, durability, resistance to fouling, and ease of repair. As a substitute for wood in specific hull applications, the higher initial costs are offset by reduced maintenance costs.

In the late 1940's, the U. S. Navy introduced glass reinforced plastics (GRP) as a hull material for a series of personnel boats. Since that time, GRP has been used in a number of commercial and naval hulls. Today, hulls as long as 200 ft. are considered feasible and the American Bureau of Shipping in conjunction with commercial and naval representatives has undertaken the development of formal rules to govern their design and fabrication. Toughness of GRP laminates cannot be directly related to toughness of the metallic systems. However, intuitive observations can be noted. It has been generally observed that under similar conditions GRP hulls withstand impact loadings in service equally as well as similar aluminum hulls.

The reinforced plastics lose strength under high temperatures and tend to creep. Conversely, they get stronger under low temperatures. Because of the tendency for the laminates



RAD FOR TITANIUM ALLOYS

Fig. 11

to absorb water after extensive immersion and thereby lose strength, it is necessary to take particular care with the surface coat when laying-up the structure. It has been shown that if proper care is taken, extensive immersions in salt water will have no deleterious effect on strength properties.

FLAW GROWTH

It is good practice to utilize "tough" metals that are insensitive to brittle fracture. Though the approved higher strength materials can withstand certain initial defects or flaws, these flaws can in time grow to critical size and possibly propagate in a rapid manner or they can grow to such a size as to require considerable maintenance.

Weldments are generally the areas most prone to crack initiation and growth. The weld itself is basically a casting laid down on the building ways and usually contains some porosity, lack of fusion, undercuts, and micro cracks. The minute micro cracks are usually a result of entrapped hydrogen resulting from the welding process. Rigorous procedures that can include preheat and postheat requirements, as well as controlled ranges of heat input, are all employed to minimize such defects. The solidification of the weld metal causes high residual stresses to be developed in the weld, thus a combination of undesirable conditions can exist at a weld. Further, many welds by their very nature are located in areas of high stress concentration which further aggravate the problem. Therefore, it seems prudent to briefly discuss sub-critical flaw growth with particular attention to weldments.

A considerable amount of fatigue data has been generated for the higher strength shipbuilding materials (greater than 80,000 psi). Unfortunately a standard specimen for all fatigue tests has not been universally decided upon. Nonetheless small specimen data, regardless of specimen used, are useful for initial material screening but not for detail evaluation. Fatigue crack growth can be divided into an initiation stage and a propagation stage. Academically both stages should be considered; however, accepting the premise that micro-cracks can and do exist at weldments, we will only concentrate on the propagation stage.

Fatigue crack growth is accelerated in hostile environments such as salt water. Further, if the material is also susceptible to stress corrosion cracking (SCC), the problem is compounded. A small flaw can grow under fatigue loading and then extend due to SCC. Given a "tough material," sub-critical flaw extension would be expected due to the combined actions of corrosion, corrosion-fatigue, and stress corrosion cracking. That is, the flaw may propagate along the length or even through the thickness, but it should not result in catastrophic brittle tearing. Thus, in most instances this type of flaw growth is associated with high maintenance costs.

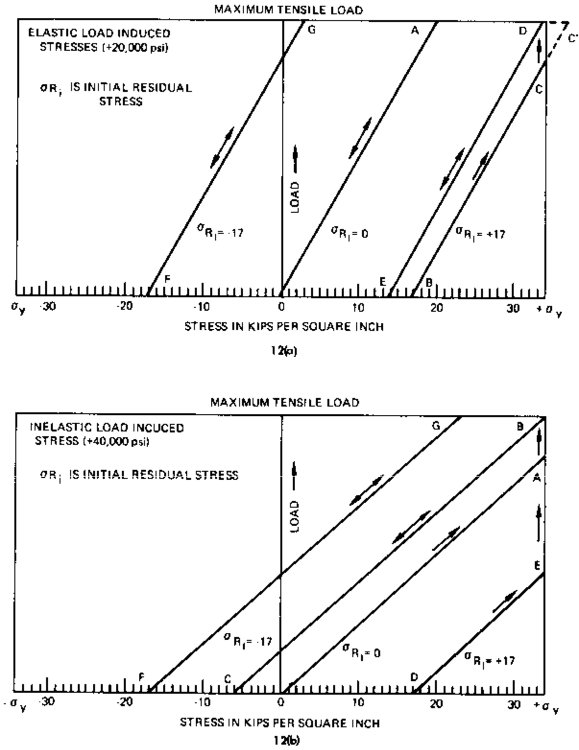
Both fatigue and SCC require tensile stress fields for flaw propagation. The problem is comparatively easy if the tensile stress field is a result of induced loads or service loadings. In such a case, the detail would be sized so that the stress level is commensurate with the flaw tolerance of the material. At welds the problem is orders of magnitude more difficult because the tensile stresses are associated with residual stresses and clearcut solutions are not available. The maximum tensile stress at the weld is usually the residual stresses associated with welding and can be as high as the yield strength of the material, therefore any discussion of flaw sensitivity must include consideration of the effects of residual stresses.

Residual Stress

All fabricated structures contain locked-in and residual stresses of varying magnitudes. In general, these stresses are the result of rolling, fitup, and welding. However, they can also be induced or modified as a result of over stressing. Residual stresses in the area of structural discontinuities do not appear to have any effect on the static strength of the structure provided elastic instability of the structure is not a problem. Equilibrium conditions indicate that residual or locked-in stresses should be self-balancing through the depth of the section, thus they should have no resultant. Accepting this premise, high residual tensile stresses on or slightly below the surface of a weld, for example, must be balanced by compressive residual stresses within the body of the weld. The surface stresses also vary at right angles to the weld with sharp gradients from tensile at the weld to compressive in the plate a short distance from the weld.

