Twenty Years of Research under the Ship Structure Committee

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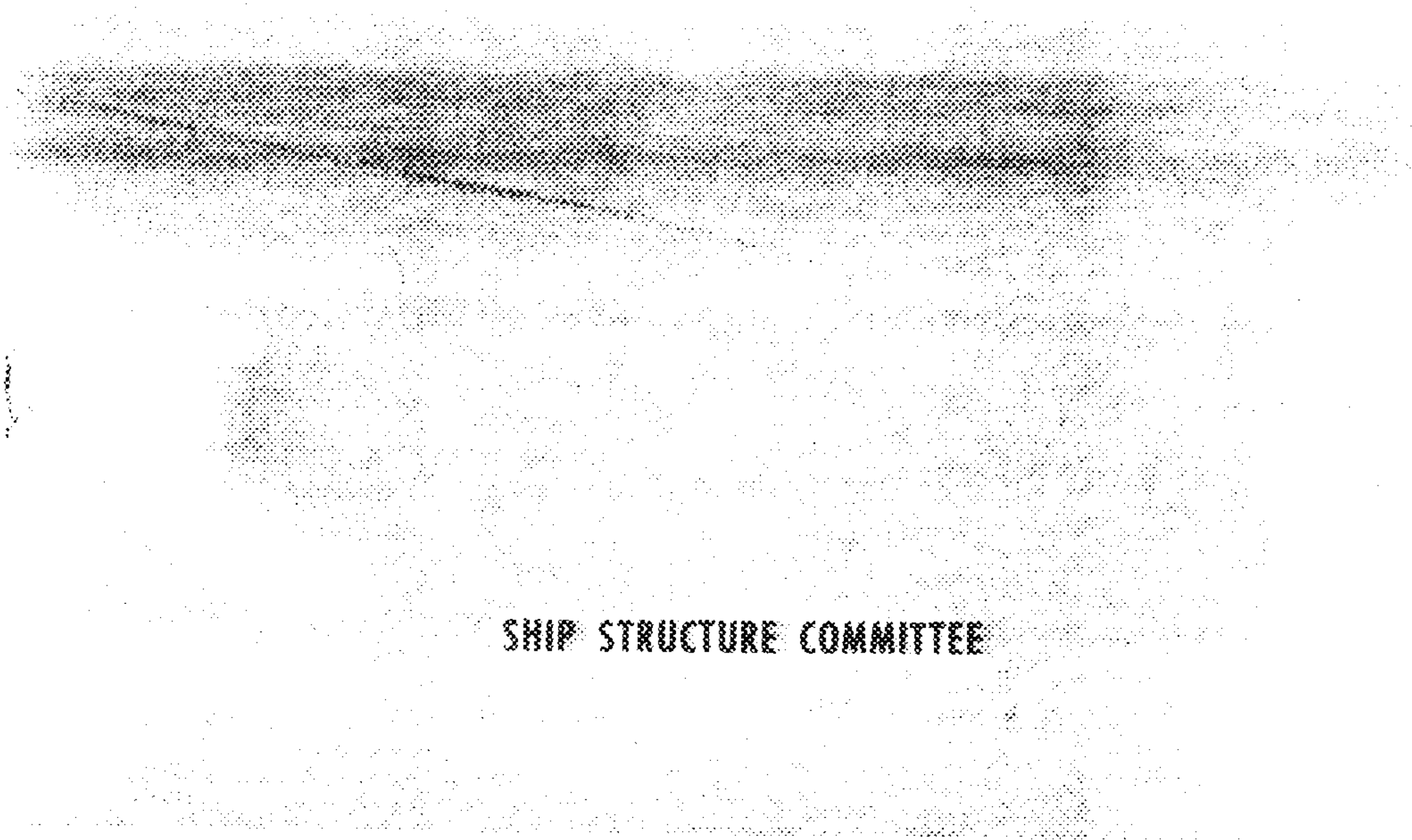

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ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U. S. COAST GUARD HEADQUARTERS
WASHINGTON, D. C. 20226

December 1967

Dear Sir:

The attached report "Twenty Years of Research Under the Ship Structure Committee" (SSC-182) summarizes the accomplishments in the series of technical reports that began with the publication of the Final Report of the Ship Structure Committee's predecessor, the Board to Investigate the Design and Methods of Construction of Welded Steel Merchant Vessels.

Comments on this report would be welcomed and should be addressed to the Secretary, Ship Structure Committee.

Sincerely yours,

John B. Oren
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-182

Special Report

TWENTY YEARS of RESEARCH UNDER the SHIP STRUCTURE COMMITTEE

by

CAPT S. R. Heller, Jr., USN
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Washington, D.C.
U. S. Coast Guard
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Twenty Years of Research Under the Ship Structure Committee[1]

By Capt. S. R. Heller, Jr., USN,[2] *Member,* A. R. Lytle,[3] *Visitor,* LCDR R. Nielsen, Jr., USCG,[4] *Member,* and John Vasta,[5] *Member*

The salient results of two decades of research into such broad areas as materials, physical and qualification tests, nondestructive testing of welds, stress distribution, data from ships in service, and bending moment determination by models are presented. The brittle fracture phenomenon is attacked from a number of fundamental views: variation of composition and microstructure, prior strain and thermal history, rate of loading, stress intensity and distribution, effect of flaws, and variation of test method. All these bits of research are shown to have contributed to the attainment of an engineering solution. Several of these areas are further discussed. Stress distributions at various geometrical discontinuities are reported as are those arising from temperature gradients. Stress intensities measured on ships in service are presented as are the long-term predictions from these measurements. The effect of mill practice on material performance is discussed. The current effort of developing generalizations from results of specific research is described. The trend of the future, the adaptation of computer to exploit generalizations for analysis of whole systems of structure, is set forth. Finally, a listing of nearly 200 reports is given along with information on how to obtain them from Federal repositories.

Introduction

THE Ship Structure Committee is a governmental activity whose mission for 20 years has been to discover how ship structures can be improved for greater safety and improved performance without adverse effect on economy. The impetus to the work was the wartime failures of many welded ships. In 1952, only six years after inception, it was possible to present a paper [1][6] before this Society recounting the accomplishments of the research effort sponsored by that committee and to state as one of the conclusions of work to date: "The excellent structural record of ships built since World War II has been the result of improvements in design, steel and fabrication, all of which have been aided by the research program of the Ship Structure Committee." Because of the natural skepticism of the research worker, the following was added to suggest the course of future research: "Since it is not known whether present requirements and practices are sufficient to prevent cracking, a large portion of the research program sponsored by the Ship Structure Committee will continue to be directed toward solution of the ship fracture problem. Once this problem is clearly solved, the research activity of

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[6] Numbers in brackets designate References at end of paper.

the Ship Structure Committee is expected to be directed toward improving the general structural effectiveness of the ship's hull and in reducing building and operating costs."

The purpose of the present paper is to recount the progress made since 1952 and to account for the six and a quarter million dollars spent in accomplishing it. The saving of just one ship would amortize the investment. There will be frequent reference throughout to Ship Structure Committee reports by the symbols (SSC-30) which are further identified in the Appendix. Only the highlights of these reports are included in this paper.

The Research Program

The priority element of the research program was the exploitation of the definite findings of earlier work which had shown that the unexpectedly poor structural performance of ships could, to a major extent, be corrected by change in the composition of steel and by design modifications of critical elements. Hence, the study of effects of material characteristics on performance and the exploration of stress-time history of ships in service received immediate attention. These were to be followed by the development of generalized theories or practices from which major improvements could be safely made.

This objective was approached along a broad front including examination of effects of variation of composition and microstructure on the behavior of steels under various loadings, the exploration of various testing methods, determination of distribution and levels of stresses in typical structures, and the effectiveness of methods of inspection for quality assurance. In addition, a major step was taken to assess the stress-time history of ships and an initial step in evaluating the benefits of a rational, as opposed to empirical, design of ship structure.

Materials

It was early recognized that brittle fracture, in addition to being influenced in specific cases by chemical and microstructural variations, was probably a phenomenon by itself conforming to laws that should have general applicability to all metals. A literature review (SSC-66) on the various modes of fracture contained the significant statement: "The literature on the general problem of fracture of metals is perhaps the most voluminous of any metallurgical subjects, and yet almost nothing is known about the fundamentals of metallic fracture. The particular type of fracture known as cleavage has been investigated to a small extent in polycrystalline metals of all crystal systems . . . . A search of the literature reveals almost no work on the cleavage of the body-centered lattice."

Although, as an immediate result of prior Ship Structure Committee research, information was available, and was used, to build ships that were relatively immune to gross brittle fracture, it was recognized generally that in no field did we know *why* the corrective or preventive measures were effective. Changes in steel composition, in design, and in fabricating practice had been introduced with very successful results. But the logical question could be asked, "In what way or to what factor were such improvements due?" The lack of understanding or even hypothesis to explain the phenomenon made it very difficult to extend the knowledge to other situations, other materials, or to be sure that the same result could not be achieved by other, perhaps lower costs, means. It was logical, therefore, that attempts to develop such understanding would be high on the priority for research.

There was clearly the possible effect of microstructure in the normal condition, the possible adverse effects that could be caused by fabrication and construction operations, the controls that could be directed at microstructure by steel production techniques (both mechanical as on rolling mill practice and chemical in material composition), and the effect of basic mechanical properties on the ease of initiating, propagating, and arresting fractures.

One strong recommendation of a comprehensive planning report (SSC-70) on future research in the materials for cargo ship hulls was "although some research could be placed in the basic area of high purity metals and single crystal behavior, the main emphasis should be on exploring the effect of impurities, microstructure and macrostructure relationships, mechanics of crack initiation and propagation and study of fracture surfaces." This report has guided the basic material program under the Ship Structure Committee since then.

Mechanical Metallurgy

A number of projects in this field have been supported by SSC—several of many years' duration. In carrying out these studies it has been necessary for the investigators to improvise new or special experimental techniques or apparatus, prepare unusual specimen shapes or sizes, propose, check, and modify alternate assumptions or hypotheses, perhaps start on a new track or introduce major changes in specific short range experimentations, and the like. Actually this mode of operation very successfully met one of the primary Ship Structure Committee aims: initiation and catalysis of research in brittle fracture with the expectation that the interest thus generated would encourage others to enter the field and the problems, both general and specific, would be answered more surely and satisfactorily. The world-wide effort on brittle fracture phenomena is a pleasing measure of the success of this effort.

Metallurgical Structure. One of the initial efforts (SSC-94) to approach the problem of relation between microstructure and properties concentrated on the mechanical behavior of high purity and single crystals of iron. This work focused interest on the possible adverse effect both from the presence of iron carbide in the matrix and of high temperature grain development as evidenced by veining. The principal import of this preliminary study of relatively pure materials, however, was to pinpoint the necessity for much more extensive studies of the relationship between microstructure in its broadest meaning and brittle fracture performance. The extended project on Metallurgical Structure at MIT was concerned with this relationship.

It was clear in early tests (SSC-102) that our ability to interpret microstructure as related to brittle behavior was quite inadequate, and that significant results could be expected from more complete knowledge of the slip characteristics of ferrite. Such elements as twinning, grain boundaries, and inclusions seemed to be relatively unimportant. To assure brittleness, where the fracture strength was dominant, most of this testing was carried out at progressively lower temperatures down to −195 deg C (−320 deg F) with coordinated metallographic examination and observation of such correlated phenomena as microcrack occurrence. Among the significant observations in this study was that fracture was always preceded by *gross*, but highly local, yielding in association with microcracks. These cracks, by inducing cleavage in adjacent areas, develop rapidly into propagating large-scale cracks. Since they served as crack initiation flaws, an understanding of their origin was highly desirable.

The results of the extended program (SSC-161) were very clear in showing that cementite at the grain boundaries readily cracks under the early plastic deformation of ferrite and thus serves as an ideal (extreme acuity) crack for initiating ferrite cracking. Whether the crack then develops into a micro- or macrocrack depends on other conditions such as temperature, loading conditions, and stress level, which affect the ability of ferrite to deform plastically. These findings can be used to explain some of the means that have been found helpful in improving brittle fracture performance of steels. For instance, increased manganese content and fast cooling from hot working temperatures have been effective in lowering the transition temperature. It is now clear (SSC-161) that these benefits result from finer pearlite agglomerates, lessened tendency of carbide to form at the grain boundaries, and a greater abundance of grain boundaries.

An attempt was made to bridge the gap between explanation of the condition under which microcracks of one grain diameter were formed and explanations of brittle cracks in thick plates. As a result of this study (SSC-171), a hypothesis has been suggested that, given data on grain size, the critical initiation stress (at which the yield stress approaches fracture stress), and the temperature at which the yield stress is one-fourth of the critical initiation stress, the suitability of a steel for safe design against brittle fracture can be evaluated. It is recognized that this is only a first approximation and that the underlying assumptions will have to be greatly refined. It, however, is an example of the type of philosophy that could contribute importantly to the eventual understanding of brittle fracture.

Prestrain and Aging Effects. Another approach to brittle fracture was used in an extended research project at Brown University. Here, the definition of the metallurgical or other environment under which a normal steel would fail in a brittle manner under *static* rather than dynamic conditions was sought to simulate service experience, wherein fractures occurred at low loads and with no dynamic initiation force. The emphasis was on the initiation phase of fracture.

Early tests on specimens of moderate size confirmed that steel, in its normal condition, retained sufficient ductility under severe testing conditions (excluding high loading rate or very low temperatures) to fracture ductility at yield stress. Thus, it was postulated that some phenomenon must adversely affect the metal or "exhaust" its ductility, in the vicinity of the point of crack initiation, so that it became prone to elastic (nonplastic) fracture at low loads.

The first confirmation of this postulate came from notched 10-in. wide plates, compressed plastically by appreciable amounts, which failed in a brittle manner under normal tension at stresses as low as one-third yield. This was the first laboratory demonstration of *low stress fractures of unwelded plates* (SSC-116).

There followed an extended study to determine the criticality of degree of compression prestraining, the effect of temperature of straining and of testing, the part played by notches, and effect of

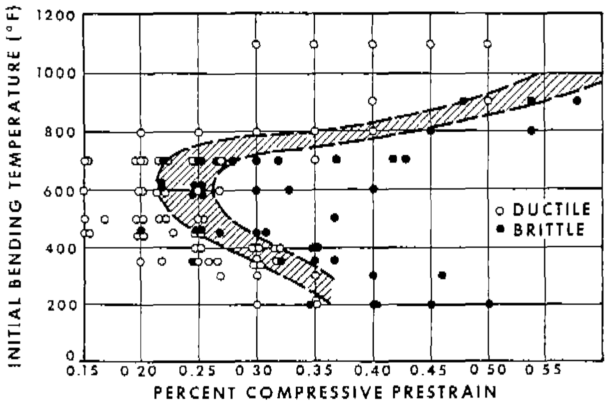


Fig. 1 Reversed bend tests of bars prestrained at various temperatures and tested at −16 deg F

aging on several grades of ship steel. The results of these tests (SSC-162) demonstrated that the *total strain and temperature histories* of a steel through production, construction, fabrication, and service have a vital influence on the subsequent ductile or brittle performance of the steel. The essential results of this project are illustrated in Fig. 1 in which it is shown that, where deformation occurs at temperatures below 200 deg F or above 900 deg F, this steel can withstand appreciable compressive deformation without severe adverse effect. In the intermediate temperature range of 400 to 700 deg F, however, the steel is quite adversely affected from the standpoint of tendency to brittle performance. The effect may be due to aging, straining, or a combination thereof.

The special significance of these results relates to the multiple warm straining events caused by normal welding. A particularly adverse response of a steel, combined with prior or subsequent damage, could readily account for low stress failure of such a structure. The work, therefore, has real pertinence to the practical problem of fracture.

Local Strain Measurement. Battelle Memorial Institute studied the distribution and growth of plastic straining around a sharp notch prior to and after crack initiation in hopes of following its progress ahead of and alongside a propagating crack. An experimental method of developing dislocations to a visible scale was found adaptable to a silicon-iron alloy which behaved plastically somewhat similarly to carbon steel. In these tests, it was confirmed that plastic flow developed first at a finite distance from the notch end—an observation made by others also—and that this point served as a hinge around which plastic strain progressed. Further work was necessary to develop the procedure for application to thicker plate (0.20 in), but this was accomplished. By sectioning and etching progressive surfaces below the exposed surface, it was shown (SSC-165) that initial plastic flow (initial yielding) took the form of a plastic hinge around the notch base, but, as strain increased, the yielding projected in front of and in the plane of the crack. It thus develops across the specimen in two shear planes at 45 deg to the surface, *forming an X pattern through the thickness of the specimen.* This planar yielding is very reminiscent of the cup-and-cone fracture of ductile material and undoubtedly is a precursor to ultimate ductile fracture. Fig. 2 illustrates the development of the plastic zone as brought out by the special etching technique.

The excellent experimental delineation of the onset and distribution of strain around and progressing from a notch during plastic tensile loading provided a logical base for applying a mathematical model previously developed (Dugdale-Muschelishvili) which simulates the local stress-strain environment observed in these tests. Current work has shown a promising qualitative relationship between experimental and calculated values. Much more work will be needed to take into consideration such effects as work hardening which are neglected in the calculation but appear in the experimental specimens. Because this approach seems to offer a possible step toward correlating the experimental and analytical approach to brittle fracture design, the work is being continued by progressively introducing environments less conducive to plastic flow and associating the findings of this work with the needs of safe structural design.

Chemical and Physical Metallurgy

Although one of the earliest changes implemented in the effort to prevent brittle fracture was the adoption of new specifications for the steels to be used, questions were raised:

(*a*) Could a similar or greater improvement be accomplished at lower cost?

(*b*) How can the gains made be protected from erosion by lack of knowledge or by technological changes in the industry?

Since "material" was clearly one of the keystones to satisfactory performance of a ship structure, much effort was directed toward answers to these and other problems.

Chemical Composition. Throughout this work it was hoped that an adequately tough semikilled manganese steel could be developed that could become commercially successful in shipbuilding. Much work (SSC-91,-99) on laboratory-produced heats was devoted to the variations in suitable deoxidizing practice, manganese and carbon

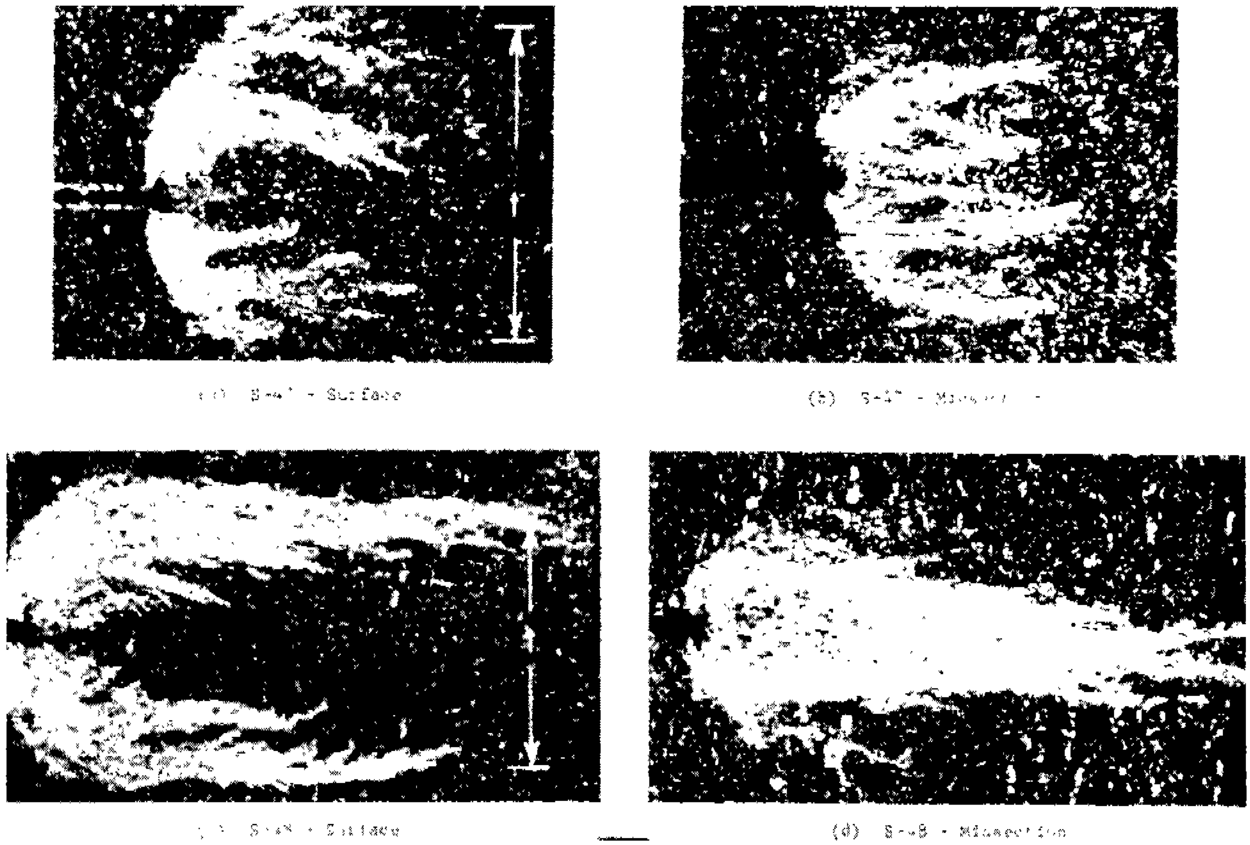


Fig. 2 Plastic zones revealed by etching the surface and midsection of notched coupons

contents, and testing methods. The critical importance of manganese and the manganese-carbon ratio as a means of developing the desired strength level with good toughness was confirmed. One of the principal conclusions of this extended study was that further important gains in notch toughness with no loss in strength would be realized by raising the manganese by 0.20 percent and lowering the carbon content to maintain strength level. As a result of these studies, confirmed by other work on larger size heats, the ABS specification for Class B steels was modified in 1956 to require higher manganese content.

