# 9. Brittle Fractures in Ship Plates

By Morgan L. Williams [1]

The principal factors contributing to structural failures of welded ships and preventive measures that have been applied are discussed. Improvements of design details and welding workmanship have materially decreased the incidence of failures, but notch sensitivity of the steel is also an important factor, as geometrical or metallurgical notches resulting from operation or maintenance, as well as from unavoidable structural details or welding defects in the original construction, can never be entirely eliminated.

Statistical interpretation of the data obtained from laboratory investigations of 113 plates removed from fractured ships indicates that the probability of a fracture starting in a plate increases markedly with increasing notch sensitivity, as measured by the 15 foot-pound transition temperature of Charpy V-notch specimens. Within the range of the chemical compositions of the ship plates, the notch sensitivity is increased with increasing carbon or phosphorus content and decreased with finer grain size or with increasing silicon or manganese content.

## Introduction

The properties of metals at low temperatures are not merely an academic problem of importance only at the very low temperatures obtainable in the laboratory, but a very practical and serious problem at ordinary outdoor temperatures. Structural failures of welded merchant ships alone have cost the Nation almost 50 million dollars in the past 9 years [1],[2] and there have also been costly failures in other structures, such as bridges, storage tanks, and pressure vessels. Most of these failures occurred at low temperatures.

Approximately 5,000 merchant ships were built during World War II, and more than one-fifth of them had developed cracks in varying degrees before April 1946, when most of these ships were less than 3 years old [2]. From November 1942 to date, about 200 ships have sustained fractures that were classified as serious [3, 4]. This number does not include casualties resulting from war damage or from external causes, such as grounding or collision. Some of these failures involved the loss of lives and of ships.

Figure 9.1 shows the forward section of a tanker that broke in two at sea. Several people were removed from this section before it capsized and was sunk by gunfire.

Eight tankers and three Liberty type cargo vessels have broken completely in two as a result of the propagation of fractures that originated at some point in the hull structure or its appendages. About 25 other vessels have suffered complete fractures of the strength deck or the bottom.

Fractures have occurred in riveted ships and structures, but in a riveted ship the fractures usually ended at the first joint, and did not

[1] Metallurgist, National Bureau of Standards.
[2] Figures in brackets indicate the literature references on p. 206.

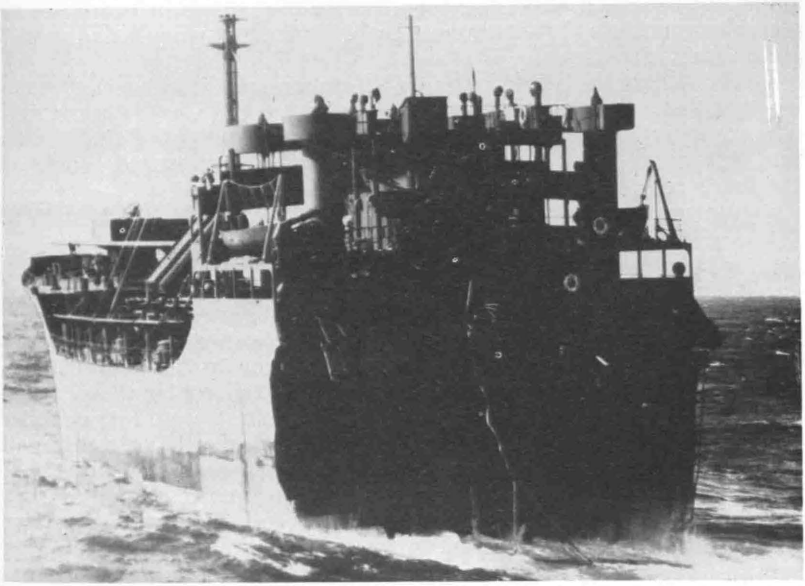

FIGURE 9.1. *Forward section of a T2 tanker that broke in two at sea.*

propagate into adjoining plates. A welded structure, however, is continuous, and a crack may propagate across the welds from one plate to the next, resulting in a complete structural failure. Therefore, the problem of fracture origin and propagation has received more attention in the past few years, because welding has largely replaced riveting in the fabrication of ships and other structures.

In April 1943 the Secretary of the Navy established a Board to Investigate the Design and Methods of Construction of Welded Steel Merchant Vessels. That Board and its successor, the Ship Structure Committee, conducted extensive technical and statistical studies of the casualties, and initiated research projects in several laboratories for the study of some of the factors involved. The Metallurgy Division of the National Bureau of Standards had already assisted in investigations of some of the earlier failures and was assigned to the investigation of the plates removed from the fractured ships. To obtain material for this investigation, the U. S. Coast Guard in November 1943 issued instructions [5] to the effect that, if steel is removed in repairing a fractured ship, samples of the fractured plates, properly identified, should be sent to the National Bureau of Standards.

Samples from some 80 ships in which fractures occurred have been received and examined, and tests have been completed on 113 plates selected from 58 of these ships. When sufficient and suitable material was available, the laboratory investigation included examination of the fracture and of welds, microscopic examination, chemical analyses of the plates, Charpy V-notched bar tests over a range of temperatures, and tension tests. Measurements of the reduction of thickness at the fracture edge were made on plates that were not too badly corroded or battered, and gas analyses by the vacuum-fusion method were completed on about half of the plates. In some instances other tests were

made, but the main effort has been to obtain as much information as possible from tests that were more or less standard when this investigation was started.

To coordinate the results of the laboratory investigations with service experience, information was obtained from the Coast Guard and other cooperating agencies regarding the circumstances of the casualties, structural features of the ships involved, location and extent of the fractures, and other pertinent details.

## Factors Involved in Structural Failures

The failures of the welded ships resulted largely from the lack of adequate knowledge of the distribution of stresses in ships under different operating conditions and of the significance of certain properties of structural steel, especially their relation to the performance of structures containing notches or similar discontinuities. The Board of Investigation, the Ship Structure Committee and its member agencies, and a number of cooperating laboratories have completed investigations to secure information on these phases of the subject.

There are three principal factors involved in the prevention of failures of welded structures. First, the material, mostly steel plates and weld metal, should possess, uniformly, the properties anticipated by the designer. Furthermore, these properties should not be affected adversely by the effects of fabricating operations or operating conditions. Second, the design should aim to produce a structure functionally suitable for the purpose intended, with adequate strength in all parts of the structure, under all possible operating conditions. Third, workmanship or fabrication—the work of the fitters, welders, supervisors, and inspectors—must carry out the ideas of the designer, and must produce joints of the strength that he intended.

Of course, these three factors are somewhat interrelated, and there may be some others involved, such as cost and availability of materials. For example, a design suitable for one material might be entirely unsuitable for a different material. The designer must consider the properties of the materials that are to be used, in relation to the design strength required and to the effects of any conditions that might be expected in fabrication or in service. Workmanship is also related to design; it is easier to make a good weld downhand than in a vertical or overhead position, or in a location that the welder cannot reach easily.

The failures in the ships usually resulted from a combination of these three factors, but each of them will be considered separately, with a brief discussion of what has been learned from the studies of the failures, and what has been done and what more can be done in the way of improvement.

## Workmanship

Many of the earlier failures originated in welds which contained obvious defects, such as the following examples:

Figure 9.2 shows a fracture source in a butt weld in the bulwark cap rail of a cargo vessel. There was no penetration of weld metal in the center of the joint, resulting in a mechanical notch, as well as a

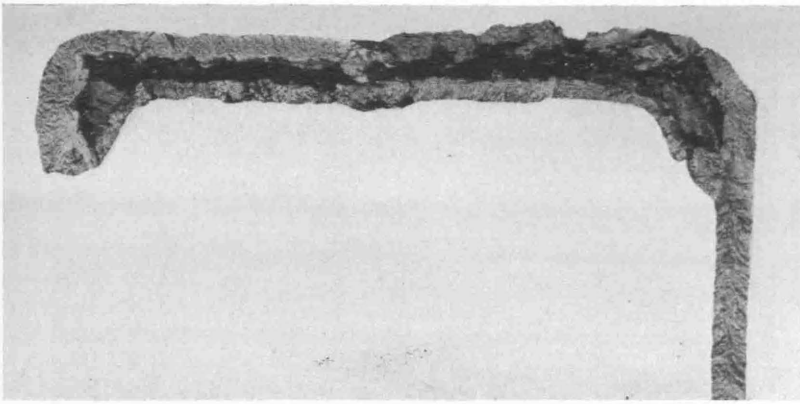

FIGURE 9.2. *Fracture source in defective weld of bulwark cap rail, ×2/3.*

reduction in the effective cross section, and resultant strength, of the weld. The herringbone markings, or chevrons, in the fracture of the bulwark plate at the right are characteristic of the brittle type of fractures that were found in most of the ship plates examined. This type of fracture was observed and reproduced at the National Bureau of Standards about 15 years ago, in tests conducted to determine the source of a brittle failure of an aircraft part. These tests, which were discussed in the first NBS report on the examination of steels from a fractured ship[6], showed that a brittle failure may be produced in a normally ductile metal by applying a tensile stress to a notched plate specimen, and also established the fact that the chevrons always point back toward the origin of the fracture, which made it possible to locate the sources of the fractures in the ships.