The effects of overstressing on residual stresses can be grossly summarized by sketches such as Figure 12. Load induced stresses unlike locked-in stresses have a resultant. Therefore, as the load is increased, the load induced stresses add to the residual stresses at one point and subtract at another. When the sum of the residual and load induced stresses at a discrete location reaches the yield of the material, the less highly stressed adjacent areas start to carry more load. Under these conditions the response of the small plastic zone of material is governed by the larger elastic zone surrounding it. This rationale is the basis for the diagram of Figure 12. For example purposes, Figure 12 is based on an elastic perfectly-plastic material with a yield strength of 34,000 psi. Assuming a load induced tensile stress of +20,000 psi, the line OA represents the loading response of the structure if the initial residual stress is zero. Assuming an initial tensile residual stress of +17,000 psi, the initial loading of the structure should follow the line BC'. But since the line BC' intersects the tensile yield strength line at point C, it means that the structure is starting to locally yield (line CD) at this point and that the stress remains constant. The point C' represents a pseudo stress not achievable with the material properties assumed, but necessary for establishing the slope of the line BC'. Upon unloading, the structural response is represented along the line DE. All future loadings and unloadings will also follow the line DE provided the maximum load induced tensile stress of the +20,000 psi is not exceeded. If we now consider the case of compressive residual stress of 17,000 psi magnitude and the load induced tensile stress of +20,000 psi, the response of the structure for all loadings and unloadings is represented by line FG. It is interesting to note that in this latter consideration the application of external loading actually causes an attenuation of real surface stress.

More drastic situations can occur if the load induced stresses are locally amplified by a stress concentration factor. This is shown in Figure 12(b) with all conditions staying the same except a stress concentration factor of 2 is now assumed. This means that the load induced tensile stress is now +40,000 psi. For the condition of no initial residual stress, yielding is experienced on the first loading, line OAB, and the unloading and all future loadings to the same maximum load follows line BC, with a resulting residual stress of -6,000 psi. For the condition of an initial residual stress of +17,000 psi, the effects are even more dramatic. The initial loading follows the line DEAB and the unloading and all future loadings to the same maximum load follow the line BC. In this case the load induced tensile stress caused a change in surface residual stress from an initial value of +17,000 psi to a final value of -6,000 psi. Only in the case of initial compressive residual stress (assumed as -17,000 psi) does the response remain linear during the entire initial loading range. The



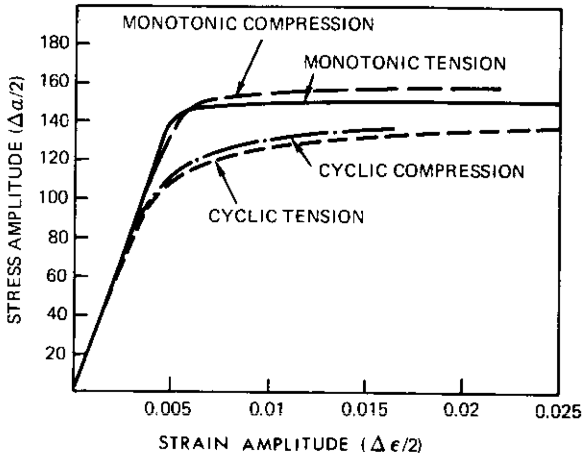
EFFECTS OF INITIAL RESIDUAL STRESS ON LOAD INDUCED STRESS

Fig. 12

loading and unloading for this case is depicted by the line FG.

The above examples represent a gross engineering simplification for the tensile loading case only. If reverse loading were to be considered, the mirror-image load ordinate would have to be plotted in order to determine the actual response of the structure. In such instances, elastic response after initial loading will occur only if the total load amplitude induces a stress of less than twice the yield strength of the material. A more exact representation of the response of the structure, particularly where the load induced stress amplitude is in excess of twice the yield strength, can be obtained by replacing the stresses on the abscissa of Figure 12 with strain. In such cases, a "shakedown" of the load-strain curve is obtained and a new material response curve is derived. This type of cyclic stress-strain curve is gaining more prominence in replacing the monotonic stress strain curve in fatigue predictions where residual stresses play a major role. A comparison of a cyclic stress-strain curve and a monotonic stress-strain curve for steel is shown in Figure 13.

In many areas of welded structures residual stresses cannot be measured directly as are load-induced stresses. In fact, the current state-of-the-art does not permit accurate prediction nor measurement of residual stresses throug the thickness of welded structures. Measurement capability is limited to surface or near surface measurements generally by physical or mechanical means. The physical approach typified by X-ray diffraction at the present tim is not readily available for field use. The mechanical methods such as Mathar's hole relaxation method are all semi-destructive in nature. Thus, the designer, particularly in the case of welded structures, is forced to live with a stress which he has little capability to control, essentially no capability to predict, and limited capability to measure. Therefore, in considering flaw sensitivity, he must rely on environmental loading tests of realistic structural details that are fabricated in a manner to closely duplicate residual stresses expected in actual structures.



