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DAVID TAYLOR MODEL BASIN
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NOTES ON THE CONDITIONS OF BRITTLE RUPTURE OF SHIP PLATES OF MEDIUM STEEL

by

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[redacted]

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PERSONNEL

This report is the work of Captain W.P. Roop, USN. The various tests referred to were performed by the Talbot Laboratory of the University of Illinois, by E.A. Davis and A. Nadai of the Westinghouse Research Laboratory, by the University of California, and by the David Taylor Model Basin.

NOTES ON THE CONDITIONS OF BRITTLE RUPTURE OF SHIP PLATES OF MEDIUM STEEL

ABSTRACT

The elastic and the plastic behavior of notched steel specimens of various shapes, tested under a variety of conditions, is briefly discussed. Results of tests of two specimens which failed by brittle fracture at a temperature of 32 degrees fahrenheit are presented. The relation between brittle failure and ductile failure is discussed, and suggestions for further tests are made.

INTRODUCTION

Extended tests of specimens of ship plating of full thickness, 3/4 inch, are planned, and some results have already been obtained at three laboratories. The load used is mainly simple tension and special emphasis is placed on the conditions of brittle rupture (1).* One purpose of this work is to find what circumstances may have contributed to the rupture of similar plates after assembly into ships. An item of special concern is the fact that elongation of the steel in the ship failures is reported to be very small. Consequently a similar result in the laboratory is especially desired. However, the question has a much wider interest than is involved in the explanation of the rupture of plating in certain specific ships. It is more and more clear that success in ship construction involves not only power to resist load, but also to withstand damage without total loss. This latter need calls for the capacity on the part of the steel to "give," to absorb energy by plastic flow, before final rupture.

From the importance of plastic flow in the service behavior of steel ships the idea emerges that the failure of steel in a ship may be caused, not by overstress, but by overstrain. Ductility has its limits; when these are over-stepped the result is fracture.

It is this general situation in which the Taylor Model Basin is primarily concerned, and it is to discuss the current situation from this point of view that the present report is submitted. The additional reports to be made up by the testing agencies must form the source of more detailed facts about the tests.

GENERAL CONSIDERATIONS

Medium steel is a ductile material.** Its power of plastic adaption

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* Numbers in parentheses indicate references on page 17 of this report.

** It will elsewhere be made clear that ductility depends on circumstances. Medium steel is ductile in the usual tensile test and in the usual conditions of hull service; the special conditions under which it is brittle are those now to be considered.

to the concentrated stresses which fall upon it in every ship structure is more important than its simple capacity to resist the even and steady load of the standard tensile test.

The measure of ductility has hitherto been found in the elongation on a given length and in the "reduction in area," both taken on the standard test specimen after rupture.

Some attention has also been given to the appearance of the surface of fracture, in which brittleness shows by three signs: (a) coarsely grained texture, (b) absence of loss in thickness, and (c) square, not oblique, parting. These, however, are symptoms; the defect is low energy absorption.

For forty years or more energy absorption in coupons has been tested in many laboratories directly in pendulum impact machines. Even wider is the usage among practical men of breaking a small piece by a hammer blow and looking for signs of brittleness in the pieces. In such tests it was found that a notch was favorable to brittleness, and in the Izod and Charpy tests the form of the notch was very carefully defined, since it was found that slight differences in the notch strongly affected the results. Impact specimens were tested also under tensile loading, but until recently all such tests were wholly comparative in nature; two identical specimens of different material would show up differences, but it was not possible from two different specimens of the same material to find a value of permissible ductility which could be used directly in design calculations.

It presently became clear that the presence of the notch was more important than the speed of the blow. In recent work special attention has been given to static tests of tensile specimens of circular section provided with a constriction of definitely specified axial profile. A common form for this profile is that of a Vee with an accurately defined radius at its apex, as shown in Figure 1.

The stress in the near vicinity of the apex of such a notch is affected by the geometry of the notch. Thus simple tension no longer exists in the reduced segment of a notched tensile specimen in which the notch is machined before loading, or even in a specimen originally uniform but necked down in the course of the test. Professor Bridgman has described the change (2) as the addition to the axial tension of an isotropic tension of three equal components.