The bulwark plate and cap rail are not ordinarily considered as strength members in the design calculations. Actually, however, these parts are at a critical location—the extreme fibers, considering the entire ship as a beam—and they are joined to the hull structure by welding. A number of other fractures started in appendages not considered as strength members, and propagated through welds into the hull structure. This illustrates one important point. As cracks originating in any part of a ship may propagate into the hull structure through the welds, the standards of quality of materials, design, and workmanship, even for nonstrength members attached to the hull by welding, should be equal to those required in the hull structure itself.

Figure 9.3 shows another butt weld, in a hatch side longitudinal girder. Again, the weld metal did not penetrate to the full thickness of the joint—the original flame-cut edge may be seen in the center of the picture. The upper side of the weld had cracked at some previous time, probably during or shortly after the welding, and the crack was covered over when the part was painted. The light area near the top is red lead paint, which had penetrated the crack. After this vessel was launched, but before it was completed, there was a sudden complete failure of the strength deck starting at this joint and a similar faulty weld on the opposite side. Repairs cost $40,000. This

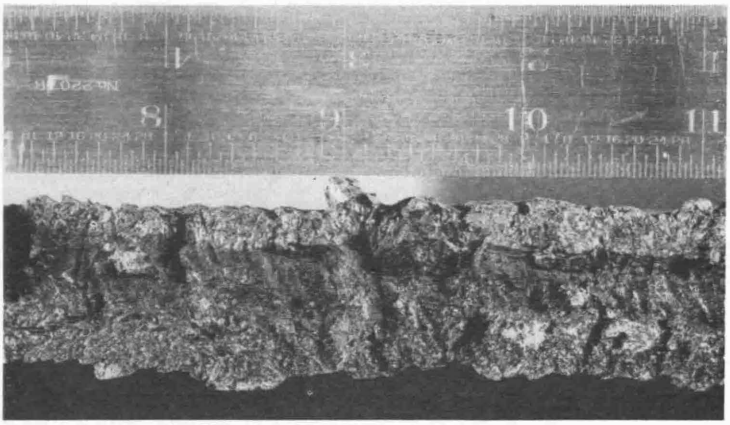

FIGURE 9.3. *Fractured weld showing paint penetration in previous crack.*

costly failure might have been averted if, by better supervision and inspection, the initial crack in one side of the weld had been found and repaired before being painted.

There are a number of other causes leading to cracks in welds, such as gas pockets, or porosity; slag and dirt inclusions in the weld metal; poor fusion; undercutting of the plate at the edge of the weld; shrinkage cracks; improper edge preparation or poor fitup of the plates; or the use of slugs to fill up space that should be welded.

In figure 9.4 the chevrons show two fracture sources in the plate near a lap-seam weld. Both sources are at small craters where apparently the welder had struck his arc on the plate, away from the area of the weld. This creates a small mechanical notch, combined with a "metallurgical notch", in which the properties are decidedly different from the properties of the parent metal. A small volume of metal is heated by the arc, but because of the short time and the small total heat input, the surrounding base metal is not heated appreciably. Consequently, the heated zone is cooled very rapidly by conduction to the surrounding mass of cold metal, which amounts, in effect, to a very drastic quench. The result is a hard, extremely notch-sensitive region, probably combined with residual tensile stresses resulting from thermal contraction. A metallurgical notch may also result from a small weld

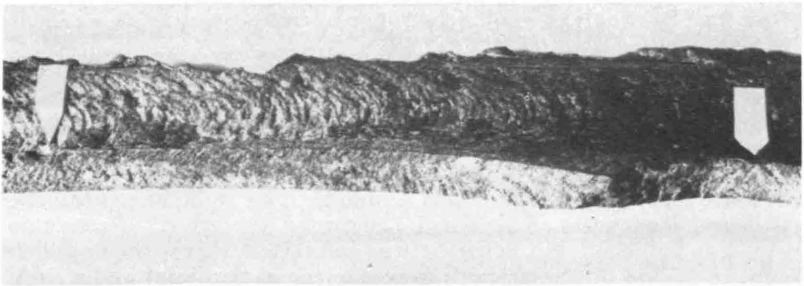

FIGURE 9.4. *Fracture sources at craters caused by touching welding electrode to plate.*

on heavy plate; a number of fractures have originated at light tack welds or at shallow welds joining small clips or brackets to heavier structural members.

As soon as it was realized that welding practices and defects of welding workmanship were a factor in the ship failures, the Board of Investigation initiated studies of welding procedures in the shipyards and in various laboratories, and started a campaign of education of welders and inspectors. A part of this effort was a small illustrated booklet [7] showing a few typical examples of serious failures resulting from welding defects, with a discussion of causes and cures of defective workmanship. The incidence of fractures resulting from welding defects has decreased noticeably in ships built since the issuance of this pamphlet in 1945.

## Design

As several of the early failures originated in defective welds, and there had been few such spectacular failures in riveted ships, all the failures were at first attributed to the effects of welding. If no obvious defects could be found, the failures were explained as a result of underbead cracking or of residual or locked-in stress resulting from weld contraction, and studies of these phenomena were initiated.

It was soon noted, however, that many of the fractures originated at structural details such as hatch corners, ladder cutouts, or other openings, or at the abrupt ending of stiffeners, such as a bilge keel or a deck superstructure. The origin of the fractures at these points may be attributed primarily to the stress concentration resulting from a geometrical or structural notch, although in every case the metallurgical effects of welding, flame cutting, or mechanical working were also present, and these effects are not separable. It is unfortunate that the nature of ship construction required large amounts of welding at such points of geometrical discontinuity, as in many cases the welding was blamed for a failure that was primarily a result of stress concentration at a structural notch.

Some structural discontinuities are necessary to the function and operation of a vessel, but the design details could be improved, and they were improved. Alterations were made on existing ships and in new construction. Reinforcements were added at critical locations, hatch corners and other openings were rounded, and the ends of some stiffeners were tapered, to reduce stress concentrations. Butt welds of appendages such as the bulwark plates or bilge keels were isolated from the hull structure, by cutting serrations or holes to break the continuity between these welds and the hull plates. Even with these improvements, cracks may start at unsuspected locations, so in many types of vessels barriers were installed to arrest such cracks before extensive damage resulted. The observation that in riveted ships the cracks usually stopped at a joint led to the installation of some riveted seams or angles in new construction. In existing all-welded vessels, longitudinal slots were cut in the deck plating, the sides, or the bottom, and the plates were then rejoined with a riveted crack-arrestor strap, similar to a riveted butt-strap joint.

The effectiveness of these improvements in workmanship and design details may be seen in the record of service performance [4]. The

original all-welded Liberty ships had 88 class I, or major, casualties in 2,100 ship-years of service, or 4.18 serious casualties per 100 ship-years. The all-welded Liberty ships with improved details, with and without riveted crack arrestors, have accumulated more than 7,000 ship-years of service to January 1, 1950, with only 37 major casualties, or 0.52 per 100 ship-years. Thus, the number of major casualties has been reduced by a factor of 8, largely as a result of design modifications in these ships. The design of the Victory ships incorporated many of the lessons learned from the earlier failures, and no major structural casualties have been reported in this type of vessel as originally built, with a service record of nearly 1,800 ship-years.

The stresses and stress concentrations in operating ships have been measured, both in this country and in England. The effects of reinforcements and of modifications of design details are being investigated, in service applications and in a number of laboratories. The designer now has available a better knowledge of the fundamental details on which to base his calculations, and we may expect further improvements in design.

## Materials

Tension tests indicated that the plates that had fractured in service were of normal ductility, and that the steels would meet the specification requirements under which they were purchased. This type of steel, in the usual tensile test, elongates under load more than 20 percent in 8 inches, and the reduction of cross-sectional area is about 50 percent, indicating that the material is capable of considerable plastic deformation before it will fracture.