Although this work showed that semikilled steels of the new composition should be satisfactory at least up to 1-in thick, it was questionable whether these favorable properties could be maintained in thickness over 1 in, where killed steel was still specified. This phase of the study (SSC-144) culminated in testing of seven commercial semikilled steels rolled to 1 to 1½ in thickness. The results were inconclusive, so it was not possible to establish the suitability of these experimental steels as a substitute for ABS Class C killed steel. Their adoption, therefore, could not be recommended.

In 1962, a survey (SSC-142) was completed to determine to what extent the changes in the steel specifications made in 1948 and 1956 had affected the average steel properties. Samples from 183 steel plates of both grades were evaluated primarily for their Charpy-V transition temperature, although some attempt was made to observe grain size, composition, and thickness effects. The principal conclusion was that, as a result of the 1948 ABS Rules subsequently revised by 1956 modifications, the notch toughness of ship plate was considerably better than that of wartime steels. The temperatures for the 15 ft-lb energy were below 10 deg F, a good margin for general commercial service. The earlier recommendations, therefore, seem to have been well founded.

Mill Practice. One of the concerns of the program has been to determine how consistent was the notch toughness of commercial ship steels and how such properties were affected by mill practice variables such as location in ingot or slab, finishing temperature, cooling practice, and chemical composition variation within specification. As a start, extensive examination and testing was conducted on large plate samples of 105 Grade B and C steels from five steel mills. This study

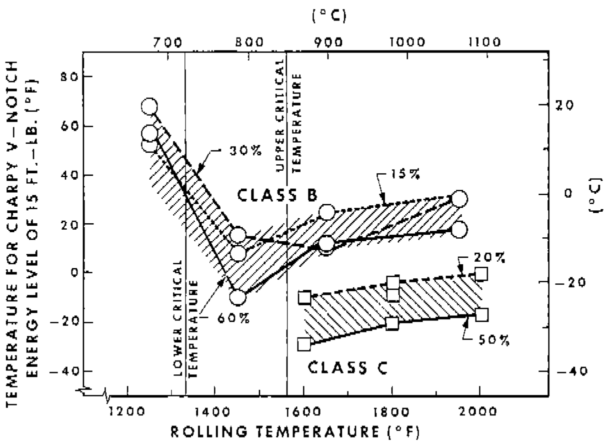


Fig. 3 Dependence of 15 ft/lb Charpy V-notch transition temperature on rolling history

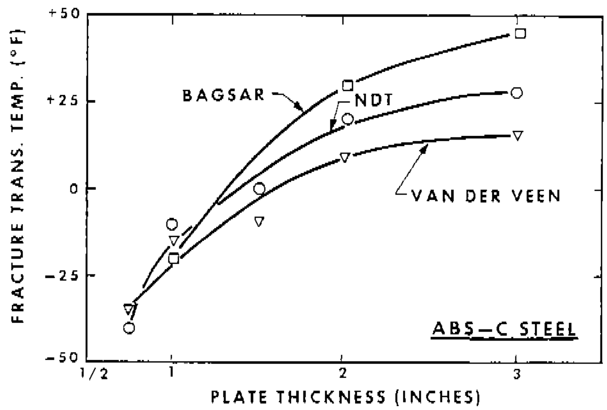


Fig. 4 Variation of transition temperature with plate thickness

(SSC-141) embraced information on manufacturing and processing history, composition, heat number, ingot location, tensile properties, Charpy V-notch transition temperatures, nil-ductility temperature, and metallography. The general result was *confidence* in the close control the manufacturers had on the important variables as related to toughness. The only significant variations within ingots occurred in the semikilled B steels; heats of killed Grade C steel were relatively consistent ingot to ingot. This may be a supplementary appraisal of general greater acceptability of Grade C steel over Grade B for more critical applications and greater thickness.

There had been a general indication that variations in mill practice, if properly controlled, might be used to upgrade quality with minimum cost and no change in specifications. This possibility sparked another program which concentrated on the rolling history of ship steel plates as related to their toughness. In essence, this was a study of the applicability of controlled rolling to ship plate. Work on two special heats confirmed the significant advantage of controlled rolling in which a major amount of the final rolling was at temperatures between 900 deg C (1650 deg F) and 720 deg C (1330 deg F).

The many factors influenced by rolling practice were extensively studied experimentally (SSC-168) using commercial ship steels. Studies included ferrite as well as pearlite grain sizes, inclusion count and shape, tensile testing over the full temperature ranges from room temperature to −243 deg C (−400 deg F), Charpy V-notch testing for 15 ft-lb energy level and 50 percent crystalline fracture appearance, and metallographic examination. Fig. 3 shows some of the relationships developed in this study. The general results were confirmation and more specific definition of the lineal lowering of transition temperature with grain size reduction and the suggestion of various modifications of rolling practice to accomplish this. It is recognized, however, that some of the modifications might be impractical from the rolling mill standpoint. The work did clearly confirm what had been suggested in prior projects: *mill rolling practice can be a major factor in determining the toughness of ship plate.*

Thick Plates. Another facet of the ship steel problem is determining the means of selecting and specifying steels of heavy section (2 to 4 in thick) for a suitable combination of strength, weldability, and resistance to brittle fracture. A program to provide guidelines in this area was carried out at Lehigh University (SSC-175).

One of the principal questions to be answered was how to measure the sensitivity of thick plates to brittle fracture since there was generally a metallurgical effect due to composition and microstructure variation as well as a geometric effect (less notch toughness is normally associated with increased thickness). Although several test methods were reasonably suitable for this study, it was recommended that the van der Veen test, a notched slow bend test of full thickness plate for testing over a range of temperatures, be used. Fig. 4 presents some of the data on which this recommendation was based. To check the suitability of this test method for evaluating thick plate, tests were made of 1-in, 2-in, and 4-in thick plates of a commercial quenched-and-tempered, carbon-manganese steel of Grade A 537. The favorable properties of this steel in the various thicknesses not only confirmed the value of the test method for evaluating thick plates, but also demonstrated that, at least, this grade of heat-treated carbon-manganese steel in thicknesses of 2 to 4 in was equivalent to or better than ABS C steel of 1-in thickness. This project, therefore, had the fringe benefit of confirming the value of heat-treated carbon steels as possible lower cost substitutes for the high strength, low alloy steels which are being actively considered and applied to shipbuilding.

Present Authors' Evaluation

It now seems possible to draw a conclusion that was impossible within the scope of the individual studies. By intent, each was limited to studying the effects of certain factors on propensity to brittle fracture. Indeed, under certain conditions, each factor studied was, in itself, critical. It should be noted, however, that, for the factor to become critical, an element of environment involved was, to some extent, *extreme*. That is, the temperature was very low, the rate of loading was of an impact nature, or the degree or type of mechanical damage or flaw was abnormal.

It will be recalled that most ship fractures were characterized by spontaneity of failure under normal environment; i.e., no clearly defined external impact, no seriously abnormal microstructure, no excessively low temperature, or no unusual fabricating damage. Therefore, in view of the many laboratory tests, it is an inescapable conclusion that *brittle fracture as experienced in practice must involve more than one cause.* Not only, for instance, did the material have improper microstructure and chemical composition for best performance, but it had been damaged by subsequent cold straining or aging, or was built into a complex or incompatible geometry where minor cracks and residual stress associated with some types of welding became of critical significance. Each of these effects is *additive* in reducing the ability of the structure to absorb energy by yielding and, hence, in increasing the probability of brittle fracture. In this sense, the Ship Structure Committee research on materials had been instrumental in solving the overall problem. The effects of individual factors have been isolated, so that their parts could be clearly recognized and studied separately or in combination as seemed best.

Great strides have been taken. For ship steel, chemical composition and microstructure are controlled through specifications of "fine grain practice," carbon-manganese relationships, and the like. Great improvement is recognized in quenched and tempered treatments even for carbon steels. Welding procedures have been developed to minimize greatly weld underbead cracking; fabricators handle the steels more knowledgeably. Structures are designed to ease the transfer or flow of stress by avoiding stress concentrations and, thereby, potential development of critical cracks. Application of this bank of knowledge and experience has wrought the situation where no ship built within the last 15 years has developed major brittle fracture. Such fractures as have occurred have been the result of gross violation of recognized and approved design or construction procedures.

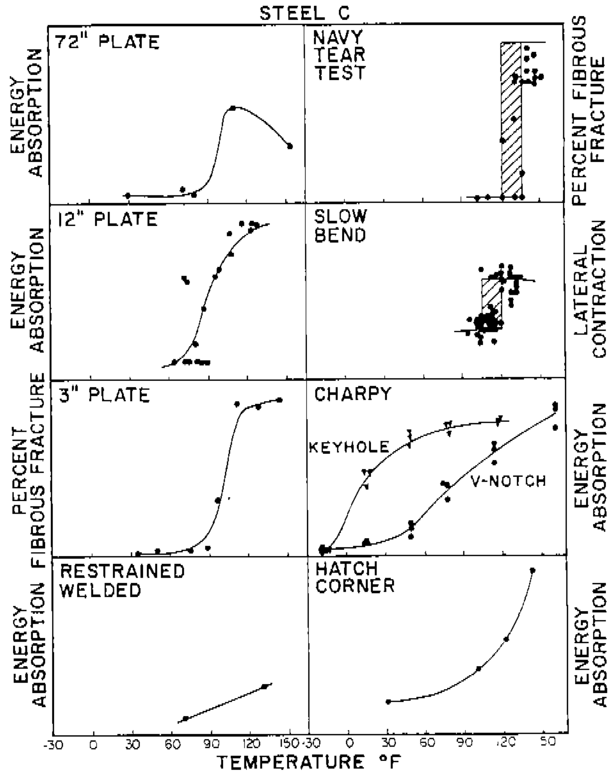


Fig. 5 Correlation of transition temperature with energy absorption and fracture appearance

Physical and Qualification Tests

Transition Temperature

An extensive testing program had been underway since 1944. This program included a variety of different sizes of specimens ranging from standard Charpy V-notch and keyhole impact specimens to full-scale hatch corner tests. Slow bend, tear, and energy absorption tests were included.

Inter-Laboratory Correlation. Pennsylvania State College (now University) held the contract to correlate the results of this entire "material" research program. In a memorable interpretive report (SSC-30), this mammoth undertaking was attempted. In consideration of the reams of test data accumulated for a wide variety of specimens tested at vastly varying loadings in several

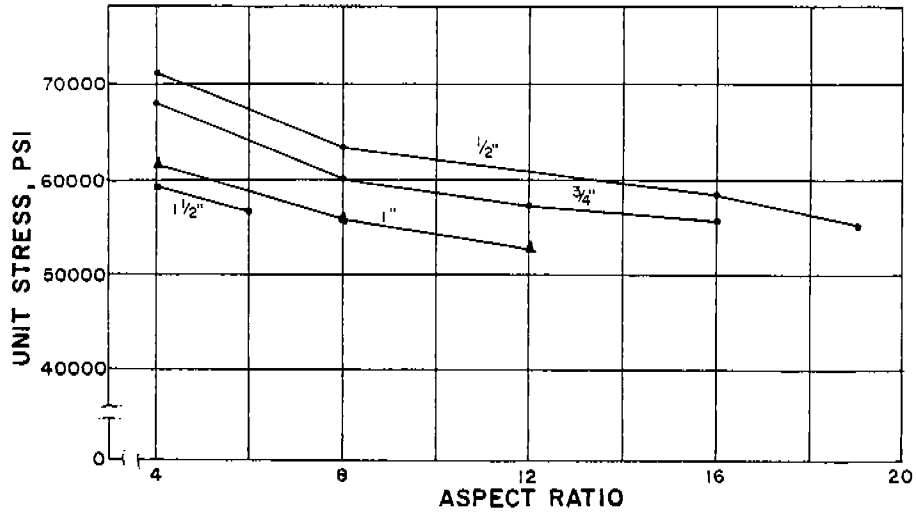


Fig. 6 Variation of unit stress at maximum load with thickness and aspect ratio (100 percent shear failures)

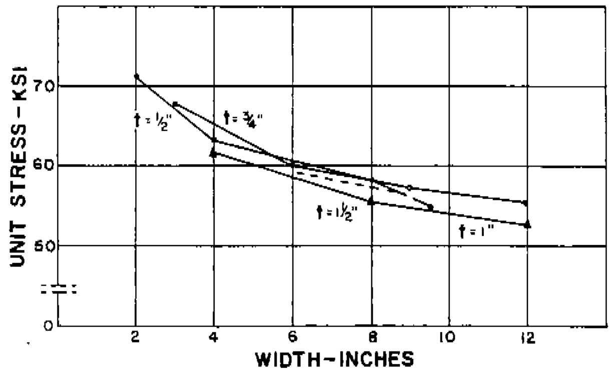


Fig. 7 Variation of unit stress at maximum load with width and thickness (100 percent shear failures)

laboratories and the multitude of criteria for determining the ductile-brittle transition of ship steel, it is little short of miraculous that any consistent correlation was obtained. Fig. 5, typical of their findings, shows that essentially complete agreement of transition temperature data existed for both the large- and small-scale tests. It will be noted that the two principal criteria for determining the ductile-brittle transition as used in Fig. 5 are energy absorption and fracture appearance.

Geometrical and Metallurgical Effects. An attempt was made to separate the geometrical and metallurgical effects on transition temperature. To do this, a family of internally notched specimens geometrically similar (same "aspect ratio"; i.e., ratio of width to thickness) was tested (SSC-47). It was reasoned that differences arising in geometrically similar specimens (same aspect ratio) could be attributed to metallurgical causes alone. Similarly it was reasoned that, for a given thickness, chemical and metallurgical properties would remain constant, so that any variation could be attributed to geometry in the form of aspect ratio (in the case at hand, width).

Fig. 6 shows the gradual decline in strength with increasing width for each thickness tested. This effect was considered to be *geometrical*. By contrast, the differences in strength for different thicknesses at the same aspect ratio were considered to be *metallurgical*.

In Fig. 7, replot of the foregoing data against gross width instead of aspect ratio, the curves for the four thicknesses are very nearly collinear. It might be concluded that strength was affected only by width and not at all by thickness. Further study revealed that such a conclusion would be erroneous. When plates geometrically similar were compared at the same aspect ratio, the thicker plate had a lower strength. But it was both wider and thicker than the thinner plate. When its width was decreased to match that of the thinner plate, its strength was increased. These opposing effects very nearly canceled each other when the comparison was made at equal width. A similar effect was noted for energy absorption in these tests.

Data regarding transition temperature are shown in Fig. 8. It will be noted that thicker plates had higher transition temperatures than thinner plates regardless of whether width or aspect ratio was considered constant. Although there was a moderate rise of transition temperature with width, the rise in transition temperature with thickness was so great that no width effect

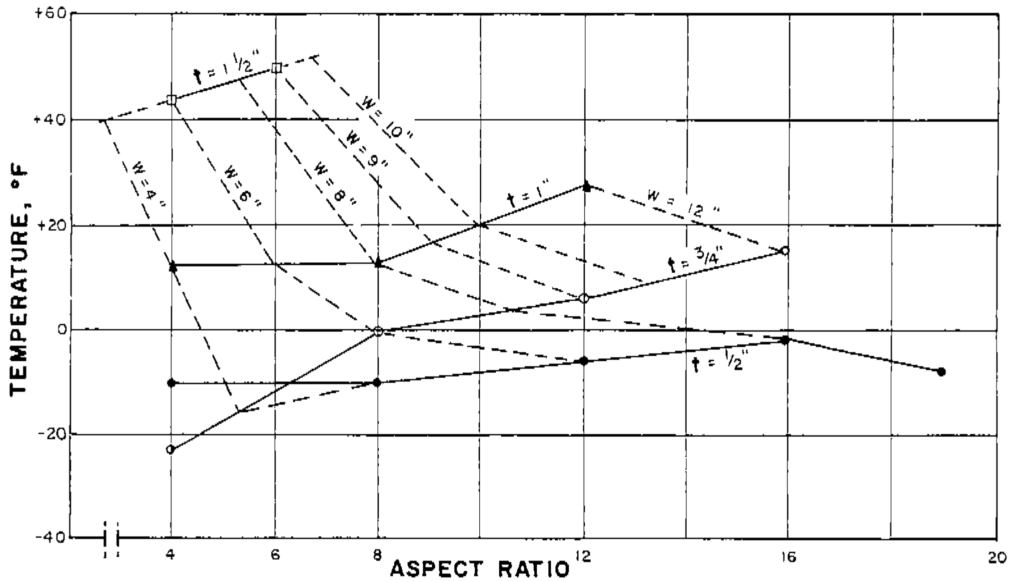


Fig. 8 Variation of transition temperature with aspect ratio, width, and thickness (100 percent shear failures)

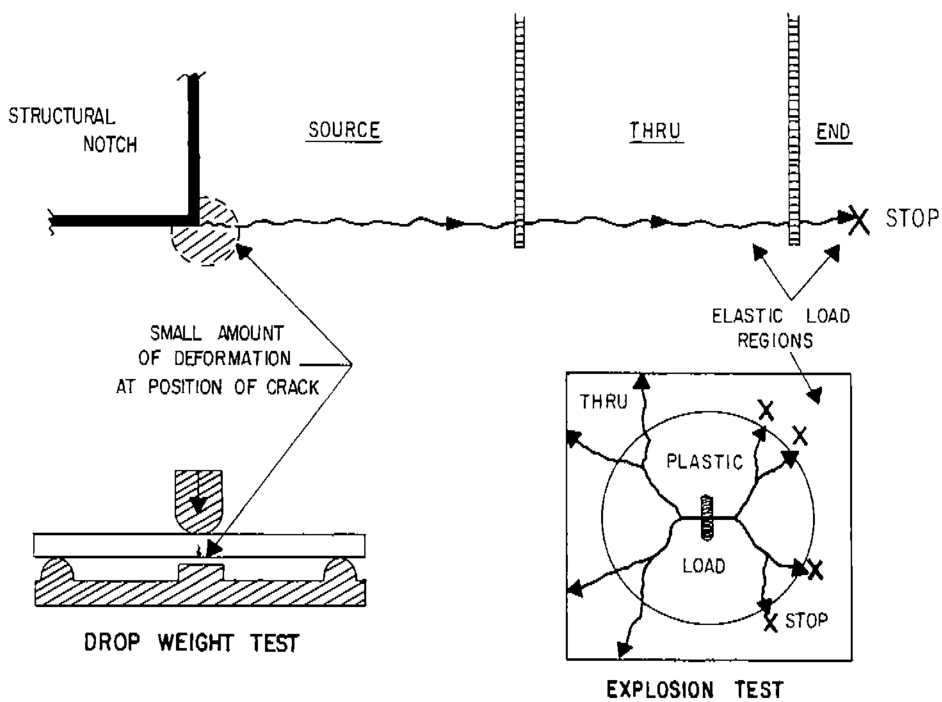


Fig. 9 Correspondence of drop-weight and explosion-bulge tests to shipboard conditions

could offset it. From this (SSC-47), it was concluded that the effect of thickness on transition temperature was almost wholly metallurgical.

Correlation of Laboratory Tests with Ship Fractures. Despite the correlation achieved (SSC-30), additional testing was conducted at the Naval Research Laboratory (SSC-77) for a similar purpose. Two "crack-starter" tests were used:

1. *Drop-Weight Test* to establish the temperature at which the steel loses its ability to develop more than a minute amount of deformation in the presence of a crack-like notch.