MONOTONIC AND CYCLIC STRESS-STRAIN CURVES FOR HIGH STRENGTH STEEL

Fig. 13

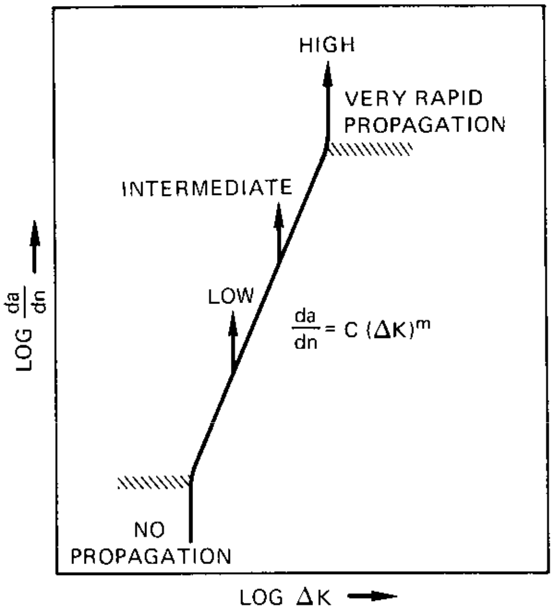
Fatigue/Corrosion Fatigue

In the past, fatigue has played a relatively minor role in the design of ship structures. One of the reasons for this is the fact that the hull girder is subjected to a very small number of high stress cycles during its lifetime. However, the use of higher strength materials with proportionately higher allowable stress levels and the ever present possibility of stress concentrations make fatigue a major factor in the design of newer more efficient ship structures. Further, relatively tough hull materials can be seriously degraded if a small flaw grows to critical size as a result of cyclic stressing.

In any assessment of fatigue response, the most desirable conditions would include shipboard observations supplemented by structural element tests and small-scale laboratory tests. One major difficulty experienced in correlating fatigue resistance of prototype details with laboratory test results stems from the differences in restraint and in loading spectrum. The loading spectrum experienced by a ship in service is rarely duplicated on a laboratory specimen, in fact the laboratory specimen is usually subjected to constant stress cycles whereas the ship sees random stress cycles. Even though these simple laboratory specimens may be inadequate for firm predictions of the fatigue strength of a detail in service, they are useful for screening and characterization purposes and for defining approaches that the designer can exploit in improving the fatigue life of structural details. The closest approximation of the fatigue response of the actual structural detail can be obtained from tests of realistic structural elements or models. Ideally such models must satisfy at least the following general requirements. They must be constructed of full-scale plate thickness; be of sufficient size to adequately reproduce the biaxial constraint of the prototype; be fabricated with the same welding consumable, procedures and tolerances specified for the prototype; and they should be loaded in a manner that duplicates the expected stress field and stress spectrum for the prototype. In practice, it is difficult to match all of the above requirements particularly duplication of the expected stress spectrum for the prototype. However, until more definitive operating data is obtained and evaluated, the designer does have other options at his disposal.

Fatigue studies of higher strength steels indicate that where local strains are very high, low cycle fatigue predominates, and that the size and shape of the laboratory specimens seem to have a negligible effect on the results obtained. Therefore, for the higher strength steels at lives less than 100,000 cycles, simple laboratory test specimens will provide data acceptable for engineering applications.

Various types of laboratory test specimens are used to obtain fatigue cracking data. In order to assess crack propagation properties, fracture mechanics principles are employed in the interpretation and presentation of the data. As shown in Figure 14, crack growth rate (da/dn) is related to stress intensity range (ΔK) to simplify the analysis. In this manner, the two controlling factors of crack size and stress are always considered in determining the stress intensity factor. This method of presentation and interpretation of data is in sharp contrast to the old S-N curves that did not consider defect size and crack growth rate. Utilization of curves such as those in Figure 14 permit rational interpretation of extent of flaw growth due to fatigue loading in order to assess structural integrity requirements. The schematic of Figure 14 is illustrative of how fatigue crack propagation data may be plotted; however, it should be noted that considerable scatter of data does exist. The scatter bands for the aluminums, titaniums, and steels are shown in Figure 15. It is noted in Figure 15 that the aluminums have the least resistance to crack propagation and the steels have the highest resistance to crack propagation.

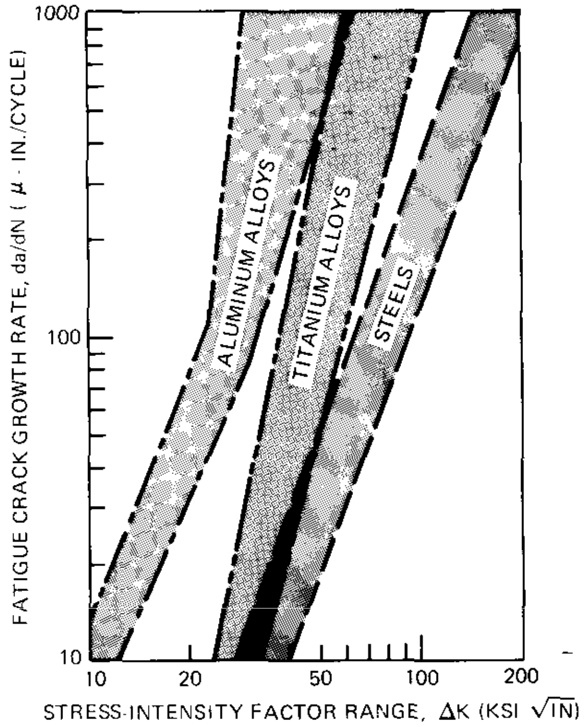


TYPICAL FATIGUE DATA FOR STRUCTURAL METALS.

Fig. 14

Utilization of fatigue data such as that in Figure 15 is dependent upon the conditions of the laboratory tests being similar to those expected in service. The presence of a hostile environment such as salt water and cathodic protection can lower fatigue crack resistance. An example of the effect of a salt water environment is shown in Figure 16 and it is noted that the effect is most pronounced at the low ΔK values where the crack growth rate in air was almost negligible.

Results obtained in U. S. Navy tests of high strength steels indicated that fatigue crack initiation and propagation was possible under purely compressive loadings. This finding was explained by the concept of surface tensile residual stresses. The concept was



COMPARISON OF LOW-CYCLE FATIGUE SCATTERBANDS FOR ALUMINUM, TITANIUM AND STEELS.