The fractures in the ships, however, showed very little evidence of plastic deformation, or ductility. Nearly all these fractures were of a brittle type, characterized by a break nearly perpendicular to the plate surfaces, and a coarse granular, or crystalline, appearance of the fracture. The reduction of thickness at the fracture edge was very small, usually less than 2 or 3 percent, and the paint or scale on the plate surfaces was not cracked, even very near to the fracture. This showed that the fractures had propagated with very little plastic deformation of the steel, and probably at low stress levels. As energy, or the capacity for doing work, is proportional to the integral of stress (or force) times deformation (or distance through which the force acts), it is evident that much less energy was absorbed in the propagation of these fractures than in the normal ductile fracture of this material.

The lack of ductility and the brittle nature of these fractures indicated that when the steel was incorporated in the structure of the ship, the mechanism of fracture, or the mechanical properties of the steel, were not the same as when determined by the usual tensile test, using relatively small specimens. This phenomenon is similar to that observed in tests of notched specimens in tension or bending, particularly at low temperatures. The similarity is also evident in the facts that the fractures in ships occurred more frequently at the lower temperatures, and that the starting points of the fractures could be traced, invariably, to geometrical or metallurgical notches resulting from structural or design details, fabrication processes, or welding

defects. This phenomenon, called notch brittleness, is not peculiar to ship plate alone, and is not confined to metals. The scoring of glass for cutting and the notching of cellophane wrappers are familiar examples in which notch sensitivity is utilized to control the location or direction of a tear or fracture.

The importance of notch sensitivity and brittle fractures of the steel as a factor in the failures was recognized early in the investigation, and notched-bar tests on V-notch Charpy specimens were included in the examinations of the fractured plates. At the same time, investigations of the notch sensitivity of selected steels were conducted in other laboratories, and several new testing techniques and test specimens were developed. However, pending the results of these investigations, very little was known about the possibility of improving the notch toughness of steel in tonnage quantities. Consequently, during the war, preventive measures were directed largely to reduction of stresses by careful loading and ballasting, elimination of notches by improvements of design details and welding workmanship, and prevention of the spread of fractures by the installation of riveted crack arrestors. The effectiveness of these crack arrestors shows quite conclusively that the propagation of the fractures is not a direct result of the loss of the strength and support of the structural members initially fractured, but is due primarily to notch sensitivity. In the presence of the sharp notch formed by the initial crack, the fractures could propagate at relatively low stress and energy levels until the continuity of metal was broken by the crack-arrestor slot. However, even in cases where the entire deck or bottom was fractured, the remaining structure, in the absence of a notch, absorbed sufficient energy to prevent further spread of the fracture.

The failure of the tanker shown in figure 9.5 placed further emphasis on the importance of the steel itself in the prevention of structural failures. This ship broke almost completely in two, while tied up at a dock for conversion after the war. This conversion was to include the installation of crack arrestors. The positions assumed by the two parts of the vessel are an indication of the bending moments that contributed to the origin of the fracture, but the calculated nominal tensile stress in the deck was only 12,000 lb/in.$^2$, or roughly one-third the yield point of the steel.

The starting point of this fracture (fig. 9.6) was at the toe of a small fillet weld joining a clip to the deck stringer plate. The clip was evidently attached after the ship was built, and was placed very near to the end of a chock base, which was also welded to the deck. Two small arc craters were formed at the toe of the weld, probably because of the difficult welding position between the clip and the chock base. These craters, combined with the overlapping welds, one of which was small and shallow, formed a metallurgical notch in addition to the mechanical notch between the welds, and aggravated the stress concentration resulting from the stiffening effect of the chock base. The deck plate itself was not abnormally notch sensitive compared to other ship plates, but in the vicinity of the welds and the arc craters the notch sensitivity was probably greatly increased, as has been observed in a number of other ship plates.

The significant point illustrated by the casualty mentioned above is that even the greatest refinements of design and workmanship in the

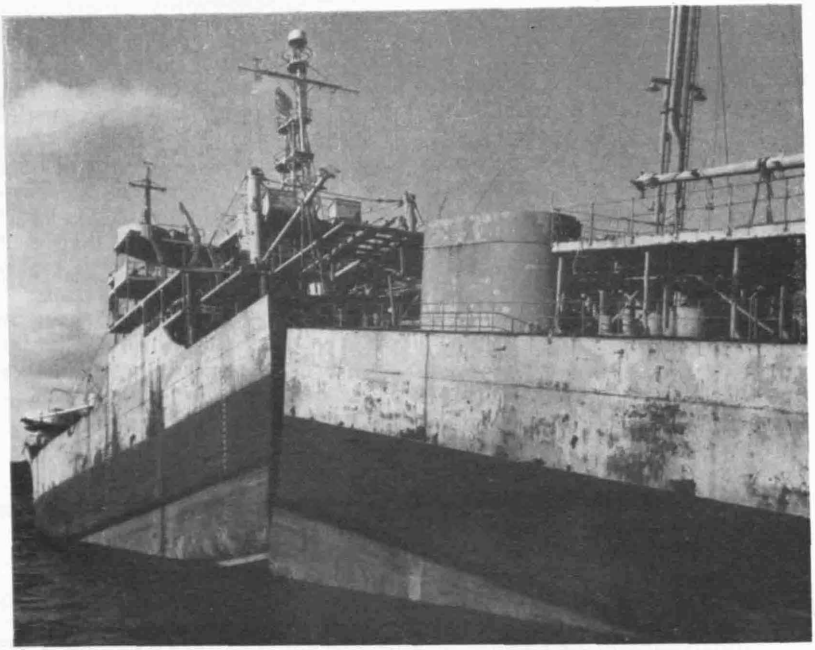

FIGURE 9.5 *Tanker that broke in two at dock.*

*original* construction cannot prevent failures that may result from notches introduced after the vessel is in service. A mechanical or metallurgical notch may be formed at any time during the life of a structure as a result of minor accidents, alterations, temporary attachments, or even accidental touching of the steel by a welding electrode or an electrical conductor. Such notches, resulting from conditions of operation and maintenance, as well as notches resulting from design details or defective welds in the original construction, can never be entirely eliminated. Therefore, it is evident that the material itself must be capable of resisting the initiation and propagation of fractures. In other words, the steel must be notch tough, and furthermore, this toughness must not be seriously impaired by fabricating operations, such as welding, flame cutting, or cold-forming, or by operating conditions, such as low temperature.

In tension, slow-bend, or impact tests of notched specimens, most steels are notch tough at higher temperatures, but as the temperature is lowered they become, suddenly or gradually, more notch sensitive. The fracture changes from ductile to brittle, and the energy required to produce fracture is reduced to a small fraction of that which can be absorbed at higher temperatures. The range of temperatures within which these changes take place, for a given steel, is called the transition range of that steel. Usually, for convenience, a specific point in this range is referred to as the transition temperature, defined by such criteria as the temperature at which brittle fractures first appear, the thickness reduction at some point in the specimen, the temperature at

FIGURE 9.6. *Source of fracture shown in figure 9.5 at arc craters in weld of small clip to deck.*

which the energy absorbed is 50 percent of the maximum, or the temperature at which the energy absorption is at a definite level, say 15 ft-lb for a V-notch Charpy specimen.

The transition range of a steel is dependent on the test method and on the geometry of the test specimen, but, in general, a series of steels will be rated in approximately the same order of merit by the various tests and by the different criteria of transition temperature. It should be noted, however, that the transition temperatures determined in laboratory tests are not necessarily the same as the transition temperatures of the same steels in a structure such as a ship, where the stress concentration, rate of stress application, notch geometry, etc., may differ widely.

It has been realized only recently that the usual tests for notch sensitivity measure, in varying proportions, a combination of two factors that may vary independently in their relations to stress concentration, temperature, and rate of stress application. The ductility transition is related to the resistance of a material to the initiation of a fracture, and is sensitive to specimen design, that is, the degree of restraint and the sharpness of the notch. The fracture transition is related to the resistance of the material to propagation of the fracture, and is relatively less sensitive to specimen geometry. Which of these transitions is of greater importance in relation to the problem of brittle fractures in ships is still a matter of debate [8, 9].

## Relation of Notch Sensitivity to the Failures of the Plates in Service

At the start of the investigation of the plates removed from fractured ships, the Charpy notched-bar impact test on V-notch specimens was chosen as a measure of the notch sensitivity of the steels. The amount of material available in the fractured plates was often limited, and this test, which was in fairly wide use at that time, requires a relatively small amount of material. It also has the advantages that tests can be conducted easily and quickly over a wide range of temperatures, and that the tests provide a numerical value of the energy required to fracture a specimen at a given temperature, which is independent of the personal judgment involved in determinations based on the appearance of the fractures.