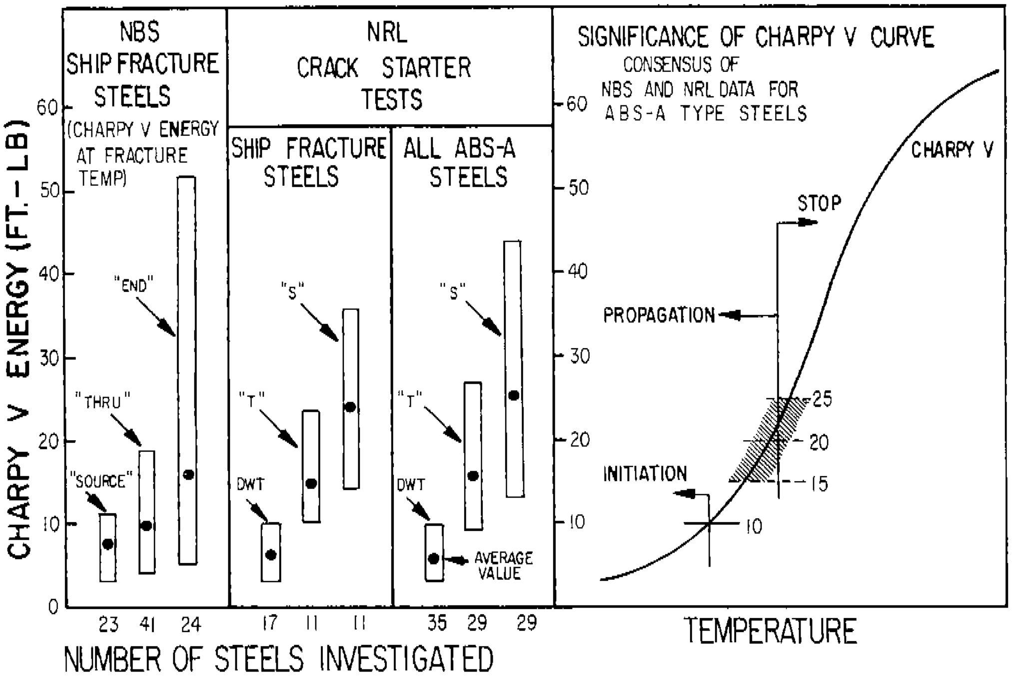


Fig. 10 Correspondence of NRL crack-starter test data to NBS ship fracture data

2. *Explosion Bulge Test* to establish the temperature range of transition from easy to difficult propagation of fractures.

Fig. 9 shows the correspondence of the two tests to shipboard conditions. Thus, the drop-weight test corresponded to the point of initiation of a crack. The edge regions of the explosion bulge test plates were supported by the die and, therefore, did not bulge (develop plastic deformation) as did the central region. Thus, the edge regions provided a critical evaluation for the fracture resistance of plates that were elastically loaded.

Fig. 10 summarizes the correspondence of the ship fracture test data from the National Bureau of Standards and the crack-starter test data from the Naval Research Laboratory. The NBS data showed that the "source" plates (samples of plates at which ship fractures started) had Charpy V-notch energy values at the fracture initiation temperatures of 11.4 ft-lb maximum and 7.4 ft-lb average. By comparison, the NRL drop-weight test data were in complete agreement that the temperature corresponding to Charpy V-notch energy of 10 ft-lb was the critical temperature for fracture initiation of ABS World War II steels. Similarly, in the NRL explosion bulge test, steels having a range of Charpy V-notch energies of 13 to 27 ft-lb demonstrated "T" ("through" or complete failure) and "S" ("stop" or partial failure) conditions in the edge regions, respectively. This meant that, if a plate had an impact energy in excess of 27 ft-lb, propagation was prevented and, if it had an impact energy of less than 13 ft-lb, propagation was permitted. This was in excellent agreement with the NBS finding that 19 ft-lb was the highest Charpy-V notch energy for a "through" plate. Thus, the NRL crack-starter tests correlated very well with service experience and bolstered the NBS findings regarding the significance of Charpy test data.

Fig. 11 summarizes the results of earlier wide plate and tear tests on several of the project steels with the NRL explosion bulge tests as related to Charpy V-notch test data. It can be seen that the explosion test fracture transitions generally occurred at a temperature range which overlapped the range for the wide plate tests. On the contrary, the tear test temperature was generally higher, and hence more conservative, than the other transition temperatures.

Weldments. In addition to performing crack-starter tests on ship fracture and project steels, the Naval Research Laboratory (SSC-78) conducted similar tests on ABS-B prime plate and weldments. The relative fracture resistance of prime and shot-peened plates was determined by the drop-weight test. The performance of the weldments was determined by the explosion bulge test.

Fig. 12 shows the embrittling effect of shot peening. Whereas prime ABS-B steel plate had a nil-ductility transition temperature of 20 deg F,

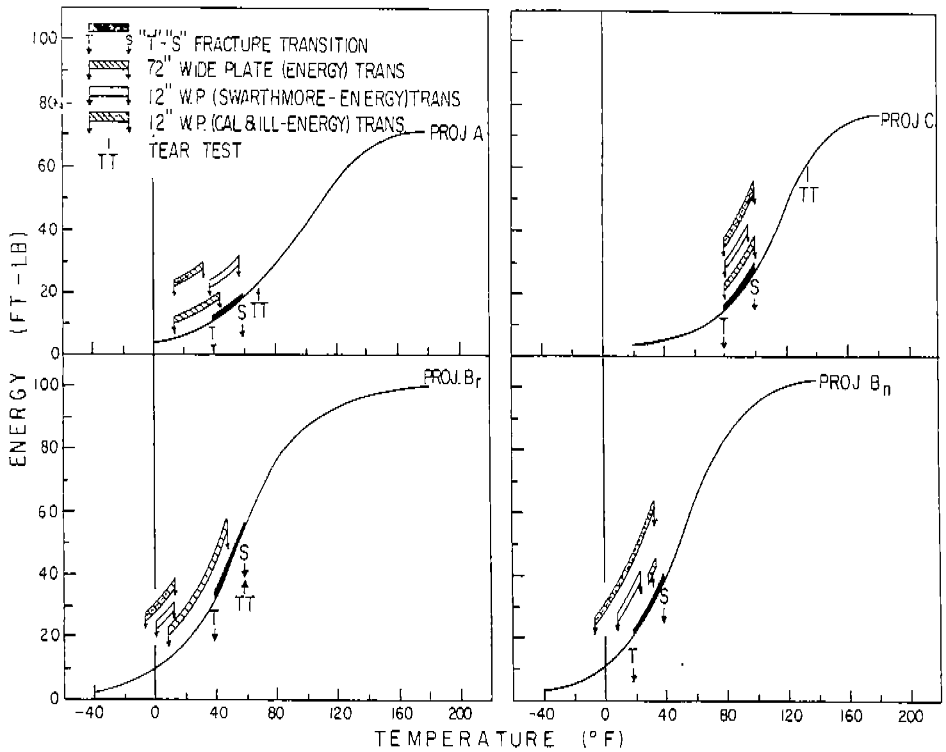


Fig. 11 Relationships of explosion, wide plate, and tear test fracture transitions to Charpy V energy transitions

shot peening raised this critical temperature to 40 deg F. This indicated the adverse effect of shot peening on the properties of this specific material with consequent degradation of the resistance to brittle fracture. A similar effect of peening the last pass of an ABS-B steel weldment had previously been noted. Also shown in Fig. 12 is the Charpy V-notch energy of 10 ft-lb corresponding to the nil-ductility transition temperature of the prime plate. This matched the relationship previously determined for ABS World War II steels.

Drop-weight tests of specimens cut from the edge regions of the explosion bulge test specimens and which had *arc strikes* applied indicated that the critical temperature was 20 deg F. This matched previous experience with National Bureau of Standards tests with ship fracture plates and coincided with actual service experience. *The size of these defects was not an index of severity; the acuity of the defects was.*

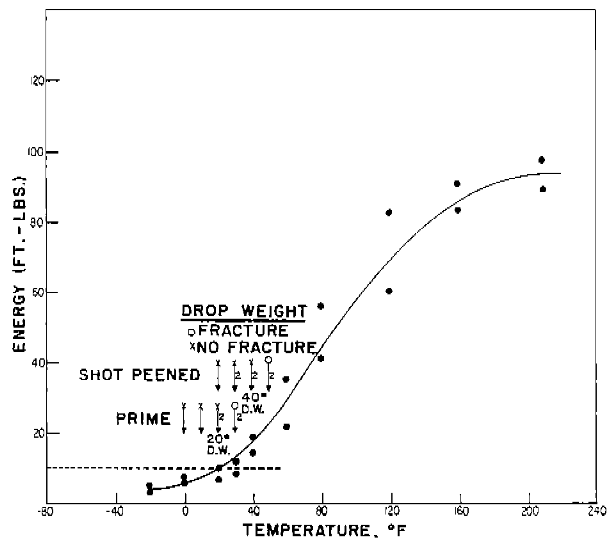


Fig. 12 Embrittling effect of shot peening on ABS-B steel

Fig. 13 shows the relative performance of prime ABS-B plate and full-penetration (double vee) butt weldments made with E6010 (cellulosic type) and G180 (low hydrogen) electrodes. Note the extremely poor performance of one G180 weldment marked "arc strike." This is another excellent example of the critical nature of minute, accidental imperfections when present on steel which is susceptible to brittle fracture at service temperatures. The performance of this specimen was in sharp contrast to the other G180 specimens at the same temperature. The presence of such accidental defects can vitiate completely the benefits expected from high quality welds.

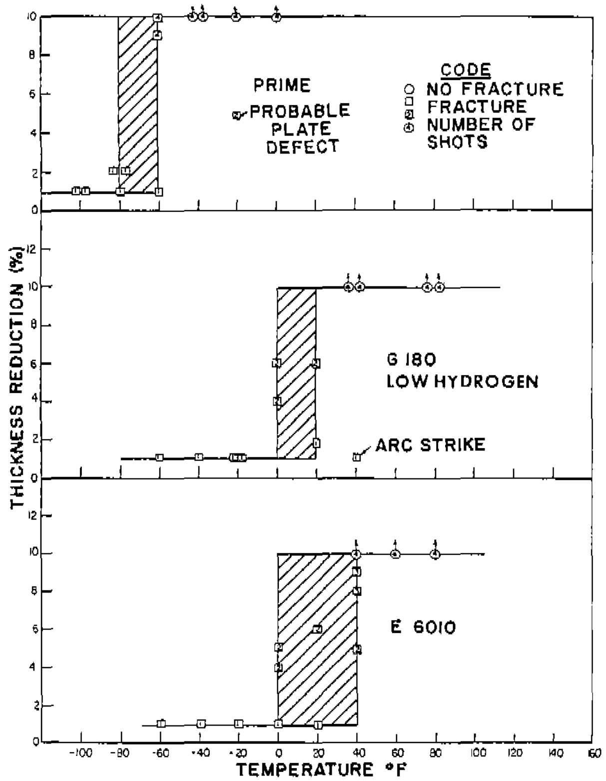


Fig. 13 Explosion bulge test ductility transitions of ABS-B steel prime plates and weldments

Although the performance of the low hydrogen and cellulosic electrodes appeared nearly the same (with a slight edge for the low hydrogen), due consideration must be taken of the fact that these weldments were prepared under laboratory conditions. Thus, weldments prepared under nearly optimum conditions may be the same. Weldments prepared in the field, where conditions are far from optimum, will surely benefit from the known effectiveness of low hydrogen electrodes in mitigating fissuring and other crack-like defects.

Fabrication Effects

In addition to the "basic material" investigations just described, a large, and seemingly unrelated, project with the general title "Cracking of Simple Structural Geometries" (SSC-79) was conducted at Swarthmore College. The overall objective was to obtain a better understanding of the effect on the fracture of steel plates of geometrical conditions introduced by fabrication procedures. Edge notching, plate edge preparation, and types of fasteners other than welding were among the diverse factors investigated.

Edge Notching. The effect of edge notching was studied from three different aspects: maximum load sustained, energy absorption, and transition temperature. The maximum load sustained increased with lessening of initial notch acuity for centrally located edge notches and reached a maximum for the semicircular shape. Similarly, there was slight improvement in maximum load-carrying capacity when one-half the reentrant profiles were separated from each other (reduced width specimens). Energy absorption generally matched maximum load-carrying capability except that notch separation had a more pronounced effect. In contrast, the transition temperatures were essentially the same for all specimens except those with semicircular notches which were about 20 deg F lower (about the same as for an *unnotched* specimen).

It was concluded (SSC-79) that:

(*a*) The acuity of the visible crack controlled the action of the specimen *rather than the initial notch geometry.*

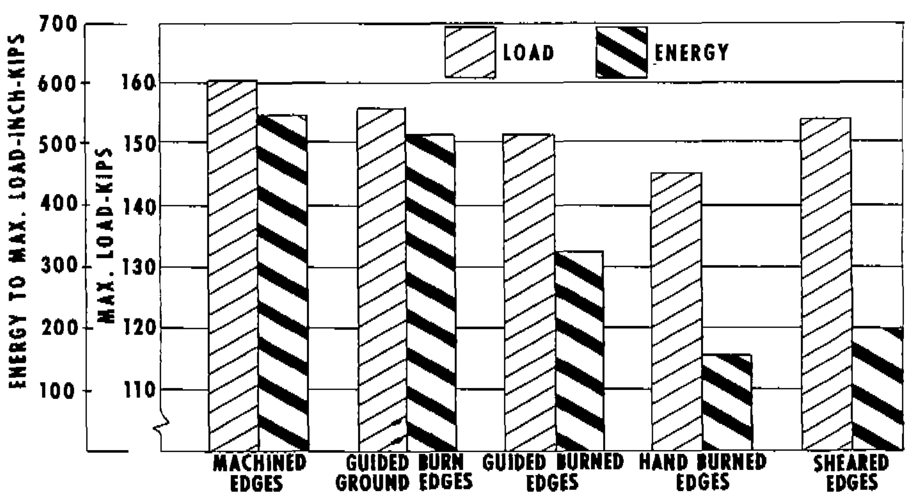


Fig. 14 Relative low temperature performance of various edge preparations

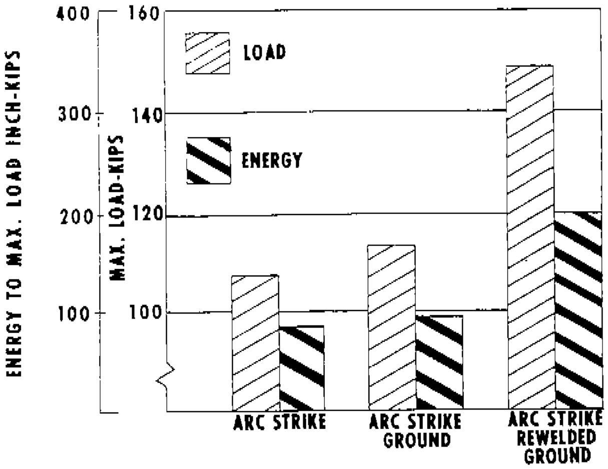


Fig. 15 Relative low temperature performance of arc strike repairs

(*b*) The improved performance of the separated notches is attributable to the formation of *two* plastic zones.

(*c*) The superior performance of the semicircular geometry is attributable to the *larger* plastic zone.

(*d*) Any notching is deleterious, but curved geometries are vastly superior to sharp ones.

Edge Preparation. Methods studied included machine planing, shearing, hand burning, machine burning, and machine burning followed by light grinding. Because edge preparation may introduce heat effects or cold working and edge notches may accompany either, machine planing was used as the standard for comparison since this operation minimizes the edge effects. At room temperature, the method of edge preparation was found to be of little significance. At low temperature, however, the relative performance is shown in Fig. 14. In addition to deliberate edge preparation, the effects of inadvertent edge defects—*arc strikes*—were also studied. The relative low temperature performance of uncorrected and repaired arc strikes is shown in Fig. 15.

The effect of edge preparation is, of course, manifest only when the plate edge is exposed such as for sheer strakes, fashion plates, and flanges of built-up members. But here the message is clear: The exposed edge should be as *smooth* as possible and *free from arc strikes.*

Fastening Methods. Types of fastening other than welding involve operations that can be expected to have some effect on the structural ability of the base material. These types of fastening may involve combinations of drilling, punching, and reaming, followed by riveting. In addition, there are patented processes involving automatic welding and explosive driving of studs. Fig. 16 shows the comparative performance of these fastening methods at low temperatures. The deleterious effects of cold working associated with punching were not offset by either reaming or riveting. The cold working effects of the explosive driving of studs ("Ramset") were similar.

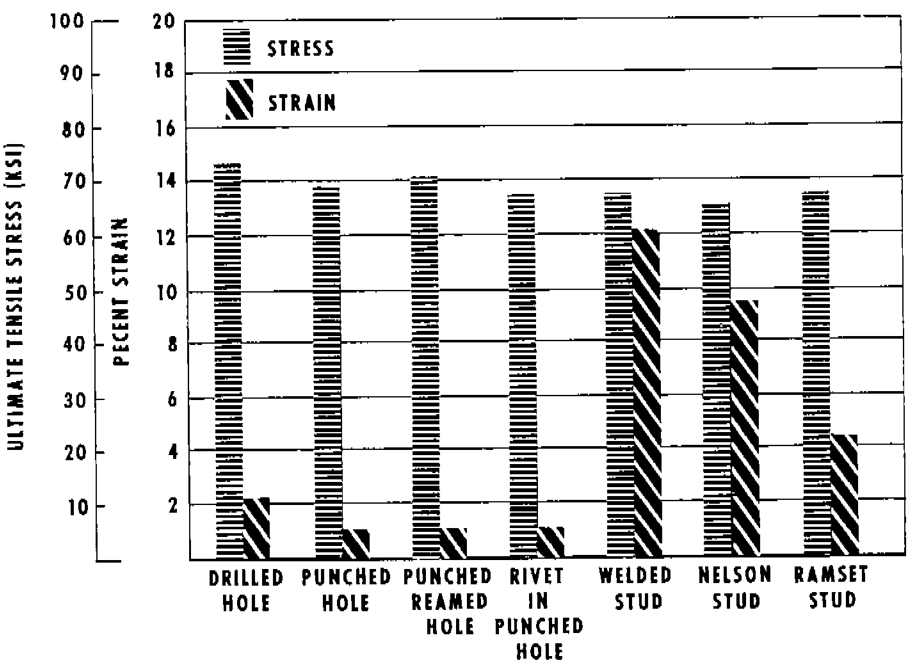


Fig. 16 Relative low temperature performance of various fastenings

Crack Arrestors. The extensive research on the brittle fracture problem had demonstrated that proper consideration for materials, geometry, and fabrication techniques could *reduce* the probability of brittle fracture. Nevertheless, a complete and thorough understanding of fracture mechanics had not yet become available, so welded ships still included riveted crack arrestors in areas where advancing brittle fractures were to be stopped. Although these riveted crack arrestors had proven to be effective in preventing catastrophic failures, their elimination was deemed desirable to:

(*a*) Eliminate need for drillers, riveters, and caulkers.

(*b*) Simplify construction.

(*c*) Simplify maintenance.

Hence, the concept of arresting a brittle fracture with a strake of notch-tough steel welded between strakes of standard ship steel was conceived.

An experimental investigation of this concept was undertaken by the University of Illinois. The program also included typical riveted crack arrestors for comparison. In addition, the effectiveness as an arrestor of an E12015 butt weld alone was studied. Large specimens (¾ in thick by 6 ft wide by 18 ft long) were tested at temperatures ranging from −54 deg F to +8 deg F at stresses ranging from 25,000 to 33,000 psi (SSC-122). These specimens had strakes of a notch-tough quenched and tempered steel of 4, 12, 24, and 36 in wide. Cracks were initiated by driving a wedge into a prepared notch at the edge of the plate. Means for measuring crack speed were included. A similar series of specimens (¾ in thick by 6 ft wide and varying in length from 8 to 19 ft) incorporating strakes of ABS-C steel (6, 18, and 60 in wide) was tested at loads ranging from 18,000 to 32,000 psi and at temperatures ranging from −22 deg F to +39 deg F.

The riveted crack arrestors performed satisfactorily in the laboratory. The presence of the abrupt discontinuity—the slot between the plates covered by the riveted straps—apparently accounted for this performance. Interesting too was the fact that rivet holes did not seem to attract propagating brittle cracks.

The findings with regard to welded "crack arrestors" were generally most encouraging:

1 ABS-C steel either entirely accepted or completely rejected brittle cracks (which had propagated 12 in) depending on temperature. Applied load had little effect on arresting ability. Regardless of width of strake, the transition from complete fracture to complete arrest occurred between +10 and +35 deg F which, by comparison with drop-weight and explosion-bulge tests, matched the fracture transition elastic (FTE) range.

2 Although an E12015 butt weld alone did not arrest a brittle crack, when used at the joint of the notch-tough quenched and tempered steel to the starter material, it did slow down the speed of crack propagation.

3 The fracture surface of cracks propagating into or through the tough steel was always on a 45-deg plane indicating a shear-type failure.