Fig. 15

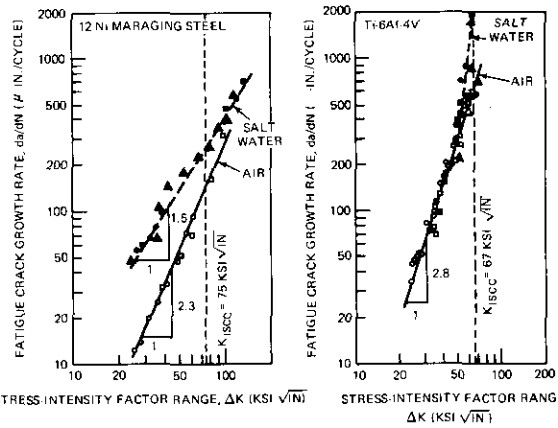
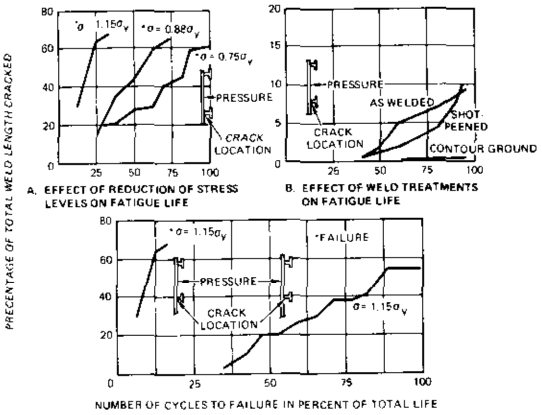


ILLUSTRATION OF THE EFFECT OF HOSTILE ENVIRONMENT ON CRACK GROWTH RATES IN LOW-CYCLE FATIGUE.

Fig. 16



TYPICAL RESULTS FROM U.S. NAVY'S FATIGUE PROGRAM

Fig. 17

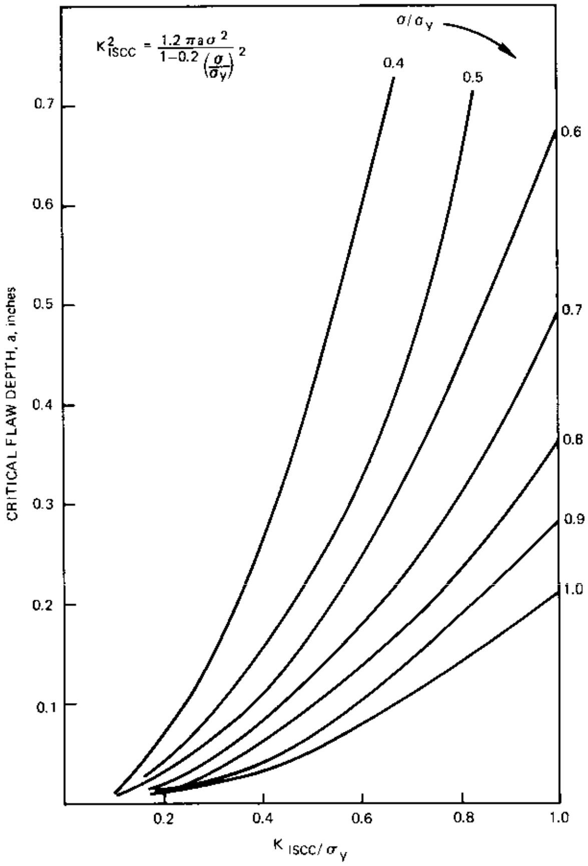
further verified for base metal, by overstressing a notched bar in compression, thus inducing tensile residual stresses at the root of the notch. A small number of compressive cyclic loadings was then sufficient to develop a fatigue crack at the base of the notch. Thus, fatigue is not just possible in areas of tensile residual stresses; it is a distinct possibility in areas of compressive service loadings.

The simplest way to improve the fatigue life is to reduce either the loading spectrum or the magnitude of the stress or both. The loading spectrum is an operational factor outside the realm of the designer; however, the stress condition can be alleviated by the designer. The most obvious option is to reduce the allowed nominal stress but this implies weight penalties and does little in areas where residual stress is an additional culprit. Other approaches include careful detailing of structural discontinuities to minimize stress concentrations, thus ample use of forgings and castings. Another possibility is post treatment of welds by grinding or contour peening to reduce stress concentrations. In this regard it is noted that contour peening provides the additional benefit of putting the weld surface into residual compression. Another possibility, where practicable, is the placement of stiffener systems in areas where the welds will always see compressive load induced stresses. The beneficial aspects of some of these procedures are shown in Figure 17. Many of the procedures for improving fatigue life are within the designers' area of responsibility. Though they may add to the cost of the construction, it should be remembered that an ounce of prevention is worth a pound of cure.

Stress Corrosion Cracking

In addition to fatigue crack propagation most of the higher strength materials have varying degrees of susceptibility to stress corrosion cracking. Stress corrosion cracking (SCC) is the propagation of a flaw due to the combined influence of a tensile stress field and the salt water environment. In the presence of cathodic protection systems, the susceptibility for SCC is increased. Traditional concern with SCC has been centered about those materials that fail in a brittle catastrophic manner after a flaw has progressed to a critical size due to stress corrosion. This is not the case for those materials envisioned for usage in ship structures (See TABLE II). Rather, because of the higher toughness of these materials, nuisance-type cracking or ductile failure due to large crack size and imposed stress levels is envisioned.