The most significant feature of stress in all notched specimens is the pattern of variation of intensities of the various components of stress in the transverse plane of symmetry of the notch; in the case of the notched tensile specimen, this is the y-z plane through the apex of the notch, as shown in Figure 1b.

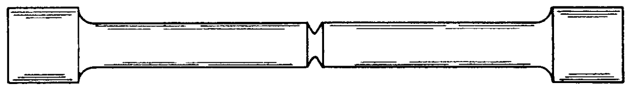

Figure 1a - Profile of the Whole Specimen

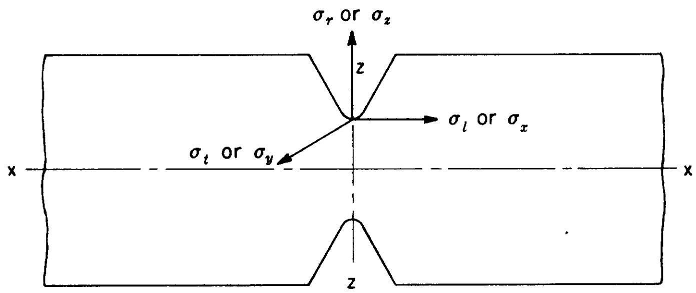

Figure 1b - Detail of the Notch
The y-axis is normal to the plane of the paper.

Figure 1 - Notched Tensile Specimen of Circular Section

Thus the relative intensities of the two elements of Bridgman's combination, axial tension and isotropic tension, vary within the cross section. In the plastic neck, the axial tension has a maximum and the principal shear a minimum at the axis of the bar.

Earlier work by Neuber (3) gave the distribution of *elastic* stress in a specimen of similar form and it turned out in this case that the maximum axial tension occurred at the surface of the metal rather than on the axis.

As a notched specimen is given its first loading, the concentrations are governed by the conditions of elastic action. The variations of the three stress components with distance from the axis, as found by Neuber, are shown in Figure 2. The shear stress calculated from these three components is also shown and it will be observed that the intensity of shear stress, as it varies with distance from the axis, has a minimum at the axis of the specimen.

At a point where the shear stress is small (because the differences between the principal components of stress are small) the metal, even though ductile, is unable to reduce the concentration of stress by plastic flow. Plastic flow, in fact, is a phenomenon of shear action entirely. Since the ductile action of the metal is thus inhibited, there is nothing to prevent the stress at the point of concentration from rising to the cohesive breaking point.

It is in this sense that a triaxial tension favors rupture. This is a point of special importance and it will be given more consideration later in this report.

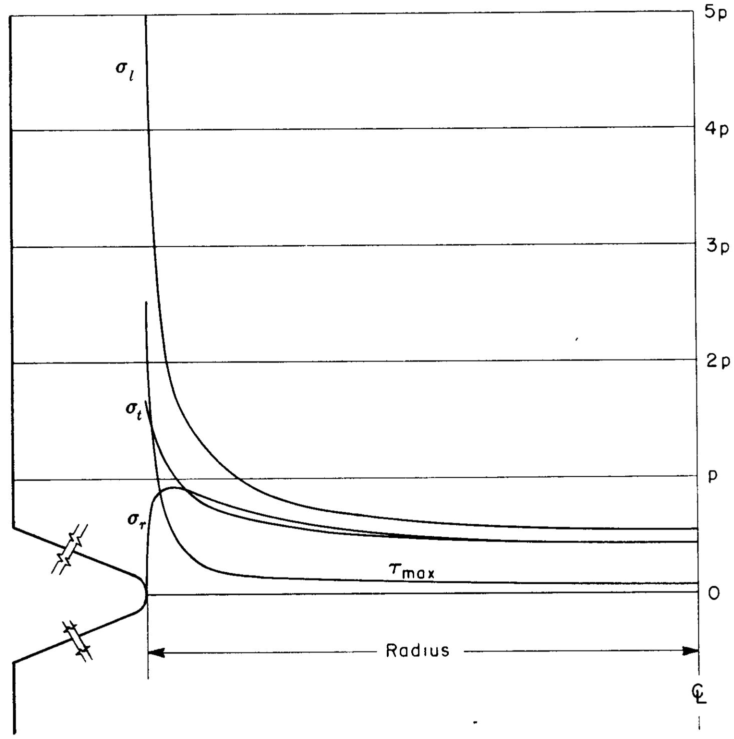

Figure 2 - Elastic Stresses at Minimum Cross Section of a Deep Notched Cylindrical Bar under Tensile Load

This figure is similar to Figure 14 of Reference (1) but has been recalculated from Neuber's original work, Figure 47 of Reference (3).