4 A strake of tough steel only 4 in wide completely rejected cracks that had propagated as much as 24 in except at −54 deg F where the crack penetrated less than one inch.

5 When cracks propagated 36 in or more, the resulting eccentric load (in these tests) created severe bending and corresponding buckling at the far edge sufficient to extend the crack. The ability of the remaining section to absorb high strain depended on the width and strength of the tough steel available.

An interesting fringe benefit of the crack arrestor program was the determination of the instantaneous strain pattern experienced during the propagation of a crack. The significant finding of this aspect of the study was that, during the first millisecond of propagation, there was generally *little or no change in the static strain level in the uncracked portion* of the plate outside the immediate vicinity of the crack tip. Although the experimentally determined crack velocity was about 3500 ft/sec giving a crack length of about 3½ ft (over one-half the plate width) in the first millisecond, the strains measured in the intact portion of the plate did not reflect the reduction in net section during crack propagation. After the crack had been arrested, however, equilibrium between load and strain was reestablished.

Fracture Propagation

At the same time that the welded crack arrestor program was being executed, the University of Illinois was also engaged in a more fundamental study of the propagation of brittle fracture (SSC-131). The emphasis of this investigation was on the determination of the strain field surrounding a propagating brittle fracture. Fracture speed was also measured.

The specimens tested were of essentially the same overall size as those used in the welded crack arrestor investigation. The same "notch-wedge-impact" method of initiating the crack was used. Instrumentation was essentially of the same type as used in the companion project, but was more extensive to determine the strain distributions.

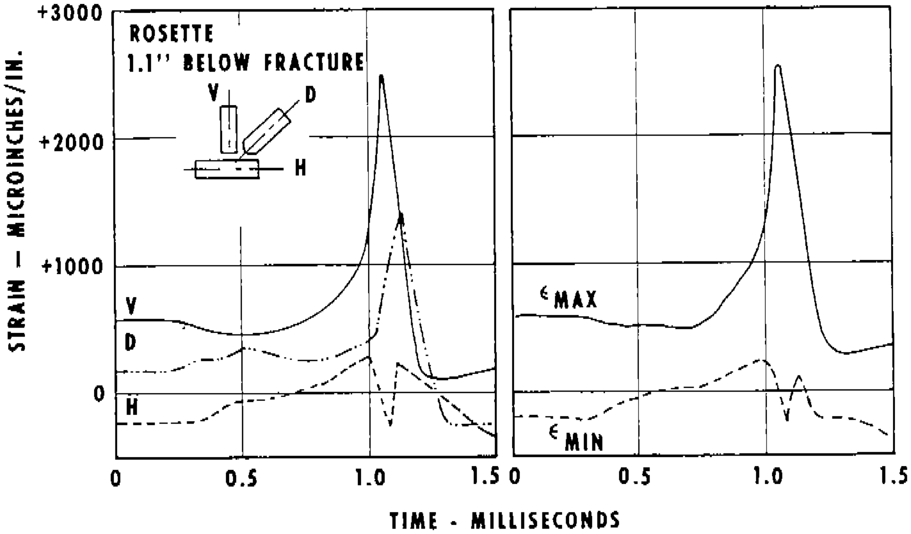


Fig. 17 Typical strain-time history for rosette close to a propagating crack

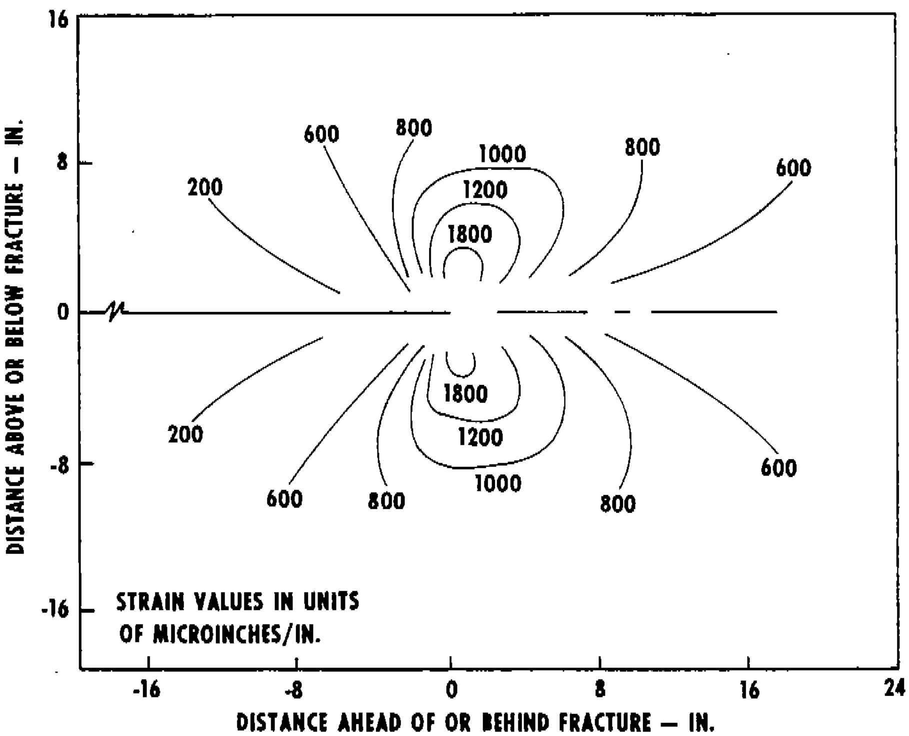


Fig. 18 Typical principal strain distribution around well-developed advancing crack

Tests were made on 6 ft wide plates. One series was externally loaded in tension to an average stress of from 15,000 to 20,000 psi with the temperature maintained at about 0 deg F. Surface strains as high as 3600 microin/in were measured, but with negligible permanent set remaining after fracture (i.e., essentially elastic response). Although fracture speeds ranged from 1800 to 7550 ft/sec, about ¾ of the measured speeds fell in the narrower range of 2100 to 3900 ft/sec.

Strain Distribution. Fig. 17 is a typical strain-time history of a strain rosette close to the propagating cracks. Both the vertical and diagonal traces were characterized by a slight decrease in strain followed by a steady increase, and then a rapid rise to a peak value as the fracture

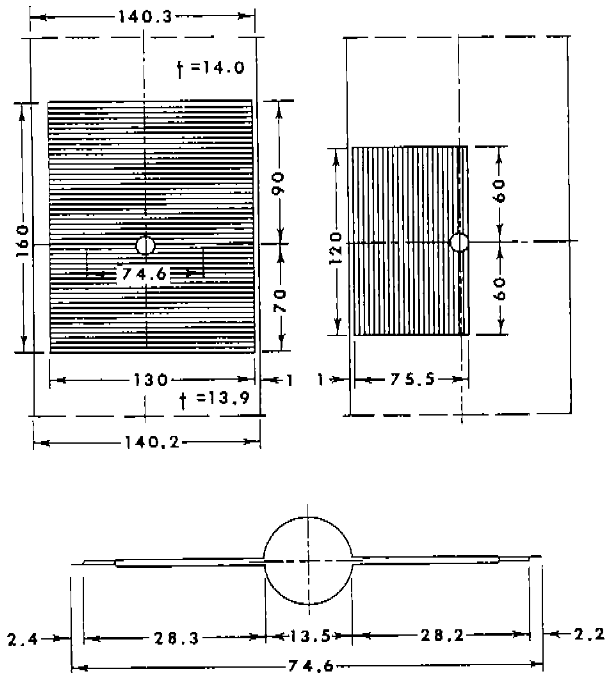


Fig. 19 Geometry of specimen with long crack showing moiré grid

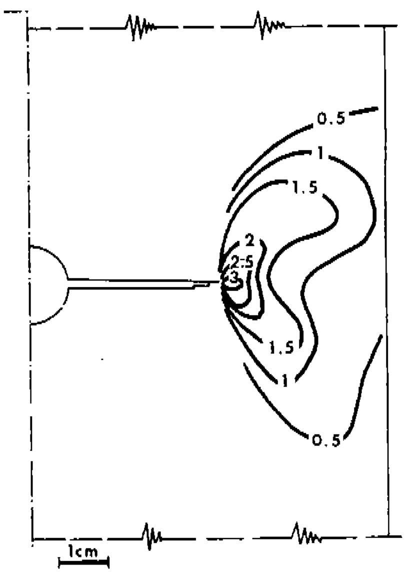


Fig. 20 Strain contours around long crack

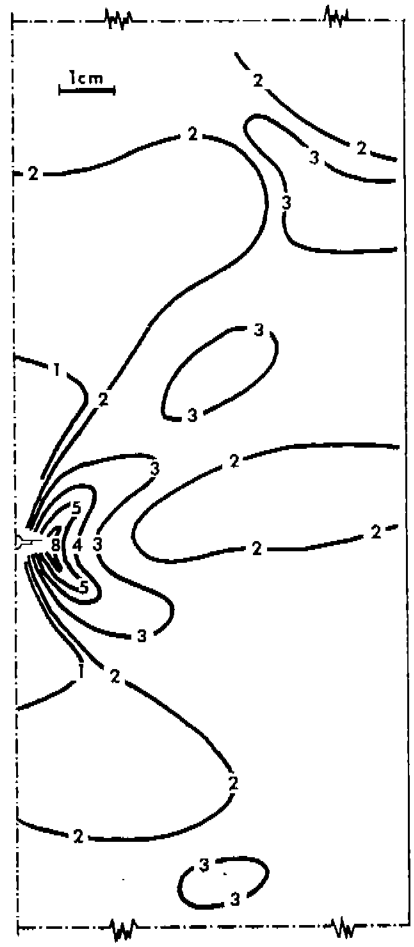


Fig. 21 Strain contours around short crack

propagated past the gage. The peak was followed by a rapid decrease in strain to a level associated with load removal. The horizontal gage (parallel to the crack path) first showed a relaxation of compressive strain, then a compressive pulse corresponding to the tension peak of the vertical gage, and, finally, the relaxation of compression to the level associated with load removal. Note in Fig. 17 that time histories of maximum and minimum principal strains closely resembled those for vertical and horizontal strains, respectively.

As the crack length increased, the magnitude and extent of the strain field associated with the crack tip also increased. For crack lengths in excess of 22 in, the magnitude of the strain field around the crack tip was essentially unchanged, whereas the extent of the strain field increased only slightly with increasing crack length. A set of typical maximum principal strain contours for a crack length of 22 to 50 in is shown in Fig. 18.

Brittle Fracture at Low Stress in Medium Steels. Brittle fractures at low stress emphasize the fact that the cause for such behavior lies in the inability of the steel to sustain overall strains. Two possible reasons for this lack of ductility are the state of stress and strain, and plastic straining prior to or during loading. To acquire knowledge of the effect on the plastic strain distribution on the behavior of centrally notched plates, experi-

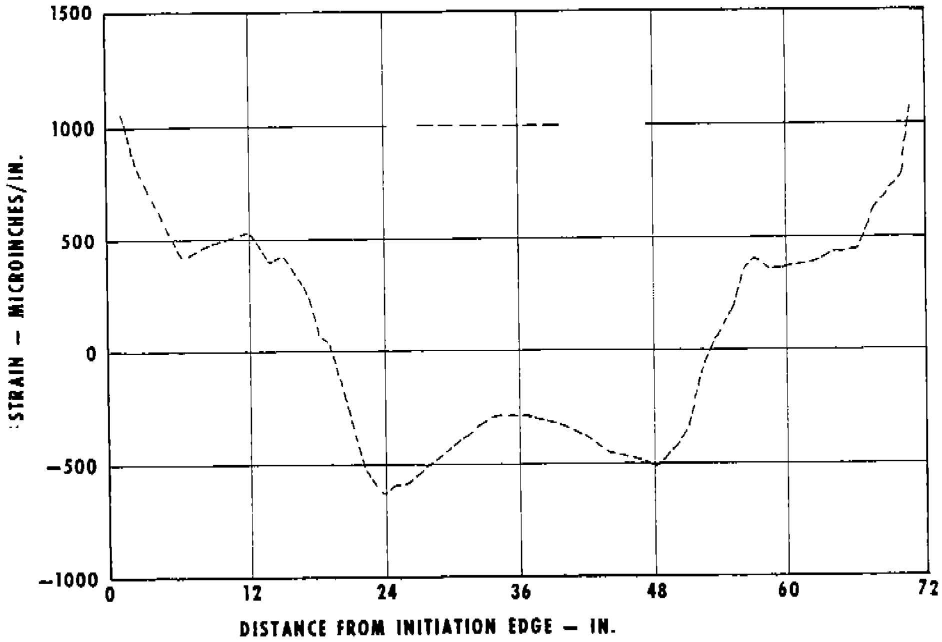


Fig. 22 Typical residual strain distribution (Test 46)

mental studies were carried out with the aid of the moiré grid technique [2]. This technique permitted observing plastic strains on a very small gage length: grid spacing of 0.0006 in. The grid spacing selected was not sufficiently sensitive to detect strains of elastic magnitude, but was adequate to detect large plastic strains. The study was carried out with flat plates containing a round central hole extended by two saw cuts and two fatigue cracks (SSC-158). As far as the strain at the tip of the crack is concerned, such a slit is equivalent to a single fatigue crack having the same total length. Two plates were tested: one with a crack length of 7 percent of plate width; the other with a crack length of 53 percent, Fig. 19.

From the moiré pattern, the permanent deformations sustained in the vicinity of the crack were directly measured, and are plotted as contours in Figs. 20 and 21 for the two cases investigated. The fan shape of the contour lines show that the highest strains are located in two narrow regions extending from the crack tip at an angle of about 45 deg to the axis of symmetry confirming thus that the principal deformation occurs mainly by shear.

The moiré technique for plastic strain measurement revealed that fairly large strains, up to 20 percent, were found locally at the crack tip while the specimen was elongated on the order of 0.003 in overall. Any fracture occurring under this condition would still be classified "brittle" despite the very large plastic flow at the crack tip. One significant finding emerging from this study was the influence of crack length on the plastic strain concentration for the same average stress. Since the moiré fan was much larger for the short crack (Fig. 21), a larger overall extension of the plate was indicated to be required to bring it to full yield than for the long crack. The plastic strain distribution, therefore, seemed to be governed by the *absolute value of the uncracked portion of the plate*, rather than by the length of the crack or the ratio of the crack to the net section. From this study, it was concluded that, to develop the full yield strength of the plate, the plasticity required at the crack tip is proportional to the uncracked width.

Effect of Residual Stress. A typical residual stress distribution in the vertical direction across the notch line of a 6 ft wide test plate is shown in Fig. 22. Fig. 23 shows the fracture speeds for this prestrained specimen and for a nonprestrained specimen with an externally applied tension of 19,000 psi. Note that the fracture speed in the initiation region of the prestrained specimen was the same as for the nonprestrained specimen, 3000 to 4000 ft/sec. Note also that, in the region of residual compressive stress, the fracture speed dropped to as low as 50 to 100 ft/sec. This indicated that residual compressive stress, if large enough and of sufficient extent, can arrest a propagating crack. Indeed, in three of the five specimens tested, the propagating crack was arrested

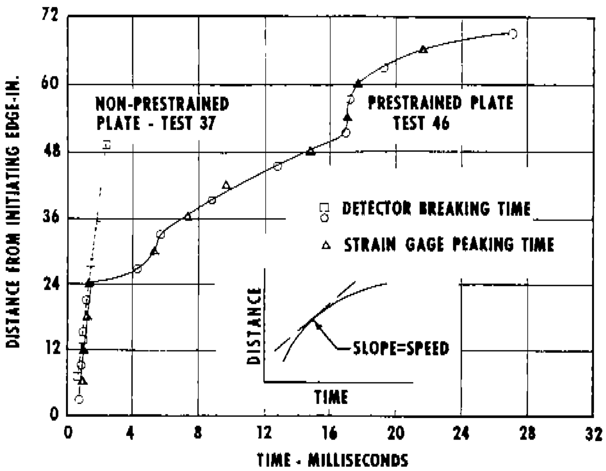


Fig. 23 Typical fracture speeds (Tests 37 and 46)

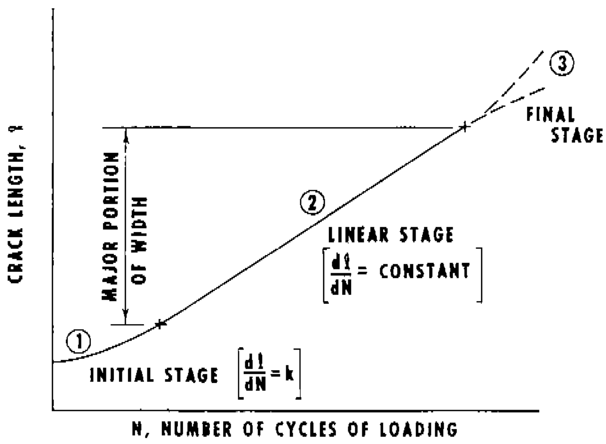


Fig. 24 Stages of fatigue crack growth

in the region of compressive stress and, in the other two, the crack was almost arrested.

Fatigue. In addition to the propagation of brittle fracture, the University of Illinois (SSC-143) has studied crack propagation in low-cycle fatigue. Based on constant-stress (push-pull) tests of ¾-in thick specimens 5 and 7 in wide, DeForest's theory that fatigue life may be divided into three stages, as shown in Fig. 24, was confirmed.

1 Crack growth in the *initial stage* was shown to be proportional to crack length so long as it did not exceed one-eighth of the specimen width.

2 In the *linear stage,* crack growth was constant and was dependent only on material, applied stress, and geometry.

3 In the *final stage* as the crack nears the edge of the specimen, edge effects and eccentricity of load dominated.

Nondestructive Testing of Welds in Ship Structures

While broad attention has been given to materials and design, the critical importance of inspection to a quality assurance program has not been forgotten. Memories of the close and direct association of weld flaws and other construction and fabrication faults with many of the early failures underscored the need to assure the availability and applicability of suitable nondestructive testing for these structures.

To provide a more factual base on which to judge the potential harm of weld defects, several investigations (SSC-86, -105, -107) were supported to evaluate weld flaws as initiating points for brittle fracture. These were essentially experimental programs studying the effect of purposely produced typical weld flaws in various stress environments such as large flat plates under static or dynamic loading and under bi- and triaxial stress. The principal finding of all these projects, however, was that the significance of flaw size was closely associated with the state of stress that existed in the area in question. Thus, in area of relatively low stress with a minimum of biaxiality, relatively large flaws may not be harmful, but some structures are difficult to design without at least some triaxiality, a condition wherein a small defect may be dangerous. It was, therefore, necessary to have suitable means of identifying the quality of welds for their acceptability in critical locations on a ship.

To fill this need, feasibility studies of several inspection techniques, back-scattered radiation for x-ray inspection (SSC-132), the use of radioisotopes (SSC-110), and, currently, ultrasonic testing have been supported. From the isotope study has come *Manual of Isotope Radiography* (SSC-121) which outlined the techniques, suitability of sources, and safety precautions for isotope radiography as applied to ship structures. Apparently, the manual served a real need as it received wide publicity. It was followed by a report (SSC-132) presenting specific test results with several then-available radioactive isotopes. The ultrasonic studies are currently aimed at developing a method of recording the oscilloscope indications of flaws and correlating them with input concerning the test conditions and judgment of operator. This is a first step in automating the process.

The most significant step in nondestructive testing has been the compilation of *Guide for Interpretation of Non-Destructive Tests of Welds in Ship Hull Structures* (SSC-177). This guide shows, by means of radiographs for all recognized classes of defects, the size and distribution that may be acceptable in ship hulls. It has been distributed broadly within the shipbuilding industry for comments and criticism with the hope of eventual acceptance. Since uniform inspection procedures and standards of acceptance do not now exist for commercial ships, acceptance and implementation of the guide (or one similar) should lead to improved fabrication.

Stress Distribution

One of the governing elements related to the strength of ship structure is the stress for which the structure is being designed. The SSC early recognized that there may be some significant differences between the stress calculated from theory, and the actual stress experienced by the hull structure. Accordingly, it sponsored a series of experimental investigations in several important fields such as the reinforcement of openings in structural members, the interaction of the deck house with the main hull, and the effects of thermal stresses. The two factors that were prevalent in these studies were geometrical discontinuities and temperature. The underlying reasons were that geometrical discontinuities, in disturbing the stress pattern, locally augment the stress intensity and make the structure prone to early cracks. At low temperatures, cracks could propagate into a catastrophic brittle fracture because of the embrittling effects on the steel.

Welded Reinforcements of Openings in Structural Members

At the outset, several perplexing questions were raised:

(*a*) Should every opening be reinforced? Cannot some be left alone?

(*b*) What is the best geometrical shape? How nearly square may the corners be?

(*c*) If reinforced, which is best: doubler, insert plate, or face bar?

(*d*) How should performance be evaluated: ultimate single load or some function of energy absorption to failure?