Threshold limits for SCC can be determined from laboratory tests. At stress intensity values below the threshold, SCC will not occur; above the threshold, it will occur. Engineering estimates of SCC effects can be obtained from curves such as shown in Figure 18.



RELATIONSHIP OF FLAW SIZE, TENSILE STRESS, YIELD STRENGTH AND K_{ISCC}

Fig. 18

As indicated in the figure, critical flaw size is controlled by the materials SCC stress intensity index, K_{ISCC}, and the applied tensile stress. Generally for the steel systems, the SCC propensity is greater for the weld metals than for the base plate. This, coupled with the premise that residual stresses are self-balancing through the thickness and varying along the surface normal to the weld, lends some ray of hope for the designer in those areas where tensile residual stresses are the primary cause of flaw growth due to SCC. In such cases, the flaw can grow out of its own stress field and self-arrest. In one case, it can grow to the edge of the weld and stop because of a higher SCC stress intensity threshold required for the plate coupled with a reduction of residual stress in the plate surface. In the other case, in proceeding through the thickness of the weld, the crack tip can enter a zone of reduced tensile stress or even compressive residual stress and the SCC growth will arrest.

Separation of SCC and corrosion fatigue for sensitive materials is almost impossible. As shown in Figure 16, as the stress intensity is increased SCC probably takes over as the determining factor for flaw growth.

DESIGN CONSIDERATIONS

Ship design is a continuous, highly iterative process. Structural design is a primary element of the process in that it provides the envelope in which the other systems are enclosed, transported, and protected. It is obvious that adequate strength and structural efficiency are primary requisites for any ship. Structural strength and stability are adequately treated in the literature and will not be dwelled upon herein. However, once this strength is assured, the structural designer traditionally plays a supporting role to the rest of the design, provided major modifications in the total ship are not imposed at a later stage of the design process. It has been rumored that the structural designer functions in such a supporting status because he deals in a "black science" and is therefore in a much better position to compromise when other system requirements so dictate. At the risk of betraying a secret, it must be stated that similar to all other designers the structural designer agonizes over any proposed design compromise before he can arrive at an acceptable solution. Fortunately the structural designer has a scientific data base to use in assessing his solutions to such problems, but many uncertainties exist in the application of this scientific data base. The primary uncertainties are in the mathematical modeling techniques and in the loading spectrum.

Design and Analysis

Structural design because of its iterative nature is rather difficult to differentiate from structural analysis. In both, materials, loads, configurations, scantlings and structural response are involved in mathematical manipulations. In the design portion, the scantlings are the output; in the analysis portion, the structural response is the output. The designer continues to manipulate back and forth between the two until he arrives at an acceptable design. He rarely, if ever, arrives at THE optimum structural design, but he does arrive at A optimum design. In this regard structural optimization is defined as a combination of least-weight, least-cost, and most-producible structure. Unfortunately, in most cases none of the three is mutually supportive.

For a conventional hull, the designer has previous proven reliable configurations to use as a point of departure. His design is then premised on and tested against established requirements for tensile, compressive, shear, and torsional stresses and strains, buckling strength, vibration limits and hull flexibility limits. Basic hull girder strength is achieved by considering the ship as a free-free beam poised on a defined wave, hogging and sagging stresses determined, and scantlings and plating sized to provide an adequate section modulus. Local structure is then sized by utilizing beam, column and plate theory as appropriate. This leads to grillage solutions for orthoganally stiffened panels and to finite element approaches for more complex structural configurations. The development of the finite element approach coupled with the advent of high-speed computers provided the structural designer with a most powerful tool for assessing the response of complex structures. It is now possible for the designer to model the mathematics to fit his structure rather than the old closed form solution approach of forcing the structure to fit the mathematics. As powerful as the finite element approach may be, its accuracy is dependent upon proper selection of boundary conditions and of mesh size, both of which are functions of user experience and existing physical test data.

The extensive data base available for conventional hulls is not available for projected high performance ship hulls. This imposes a more demanding set of requirements on the designer. Basic concepts for hull girder strength determination will probably be very similar to conventional hull practice, but all other elements of the design will appear to be different. The difference will be in appearance only, because it will really entail application of modern technology to obtain a data bank of information similar to the data bank available for conventional hulls. Our conventional hull data bank is based on decades of trial and error approaches backed up by physical model testing and at-sea measurements. For high performance hulls accelerated development of such a data bank can be obtained by judicious applications of sophisticated computer programs coupled with selected large-scale structural model tests and supported by extensive structural element tests and newer modeling and experimental techniques (such as rigid vinyl models and holography).

Design and analysis of high performance hulls will require cooperation between researcher and designer. The researcher will provide the information for the accelerated data base, simplify the input and output of sophisticated computer codes, and provide limiting material property data. The designer will insure that the goals of the research efforts are adequately defined, will properly utilize the research results in his design, and will provide a feed-back loop to the reseacher concerning design problems and at-sea experience. Proper integration of the interactive roles of researcher and designer are mandatory for rapid attainment of the capability to provide adequate hull structure for high performance ships. An example of such an approach in action today is the SEALAND/American Bureau of Shipping/Ship Structure Committee cooperatively sponsored SL-7 program that includes mathematical and physical models for hull response and hydrodynamic motions, at-sea measurements of structural response and sea spectra, and feed-back loops of coordinated data results.

Inherent in the design of high performance hulls will be an intensification of effort on the design of details very early in the design process. Once basic material trade-off studies have been conducted and a configuration arrived at, it will be necessary to perform rigorous analysis of stress and strain distributions in the areas of structural discontinuities. The application of sophisticated computer programs for accurate stress distribution is dependent upon the degree of accuracy of the loading spectrum and the dollar cost for running such analysis. This imposes requirements on the designer to limit the number of unique details in his designs, and to utilize simpler computer programs where the detail permits. In short, the designer must allot his time and dollars in direct proportion to the degree of criticality of the detail in question.