The ordinate is in terms of $p = P/\pi a^2$, where P is the load and a is the radius of the specimen.

NOTCH-FORM IN CURRENT SPECIMENS

The special tests now in progress utilize specimens of rectangular section, some of them of width as great as 72 inches. The specimens used in these tests are also notched, but in another way which will now be described.

Three specimens recently tested at Talbot Laboratory, though they differed in other respects, all agreed in having a notch which consisted, first, of a rectangular slot 15 inches long at midlength of the plate, disposed across the plate as shown in Figure 3, so as to reduce the effective width subject to direct tension. The width of the slot, measured parallel to the tensile load, was 1 inch.

The effective width of the plate was still further reduced by a fine cut made with a thin-bladed hacksaw, at each of the two upper corners of the slot. These cuts extended outboard 1/2 inch in each direction and in this way the net width was reduced by 1 inch. The whole width of the notch was thus 16 inches, the remaining net width was 56 inches, and the net area at the beginning of the test was 42 square inches.

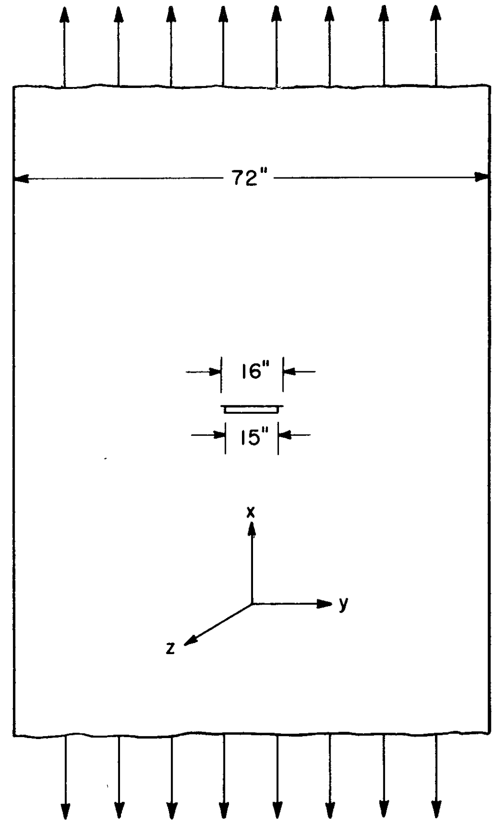

Figure 3 - Tensile Test Specimen

The designed thickness of the specimen was 3/4 inch.

The notch was located at the center in length and width; the rectangular slot, 1 inch by 15 inches, was prolonged by other 1/2-inch hack-saw cuts to a total length of 16 inches. The remaining area of section was 3/4 (72 - 16) = 42 square inches.

PLASTIC AND ELASTIC BEHAVIOR CONTRASTED

When the chief value of a structure lies in its load-bearing capacity the quantity of primary interest to the designer is the stress caused by the loads occurring in service. The capacity of the material for resisting that stress is expressed as the *permissible* value of stress, and the process of design consists in bringing the stress caused by service load below the *permissible* limit. This limit will be assigned so that the metal will receive no permanent strain beyond that occurring in the process of smoothing out the concentrations in such a way that the structure will receive no permanent deformations after the proof load or period of shakedown. A ship, however, is not this kind of structure; its function is not simply to resist load without deformation, but also to withstand damage. In a ship, permanent deformation may cause no serious damage and very extensive plastic deformation may occur without total loss or even serious delay in return to normal service.