(*e*) Which is of greater concern: elastic stress concentration or plastic strain concentration?

(*f*) Should not fatigue resistance be considered? In view of these questions, the problem of reinforcing an opening is extremely complex.

A test program (SSC-75) included plates 36 and

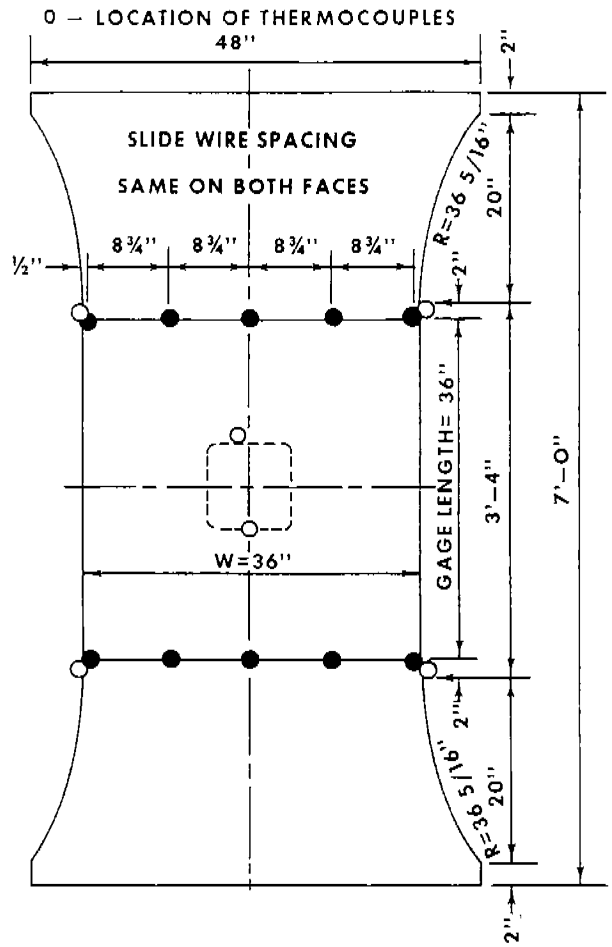
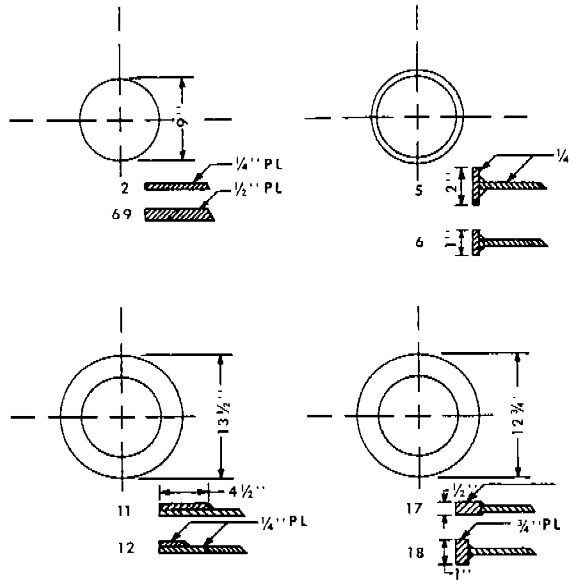


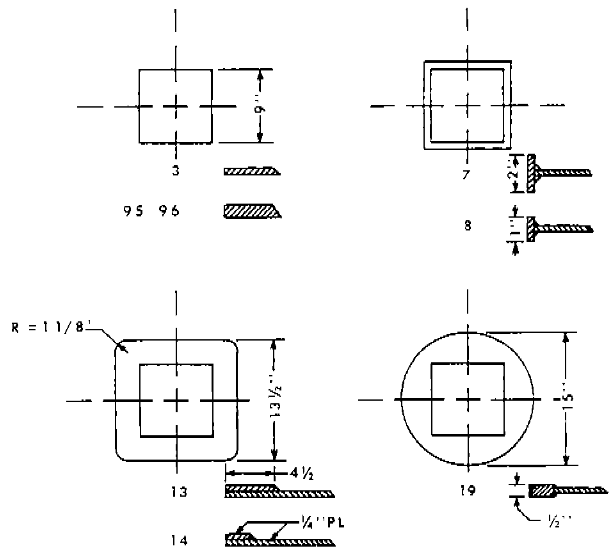
Fig. 25 Geometry of 36-in specimen used in study of reinforced openings

Table 1 Circular Openings

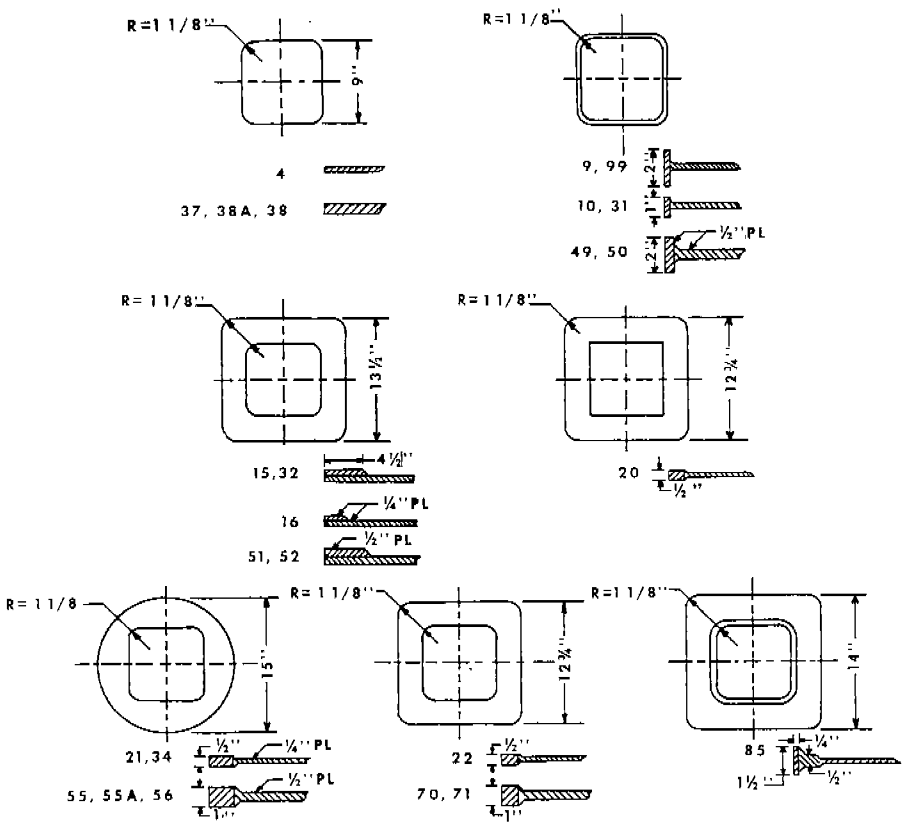
Spec. no.	Ult. ave. stress, ksi	Percent reinf.	Type of reinf.	Energy abs. to failure, in-kips	Max. elastic stress conc.
2	65.16	0	None	1164	3.0
5	67.8	40	Face bar	1420	4.19
6	64.2	17	Face bar	910	3.51
11	61.67	102	Doubler	1569	4.15
12	62.0	50	Doubler	983	2.44
17	64.39	39	Insert plate	1361	2.23
18	66.3	50	Insert plate	1400	1.78
1	65.39	...	Plain plate	5276	...
23	64.78	...	Plain plate	6779	..



(*a*) circular openings



(*b*) square openings with sharp corners



(*c*) square openings with rounded corners

Fig. 26 Details of reinforced openings

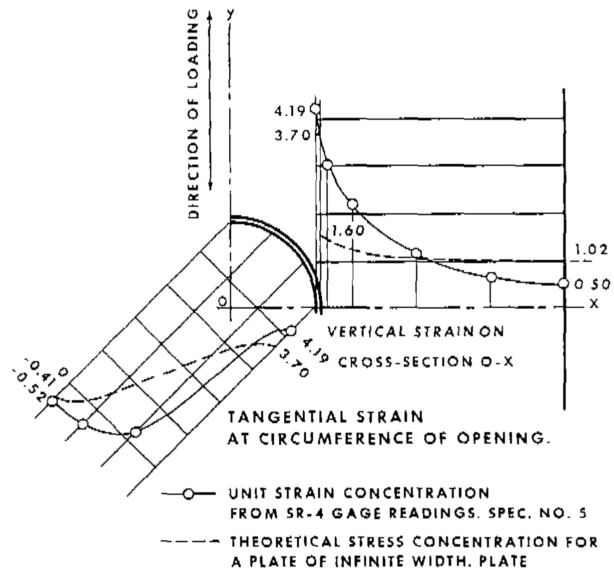


Fig. 27 Typical elastic stress distribution for reinforced circular opening

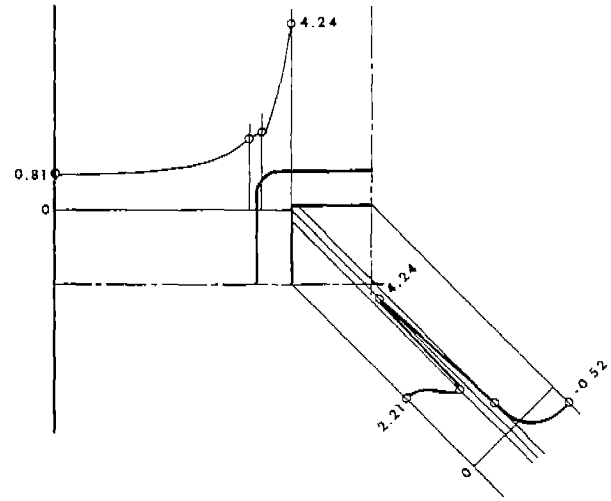


Fig. 28 Typical elastic stress distribution for reinforced square opening with sharp corners

48 in wide, each of two plate thicknesses, ¼ and ½ in. The geometry of the 36-in wide specimen is shown in Fig. 25; details of the several openings and reinforcements are summarized in Fig. 26. Comprehensive strain gaging was employed to explore the pattern of the strain distribution both in the body of the plate and in the immediate region of the opening. In addition to elastic stress and plastic strain distributions, the tests provided also the total energy absorption to failure.

Circular Openings. The most significant experimental data for the circular opening specimens tested at room temperature are summarized in Table 1. Elastic stress distribution for one geometry is shown in Fig. 27. From Table 1, it may be seen that, regardless of whether or not the opening is reinforced and irrespective of the type and percentage of reinforcement used (ratio of area of reinforcing material to area of cutout), *the average net stress at failure remains essentially constant,* close to the ultimate strength of the material. This strength was achieved in spite of the variation of maximum elastic stress concentration from 1.78 to 4.19. One possible clue as to relative superiority of one structural detail over another may rest with the energy absorbed at failure. But, as seen in Table 1, even this parameter did not consistently define the structural behavior. Specimen No. 5 with a relatively high elastic stress concentration of 4.19 developed the same energy absorption as Specimen No. 18 with the much lower concentration factor of 1.78. Though ultimate material strength was achieved in every case, the maximum energy absorbed (1569 in-kips) was about one fourth that developed by the unperforated plates (5276 to 6779 in-kips).

Square Openings with Sharp Corners. The test results (SSC-39) at room temperature for the plates containing a square opening with sharp corners are summarized in Table 2 for the various types of reinforcements used. Elastic stress distribution for one geometry is shown in Fig. 28. In this group, the maximum elastic stress concentration factor measured was 4.24, for a specimen which had an insert plate type reinforcement. Two significant points emerge from the data of Table 2. First, a square opening with sharp

Table 2 Square Openings with Sharp Corners

Spec. no.	Ult. ave. stress, ksi	Percent reinf.	Type of reinf.	Energy abs. to failure, in-kips	Max. elastic stress conc.
3	52.9	0	None	538	3.06
7	52.07	40	Face bar	750	2.32
8	54.95	16	Face bar	780	4.10
13	50.17	104	Doubler	728	1.49
14	51.6	51	Doubler	621	3.88
19	47.69	33	Insert plate	548	3.56
20	55.54	39	Insert plate	836	4 24

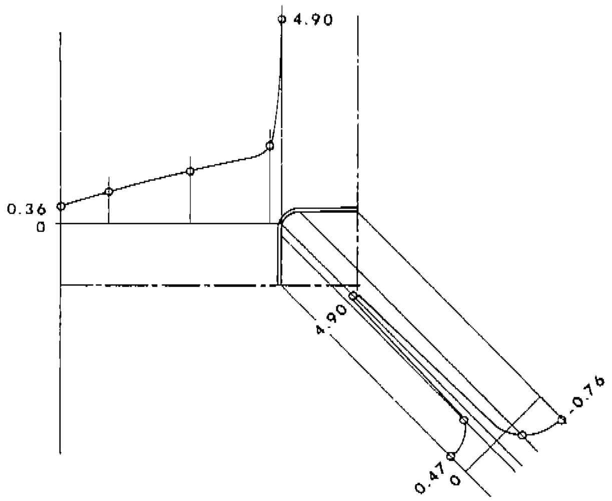


Fig. 29 Typical elastic stress distribution for reinforced square opening with rounded corners

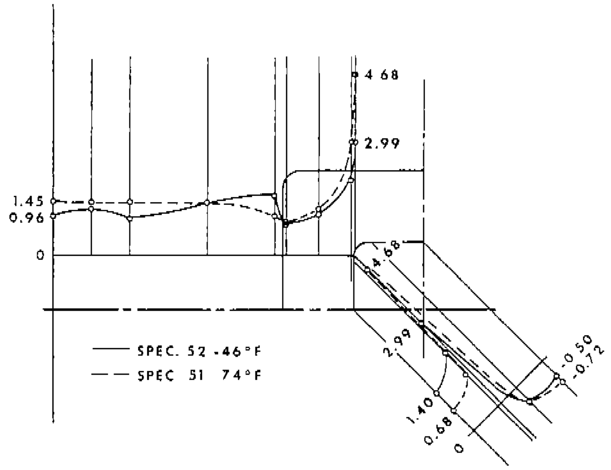


Fig. 30 Typical elastic stress distributions for reinforced opening at normal and low temperatures

corners, whether reinforced or not, is not so efficient as a circular opening as evidenced by the lower average ultimate stress. The second point is that energy absorption, an index of the ability of the geometry to accept large plastic flow, also suffered irrespective of the intensity of the elastic stress concentration present in the geometry. For example, a comparison of Specimens Nos. 11 and 13 (Tables 1 and 2) reveals that both specimens were reinforced about 100 percent by doublers, yet Specimen No. 11 (circular opening) carried more load and absorbed far more energy than Specimen No. 13 (square opening) in spite of a larger elastic stress concentration, 4.15 as compared to 1.49.

Square Opening with Rounded Corners. The test results (SSC-39) at room temperature for the plates containing a square opening with rounded corners are summarized in Table 3. Elastic stress distribution for one geometry is reproduced in Fig. 29. In this group, a maximum elastic stress concentration of 4.90 was measured in Specimen No. 10 which was reinforced (40 percent) by face

Table 3 Square Openings with Rounded Corners

Spec. no.	Ult. ave. stress, ksi	Percent reinf.	Type of reinf.	Energy abs. to failure, in-kips	Max. elastic stress conc.
4	62.35	0	None	899	4.64
9	59.15	40	Face bar	1063	4.90
10	65.54	16	Face bar	1504	4.44
15	58.06	103	Doubler	1099	3.70
16	61.90	52	Doubler	1154	4.32
21	57.94	62	Insert plate	1484	3.29
22	56.84	39	Insert plate	974	4.55

Table 4 Square Openings with Rounded Corners

Spec. no.	Test temp, deg F	Ult. ave. stress, ksi	Percent reinf.	Type of reinf.	Energy abs. to failure, in-kips	Max. elastic stress conc.	Type fracture (percent cleavage)
49	70	59.0	33	Face bar	4710	2.52	0
50	−20	66.8	33	Face bar	5610	2.80	99
51	74	57.7	96	Doubler	5360	4.68	0
52	−46	60.8	96	Doubler	4187	2.99	100
55	70	57.7	66	Insert plate	4660	3.60	57
55A	69	58.3	67	Insert plate	4328	4.06	0
56	−46	61.5	66	Insert plate	3220	5.26	100
70	76	59.7	39	Insert plate	3699	2.15	1
71	−46	55.0	39	Insert plate	2084	1.85	100

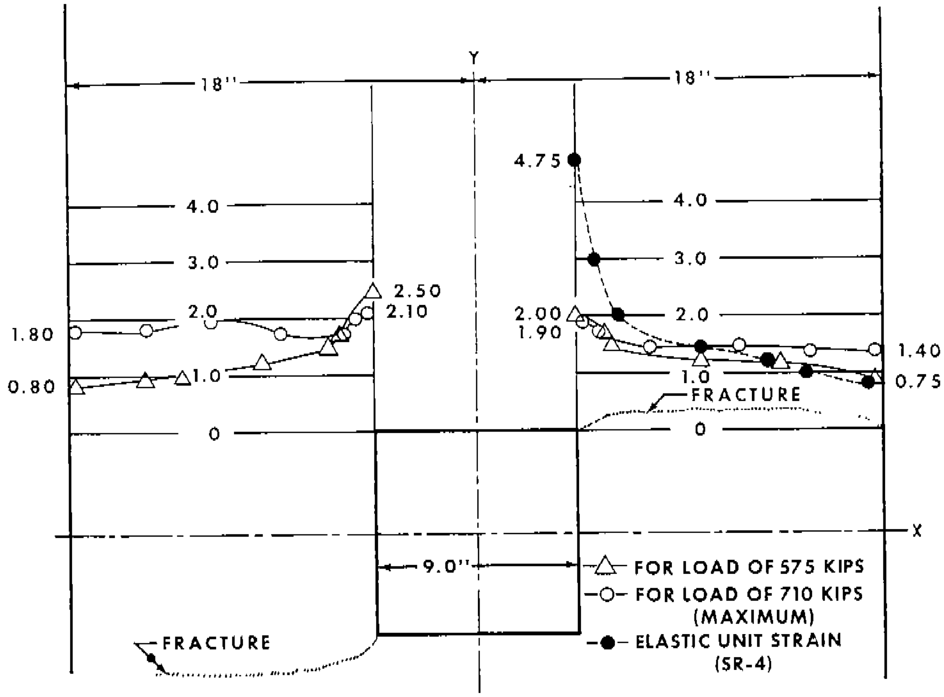


Fig. 31 Comparison of elastic and plastic strain distributions for unreinforced openings

Table 5 Unreinforced Openings

Spec. no.	Test temp, deg F	Ult. ave. stress, ksi	Type of geometry	Energy absorption to failure, in-kips	Concentration: Elastic stress	Concentration: Plastic strain	Type fracture (percent cleavage)
38	−20	67.7	Square with rounded corners	2778	3.09	1.81	91
69	76	62.5	Circle	2533	3.23	1.80	0
95	76	52.6	Square	1597	4.75	1.90	0
96	−46	48.0	Square	486	3.85	1.50	100

bar. Some specimens in this group developed the ultimate strength of the material even though they had elastic stress concentrations in excess of four. From Table 3, it may be seen that energy absorption of this particular geometry falls between the circular opening and the square with sharp corners.

From this group of specimens which were tested at room temperature the following conclusions were reached:

1 All plates failed with a completely ductile fracture; the type and size of reinforcement did not seem to affect this behavior.

2 All three types of openings decreased markedly the energy absorption, much more than their ultimate strength.

3 Variations in elastic stress concentration did not appear to play a dominant role in the ultimate strength nor in the energy absorption.

Temperature Effects. A selected geometry was retested in ½ in thick by 96 in wide plates. These tests were made at both room and lower temperatures. The shape selected was a 9-in square with 1⅛-in corner radii. The data (SSC-55) from this group are summarized in Table 4. A typical elastic stress distribution for one of the tested geometries is reproduced in Fig. 30. This figure shows that the stress distribution is not significantly affected at the testing temperature. There were, however, significant changes in the gradient.

Energy absorption decreased with lower test temperature, as expected. However, some paradoxes were noted. For example, Specimen No. 50 which failed with a 99 percent brittle fracture developed more energy than Specimen No. 49 which failed in shear. As with other specimens, these tests showed that the energy absorption to failure appeared to be independent of the elastic stress concentration present in the particular specimen.