After notched-bar tests were completed on only a few plates, it was observed that the plates in which the ship fractures originated showed lower energy absorption (or higher notch sensitivity) than plates that did not contain a fracture source. Therefore, the fractured plates for which definite information was available were classified into three categories: those which contained a fracture source (in the ship failures), those which were fractured through, and those which contained the end of a fracture. The plates were also classified in groups on the basis of plate thickness, to permit comparisons of data for similar material, and plates that were not strictly "hull plates of welded ships fractured under normal operating conditions" were placed in a separate miscellaneous group.

Figure 9.7 shows the notched-bar test curves in the transition range for plates in the "fracture-source" and "fracture-end" categories, for one thickness group. For each plate, points representing the average energy absorbed in tests at different temperatures are connected by straight lines ,with no attempt to smooth the curves. "T" on some of the curves indicates the temperature, if known, at the time of the ship failure. The 15 ft-lb transition temperature of each plate, defined as the temperature at which the notched-bar test curve crosses the line of 15 ft-lb energy absorption, is used to compare the plates at the same energy level. The horizontal bars superimposed on each set of curves represent the range of 15 ft-lb transition temperatures of the plates in each category, and the vertical bars represent the range of average values of energy absorbed in tests at 30° and at 70°F. It may be seen that the fracture-source plates (above) had higher transition temperatures, and lower values of energy absorption at corresponding temperatures than the plates in the fracture end category (below). That is, the plates in which fractures originated were considerably more notch sensitive than the plates in which the fractures ended. Similar sets of curves were drawn for the plates in the "fracture-through" category and for the other thickness groups, and the results are summarized in the following figures.

Figure 9.8 shows the energy absorbed by Charpy V-notch specimens at the temperatures of the ship failures in which the plates were involved. The horizontal bars represent the range of values of energy absorption at the failure temperatures, for each group of plates. The vertical lines in the bars show the values for individual plates, and

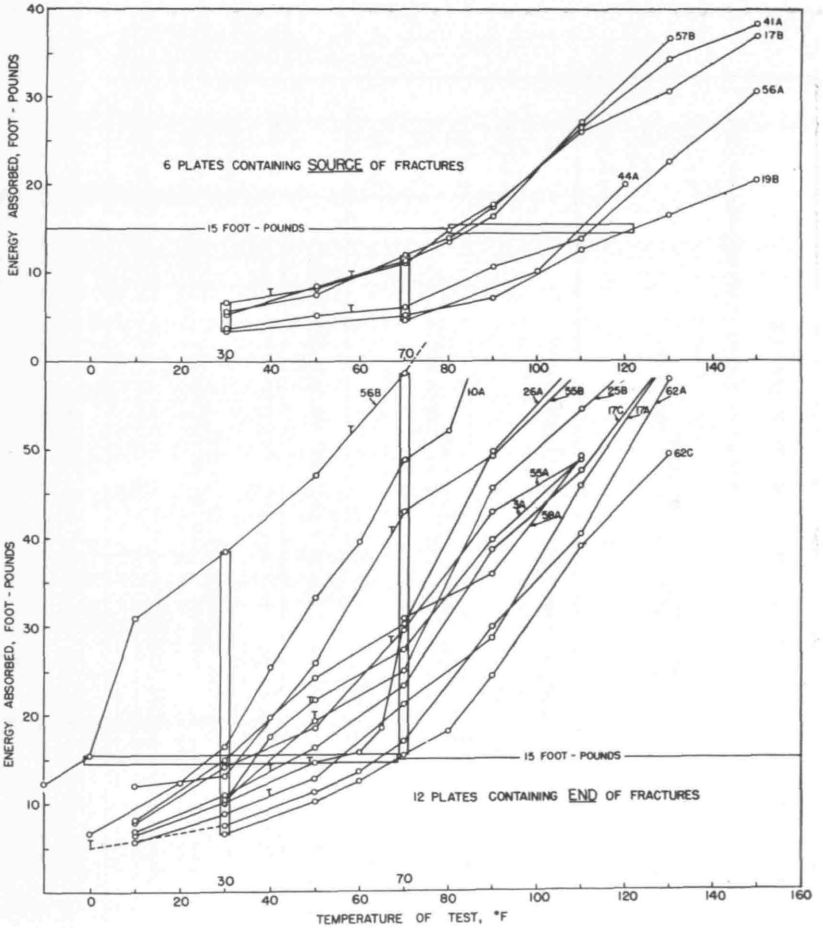


FIGURE 9.7. *Notched-bar test curves for plates containing sources and ends of fractures in the ships.*

the circles above the bars indicate the average value for each thickness group.

The 15 ft-lb transition temperatures of the plates are compared in figure 9.9. In addition to the average, individual values, and range of observed values for the plates in each category, the arrows show the range of plus or minus twice the standard deviation of the observed transition temperatures, which should include about 95 percent of the total observations. The upper three sections of the figure show the transition temperatures of fractured hull plates in the source, through, and end categories for each of the three plate-thickness groups, and the fourth section shows the data for all of the above thickness groups combined. In the lower section of the figure the data for the miscellaneous plates are shown. These are plates from riveted ships or from

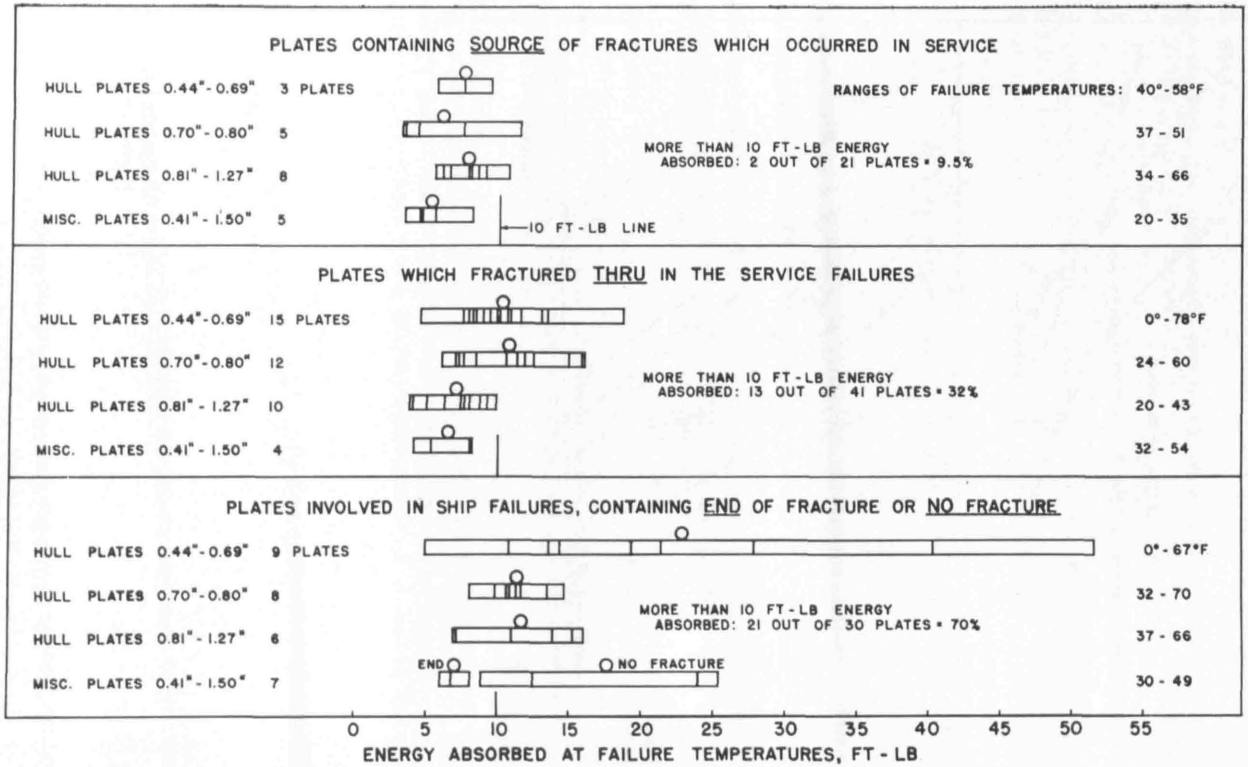


FIGURE 9.8. *Relation of energy absorbed by Charpy V-notch specimens at the temperatures of the ship failures to the nature of the fractures that occurred in service.*