Between the beginning of plastic flow, which from the elastic point of view is called failure, and the total loss of the ship, there is a very wide margin which must be utilized if an efficient design is to be had. Moreover stress does not offer a suitable measure of this margin, since the rise of plastic stress beyond the yield point consists only of that which results from the action of strain-hardening. The true measure of the merit of the structure in resisting damage lies in its capacity to absorb energy, and this depends far more on its capacity for deformation than on the value of the plastic stress against which the metal is strained.

The limit of strain which the metal can accept is set by the incidence of rupture. The habit has grown up, from the universal use of the tensile test for assessing the quality of steel, of thinking of rupture in terms

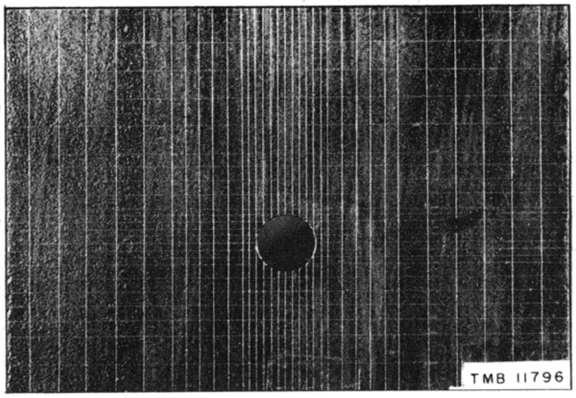

Figure 4a - Condition A, Specimen before Loading

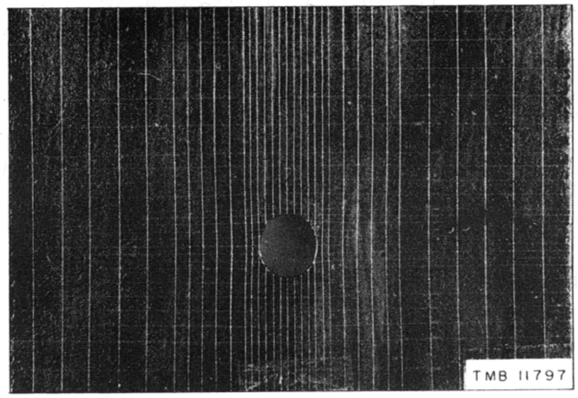

Figure 4b - Condition B, Specimen after Moderate Elongation

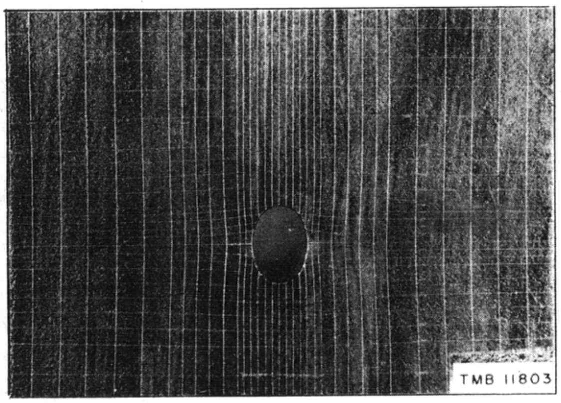

Figure 4c - Condition C, Specimen at Incipient Fracture

Local strain has risen to about 100 per cent.

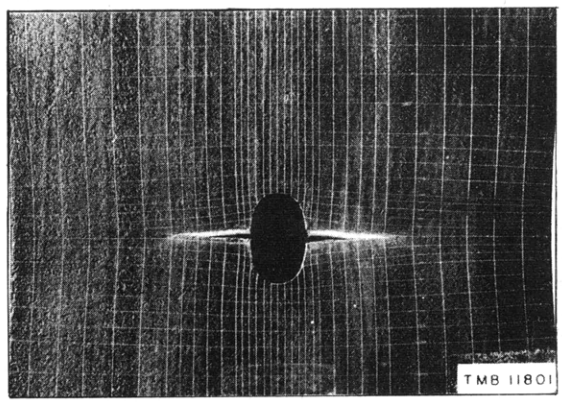

Figure 4d - Condition D, Specimen after Fracture

Figure 4 - Plastic Flow in a Plate in Tension

of ultimate *stress*. Though difficult, it is necessary to change this habit and think of the *ductility* of the metal as first in importance.