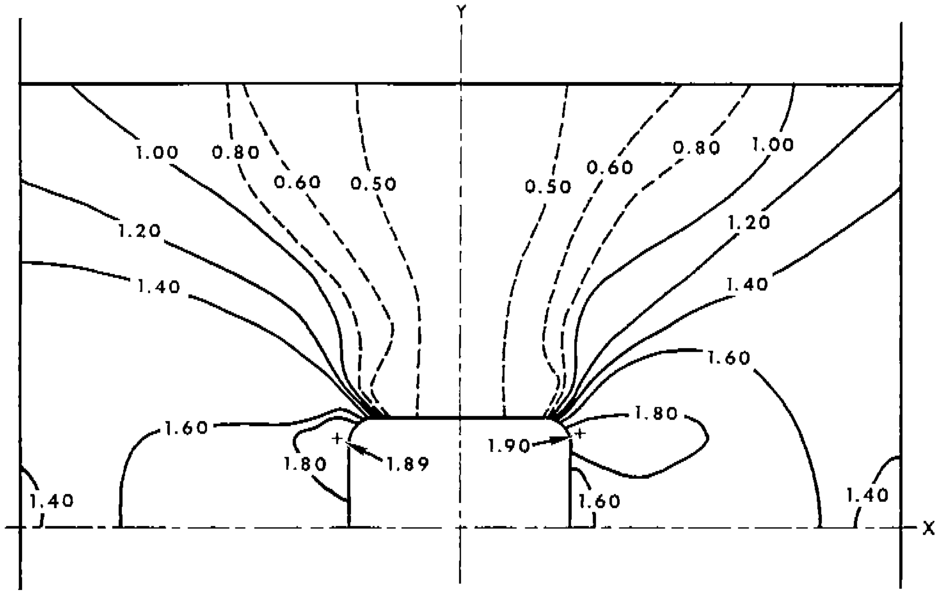


Fig. 32 Contours of equal plastic strain around unreinforced openings

The tests, however, indicated that the best reinforcement for any opening when tested at temperatures well below the steel transition temperature is that one which concentrates the reinforcing material fairly close to the edges of the opening. *In this position the reinforcement appears to do the most good!*

Elastic Stress Concentration vs. Plastic Strain Concentration. Additional tests with plates ½ in thick by 36 in wide were carried out (SSC-56) to determine more specifically the concentration factors both in the elastic and plastic range. These specimens contained the three basic geometries studied but, for simplicity of instrumentation, had no reinforcements. Concentration factors are tabulated in Table 5; typical elastic and plastic strain distributions for one of the geometries tested is reproduced in Fig. 31; and iso-strain contours are shown in Fig. 32. The most significant findings from these tests were:

(*a*) The concentration diminished from its maximum elastic value as the applied load brought about plastic behavior.

(*b*) At the ultimate load, the concentration approached a constant minimum value and lost its steep gradient.

From Table 5, it is seen that the energy absorbed is dominated by the shape of the opening and is almost independent of the elastic stress concentration factor. The square opening with rounded corners developed almost six times the energy of the square opening with sharp corners, even though both failed with an almost completely brittle fracture.

The experimentally determined maximum elastic stress concentration for the unreinforced square opening with rounded corners, compared very well with the theoretical value obtained by Beskin [3]. The plastic strain concentrations, however, are not amenable to theoretical predictions as yet. The tests showed that the plastic strain gradients were steeper in the specimens that failed with a predominantly cleavage fracture than in identical specimens that failed with a shear fracture.

General Conclusions. From these extensive experiments the following general conclusions were reached:

1 Cleavage fracture in itself should not be the sole criterion of failure. Energy absorption, whether failure is by cleavage or shear, is the decisive factor.

2 The shape of the opening is more important than the amount or type of reinforcement.

3 A corner radius of ⅛ the width of the opening is sufficient to develop the required static strength.

4 Adequately reinforced openings restore the ultimate strength of the structural member loaded in tension, but, at best, can develop only about 25 to 30 percent of the energy absorbing capacity of the unperforated plate.

5 The cross-sectional area of reinforcement for an opening is most effective when it is concentrated near the opening. Optimum reinforcement of the face bar type is about 35 to 40 percent of the area of the opening whereas, for the insert type, 30 to 60 percent of the area is required and, for the doubler type, almost full area compensation is needed.

6 Elastic stress concentrations, per se, do not have a too strong effect on the behavior of plates with openings loaded in tension. It is the shape of the opening and the subsequent distribution of plastic strain (steep versus moderate gradients) that has an important influence on both ultimate strength and energy absorption.

Though no fatigue tests were made on these geometries, it is suspected that fatigue would alter some of these conclusions.

Cracking of Simple Structural Geometries

Experience with ship fractures indicated that *over one-half of the fracture origins were in the immediate vicinity of welded structural discontinuities.* These were found, for example, at hatch corners, the endings of bilge keels, interrupted tanker longitudinals, and the junction of the fashion plate with the sheer strake. A series of tests (SSC-57) simulating some of these geometries was carried out on simplified specimens. The aim was to evaluate the efficiency of these structural details in terms of their ultimate strength and energy absorption. From the limited strain data taken from a specific geometry representing a longitudinal attached to the shell plating, it was possible to determine how the applied load is distributed between the two structural members.

One general conclusion arising from these tests was that the geometric notch effect of the abrupt termination of a longitudinal, for example, can lead to a relatively early failure partially because of the direction of the principal stress at the terminal point. The study indicated that the direction of the maximum principal stress, which, for square ends, was nearly perpendicular to the principal load-carrying member, could be brought nearly parallel to this main member by a curved end. The latter geometry was found to develop the highest energy absorption.

Hull-Deck House Interaction

The full-scale structural tests on SS *President Wilson* [4] clearly showed a nonlinear longitudinal stress distribution across the midship section, indicating thereby departures from simple beam theory. It was considered important to determine, by model studies, the factors that contributed to this nonlinear behavior. Accordingly, tests (SSC-67) were carried out on a 20-ft simplified structural model with several deck house configurations. The most significant result from this study is graphically presented in Fig. 33 which shows a stress distribution pattern very similar to that observed on SS *President Wilson.*

The behavior of the different types of deck houses tested, representing variations in stiffness

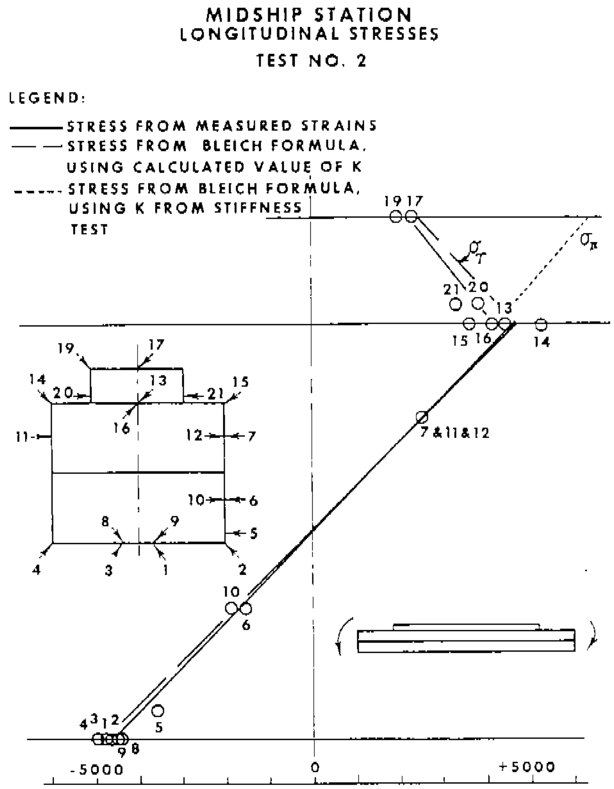


Fig. 33 Distribution of longitudinal stress of hull-deckhouse model

and length, proved most interesting, but their stress distribution patterns could not be predicted theoretically because of difficulty in defining the "foundation stiffness" of the main deck supporting the house. This parameter, which still remains elusive today, generally depends on the stiffness properties of the main deck framing system, the number and stiffness of the transverse bulkheads below the deck, and any other bulkhead system contained within the house proper.

With the extensively instrumented models, it was possible to study how the longitudinal hull girder stresses build up into the house side. Relatively high vertical stresses were measured at the house ends. This qualitatively confirmed why ships have experienced cracking in this region.

Thermal Stresses in Ships

The brittle fractures experienced in ships during World War II appeared to have one common denominator—*low temperature.* The record indicated that the incidence of fractures increased with decreasing air temperature. While it was generally known that low temperature predisposed the material to brittle fracture, what was not appreciated then was that a thermal stress, even

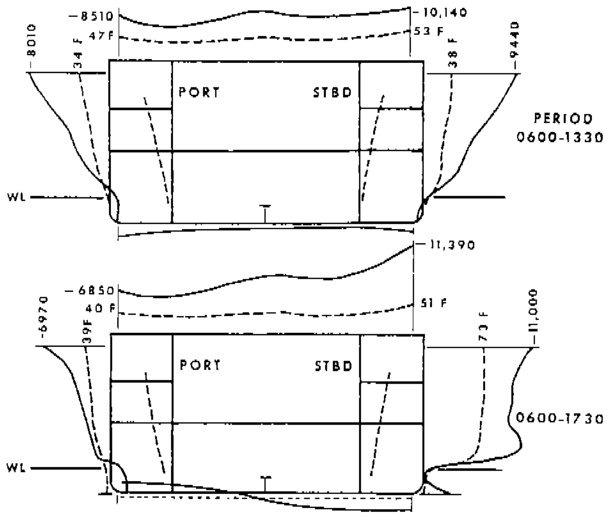


Fig. 34 Diurnal change in temperature and stress measured on LST 1075

if existing alone, could, under some circumstances, act as the "straw capable of breaking the camel's back." The effect of thermal stresses on the behavior of ship structure was, therefore, examined in depth.

This study (SSC-95) focused attention on the principle that governs how thermal stresses develop. The action is rather simple. In summer, when the exposed structure is heated by the sun, it tends to expand; but, since it is restrained from free expansion by the cooler structure below water, a compressive thermal stress develops. Conversely, in winter, when the upper structure is exposed to near zero temperatures, the warmer structure below water, restrains the upper structure from contracting. The net result is that the upper structure is subjected to a tensile thermal stress.

Experience with T-2 tankers, for which many brittle fractures originated in the bottom structure, was also consistent with the thermal stress principle. Most fractures initiated after the oil in the center tanks had been heated preparatory to discharge. Since the temperature of the wing tanks was lower than that in the center tanks, tensile thermal stresses were induced in the shell in the region of the bilges. It was at this location that most fractures occurred in tankers.

Diurnal observations, made on LST 1075, are shown in Fig. 34 (SSC-95). It can be seen that a maximum thermal compressive stress of 11,300 psi was observed on the starboard main deck for a deck temperature rise of 51 deg F. Such a stress is not insignificant. It could contribute to premature plate buckling!

The principal recommendations from the survey (SSC-95) led to two additional studies. One was carried out on SS *Boulder Victory* under partial sponsorship of SNAME [5]; the other was made in the laboratory with a 10-ft structural model (SSC-152). The main objective of the test program on *Boulder Victory* was to provide a reliable number of plate temperatures and corresponding thermal stress distributions over a complete transverse section under *diurnal temperature*

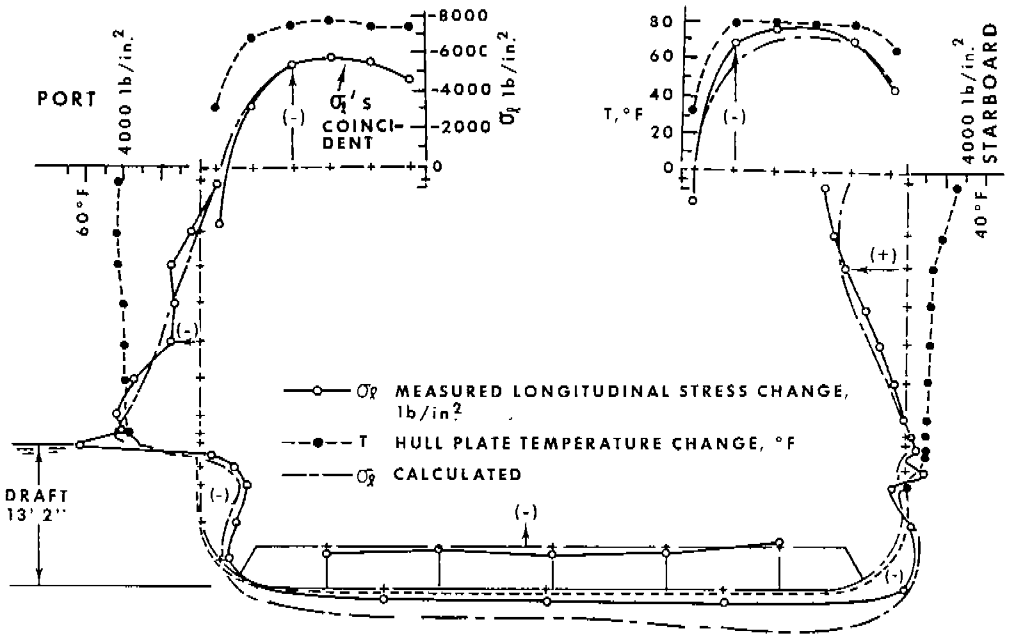


Fig. 35 Comparison of measured and calculated thermal stresses on SS *Boulder Victory*

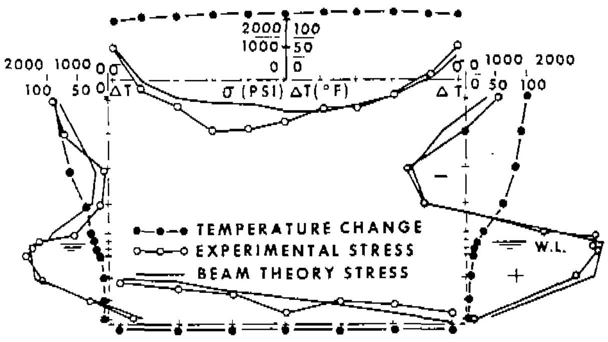


Fig. 36 Comparison of measured and calculated thermal stresses for symmetrical temperature distribution

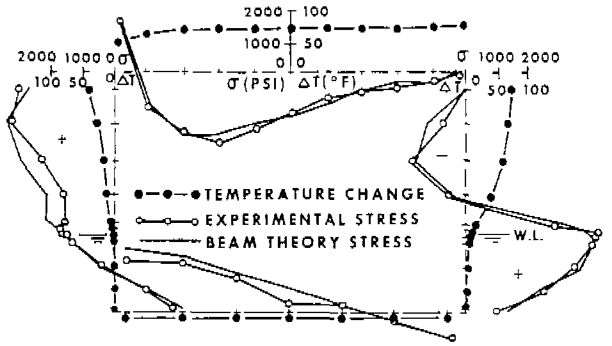


Fig. 37 Comparison of measured and calculated thermal stresses for asymmetrical temperature distribution

variations. The ship was, exclusively for these tests, taken from the reserve fleet. The tests were carried out in the San Francisco Bay area over several months. The test results showed very good agreement between the *measured* thermal stresses and those *computed* by the method of Jasper [6] from temperature measurements. A typical thermal stress distribution is shown in Fig. 35. The shape is very similar to that obtained from LST 1075. Moreover, for the temperature differential considered here, the compressive stress in the deck reached a maximum of 6000 psi and was very nearly uniformly distributed. Although no ship measurements have been made where the measured deck thermal stress was tensile, the possibility of its existence in winter must not be discounted.

The laboratory study on a 10-ft floating structural model (SSC-152) was undertaken to permit the simultaneous observation of thermal stresses at several transverse sections, and, thus, be able to check more rigorously the simplified beam theory by Jasper in predicting the structural behavior of a hull girder to thermal effects.

Floating the model in the test tank served two functions:

1 The water provided a realistic support for the ship model.

2 It provided an adequate heat sink which was necessary to maintain the required thermal gradients in the structural model.

The test procedure was simple: heated air was ducted to a hood over the model and distributed by baffles while the water was maintained at a constant level and at a constant temperature by a regulated flow of cold water into the tank.

A typical test result is reproduced in Fig. 36 for the case of *symmetrical* temperature distribution. Several aspects of this figure are interesting. First, a uniform temperature rise in the deck plating of about 100 deg F induced very small thermal stresses across the deck. As expected, these were compressive. In the side shell, however, a tensile stress of about 4000 psi was developed near the waterline where an abrupt nonlinear temperature gradient existed. The calculated and experimental thermal stresses are in good agreement both in magnitude and distribution. This agreement is more markedly portrayed in Fig. 37 for the case of the *asymmetrical* temperature distribution. In this case, moderate tensile stresses of 3000 psi were developed in the port sheer strake whereas in the starboard side shell near the water line the stress level was about 4000 psi. One significant conclusion from this study was that *regions of high thermal stresses will always occur at points where the temperature distribution becomes nonlinear.*

Moderately high thermal stresses in ships normally will occur near the water line. Practically, however, this is not too important because the longitudinal stresses there are minimum. Critical areas may occur, however, at shadow boundaries on the deck and sides. At these places, the thermal stress, if tensile, can become a significant factor since it would be additive to existing hull girder bending stress. The important conclusion from this study is the reconfirmation of a thermal stress theory which checks controlled experiments reasonably well even for the three-dimensional case.

Data from Ships in Service

A knowledge of the hull structural response at sea is necessary to the understanding of the forces that the structure experiences in service. To this end, the SSC has sponsored a ships-at-sea project to obtain long-term statistical data on wave-induced bending moments and, more recently, on the slamming loads sustained by dry cargo ship types. The immediate objective of the project was to obtain statistical records of the vertical

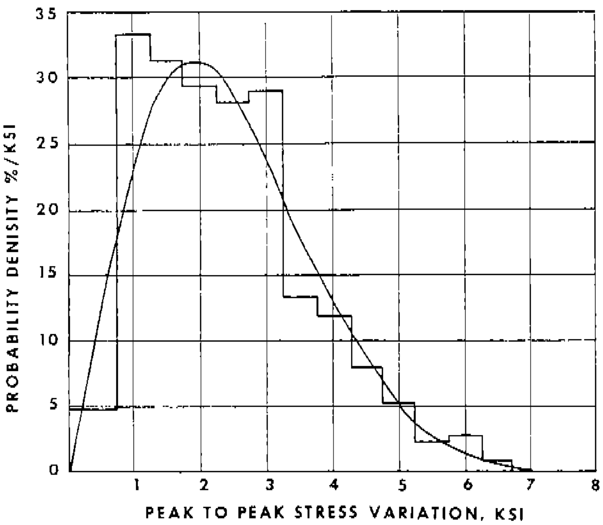


Fig. 38 Typical stress histogram and Rayleigh distribution

longitudinal bending moment (stresses) experienced by dry cargo ships operating on different trade routes with emphasis placed on recording extreme values. The long-range objectives were to provide information for the direct use of ship designers and to evaluate statistical methods for predicting bending moments.

The first two ships selected for instrumentation were SS *Hoosier State* (November, 1960) and SS *Wolverine State* (December, 1961). A detailed description of the instrumentation used and how it operates is given in SSC-150. These dry cargo ships have the designation C4-S-B5 and are operated by the States Marine Lines in the North Atlantic route. One ship was instrumented for the unmanned recording of wave-induced strains on magnetic tapes. The instrumentation aboard the second ship included additional channels for recording both wave-induced strains and accelerations. The recorded strain data obtained during the past six years of operation have been analyzed by a special statistical technique which will be discussed later.

Statistical Approach

The mathematical model applicable to the statistical analysis of wave-induced bending moments in ships is identical to that used in describing the wave system, and is based on the reasonable assumption that there exists a linear dependence between bending moment and wave height (SSC-153). In dealing with the statistical description of ocean waves, it is convenient to confine the analysis to a given wave system; i.e., a specific wind generated sea. In treating bending moments, it is essential that the direction and speed of the ship be constant during the data acquisition period. Implicit here is that the wave system also remains constant. For the purpose of this analysis, data obtained during a single recording interval, 30 min duration in this instance, were assumed to qualify as "short-term data."

For the analysis of the short-term data, the Rayleigh distribution technique was used. This technique, however, had some limitations. Bending moment data did not exactly fit the Rayleigh distribution, and there is no theoretical basis why this should be so. The departure from the Rayleigh curve was, however, slight for the range recorded which was most encouraging. The agreement became progressively less satisfactory at large values of variate (for which proportionately less recorded data were available) which emphasized the need for taking ship data at extreme sea conditions.

To derive a long-term prediction of the bending moment experienced by the ship, histograms were first drawn from the actual data similar to that reproduced in Fig. 38. The data for all the other recorded intervals were then similarly treated. The significant factor that emerged from the histograms was the quantity E, the mean square variation, which is defined as

$$E = \frac{\Sigma x^2}{N} \qquad (1)$$

where

x = the magnitude of a data sample (peak-to-peak stress variation) and
N = number of samples

The basic equation describing the Rayleigh distribution is

$$p(x) = \frac{2x}{E} e^{-\frac{2x}{E}} \quad \text{for} \quad x \geq 0 \qquad (2)$$

where $p(x)$ = probability density of x.