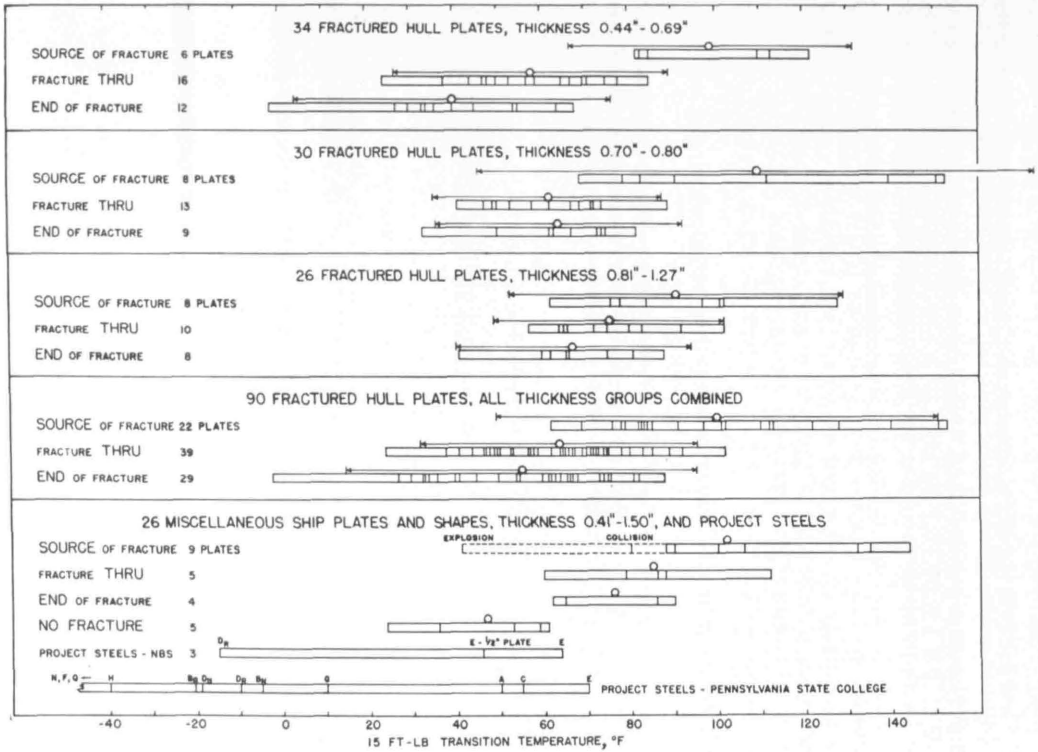


FIGURE 9.9. *Relation of 15 foot-pound transition temperature to the nature of the fractures in ship plates.*

parts other than the hull structure, plates in which the damage resulted from collision or explosion, plates in which the nature of the fracture was doubtful, or plates that contained no fracture, although fractures occurred in adjoining plates or welds. The 15 ft-lb transition temperatures of some of the Ship Structure Committee "Project Steels," are also shown for comparison.

A relation between the plate thickness and the transition temperatures of the plates is shown in the upper three sections of the figure. The thinner plates (top) show generally lower transition temperatures, and a greater spread of values than the thicker plates. This indicates that the notch toughness of a steel may be improved by the lower finishing temperature or the greater amount of hot-working, or other factors involved in rolling to thinner dimensions. However, the greater spread of values for the thinner plates suggests that the notch sensitivity is influenced also by other variables in the rolling process, such as reduction per pass or rate of cooling, since these variations would naturally be greater for thinner plates.

In each thickness group, and in the miscellaneous group, the average transition temperature of the plates in the "fracture source" category is higher than the average values for plates which did not contain the source of a fracture in the ship failures. Plates in which the ship fractures ended show (with one exception) lower average transition temperatures than plates in the fracture-through category, although this difference is not as great. The same consistent relationship is indicated also by both the upper and lower limits of the ranges of observed values of the transition temperatures, and the ranges of the scatter bands defined by the average value plus or minus twice the standard deviation.

Among the fractured hull plates, for the three thickness groups combined, only 2 out of 22, or 9 percent, of the plates in which fractures originated had transition temperatures below 70° F, the lowest being 62° F. In both of these plates, the fracture originated at an arc crater—a metallurgical notch. The transition temperatures of 64 percent of the fracture-through plates and of 76 percent of the fracture-end plates were below 70° F. In the miscellaneous group, the trend is similar. None of the fracture-source plates, except one damaged by an explosion, 20 percent of the fracture-through category, and 78 percent of the plates containing the end of a fracture or no fracture had transition temperatures below 70° F.

This evidence shows a very definite difference of the notch sensitivity of the plates in the different categories, which may be interpreted as follows: The plates in which fractures originated were, so to speak, "selected" because of lower than average notch toughness at critical locations in the structure. The fact that the majority of the ships of the same design and construction did not fracture, and that the fractures originated in different locations in the ships, indicates that this low notch toughness was a borderline deficiency of the steel. The plates in the "through" and "end" categories were "run-of-the-mill" plates that happened to be in the path of the fracture as it propagated. In some cases, higher than average notch toughness of the plates (that is, greater ability to absorb energy) contributed to the halting of the fractures, although there were many other contributing factors, such as dissipation of elastic energy,

changes in stress levels due to transient loads, readjustment of stress distribution, or the effect of nearby structural reinforcements.

It appears reasonable to believe that plates of the quality used in ship construction would show a distribution of notch sensitivity similar to the familiar Gaussian probability curve, that is, the great majority of the plates would have notch-sensitivity values near the normal or average for the type of material under consideration, and relatively few would have abnormally high or low values. Thus there is little probability that a small sample taken at random would include any plates with abnormally high or low values. This is shown by the ship plates which did not contain fracture sources and by samples taken from steel mills and from shipyard stocks [2]—these relatively small random samples did not include any steels with transition temperatures as high as those found for some "fracture-source" plates. However, if a much larger sample were taken, it is probable that such steels would be found. The fracture-source plates were not taken at random, but were "selected" because they contained the origin of a fracture. This selection was from a large sample (all of the plates in service at numerous critical locations in some 5,000 ships), and consequently the probability of finding plates with the abnormally high transition temperatures was much greater.

In figure 9.10 this interpretation is tested by analyzing the frequency distributions of the observed 15 ft-lb transition temperatures of the plates in each of the categories. The vertical bars indicate the number of plates (left-hand scale) or the percentage of the total number of plates in each category (right-hand scale) in each 15° F interval of transition temperatures. Fractured hull plates are represented by the center-lined portion of the bars, and the open parts of the bars represent the additional plates of the miscellaneous group. The average transition temperature of all plates in each category is indicated by the circles, and the arrows show the range of plus or minus one, two, or three times the standard deviation. The symbol × indicates the average for the hull plates alone. The essential data are given in table 9.1.

TABLE 9.1. *Comparison of average transition temperatures of all plates in the source, through, and end categories*

| Nature of fracture | Number of plates $=N$ | Average 15 ft-lb transition temp $=\overline{X}$ | Standard deviation $\sigma=\sqrt{\Sigma(\overline{X}-X)^2/N}$ |
|---|---|---|---|
| | | *° F* | *° F* |
| Source | 30 | 102.5 | 25.0 |
| Through | 45 | 65.7 | 17.5 |
| End | 38 | 56.3 | 20.1 |

The distribution curve for the fracture-through plates is nearly symmetrical, and closely approximates the normal curve (dashed line) computed from the values of the average and standard deviation. The curve for the fracture-source plates (top) is decidedly unsymmetrical, and the average transition temperature is 37 deg F higher than the average for the fracture-through plates. The distribution of the plates containing the end of a fracture or no fracture is also