The structural design of high performance ships requires definition of the life cycle loading and stress distributions in order to properly proportion the material. Coupled with this is the need for material property data to adequately assess fracture potential. The major problem areas will be in that small percentage of the total hull in the area of weldments. Structural design methods and criteria are available now to support first generation designs. However, additional developments are necessary in the area of structural criteria (safety factors), improvements in computer models, and in application of fracture mechanics principles for flaw propagation and fracture. Coupled with all of the above is the need to accurately define the applied loads.

Loading Spectrum

The ship system is subjected to a complex spectrum of external and internal forces. Wave loadings, sea slap, slamming, vibration, thermal, cargo, buoyancy, aircraft landing, weapons, and docking are some of the applied loading considerations that must be addressed. Unfortunately the magnitude and distribution of many of these loads are, in some cases, handled in an imprecise (though totally adequate) manner. Coupled with the applied loadings are the built-in residual stresses due to fit-up and welding. The technological state-of-the-art is not sufficiently advanced to permit accurate prediction of welding residual stresses through the thickness of the material, thus assumptions are necessary.

The commercial ship certification societies, the U. S. Coast Guard, the U. S. Navy, etc., have all established guidelines and criteria for treating the various loadings. In addition, on-going research is directed toward a more scientific definition of sea loadings. For longitudinal strength, efforts are directed toward replacing the evolutionary method of assuming wave size and shape based upon empirical formulations with a statistical deterministic approach based on observations of sea spectra. Comparable efforts are underway to improve the understanding of sea slap, slamming, vibration, and springing loadings.

Present day design practices are adequate even though the loads are somewhat imprecisely defined. However, efficient utilization of higher strength, more flaw sensitive materials requires a rather precise definition of stress levels at critical details. In order to provide such definitions of stress, sophisticated mathematical modeling coupled with more precise load definition will be necessary. In most instances, the need for such precise stress contours will be limited to a relatively few critical details. Criticality can be defined as highly stressed or "inaccessible" moderately stressed connections, or any connection the failure of which could precipitate a mission abort. Implied in the foregoing statement is the requirement for utilization of a few "standard" details throughout the design rather than following a concept that would permit a myriad of customized details.

A generalized matrix of types of applied loading to be considered for various structural elements is given in TABLE III. The applied loadings are broadly classified into two groupings, those that should be considered in combination and those that should be considered independently. It is obvious from the matrix that the interaction of the loadings is such that for specific detail evaluations to be meaningful, a more rational definition of the seaway loadings is required.

In any discussion of loadings, it is tacitly assumed that primary hull girder strength requirements are satisfied. The wealth of operational experience is such that considerable confidence exists concerning structural adequacy. This degree of confidence cannot be extrapolated to new structural configurations or materials. In short, conventional designs are characterized by adherence to design rules developed over the years; new ship types may not be amenable to such rules. In any treatment of loading spectrum, the unknown undefined loads should always be considered. These are the loads that may have at best a tertiary effect. For example, in conventional hulls the side shell plating is often sized according to a standard that specifies a minimum plating thickness requirement. There is no scientific support for such requirements, but this ruggedness factor is built in because of past experience as good design practice. Hard to explain as it may be, it is a very comfortable insurance for ship operators during docking, loading or unloading operations when tugs, lighters or other small craft accidently bump (not too gently) into the side plating. For the more exotic materials, the unknown-undefined loads may be even more pronounced. Minor nuisances for today's hull may prove most disastrous for novel hulls. For example, when a moored steel hull ship rubs against pilings due to small wave action, it may result in a minor paint patch-up requirement. Yet for a ferro-cement craft, this piling bumping while moored resulted in side shell spalling and cracking in a matter of a few days.

Trivial as the above example may be, it does alert the designer to the fact that negligible loads on conventional ships may assume disastrous proportions on hulls of more exotic materials. In the same vein, major modifications or changes in mission requirements may not be as easily accommodated with the exotic material designs as compared to today's steel hulls. Improvements in load definition, as essential as they may be, do not necessarily give the designer the freedom and latitude as would be indicated at first glance. Prudent engineering judgment must be exercised in establishing loading criteria lest we fall into the trap of designing an optimum hull that is only capable of specialized missions without costly revisions at a later date.

Requirements to reduce weight, while still maintaining economic viability, will probably dictate development of new approaches for the design of novel ship types. Inherent in such new approaches will be a more efficient utilization of material, and thus a probable reduction of conventional safety factors. This means establishing