The cumulative distribution of equation (2) is given by

$$P(x) = 1 - e^{-\frac{x^2}{E}} \qquad (3)$$

where $P(x)$ = probability of the variation being less than x in the time interval.

The most probable maximum value (X max) in a sample of N variations is given by

$$X_{max} = \sqrt{E \log N} \qquad (4)$$

where N is large as is the case in this investigation.

To have practical significance in ship design, it was apparent that long-term predictions were desired. This meant that the time intervals would

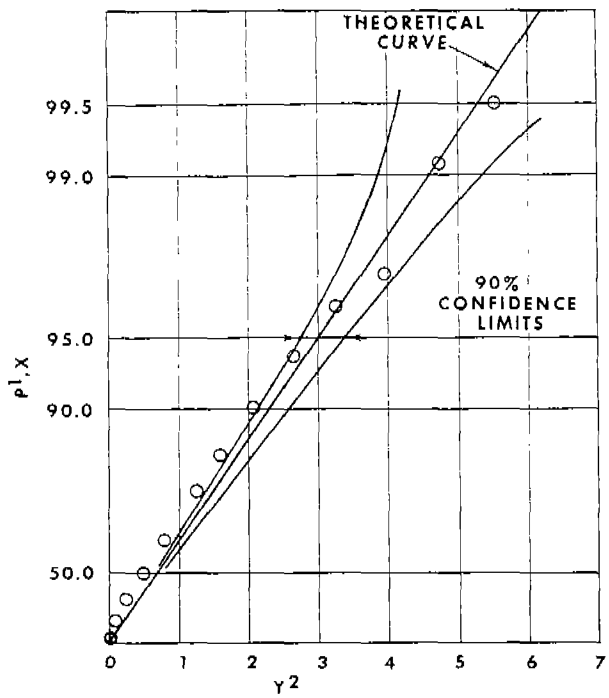


Fig. 39 Cumulative probability of Rayleigh distribution

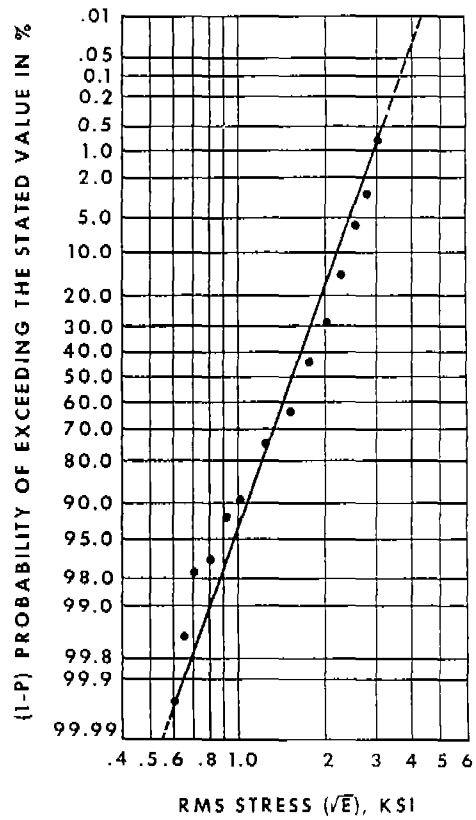


Fig. 40 Log-normal distribution of RMS stress

have to be far longer than the relatively short period used to develop the Rayleigh distributions. One approach suggested for predicting the long-range extreme stress values was to use as the basic units the mean-square values derived from a number of short-term distributions. Studies to date have indicated that a long-term collection of mean-square values of stress variation seemed to fit satisfactorily the normal or log-normal distribution. The log-normal distribution of $\sqrt{E}$ can be expressed as

$$p(\sqrt{E}) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\log\sqrt{E} - \mu)^2}{2\sigma^2}} \qquad (5)$$

where

μ = mean value of $\log\sqrt{E}$

σ = standard deviation of $\log\sqrt{E} = \frac{1}{p}\sqrt{\frac{P(1-P)}{N}}$

From these five relatively simple expressions, the analysis of the recorded data proceeded, in logical steps, from the histograms of Fig. 38, to the cumulative probability of Fig. 39, and finally to the log-normal distribution of Fig. 40. A detailed description of the numerical procedure used in the analysis of the recorded data from several specific voyages may be found in SSC-153.

Midship Bending Moment Stress for Two Ships in North Atlantic

By the end of 1963, after approximately five ship years of operation, the two instrumented ships had collected data representing a total of about 12,000 hr of ship operation (SSC-164). At this point, the instrumentation from *Hoosier State* was removed for reinstallation aboard a different type of dry cargo ship, SS *Mormacscan*, and the equipment remaining aboard *Wolverine State* was converted to record the outputs of the port and starboard gages separately. The output from these two gages then could be either combined during the data reduction or examined separately. During 1963 all available data were reduced and analyzed by means of a probability analyzer as opposed to early manual methods. This drastically shortened data reduction time.

The data for both ships were reduced in the form shown in Fig. 41 for the case of peak-to-peak stresses, then normalized for each Beaufort sea state, and combined as in Fig. 42. Each dot in Fig. 41 corresponds to the reduced data from a

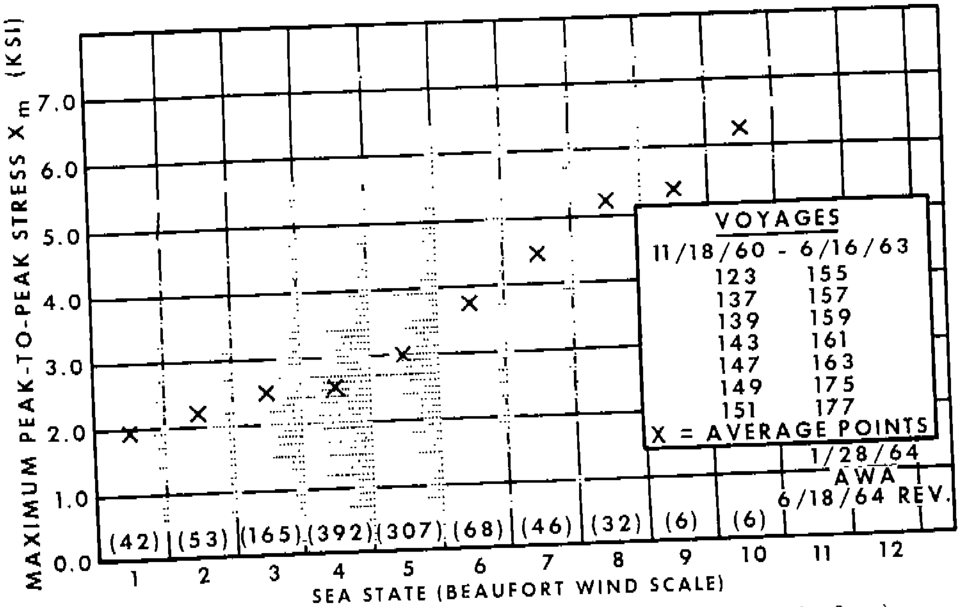


Fig. 41 Maximum peak-to-peak stress versus sea state (SS *Hoosier State*)

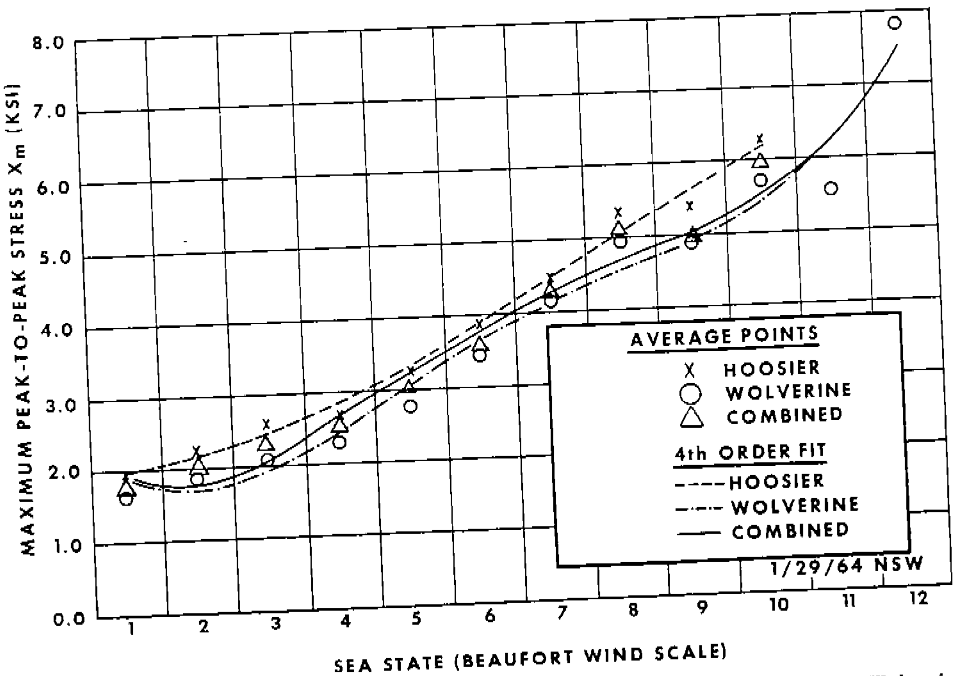


Fig. 42 Maximum peak-to-peak stress versus sea state (SS *Hoosier State*, SS *Wolverine State*, and combination)

half-hour record representative of 4 hr of ship operation. The average values of all the data points within each sea state were calculated, and are shown in Fig. 41 by the symbol (X). Curves of the best fourth-order, least-square polynomial fit to these average values were determined by digital computer. The resulting curves for the individual ships and for the combined data from both ships are presented in Fig. 42, where it is noted that remarkable similarity exists in the stress pattern for the two ships. The distribution of the time spent by each ship in various sea states during the total time represented by the reduced data (4964 hr for *Hoosier State* and 6828 hr for *Wolverine State*) are shown in Fig. 43.

The maximum hull girder deck stresses (peak-to-peak) of Fig 42 are moderately low, about 8000 psi, even for the high sea states (Beaufort 11–12).

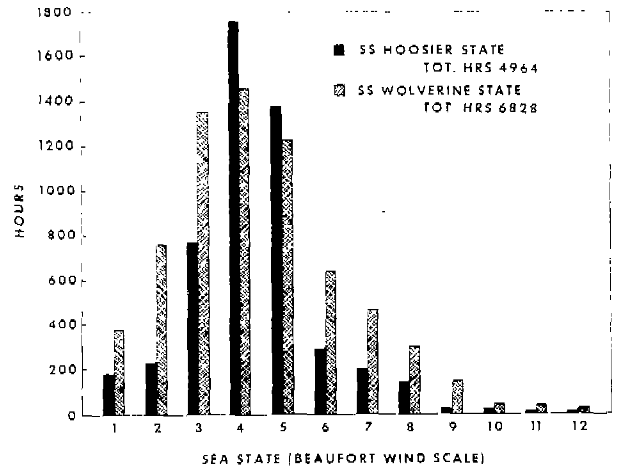


Fig. 43 Distribution of time at various sea states

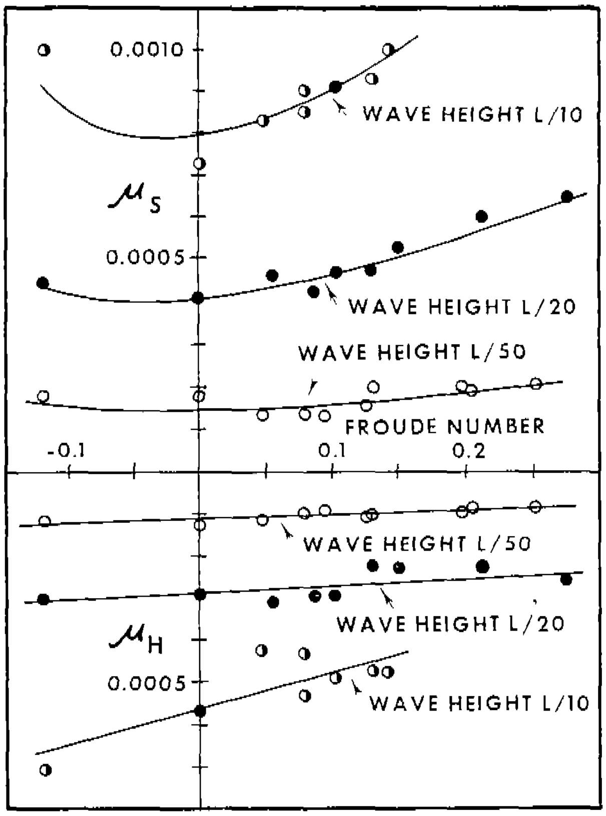


Fig. 44 Variation of bending moment with speed for Mariner in head seas

A statistical prediction based on the limited amount of long-term data available from two analyzed voyages yielded an extreme peak-to-peak stress of 10,300 psi for a year's operation of this ship type on the North Atlantic route. It should be emphasized here that there was a limited number of occurrences of high sea states which may partially explain why the predicted stress was not closer to the measured value. Until this critical area is explored more fully, the trend of the stress curve in this region should be considered with caution. Sea states in this analysis were inferred from the corresponding Beaufort wind scale. It is suspected that the sea state thus derived does not correctly define the spectral energy density of the wave system that excites the ship to its maximum stress. Only directly measured wave data can establish this most important technical point The subsequent installation of a sea state meter in *Wolverine State* is thus amply justified.

The additional hull girder response data collected by *Wolverine State* and *Mormacscan* from January, 1963–February, 1966 have been analyzed by the technique already described. The data for this period represent an additional total of 6528 hr at sea for the two ships. The maximum peak-to-peak stresses, when plotted as in the previous voyages, resulted in a curve very similar to Fig. 42. Nothing significantly different has been revealed by this additional period of data collecting. The measured maximum peak-to-peak wave-induced stress for the high Beaufort sea state of 11 is still moderately low, about 7000 psi.

From this study it was concluded that

1 A comparison of the long-range stress data from sister ships versus sea states indicated that the data from each ship are typical for the type.

2 The log-normal distributions were essentially the same whether developed by manual data reduction or by the probability analyzer.

3 The prediction of the maximum peak-to-peak stress from the log-normal distribution appeared to have a fair correlation with measurements at sea within the range recorded. This strengthens the case for eventual use of statistical analysis in designing a ship's hull girder.

Acceleration Data

For a period of 15 months, ending February, 1964, acceleration data were recorded from seven linear accelerometers on *Wolverine State* on its regular North Atlantic service (SSC-159). The specific purpose here was to establish the basis for predicting the extreme values of acceleration which would be felt by sensitive cargo. Acceleration has significance not only to the structural behavior of the hull, but to cargo packaging design as well. The data acquisition system for this study operated satisfactorily for 14 of 15 round trip voyages. This represented over 8000 hr of ship operating time of which 6200 hr were in the open ocean.

The acceleration records were analyzed using a

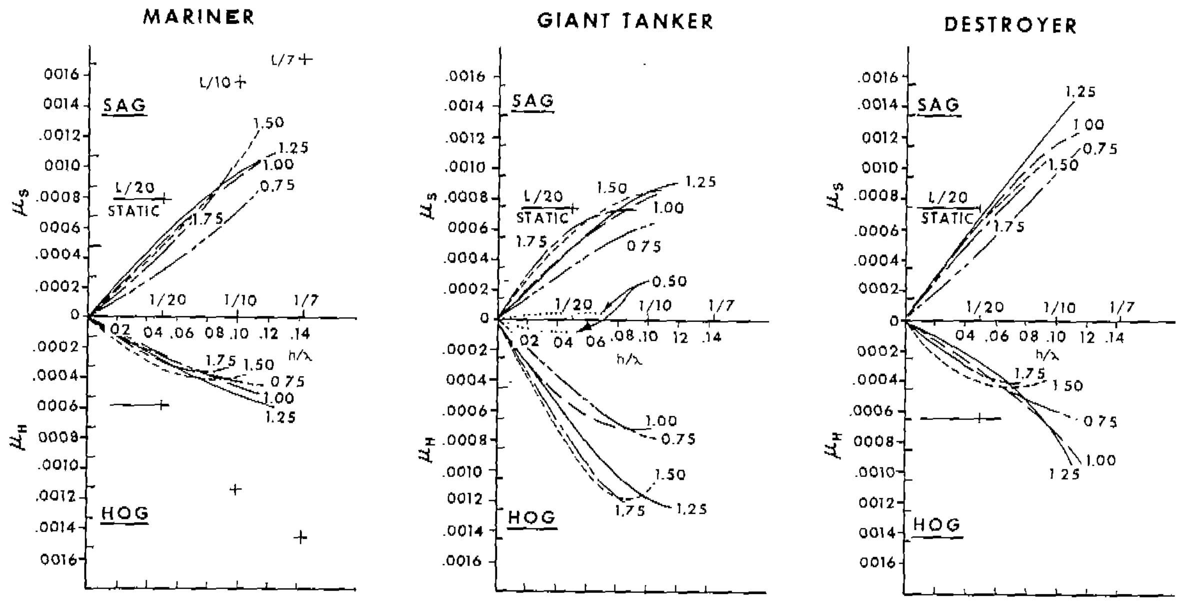


Fig. 45 Variation of bending moment with wave steepness for various head sea wave lengths (Mariner, supertanker, and destroyer)

special purpose probability analyzer. The maximum observed wave-induced bow acceleration for this period was 1.76 g (peak-to-peak) which occurred in state 8 sea. This acceleration is within 6 percent of the predicted value using the statistical approach already described. The long-term prediction for a seven-year operating span using the log-normal distribution was a probable maximum bow vertical acceleration of 2.97 g (peak-to-peak). It was noted that the bow acceleration histograms and the corresponding log-normal distributions were similar in appearance to those for stress. It was concluded, therefore, that acceleration data, like wave and stress data, could be analyzed by the Rayleigh and log-normal distribution statistical technique, subject to the basic limitations inherent to the statistical approach.

Determination of Bending Moment from Models

Concurrent with obtaining hull girder response of actual ships at sea in their natural environment, a comprehensive model study has been carried out in the test tank with ship models representing a Mariner, a tanker, and a destroyer. The experimental investigation was aimed at obtaining a physical upper limit on the midship bending moment when excited by extreme regular waves approaching a length-to-height ratio of 8.5. The study was a comprehensive one, including variations of load distribution, freeboard, speeds in head and following waves of several different lengths, and a wide range of wave heights.

The trend in bending moments obtained for the Mariner hull in head seas and various speeds of advance (SSC-155) is summarized in Fig. 44. It can be seen that the general trends of bending moments in very steep waves are not too different from those in moderate waves. For the conventional L/20 wave, the hogging bending moments are approximately constant throughout the speed range, whereas in sagging there is a noticeable increase in moment with speed. Another way of expressing the experimental data is given in Fig. 45. The trends in bending moment here were typical of those observed for other ship parameters and clearly showed that the bending moments increased linearly with wave steepness.

The second part of this broad study (SSC-156) involved the model performance of a supertanker and a destroyer. For the tanker, the data showed a tendency for the bending moment to be nonlinear with increasing wave steepness, see Fig. 45. The highest recorded bending moments for this hull in head seas for the highest wave were between 10 and 20 percent greater than those obtained from the conventional static L/20 calculations. This trend in bending moment with wave steepness appeared to indicate that some limiting value exists at very high wave steepnesses. This tendency, however, was not observed for either the Mariner or the destroyer.

On the basis of this experimental investigation, limited as it was to regular waves, the conclusion was drawn that wave bending moments for the Mariner and a destroyer are essentially proportional to wave heights. Data for the supertanker, however, indicated a leveling-off tendency. By establishing more firmly the *gross linear dependence of bending moments on wave heights* over a considerable range of wave severity, this study has strengthened the case for determining design moments on the basis of statistical analysis of sea waves. No significant limit on wave-induced bending moments amidships in head or following seas was observed as wave steepness was increased up to a value of about $1/9$.

One of the basic assumptions made in the structural design of the hull is that the maximum hull girder bending moment occurs amidships. To check out this generally accepted assumption, the experimental investigation on the Mariner was expanded (SSC-163) by testing a model which was instrumented to record the vertical wave bending moment at several stations within the midship half-length. The tests were carried out in regular head and following waves with the waves having a ratio of height to length (steepness) from 0.05 (the conventional L/20) to 0.11, and ratio of wave length to ship length from 0.75 to 1.75. For the forward runs, the model Froude number was maintained between 0.13 and 0.14 which corresponded to a ship speed of 9.2 to 10.7 knots.