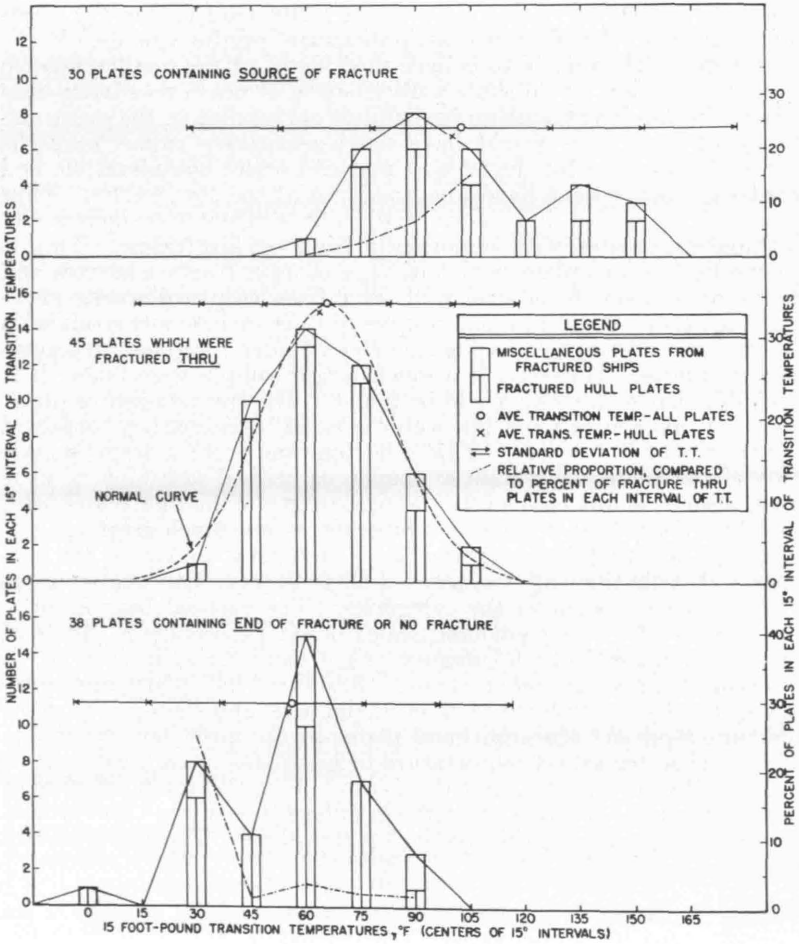


FIGURE 9.10 *Frequency distribution of 15 foot-pound transition temperatures of plates in the fracture source, fracture-through, and fracture-end categories.*

somewhat unsymmetrical, and the average transition temperature is 9 deg F lower than the average for the fracture-through plates.

Twenty percent of the plates in the fracture-source category had transition temperatures in the 75-deg interval, which is only a few degrees above the average transition temperature of the fracture-through plates. This might appear to indicate that there is no sharp demarcation between the transition temperatures of the run-of-the-mill plates and those that contained a fracture source. However, we must consider that these fracture-source plates were selected from a population in which the distribution of transition temperatures was not uniform. For example, in the general population (represented approximately by the sample of fracture-through plates) the 75-deg interval included about six times as many plates as the 105-deg inter-

val, but these two intervals included equal numbers of fracture-source plates.

The dot-dash line in the upper part of the figure shows the relative proportion of fracture-source plates to fracture-through plates in each interval of transition temperatures. This curve indicates that the probability of a fracture starting in a plate, under the conditions existing in a structure such as a ship, increases markedly with increasing notch sensitivity of the plate, as determined by the 15 ft-lb transition temperature of V-notch Charpy specimens.

The frequency-distribution curves also show that the plates with abnormally high transition temperatures, in which fractures are most likely to originate, represent the relatively few plates whose notch sensitivity falls in the tail of the probability curve for steels of the quality used when these ships were built—the borderline deficiency previously mentioned. This suggests two possible remedies (1) improvement of the average quality of the steel with respect to notch sensitivity. (In effect, moving the entire probability curve in the direction of increased notch toughness, so that a much smaller proportion of the plates in the tail of the curve would fall beyond acceptable limits of notch sensitivity); (2) determination of the notch sensitivity of every heat of steel by inspection tests, and rejection of all heats that fail to meet suitable prescribed standards. (In effect, "cutting off the tail" of the probability curve.)

In the application of these remedies, however, due consideration must be given to the possibility that the notch sensitivity of the steel as fabricated in the ship may be considerably greater than the notch sensitivity as determined by mill tests of the prime plate. It has been noted that all of the fractures originating in plates were associated with the effects of welding, flame cutting, or previous deformation of the plate. Notched-bar tests on a number of the fractured plates, and investigations in other laboratories, have indicated that the notch sensitivity is increased locally as a result of these operations. There is evidence also that this effect might be greater in some steels than in others, but more knowledge is needed in this field.

## Relation of Notch Sensitivity to Chemical Composition

To determine the effect of chemical composition on the notch sensitivity of the steels, scatter diagrams similar to figures 9.11 and 9.12 were plotted for each chemical element. The content of the element under consideration was plotted against the 15 ft-lb transition temperature, for the individual plates in each thickness group, using different symbols to indicate the nature of the fractures that occurred in the plates in service. The vertical bars at the left represent the range of element content for plates in the source, through, and end categories, respectively, and the symbols within the bars indicate the average values.

Carbon (figure 9.11) has a pronounced effect on both the nature of the fracture and the transition temperature. In each thickness group, the range and the average values of carbon content of plates in the fracture-source category are higher than for plates that did not contain a fracture source. Only one fracture-source plate (in all thickness groups) had a carbon content as low as 0.20 percent, whereas the carbon was at least this low in 28 percent of the fracture-through

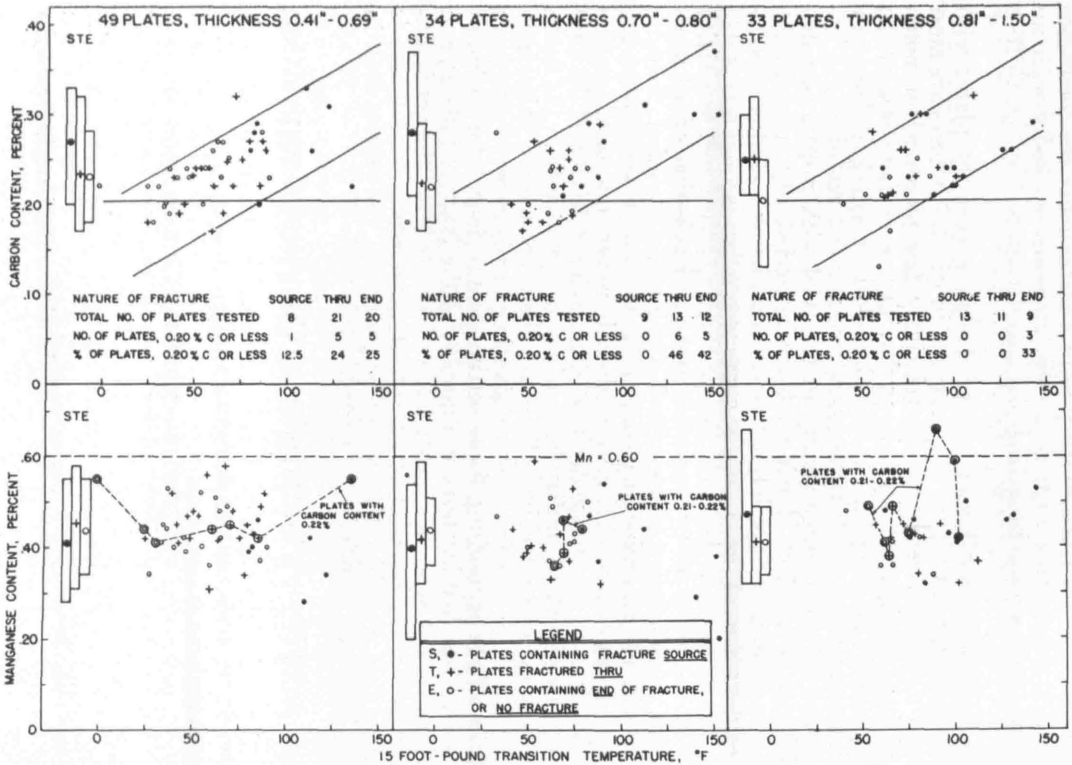


FIGURE 9.11. *Relation of carbon and manganese content to nature of fractures and to 15 foot-pound transition temperatures.*