Ductility is the capacity for plastic flow. It expresses itself in the standard tensile test by simple elongation or by "reduction in area," but a more general concept of ductility is illustrated in Figure 4. A plate of soft steel, 5 inches by 1/8 inch in section, was loaded in direct tension. This produced elongation and reduction in width. A rectangular grid ruled on the plate before the test shows by its changes in form the nature of its strain distribution.

Changes in thickness may also be inferred from the changes in the grid, since in the plastic range of behavior of steel, the change in dimensions is always such as to leave the density of the metal unchanged. This may be expressed by saying that the value of Poisson's Ratio in the plastic range is 50 per cent.

In the case illustrated in Figure 4, the simplicity of the tensile strain pattern was disturbed by the presence of a hole at midwidth and mid-length of the specimen. This hole was originally circular.

The distortion of the metal around this hole under loads below the *elastic limit* was not discernible by this method of observation; the limit of elastic strain is only one tenth of one per cent.

After the elastic limit is passed, however, strains occur with only very moderate increases in stress such as are caused by strain-hardening. In Figures 4b, 4c, and 4d successive stages of strain in the specimen are shown. Only a very moderate increase in load was needed to pass from Condition B to Condition C, and after the section had been reduced as in Condition D, the load dropped off.

At the sides of the hole the concentration of stress in the elastic range is known to be 300 per cent. As the load on the specimen is increased, the stress at these points reaches the yield point sooner than elsewhere and the metal there begins to flow.

In this way the concentration of stress is smoothed out and the result of further elongation of the specimen is mainly to increase the area over which the flow extends. By the ovalization of the hole and the divergence of the ruled transverse lines (along the y-axis) it is seen that the values of strain in a small area rise to 100 per cent or higher. Eventually, the metal is worked to its limit, which is shown in Figure 4c. When further elongation is imposed, rupture occurs, as in Figure 4d.

Now it may happen that the final result, rupture, can occur much sooner, after much less stress, than is shown in Figure 4. This may follow from either, or more likely from both, of two causes. Structural designers are apt to blame such a result on *brittleness of the material.** However the steel makers are quite right in pointing out that medium steel will always fail in ductile mode unless something acts to prevent this. Ductility of medium steel can be *inhibited* by the conditions under which it has to work.

Such inhibitions can occur in different ways all of which, however, can be grouped under four heads as follows:

a. History of the previous straining of the metal.

b. Geometry, referring to concentrations such as are caused by notches.

c. Temperature at which the test is performed.

d. Time effects, such as the rate of straining.

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* See the second footnote on page 1.

In general, high speed of straining is considered to favor brittleness and low temperature is known to do so. These two effects will not receive further attention just now, but emphasis will be given rather to the other two groups of influences, the geometry of the specimen and the history of the metal of which it is made.

GEOMETRY

The stress concentrations revealed by photoelastic studies have become widely known and understood. For exhibiting the distributions of *plastic* strains, use has been made rather of a grid ruled on a steel specimen before straining and directly photographed after the strains have been carried to an advanced stage. Examples of this have been shown in Figure 4. Like the photoelastic method, however, this shows only two-dimensional distributions.

The strain in the third or z-coordinate is of special significance. An especially important case in point occurs when one component of strain, say the y-component, taken parallel to the width of the plate, is constrained to be equal or nearly equal to zero, as in a very wide plate without a notch.

It is a basic fact in plastic action that the density of the metal remains unchanged, within negligible limits of error. The result is that when strain in width parallel to y is zero, strain in the axial or x-coordinate must be offset by equal and opposite strain in thickness, or along the z-coordinate. This straining is essentially uniform throughout the length of section until just prior to rupture, when distinct local necking is observed. This necking in thickness is confined to a very small portion of the length of the specimen and the result is a fracture which needs close examination to be distinguished from that found in a material inherently brittle, such as medium steel at the temperature of liquid air.