A typical plot of the bending moment variation along model length for one type of load distribution is reproduced in Fig. 46. Similar trends were observed for the other parameters investigated. In this plot, as well as Figs. 44 and 45, the quantities have been nondimensionalized. The terms μ_S and μ_H refer to the bending moment coefficient defined as

$$\mu = BM/\rho g B L^2 \tag{6}$$

where

ρg = weight density of water
L, B = model length and maximum beam, respectively
subscripts S, H refer to sag and hog, respectively

The maximum sagging moments for the normal load distribution case were found to be located between stations 8 and 9 for the steeper waves ($h/\lambda > 0.07$), and amidships for the less steep waves ($h/\lambda < 0.07$). The maximum hogging moments were located between stations 11 and 12 except for wave lengths equal to ship length and to $5/4$ ship length. For the latter case, large keel emergence was observed, and examination of the bending moment oscillogram showed evidence of flexural vibration. These factors suggest that slamming occurred which may account for the high midship bending moment values. It was also observed that the bending moments for a wave length equal to $5/4$ ship length were well in

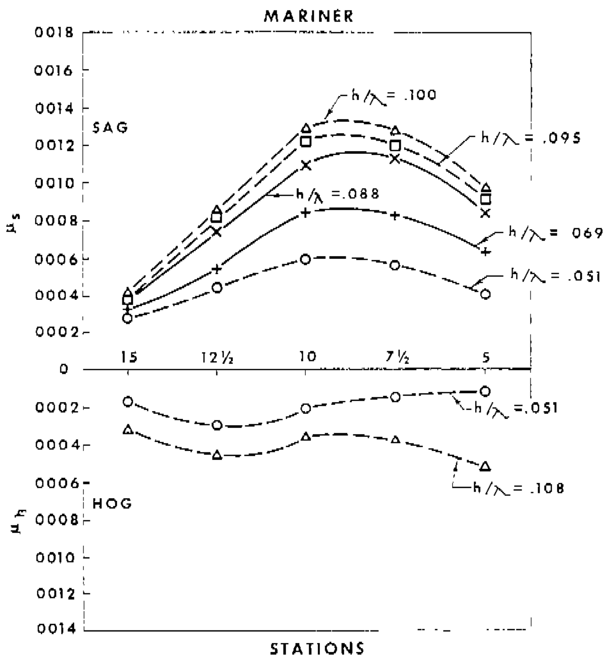


Fig. 46 Longitudinal variation of bending moment

excess of the standard calculated moment amidship.

The general conclusions derived from this study, which investigated variation in wave steepness, wave length, speed, and load distributions, were that

1 Hogging and sagging bending moments are generally proportional to the steepest regular wave generated ($h/\lambda = 0.11$).

2 The maximum wave-induced bending moment for the Mariner in extreme regular waves occurs within the midship half-length.

The last finding is significant since it matches the current design practice of maintaining the basic hull girder strength constant over the midship half-length.

Future Research

The present long-range goals of the Ship Structure Committee (SSC-176) include sponsoring a program of research which will provide a sound basis for

1 Designing more efficient ship structures of the same or greater safety than are currently used.

2 Adopting new materials of greater strength-to-weight ratios than are currently used as a possible avenue to increased cargo carrying capacity.

3 Assuming the adequacy of ship construction incorporating the new design methods and the new

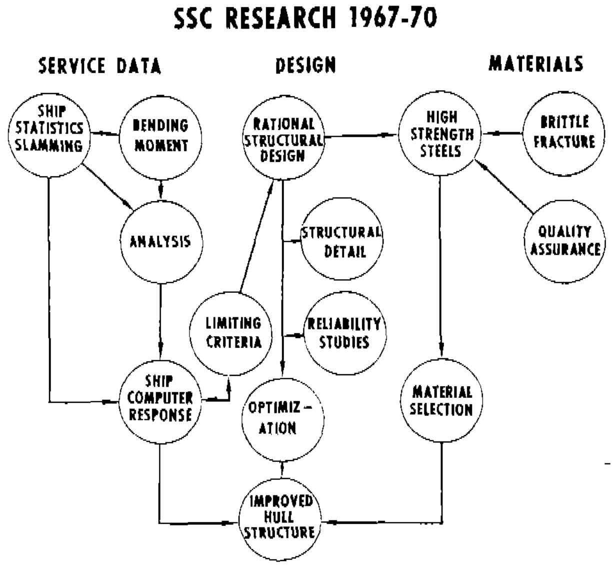


Fig. 47 Interrelation of present and future SSC research

materials with a view to decreasing the cost of the life cycle of ships.

The present five-year program to accomplish the ends of the long-range research goals can be conveniently divided into three areas of research: load and response studies, structural analysis and design, and materials. The interrelation of all current and contemplated research is shown in Fig. 47.

Load and Response Studies

The scope of this area of research includes

1 Obtaining directly comparative information for several typical ships on trends of seaway-induced maximum bending moment with wave proportions and spectrum, ship characteristics, loading, and speed.

2 Improving the understanding of the nature, level, and distribution of the hydrodynamic loads on ship hulls, including slamming and other seaway loads.

3 Determining the correlation of model and full-scale structural response and the applicability of computer techniques to structural design.

Structural Analysis and Design

The scope of this area of research includes

1 Establishing bases for rational structural design of ships.

2 Determining means for liberalizing certain criteria that restrict flexibility.

3 Determining the optimum distribution of material.

4 Establishing bases for structural design of larger, longer, or faster ships; of ships having unusual cargo requirements such as very wide hatches, cryogenic material, or high-temperature liquids; and for ships with combinations of these features.

Materials

The scope of this area of research includes

1 Evaluating higher performance steels and alloys.

2 Improving fabrication quality control criteria.

Computer Impact

Although the current and contemplated projects do not depart greatly from those previously recommended (SSC-126), the greatly increased computer capabilities since 1959 foretell exciting changes in approach. It is certain that all future research of the Ship Structure Committee will bear the heavy stamp of computer science. Indeed, the present work of the Committee is already marked by the inroads of this marvelous capability.

The major reason that ship structural design presently consists of application of large numbers of empirical formulations is that, heretofore, the mass of data which was required to be assimilated by the designer was beyond the capabilities of one man or a team of men. This is no longer true. What was tedious, difficult, and possible for man is made to order for computer applications.

The major structural problem facing the naval architect today is the *determination of the loads on a ship*. With appropriate load input, the analytic tools available today can, for the most part, predict the stress distribution. This, in turn, simplifies material selection.

The Ship Structure Committee has, as has been described in the section *Data from Ships in Service*, accumulated full-scale stress measurements at sea on three classes of dry cargo ships. As is shown in Fig. 47, these data are expected to assist in the development of a mathematical model for predicting stresses arising from an irregular sea spectrum. In this endeavor, both digital and analog computers will probably be used to the fullest. Hopefully, the time is not far off when the maximum wave-induced stress can be predicted solely on the basis of a computer run on the mathematical model of the ship in question for the sea spectrum of the route for which it is being designed.

Presently under development is a computer program which will analyze longitudinal, grillage, and plate stresses in an integrated fashion. One advantage of computer formulation is the requirement that each step of the design cycle be explicit. Hence, each step must be carefully documented. Because of this, weak links of a design are constantly highlighted. These, in turn, lend themselves to improvement since each subroutine of the computer program can easily be modified separately. As the overall structural solution is formulated, the Ship Structure Committee expects to apply the best available analytic techniques, such as the finite element approach, to the difficult aspects of detail design; e.g., brackets. Once the structural design computer program is complete, the optimization of design can proceed.

Optimization of Ship Structures

The optimum ship structure has been defined as "*the design which meets defined strength and stiffness as well as operating requirements under defined loading conditions with the lowest capital, maintenance, and running costs during a defined ship life*" [7]. It is obvious also that an optimum ship structure is interrelated with the selection of the principal ship characteristics. Such questions can only be answered by extensive operational research to account for the myriad of parameters which must be considered. Once the arrangements and principal ship characteristics have been determined, optimization of the ship structure may proceed on a rational basis. Only the computer permits solution of this vast information handling system. Such factors as number of pieces, size of welds, and type of edge preparation influence production costs and may prevent the least-weight structure from being the least-cost structure.

Nevertheless, increased interest in faster ships has intensified the demand for weight reduction which, in turn, requires more refined structural design. It is to this facet that the Ship Structure Committee has directed its future work—but always with an eye toward costs.

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Appendix

SSC-1 *Cleavage Fracture of Ship Plate: Hatch Corner Tests* by E. P. DeGarmo, J. L. Meriam, R. C. Grassi, J. W. Harman, and M. P. O'Brien. PB 36918 AD 636741

SSC-2 *Causes of Cleavage Fracture in Ship Plate: Flat Plate Tests* by H. E. Davis, G. E. Troxell, A. Boodberg, E. R. Parker, and M. P. O'Brien. PB 39555 AD 636742

SSC-3 *Cleavage Fracture of Ship Plates as Influenced by Size Effect* by W. M. Wilson, R. A. Hechtman, and W. H. Bruckner. PB 48640 AD 643363

SSC-4 *Direct Explosion Test for Welded Armor and Ship Plate: Prime and Welded Plate Tests* by W. A. Snelling. PB 48639 AD 635769

SSC-5 *Causes of Cleavage Fracture in Ship Plate: Hatch Corner Tests* by E. P. DeGarmo, J. L. Meriam, and M. P. O'Brien. PB 48090 AD 636743

SSC-6 *Investigations of Brittle Cleavage Fracture of Welded Flat Plate by Means of a Bend Test* by H. E. Davis, G. E. Troxell, E. R. Parker, and A. Boodberg. PB 91928 AD 72181

SSC-7 *Fatigue Tests of Ship Welds* by S. C. Hollister, J. Garcia, and T. R. Cuykendall. PB 53956 AD 636749

SSC-8 *Causes of Cleavage Fracture in Ship Plate: Flat Plate Tests and Additional Tests on Large Tubes* by H. E. Davis, G. E. Troxell, E. R. Parker, A. Boodberg, and M. P. O'Brien. PB 610485 AD 636746

SSC-9 *Correlation of Laboratory Tests with Full-Scale Ship Plate Fracture Tests* by M. Gensamer, E. P. Klier, T. A. Prater, F. C. Wagner, J. O. Mack, and J. L. Fisher. PB 15865S AD 636752

SSC-10 *Cleavage Fracture of Ship Plates as Influenced by Size Effect* by W. M. Wilson, R. A. Hechtman, and W. H. Bruckner. PB 78748 AD 635148

SSC-11 *Metallurgical Quality of Steels Used for Hull Construction* by C. E. Sims, H. M. Banta, and A. L. Walters. PB 79553 AD 635182

SSC-12 *Investigation of Means for Evaluating the Quality of Hull Plate Steel by Tests Conducted on Furnace or Ladle Samples* by W. G. N. Heer, S. A. Herres, and C. H. Lorig. PB 85706 AD 635763

SSC-13 *Metallurgical Quality of Steels Used for Hull Construction* by C. E. Sims, H. M. Banta, and A. L. Walters. PB 86270 AD 635149

SSC-14 *Fatigue Tests of Ship Welds* by S. C. Hollister, J. Garcia, and T. R. Cuykendall. PB 91898 AD 635181

SSC-15 *Correlation of Laboratory Tests with Full-Scale Ship Plate Fracture Tests* by M. Gensamer, C. Wagner, and E. P. Klier. PB 88495 AD 72679

SSC-16 *Causes of Cleavage Fracture in Ship Plate: Hatch Corner Design Tests* by E. P. DeGarmo and A. Boodberg. PB 92112 AD 636739

SSC-17 *Correlation of Laboratory Tests with Full-Scale Ship Plate Fracture Tests: A Study of Strain. Gradients* by E. P. Klier, F. C. Wagner, J. L. Fisher, and M. Gensamer. PB 97726 AD 635794

SSC-18 *Correlation of Laboratory Tests with Full-Scale Ship Fracture Tests* by C. Wagner and E. P. Klier. PB 92914 AD 71728

SSC-19 *Correlation of Laboratory Tests with Full-Scale Ship Plate Fracture Tests: Analysis of True-Stress True-Strain Data on Project Steels* by E. P. Klier, J. O. Mack, F. C. Wagner, and M. Gensamer. AD 635766

SSC-20 *Investigation of Means for Evaluating the Quality of Hull Plate Steel by Tests Conducted on Furnace or Ladle Samples* by J. A. Davis, S. A. Herres, C. T. Greenridge, and C. H. Lorig. PB 98199 AD 635787

SSC-21 *Twelve-Inch Flat Plate Tests* by S. T. Carpenter, W. P. Roop, N. Barr, E. Kasten, and A. Zell. AD 635172

SSC-22 *Correlation of Laboratory Tests with Full-Scale Ship Plate Fracture Tests* by C. Wagner and E. P. Klier. PB 92914S AD 635793

SSC-23 *Evaluation of Improved Materials and Methods of Fabrication for Welded Steel Ships* by R. W. Bennett, P. J. Rieppel, and C. B. Voldrich. PB 97684 AD 72963

SSC-24 *The Fundamental Factors Influencing the Behavior of Welded Structures under Conditions of Multiaxial Stress and Variations of Temperature, Stress Concentration, and Rates of Strain* by G. Sachs, L. J. Ebert, and A. W. Dana. PB 100737 AD 635171

SSC-25 *Metallurgical Quality of Steels Used for Hull Construction* by C. E. Sims, H. M. Banta, and A. L. Walters. PB 97725 AD 72961

SSC-26 *Metallurgical Quality of Steels Used for Hull Construction* by C. E. Sims, H. M. Banta, and A. L. Walters. PB 97724 AD 72962

SSC-27 *Causes of Cleavage Fracture in Ship Plate, Tests of Restrained Welded Specimens and Hatch Corner Specimens of Mild Steel* by A. Boodberg and E. R. Parker. PB 98508 AD 635795

SSC-28 *Causes of Cleavage Fracture in Ship Plate, High Yield Strength Structural Steel* by A. Boodberg and E. R. Parker. PB 99971 AD 635108

SSC-29 *Application of the Explosive Test to Evaluate Shock Properties of High Yield Strength Steels Part I: Preliminary Investigation of Techniques for Direct Explosion Testing of High Yield Strength Steels* by A. Muller, W. G. Benz, and W. A. Snelling.
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SSC-30 *Correlation of Laboratory Tests with Full-Scale Ship Plate Fracture Tests* by E. P. Klier and M. Gensamer. AD 8710

SSC-31 *The Effect of Cyclic Stress on the Transition Temperature of Steel* by H. E. Jacques. PB 98409 AD 635109

SSC-32 *High-Speed Rotating Disk Project* by C. W. MacGregor, W. D. Tierney, and H. Majors, Jr. PB 99629 AD 134702

SSC-33 *Evaluation of Improved Materials and Methods of Fabrication for Welded Steel Ships* by R. W. Bennett, R. G. Kline, M. Forman, P. J. Rieppel, and C. B. Voldrich. PB 99866 AD 635762

SSC-34 *The Fundamental Factors Influencing the Behavior of Welded Structures under Conditions of Multiaxial Stress and Variations of Temperature, Stress Concentration, and Rates of Strain* by L. J. Klingler, L. J. Ebert, and W. M. Baldwin, Jr. PB 99868 AD 635791

SSC-35 *Part I: Twelve-Inch Flat Plate Tests Part II: Aspect Ratio Program* by S. T. Carpenter, W. P. Roop, E. Kasten, and A. Zell. PB 99867 AD 635797

SSC-36 *Evaluation of Improved Materials and Methods of Fabrication for Welded Steel Ships* by R. F. Baysinger, R. G. Kline, P. J. Rieppel, and C. B. Voldrich. AD 73103

SSC-37 *Considerations of Welded Hatch Corner Design* by Ship Structure Committee. PB 109212 AD 29400

SSC-38 *A Study of Plastic Deformation and Fracturing by Strain Energy Distribution* by S. I. Liu and S. T. Carpenter. AD 635785

SSC-39 *Welded Reinforcement of Openings in Structural Steel Members* by D. Vasarhelyi and R. A. Hechtman. PB 137556 AD 72097

SSC-40 *Evaluation of Improved Materials and Methods of Fabrication for Welded Steel Ships* by R. F. Baysinger, R. G. Kline, P. J. Rieppel, and C. B. Voldrich. AD 73101

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SSC-42 *Determination of Initial Stresses in Steel Plates* by C. Riparbelli, E. W. Suppiger, and E. R. Ward. AD 218860

SSC-43 *Evaluation of Notch Sensitivity of Mild Steel Ship Plate by Direct Explosion Test* by G. S. Mikhalapov. AD 635107

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SSC-45 *Evaluation of Improved Materials and Methods of Fabrication for Welded Steel Ships* by R. F. Baysinger, P. J. Rieppel, and C. B. Voldrich. AD 73103

SSC-46 *Evaluation of Ship Welding Procedures by Direct Explosion Testing* by G. S. Mikhalapov. AD 72118

SSC-47 *The Strength, Energy Absorption, and Transition Temperature of Internally Notched Flat Steel Plates* by S. T. Carpenter and W. P. Roop. AD 29340

SSC-48 *A Study of the Structural Action of Superstructures on Ships* by H. H. Bleich. AD 635792

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SSC-57 *Cracking of Simple Structural Geometries: Investigation of Welded Ship Details* by S. T. Carpenter and R. F. Linsenmeyer. AD 29403

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SSC-59 *Critical Stress for Slip, Twinning, and Cleavage in Single Crystals of Iron* by J. J. Cox, Jr., G. T. Horne, and R. F. Mehl. AD 29769

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SSC-62 *Review of Past Structural Studies Related to the Ship and Ship Components and for Determining Loads and Strains on Ships at Sea* by J. H. Evans. AD 73876

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SSC-78 *Part II: Investigation of the Performance of Weldments and Prime Plate of ABS-B Steel* by W. S. Pellini and E. W. Eschbacher. AD 45653

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SSC-85 (Issued as SSC-92)

SSC-86 *Evaluation of Weld-Joint Flaws as Initiating Points of Brittle Fracture* by D. C. Martin, R. S. Ryan, and P. J. Rieppel. AD 106299

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SSC-91 *Investigation of the Influence of Deoxidation and Chemical Composition on Notched-Bar Properties of Ship Plate Steels* by F. W. Boulger, R. H. Frazier, and C. H. Lorig. AD 75455

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SSC-94 *Mechanical Properties of High Purity Iron-Carbon Alloys at Low Temperatures* by R. M. Brick. AD 219817

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SSC-98 *Energy Release Rates during Fracturing of Perforated Plates (NRL Memorandum 370)* by M. W. Brossman and J. A. Kies. AD 79009

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SSC-100 *Index of Ship Structure Committee Publications* by M. B. Fisher. AD 161084

SSC-101 *Improved Notch Toughness of Experimental Semikilled Steels over One Inch in Thickness* by R. W. Vanderbeck. AD 106452

SSC-102 *The Relation of Microstructure to the Charpy Impact and Low-Temperature Tensile Properties of Two Ship Steels* by W. S. Owen, D. H. Whitmore, C. P. Sullivan, B. L. Averbach, and Morris Cohen. AD 106390

SSC-103 *The Tensile Yield Behavior of Ship Steel* by W. S. Owen, B. L. Averbach, and Morris Cohen. AD 108862

SSC-104 *Development of Filmless Technique for Recording Defects in Ship Welds* by J. I. Bujes. PB 137557 AD 635678

SSC-105 *Weld Flaw Evaluation* by S. T. Carpenter and R. F. Linsenmeyer. PB 161322 AD 201631

SSC-106 *Mill Sampling Techniques for Quality Determination of Ship Plate Steel* by C. L. Staugaitis. AD 160562

SSC-107 *Evaluation of Weld-Joint Flaws as Initiating Points of Brittle Fracture* by R. P. Sopher, A. L. Lowe, Jr., and P. J. Rieppel. PB 161323 AD 203935

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SSC-171 *Micro- and Macrocrack Formation* by B. L. Averbach. AD 433496L

SSC-172 *Crack Extension and Propagation Under Plane Stress* by A. R. Rosenfield, P. K. Dai, and G. T. Hahn. AD 480619L

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SSC-177 *Guide for Interpretation of Non-Destructive Tests of Welds in Ship Hull Structures.* AD 639053

SSC-178 *A Survey of Some Recent British Work on the Behaviour of Warship Structures* by J. Clarkson. AD 644738

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The salient results of two decades of research into such broad areas as materials, physical and qualification tests, nondestructive testing of welds, stress distribution,data from ships in service, and bending moment determination by models are presented. The brittle fracture phenomenon is attacked from a number of fundamental views: variation of composition and microstructure, prior strain and thermal history, rate of loading, stress intensity and distribution, effect of flaws, and variation of test method. All these bits of research are shown to have contributed to the attainment of an engineering solution. Several of these areas are further discussed. Stress distributions at various geometrical discontinuities are reported as are those arising from temperature gradients. Stress intensities measured on ships in service are presented as are the long-term predictions from these measurements. The effect of mill practice on material performance is discussed. The current effort of developing generalizations from results of specific research is described. The trend of the future, the adaptation of computer to exploit generalizations for analysis of whole systems of structure, is set forth. Finally, a listing of nearly 200 reports is given along with information on how to obtain them from Federal repositories.

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Index of Ship Structure Committee Publications (1946 - April 1965)

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