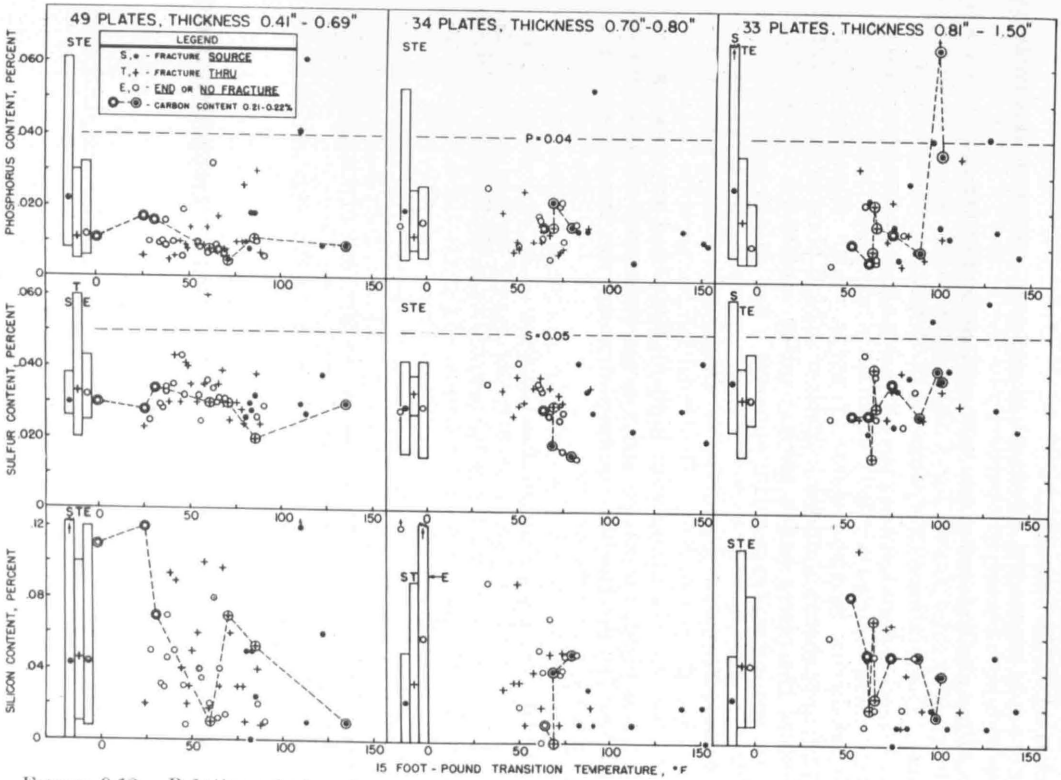


FIGURE 9.12. *Relation of phosphorus, sulfur, and silicon content to nature of fractures and to 15 foot-pound transition temperatures.*

and fracture-end plates. In the scatter diagrams, the majority of the points fall within a broad band (sloping lines), showing a general increase of the transition temperature with increasing carbon content.

Manganese content does not show any consistent relationship to either the nature of the fractures or the transition temperatures of the plates, even when plates of the same carbon content are compared, as indicated by the dashed lines.

Figure 9.12 shows the effects of phosphorus, sulfur, and silicon. Plates with high phosphorus generally had higher transition temperatures, although the trend is not very evident, as high transition temperatures were also found for a number of plates with low phosphorus. The relation to the nature of the fractures is more apparent, as in all thickness groups the plates with high phosphorus were in the fracture source category. This is probably related to the increase of notch sensitivity in the vicinity of welds, which other investigators [10] have shown is greater in steels with high phosphorus content.

Most of the plates had a normal sulfur content of 0.02 to 0.04 percent, and in this range sulfur apparently has little or no effect.

Silicon content, in the range zero to 0.12 percent, affects the transition temperature and the nature of fracture in the opposite direction to the effect of carbon. The transition temperatures were generally lower for the plates with higher silicon, and with the exception of one plate, the range and average values of silicon content were lower for the fracture source plates than for the plates which did not contain a fracture source.

Similar plots were made for each of the other elements determined in the chemical analysis, and for the gases. No definite relations could be observed between the content of any of these elements, considered individually, and the notch sensitivity as indicated by either the transition temperature or the nature of the fractures. This suggests that the effects of carbon, phosphorus, and silicon are considerably greater than the effects of other elements, in the amounts in steels of this type. However, many of these other elements were present only in small amounts, or, as in the case of manganese, in limited ranges, in the group of steels under consideration. Thus, it is possible that the effects of the relatively small variations of these other elements might be obscured by the effects of carbon, phosphorus, and silicon.

An attempt was made to find the effects of these other elements by a method of successive elimination of variables, assuming, provisionally, that the effects of the individual elements might be additive. Tentative correction factors for the effects of carbon and silicon, estimated from the scatter diagrams for these elements, were added to the observed transition temperatures of the plates in each thickness group, and the content of each element was plotted against the corrected transition temperature. With the variations due to carbon and silicon at least partially eliminated, the effects of other elements could be seen, and tentative correction factors for these elements were also added. This process was repeated several times, and at each step the estimated correction factors for each element were checked by the slope of the scatter diagrams, and modified if necessary. As it is well known that the transition temperature of a steel is affected by the grain size, a correction factor for the fracture grain size was determined in a similar manner.

The corrections for the content of the chemical elements reduced the spread of the corrected transition temperatures of the plates in each thickness group, so that most of them fell within a band of plus or minus 30 deg. F, but the positions of these bands were different for the three thickness groups. The addition of the correction for grain size practically eliminated the differences between the thickness groups, indicating that the generally higher transition temperatures of the thicker plates were due primarily to larger grain size.

The corrected transition temperatures of about 95 percent of the ship plates tested, in all thickness groups, now fell within the same plus or minus 30-deg band, or stated in mathematical terms: 15 ft-lb transition temperature (°F) + correction factors for chemical composition and grain size = constant ± 30° F (for 95 percent of the plates tested). Most of the plates that had corrected transition temperatures higher than this band had been severely deformed in fabrication or incident to the casualty, and the high transition temperatures of these plates may probably be attributed to the deformation or to subsequent strain aging.

This looks like a formula for predicting the transition temperature of a steel, but the assumed additive relation on which the method was based had not been proved, and the results were applicable only in the limited range of compositions of the ship plates. The correction factors could not be determined accurately for some of the elements that were present only in small amounts, but the results obtained appeared to indicate that the transition temperatures of the steels were increased with increasing content of carbon, phosphorus, molybdenum, and arsenic, and decreased with finer grain size and with increasing amounts of manganese, silicon, copper, and nickel.

While this work was still in progress, results of an investigation at the Naval Research Laboratory became available. The investigators [11] determined the effects of various elements on the transition temperatures of controlled laboratory heats of steel in which only one element was varied, and also showed that the effects of carbon, manganese, and nickel are very nearly additive.

In the range of compositions covered by both investigations, the results obtained by "working backward" from the compositions of the fractured ship plates were in good agreement with the results for the 15 ft-lb transition temperature obtained at NRL by the more straightforward laboratory method. This appears to validate the assumption of an additive relation for the effects of the other elements. However, the two investigations did not agree on the effects of copper and silicon, which illustrates the dangers of optimistic extrapolation. In the low ranges of copper and silicon content found in the ship plates, these elements appear to lower the transition temperature, but in the higher ranges covered by the NRL investigation, the transition temperature is raised by further additions of these elements.

Further investigations at NRL, and similar research at another laboratory [12], using different specimen types, have shown that the notch sensitivity is first lowered, and then raised, as the silicon content is increased. The effects of some other elements also change, either in magnitude or direction, as the content of the element is increased, and there may also be interactions between certain elements that do not show up when only a single element is varied. The work

at NRL also showed that some elements, such as carbon, change the shape of the transition curve for Charpy V-notch specimens, so that the effects of these elements are not the same for different criteria of the transition temperature. All of these factors must be considered in evaluating the effects of composition on the notch sensitivity of hot-rolled steels.

Using the published data from the NRL investigation, combined with the ship-plate data, better values for the correction factors were obtained. A tentative formula including 11 correction factors, for 8 chemical elements and the grain size, was tried out on more than 200 steels, covering a 400-deg range of observed 15 ft-lb transition temperatures. The calculated transition temperatures of more than 90 percent of these steels were within ±30 deg of the observed transition temperatures, but it is hoped that this formula can be improved, and it will be necessary to try it on a larger variety of steels to determine its limitations.

A simpler short form of the formula would probably be more useful in the range of compositions of the usual hot-rolled structural or ship-plate steels. Nine-five percent of the 113 ship plates, and a number of other steels of similar composition, had transition temperatures less than the maximum indicated by the formula

$$\text{(Max) 15 ft-lb transition temperature } (^\circ\text{F}) = 100 + 300 \times \%\ \text{C} + 1000 \times \%\ \text{P} - 100 \times \%\ \text{Mn} - 300 \times \%\ \text{Si} - 5 \times \text{fracture grain-size number}$$

This formula, however, is not applicable for compositions containing more than about 0.35 percent of carbon, 0.10 percent of phosphorus, 0.25 percent of silicon, 0.20 percent of copper, or 0.2 percent of molybdenum, chromium, and arsenic combined, inasmuch as such amounts of these elements may raise the transition temperature above the limit indicated. Residual copper in amounts less than 0.20 percent, and nickel in any amount, are beneficial, and need not be considered in this calculation of the maximum transition temperature to be expected. Other elements generally are present in such small amounts in steels of this type that their effects appear to be negligible.