TABLE III LOAD MATRIX

LOAD MATRIX		LOADS TO BE COMBINED							INDEPENDENT LOADS							
	LOAD STRUCTURE	PRIMARY (HULL GIRDER)	HYDROSTATIC (EXTERIOR)	TANK LOADS (TO TOP OF TANK)	DEAD LOAD	LIVE LOAD	WIND, ICE SNOW	STOWAGE (CARGO, HELO)	SEA SLAP/ SLAM	TANK LOADS (TO OVERFLOW)	FLOODING	GUN & MISSILE BLAST	INTERIOR OVER PRESSURE (MISSILE STOWAGE)	DRY DOCKING	OPERATING (UNREP BOATS, & ETC)	AIRCRAFT/HELO LANDING
I	SHELL PL & FRAME															
	A. MIDSHIPS	X	X	X	X	–	–	–	–	X	–	–	–	X	X	–
	B. FWD	X	X	X	X	–	–	–	X	X	–	–	–	X	X	–
	C. AFT	X	X	X	X	–	–	–	–	X	–	–	–	X	X	–
	D. SPONSON SHELL	–	X	–	X	–	X	–	X	–	–	–	–	–	X	–
	E. WEB FRAMES	–	X	X	X	–	X	X	X	X	X	X	–	X	X	–
II	BULKHEADS															
	A. LONG'L	X	–	X	X	–	–	–	–	X	X	–	X	–	–	–
	B. TRANS	–	–	X	X	–	–	–	–	X	X	–	X	–	–	–
	C. BENTS	–	–	–	X	X	–	X	–	–	–	–	–	–	–	X
	D. MISC	–	–	X	X	–	–	–	–	X	X	–	X	–	–	–
III	DECKS															
	A. INTERIOR	X	–	X	X	X	–	X	–	X	X	–	X	–	X	–
	B. WEATHER	X	X	–	X	X	X	X	X	X	–	X	X	–	X	X
	C. PLATFORMS	–	–	X	X	X	–	X	–	X	X	–	X	–	–	–
IV	STANCHIONS	–	X	X	X	X	X	X	–	X	X	X	X	–	X	X
V	SUPERSTRUCTURES															
	A. LONG	X	X	–	X	X	X	X	–	–	–	X	X	–	X	X
	B. SHORT	–	X	–	X	X	X	X	–	–	–	X	X	–	X	–
VI	APPENDAGES															
	A. STRUTS	–	–	–	X	X	–	–	X	–	–	–	–	–	–	–
	B. FOILS	–	–	–	X	X	–	–	X	–	–	–	–	–	–	–

design limits based on yield, ultimate, fatigue and fracture strengths as a function of ship configuration and material. In order to rationally accept such departures from proven past procedures, all elements of the necessary design matrix must be defined and one of the primary considerations is the applied loads. Early efforts in novel ship structural concepts will not be able to take full advantage of potential capabilities. The establishment of limiting values must by its very nature be a progressive and iterative procedure. At-sea measurements will be necessary to verify the adequacy of load predictions and structural response. These data will then be the basis for modifications and improvements to the load criteria definition. Such at-sea measurements are not new; they are obtained on conventional designs today; for tomorrow's designs, they will be mandatory.

Once the concept of a specific novel configuration and material system has been verified in service, that specific concept will then by its very nature become conventional. Future improvements and modifications of the concept will then follow the same evolutionary cycle evident in today's designs. In short, once the "quantum-jump" has been made, improvements will be evolved in the systematic conventional manner of today's ships.

FABRICATION AND MAINTENANCE

Inherent in the application of structural integrity requirements is consideration of fabrication and maintenance in the initial stages of the design. Decisions made in the conceptual design stage can have far reaching implications in the fabrication and service life of the ship. For this reason the structural integrity approach is a totally integrated design concept wherein all phases of the ship's life must be consciously considered right from the start. Implicit in such a concept is the requirement that participation of engineers in the areas of design, fabrication, and maintenance be complete and interactive from inception to completion. Lead responsibility will change hands as the ship progresses through the various stages, but continuity must be maintained and ultimate technical responsibility can never be abrogated.

Fabrication

Poor fabrication practices can doom the best design. It is incumbent upon the designer to recognize unique fabrication requirements for his design as well as to be knowledgeable of and sympathetic to the fabricator's limitations. It is equally incumbent upon the fabricator to be knowledgeable of and sympathetic to the designer's technological limitations.

Tolerances, structural arrangements, and structural details should never be changed without the designer's knowledge and approval. Conversely, unique requirements in these areas should never be specified without prior consultation and agreement with the fabricator.

Rigid adherence to welding requirements is necessary. For some material systems, improper heat inputs can degrade strength and/or toughness of the weldment. Excessive distortion or mismatch can cause the introduction of unduly high residual or locked-in stresses as well as possibly introduce premature instability failures. Further, improper welding techniques can be the cause of weld cracking, porosity, lack of fusion, and slag inclusions, all of which can lead to subcritical and/or rapid flaw growth in service.

During the design stages, details are optimized and the optimized details are then subjected to analytical scrutiny to determine potential stress concentrations. The most rigorous analysis can be obviated by poorly contoured or undercut welds, as well as by excessive mismatch of mating elements. While the use of extrusions, rolled shapes, forgings and castings help to eliminate some of the potential problems, all critical connections will never be eliminated. Thus, scrupulous attention to detail must be the rule rather than the exception.

Obvious structural detail requirements have evolved over the years and they all have the same goal - elimination of structural hard spots. Such requirements as continuous longitudinal, rounded corners, gradual taper in changing section sizes, landing bulkheads and stanchions on supporting structure, reinforcing large openings, minimizing numbers and sizes of adjacent openings, ending beams on supporting structures, etc., are obvious but can easily be violated. Such violations can occur because of expediency, poorly defined requirements or imagined cost savings.

The structural designer, in specifying his requirements, recognizes the mission, the material, the stress calculations, the fabrication requirements, and any special inspection requirements. Violation of the specifications during fabrication can undo the designer's efforts and degrade the utility, if not the adequacy, of the design.

Inherent in the requirements for fabrication of novel ship types with higher strength materials is the goal of minimizing production problems while maximizing economy. This is a prime area for designer-fabricator cooperation. The designer in his desire to produce optimized structural details must hold his artistic endeavors in bounds and specify relatively few different types of structural details. In this way by standardizing details he provides the fabricator the opportunity to more efficiently mechanize his entire production process. Such an approach will minimize requirements for special jigs and fixtures, maximize the potential for use of automated cutting and welding, thus providing an atmosphere more conducive to economic improvements.

For most steels, mechanized welding is an economical necessity; for the very high strength steels and the more exotic metals, it is a technological necessity. For these later materials shielded metal arc welding procedures will probably not be available. Full exploitation of new mechanized welding processes will only be possible if the designer configures his design for welding accessibility, thus the synergistic effect of less restraint. This means a constant interactive dialogue between designer and welding engineer during the detail design stage.