The basic question of overall elongation, however, cannot be answered simply by visual examination of the fracture. It is quite possible, if the geometry permits uniform reduction in thickness over large areas, that rather large elongations may occur prior to necking. This is exactly what happens in thin plates, where the width is sufficient in ratio to the thickness so that the metal at a distance from the edges is constrained against flow in width by the metal nearer to the edges. It was for the purpose of obtaining such constraint that the high width-thickness ratio of 96 to 1 was chosen for the specimen shown in Figure 3.

However, it is a widespread opinion that absolute thickness also influences the result. The apex of the notch of Figure 3, extending as it does parallel to the thickness or z-coordinate, has in these specimens a length of 3/4 inch. The inward flow of the metal, which must occur if thickness is to diminish, can proceed readily enough at points near the surface, but near the point of mid-thickness the situation approaches that which was mentioned earlier in this report, the case of notched tensile bars of circular section. The axial or x-component of tension is accompanied near the apex of the notch by both y- and z-components, also tensile in their action.

Now it must again be noted that plastic flow is mainly or entirely a phenomenon of shear strain, i.e., parallel slip within the crystal structure of the metal. Since shear action is measured by *differences* between principal stress components, the shear stress is nearly zero wherever all three principal components of stress are nearly equal, and where all three components are tensile the shear stress is less than if one of the components were compressive.

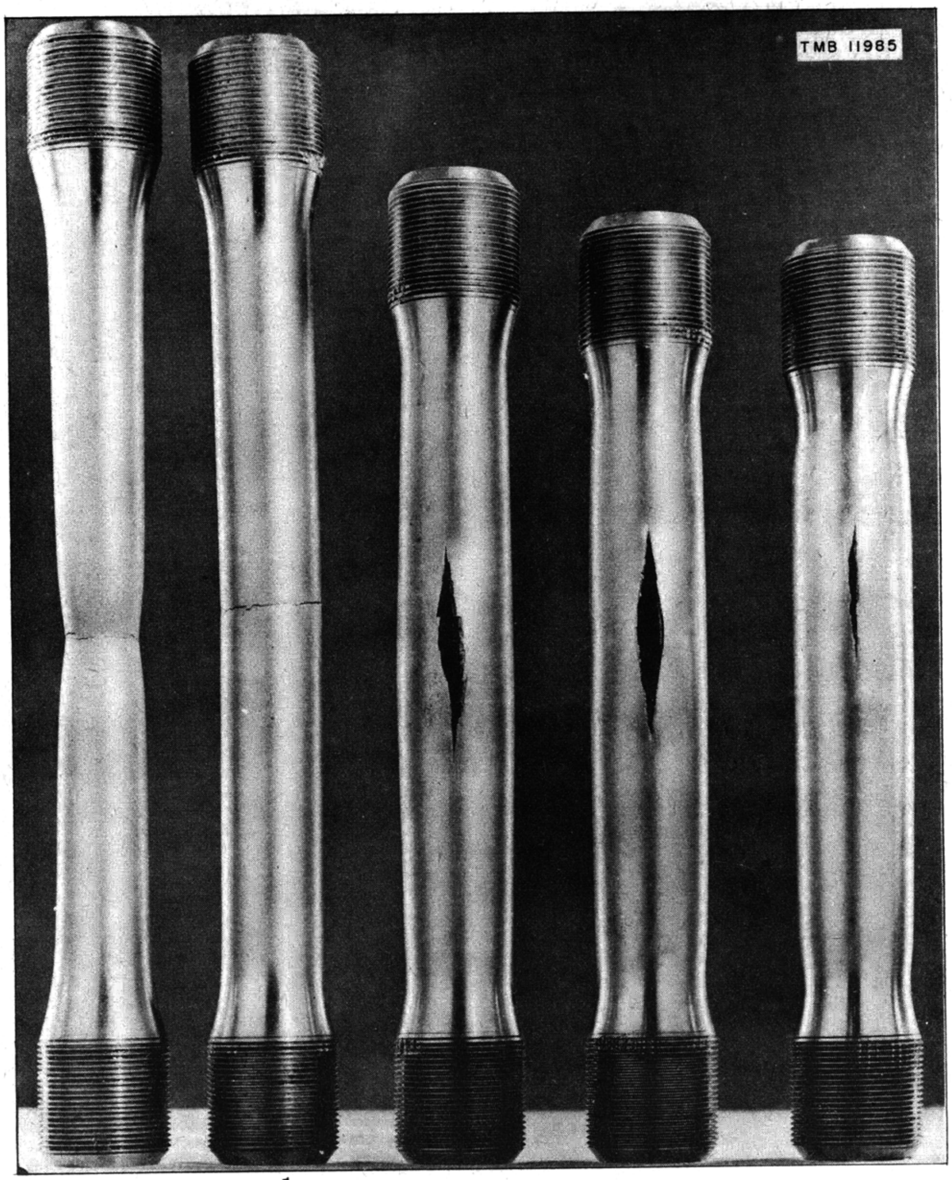
If, in addition, a region of triaxial tension is also a region of high concentration of stress, the relief of this concentration by plastic readjustment is inhibited and the stage is set for cohesive failure, even though the metal appears by the ordinary tensile test to be ductile.