This formula shows that the notch toughness of hot-rolled steels may be improved by reducing the carbon or phosphorus content, by increasing the manganese or silicon content, or by mill practices that produce a finer grain size. It also shows that silicon, in amounts up to about 0.25 percent, is three times as effective as manganese, which may be important if the manganese situation gets worse.

The metallurgical effects of welding and flame cutting, and the increase of notch sensitivity resulting from deformation or strain aging, must also be considered, and we need to know more about the relation of these phenomena to the composition of the steels. However, experience shows that these effects will be less serious in steels of lower notch sensitivity than in steels that are more notch sensitive to begin with.

## Summary

Structural failures of welded merchant ships have cost the Nation almost 50 million dollars in the past 9 years, and there have been other costly failures in such structures as bridges and storage tanks. The failures usually occurred at low temperatures, and the origin of

the fractures could be traced, invariably, to a point of stress concentration at a geometrical or metallurgical notch resulting from design details or welding defects. The fractures in the ships generally were of a brittle type, showing little evidence of ductility, although the steels showed normal ductility in the usual type of tensile test. The principal factors contributing to these failures—workmanship, design, and materials—and the preventive measures that have been applied are discussed. The incidence of failures in ships has been reduced materially by improvements of design details and of welding workmanship, but it is evident that stress concentrations resulting from unavoidable structural notches, welding defects, or conditions incident to operation and maintenance can never be entirely eliminated. Therefore, the quality of the steel, especially with regard to notch sensitivity, must be regarded as an important factor in the prevention of failures.

Charpy V-notch bar tests of 113 plates removed from fractured ships show that the plates in which the fractures originated were generally more notch sensitive than plates that did not contain a fracture source. Statistical interpretation of the data indicates that under the conditions existing in a structure such as a ship, the probability that a fracture will originate in a plate increases markedly with increasing notch sensitivity of the steel, as measured by the 15 ft-lb transition temperature of Charpy V-notch specimens. Relations between the 15 ft-lb transition temperatures of the plates and their chemical composition show that the notch sensitivity is increased with increasing amounts of carbon and phosphorus, and decreased with finer grain size and with increasing amounts of silicon and manganese, within the range of the chemical compositions of the ship plates.

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Investigations of failures in welded ships have been conducted at the National Bureau of Standards over a period of several years, starting early in 1943. Until July 1, 1946, the examinations of fractured ship plates were carried on as a part of an extended research program sponsored by the Bureau of Ships, Navy Department. When that program was terminated, the work was continued by the National Bureau of Standards as a fundamental part of a study of the nature of fracture and of fracture propagation in metals. Since July 1947 the Ship Structure Committee has sponsored the investigations of failures in welded ships, and this work has been conducted by the same personnel and closely coordinated with the work on the nature of fracture in metals.

The early part of this investigation was conducted under the supervision of George A. Ellinger, who has continued to show an active interest in the project and has given valuable counsel throughout the investigation. Other present and former members of the Metallurgy Division of the National Bureau of Standards who have contributed to the work are Melvin R. Meyerson, Gordon L. Kluge, Leo R. Dale, James T. Sterling, H. G. MacKerrow, and Lura F. Roehl.

Much credit is due also the U. S. Coast Guard inspectors, who were responsible for the selection and marking of the samples of fractured plates, and to members of the Ship Structure Committee and of the Merchant Marine Technical Division, U. S. Coast Guard Headquarters,

who supplied information regarding the structural features of the ships and the circumstances of the failures, and assisted in many other ways.

## Discussion

Mr. J. J. Kanter, Directing Engineer, Engineering Division, Crane Co., Chicago, Ill.: Has any attempt been made to correlate the transition temperature with the aluminum content of the plates? Did you make any attempt to distinguish between soluble and total aluminum?

Dr. M. L. Williams: Aluminum was plotted in the same manner as the other elements, but we did not find any consistent relation between the transition temperature and the aluminum content. The chemical analyses of the plates did not distinguish between soluble and total aluminum.

Mr. S. Tour, General Manager, Sam Tour & Co., Inc., New York, N. Y.: Dr. Williams has chosen 15 foot-pounds as the line of demarcation between a brittle condition and a tough condition for ship plates. This is an arbitrary line and not a transition line. In fact, it has no relationship to transition temperatures. It is possible to have steel that will have this 15 foot-pound notched-bar Charpy impact strength below its transition temperature. On the other hand it is possible to have steel that, even above its transition temperature, will have less than 15 foot-pound Charpy notched-bar impact strength. What justification is there for this arbitrary selection of 15 foot-pounds as a criterion of anything? Is crack propagation dependent solely on notched bar impact strength and independent of whether the fracture is of the brittle or nonbrittle type?

Dr. Williams has referred to defective welds as being the point of initiation of certain of the brittle fractures that have occurred in ship plates. That brittle fractures of great length can develop in relatively soft steel has been demonstrated in the case of certain gas pipelines. That brittle type fractures can travel through several plates for a distance of 100 or 200 feet has been demonstrated in ship plates. The longest crack of this nature that has come to the writer's knowledge did not occur in a ship. It developed in a 30-inch-diameter pipeline laid in a trench and traveled a total of 3,300 feet. It did not originate in a defective weld, it traveled longitudinally of the pipe, through more than 100 circumferential welds and was not deflected by such welds. There is no indication that a steel with a 15 foot-pound notched-bar Charpy impact strength would be satisfactory for a gas pipe or for a ship plate.

Designs should be based on stress levels and on length of steel involved. In the case of pressure pipelines the lengths involved are the circumferences involved. At a given stress level when failure is initiated in a 30-inch-diameter pipe, the crack will progress farther than it will in a 15-inch-diameter pipe stressed to the same degree. The larger the length of steel in which elastic energy may be stored the greater the tendency to brittle fractures. In other words, the notched bar impact strength necessary to stop or retard the propagation of brittle fractures must be higher for large structures than for small structures. No arbitrary figure such as 15 foot-pounds may be selected for all structures.

Dr. Williams: The subjects of notch sensitivity and transition temperatures are discussed more fully in the written paper, but in the condensation of this paper for oral presentation it was necessary to omit part of this discussion.

It might be well to emphasize here that the 15 foot-pound value was chosen as a means of comparing all plates at the same energy level, and not as a line of demarcation between tough and brittle behavior. It is true that the temperature at which the energy absorption is 15 foot-pounds (for V-notch Charpy specimens) is not strictly a transition temperature for all types of steels, and perhaps it might have been better to call it by some other name. However, for steels of ship plate quality, the 15 foot-pound level lies within the transition range, and the temperature at which the notched-bar test curve crosses the 15 foot-pound line provides a convenient and easily determined numerical value which is one of the many possible indices of notch sensitivity. The value of 15 foot-pounds was chosen arbitrarily because it was the minimum acceptable value specified for notched bar tests under certain of the ASME pressure vessel codes, and because it appeared to be a reasonable value based on experience in the field.

The justification of this tentative selection of the 15 foot-pound transition temperature as an index of notch sensitivity lies in the fact that it does provide a reasonably good correlation between laboratory tests and service experience. Similar correlations are shown also for the other indices of notch sensitivity which were used: the energy absorbed by Charpy V-notch specimens at the failure temperatures of the respective plates or at fixed temperatures of 30° or 70° F. Possibly the correlation might be even better at a different fixed temperature, say 40° F, or at a different energy level, for example, the 10 foot-pound transition temperature, and further work in this direction is contemplated.

From these correlations with service experience, using any one of these indices, acceptable limits of notch sensitivity may be determined for steels intended for service under similar conditions. For other service conditions, such as in pipelines or pressure vessels of different sizes, it would be necessary to establish similar correlations with service experience, and the acceptable limits of notch sensitivity would probably be different. For example, the accumulated data for ship plates indicate that steels having a 15 foot-pound transition temperature somewhat higher than the lowest operating temperatures (that is, steels capable of absorbing somewhat less than 15 foot-pounds at the operating temperatures) would be acceptable. To maintain the same energy absorption at lower operating temperatures, a correspondingly lower transition temperature would be required. For more severe service conditions, more than 15 foot-pound energy absorption at the operating temperature might be found necessary, which would require a 15 foot-pound transition temperature lower than the operating temperature.

Mr. Tour's comments on the failures in gas pipelines are appreciated. It would be interesting and instructive to compare the operating conditions, circumstances of the failures, and the properties and chemical compositions of the steels involved with the similar data that have been obtained in connection with the ship failures.

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