Another important factor is the development and implementation of an overall production plan complete with a detailed process control system. Such a plan, tailored to fit existing facilities, must provide for in-process quality control check points.

Nondestructive evaluation techniques and methods must be specified and adhered to at all steps in the operation. Utilization of higher strength more flaw sensitive material will require more rigorous in-process weld inspections. Again consideration must be given to maximizing the mechanization process to reduce costs. Automated ultrasonic (UT) systems with digital recorders to provide permanent record tapes can be used for weld inspections in many areas in lieu of radiographic methods. Surface defects can be located rapidly and inexpensively with eddy current techniques in many areas in lieu of magnetic particle techniques.

Today's conventional hull designs provide many instances where closer designer-fabricator interaction will result in initial as well as life-cycle maintenance potential cost reductions. Emerging hull concepts and material systems will make such interaction mandatory.

Life Cycle Maintenance

Generally hull maintenance requires inspections for corrosion, reapplication of protective coatings and occasionally repair of service generated defects. The general corrosion inspection and repainting are scheduled at regular intervals; service connected defects are generally repaired on a case basis. The corrosion inspection is conducted by taking caliper readings on framing webs and flanges, and by UT measurements of the shell plating. In extreme cases a small hole may be drilled in heavily corroded plate in order to obtain thickness measurements. In certain areas subject to excessive corrosion (i.e., under boilers, etc.) where inspection is difficult and repair even more difficult, it is a standard design practice to use a slightly heavier section than that required for strength purposes. In this way, a corrosion allowance is made in the early design and fabrication stage. Inspection documents, by ship class, specify minimum or allowable corroded thicknesses for specific members. Further, these documents also specify minimum total cross-sectional area requirements for the main strength deck and bottom structure in order to ensure adequate hull girder strength. Active (impressed current) and/or passive (sacrificial anodes) systems are used to minimize corrosion and pitting. Generally when pitting is encountered repairs are made by clad welding; however, complete renewal is required for extreme cases.

Utilization of higher strength, more flaw-sensitive materials in the ship structure will necessitate another level of life cycle inspection. Surface defect inspections will have to be conducted with magnetic particle, liquid penetrant, eddy current and/or expanded ultrasonic techniques by highly trained and qualified personnel. The first three techniques usually require a fairly smooth weld surface. Thus, it may be necessary to require weld dressing (i.e., grinding, contour peening, TIG remelt pass) in the fabrication stage. It should be noted, however, that such weld dressings have a possible synergistic effect in that they not only improve inspectability but also may reduce stress concentrations, thus impeding flaw initiation and growth. The through-thickness integrity (sub-surface flaws) will have to be evaluated using UT methods (radiographic methods may be necessary during initial fabrication). The periodicity and scope of these inspections will be based on results of large-scale fatigue and stress corrosion tests of specific details, as well as on assessments of the criticality of the detail.

Inspection and possible repair of critical details make it mandatory that to the maximum extent possible these details be at inspectable locations. In those cases where such details or portions of such details are in "inaccessible" locations, safe-life design procedures (including possible use of lower strength, less flaw-sensitive material) must be employed.

For certain high velocity areas, claddings may be required on structural members. In these cases special inspections will be required to ensure the integrity of the cladding. Visual inspections supplemented by periodic UT inspections may suffice. Again, the periodicity and scope of such inspections must be based on proper evaluation of large-scale tests of the details in question.

SUMMARY

Efficient exploitation of new material and hull configuration concepts dictated by economic or military requirements is possible if material, structural, and fabrication technologies are utilized in an integrated approach to hull design. The principles involved, technologically mandatory for new high performance ship hull systems, if judiciously applied can offer attractive economic advantages for conventional hull systems. This structural integrity approach entails a further refinement of and in some instances development of scientific rationale for what is termed good design and shipbuilding practice.

Proper application of structural integrity principles requires consideration of material properties, flaw sensitivity, design and analysis capability, fabrication and life cycle maintenance during all phases of the design. Heavy reliance on existing experience and, if necessary, generation of material and response characterization information, is inherent--just as in today's conventional designs.

In defining properties and response, a range of characterization tests is employed. Depending upon the application in question, the more complex type testing may not be necessary but the rudimentary tests are mandatory. The hierarchy of these tests is as follows:

Laboratory specimens	basic screening tests for material properties (handbook data)
Structural elements	determine response of details in fabricated condition
Scaled models	primarily to optimize specific structural details
Full-scale evaluation	final evaluation of detail under all environmental conditions

More accurate definition of loading spectra coupled with more tractable design methods for complex details will permit the structural designer to minimize the number of unique details and provide a clean design. In addition, the concept of design for fabrication (clean design) that would make all details amenable to mechanized welding procedures would not only result in less restraint in the weldments but would ease the fabrication and inspection process. The minimization of residual stresses and of entrapped hydrogen, achieved by providing lower restraint, mechanized weldments, will result in a marked reduction of flaw initiation and propagation both during fabrication and in service.

All of the answers are not presently available, but research is ongoing. The methodology for structural integrity has been available for many years. The marine industry has practiced structural integrity in total or in part since the first ship went to sea. Requirements for tough hull materials were evidenced in the 40's; the emergence of a coordinated fracture technology came in the 50's; advanced computer capabilities providing increased design sophistication and mechanization of fabrication processes were products of the 60's; newer ship types and missions and the development of higher strength materials are evident in the 70's; complete integration of all of the above technologies will be necessary to progress into the 80's.

"Ships are not designed for finite life, just for an indefinite one."[1]

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