BIAXIAL LOADING

The purpose of the choice of a high width-thickness ratio in specimens like that in Figure 3 was to simulate the conditions of transverse action found in a ship's deck in tension. When a bar of round section is pulled it contracts equally in both transverse directions, but if the section is wide and thin, edge contraction and thickness contraction differ from each other in their action; the metal can not neck in width by drawing in at the edges to the same extent as in a bar of round section and the result of the resistance offered to this tendency is that a transverse component of stress, σ_t or σ_y, is built up even though the external load is in the x-direction only.

If the edges of the plate are constrained by an adjoining plate also under axial tension, each of the two will act to increase the resistance of its neighbor to edge contraction. If edge contraction is wholly prevented, as when the seams are welded up into solid joints, the transverse stress component may build up to a high value. Conversely, even the small degree of compliance found in an eccentric joint like a strapped seam may be sufficient to reduce the transverse component of stress to a low value. It is not necessary that large strain in the y-direction should intervene to accomplish this, as the *relief* of a stress, even after heavy plastic flow has occurred, is accompanied only by a *recovery* strain, in the elastic mode.

By simple increase in width-thickness ratio it is not possible to completely eliminate edge contraction. This can only be done in a tubular specimen, and even there it is necessary to adjust the proportions of the x- and y-components of stress in the right way to obtain the desired result.



$\sigma_y = 0$ $\sigma_y = \frac{1}{2}\sigma_x$ $\sigma_y = \sigma_x$ $\sigma_y = 2\sigma_x$ $\sigma_x = 0$

Figure 5 - Tubular Specimens under Various Stress-Component Ratios

Thus, in Figure 5, the specimen on the left was loaded in axial tension only, without internal pressure and without a y-component of stress. The contraction in girth which corresponds to that in width of a flat plate, shows as a reduction in diameter. Failure occurs in a transverse section, and is preceded by local necking in girth.

At the opposite end of the series, on the right, is a specimen in which σ_t or σ_y was the only stress component; even the axial stress which would be caused by the hydrostatic pressure on the ends of the tube was removed by a special arrangement. The failure was by splitting where the metal reached the limit of its resistance to the hoop stress, but prior to that a considerable increase in diameter and some shortening had occurred.

The intermediate terms in the series show intermediate results. Next to the extreme right is the case of loading by hydrostatic pressure only, without relief of pressure on the ends. This produces a hoop stress σ_y just twice the value of the axial stress σ_x. It happens that in this case the elongation is zero; the fractional loss in thickness must therefore equal the fractional increase in diameter. For purposes of comparison, it is noted that the length of this specimen equals that of each of the other specimens before loading.

The specimen next to the extreme left is that in which the axial tension σ_x was kept at a value twice that of the hoop stress σ_y. This required careful adjustment of the tensile load during the test so as to keep it in the right ratio to the internal pressure. It is an important fact that in this case the diameter remains unchanged, and in the specimen as shown after failure it still has the same value as in all the specimens prior to loading. This is therefore the case of complete transverse restriction, and the fractional loss of thickness must equal the fractional increase in length. It represents the limiting case of a plate of infinite width-thickness ratio.

These excellent results were obtained by E.A. Davis under the direction of A. Nadai of the Westinghouse Research Laboratory. Their more complete report on these tests will appear soon.

The specimens were in all cases without notches, and in that respect they are not comparable with the flat plates shown in Figures 3 and 4. Plans are in hand for the introduction of notches into tubular specimens.

STRAIN AGE-EMBRITTLEMENT

The most familiar example of completely brittle failure of ductile material is found in fatigue. An explanation of this phenomenon, adapted from the work of W.M. Wilson and W.H. Bruckner at the University of Illinois, is as follows:

At the apex of a stress-raiser, even though it be microscopic in size, high local values of stress occur even when the average values are quite moderate. These cause highly localized plastic action, with strain-hardening, followed by age-embrittlement. Under this treatment the metal ruptures locally. However, the extension of the surface of fracture is slow for two reasons. First, the concentration is so localized that the action occurs on only one grain at a time; and then the embrittlement takes time, so that the crack may need a long time even to go from one grain to the next. The essential correctness of this explanation has been confirmed by Bruckner by direct micrographic observations.

Age-embrittlement (4) is a phenomenon which is well known in duralumin; its action in medium steel has had less notice, at least from Naval ship designers. In the tests at Talbot Laboratory it has been demonstrated that it may have an important influence on the brittleness of fracture in medium steel, as explained under the section on the Talbot Laboratory Test.

The presence of welds might be supposed to favor brittleness caused by shrinkage strain in the adjoining metal, with aging accelerated by the high temperature of the welding operation.

TESTS AT TAYLOR MODEL BASIN

Numerous tests of welded specimens without notches have been made at the Taylor Model Basin and these have disclosed no case of brittle rupture.

Tests of specimens notched as in Figures 3 and 4 are in progress. In a specimen of 3/4-inch thickness these are limited to a width of about 12 inches by the limited capacity of the testing machine.

A progress report, with critical comment on these tests, may be expected soon.

DETAILS OF THE TEST OF THREE PLATES AT TALBOT LABORATORY

The three plates were of the form shown in Figure 3. They differed in the following particulars:

The first to be tested was Specimen 2. Its surface was ruled with grids around the ends of the sawcuts, and these were photographed on an enlarged scale at several stages of elongation. Progressive changes in various dimensions were also measured, and, for other reasons, elastic strain data were taken. The load was increased gradually, with occasional release; three increments, with release after each, were applied after rupture had reached the point of showing a visible crack opening.

The second to be tested was Specimen 1. This was mounted for test before the slot had been cut, and was pre-strained to an elongation of about 1 per cent. The strain-aging was accelerated by steam heat for two hours, after which the slot was cut. An ice bath was applied in way of the slot and the plate was pulled to rupture without release and without intermediate observation. The grids were photographed and dimensions were taken before and after pre-strain, after aging, and after rupture. No other data were taken for this plate.

The last of the three was Specimen 3. It was similar to Specimen 2 with respect to observations and loading, but was provided with transverse reinforcing bars to add to the resistance to edge necking. In this way the transverse restraint was raised to the maximum value obtainable by any means except the use of tubular specimens, as in other tests to be separately reported.

Report of the numerical observations will be made by the Talbot Laboratory after they have been fully reduced and after the photographic records have been carefully studied. Prints of the assemblies and of the grids will then be used to show the nature and results of the tests. In this preliminary report the character of the fractures will be briefly described, with some reference to the general inferences which can be drawn.

SPECIMEN 2

The failure generally was in the ductile mode. The sequence of events was roughly as follows.

Quoting mean stress values as gross load divided by remaining area of section, the first discernible increase in width of the sawcut occurred at less than 5 kips per square inch. As load was increased the notch opened continuously in width of the cut until at 30 kips per square inch the sawcuts were about 4 times their original width and the slot had widened by about the same amount in the x-direction.

Shortly after this, visible fracture made its appearance, at first restricted to the mid-thickness of the plate. From there it gradually spread in the z-direction to the ends of the sawcut at the surface of the plate.

Meantime micrometer measurements of thickness at the apex of the notch showed a z-component of strain of about 1 per cent, enough to give rise to a well-marked dimple. This depression was in the form of a wedge with point at the apex and base outboard; the area was defined by Lüders' lines which made a step downward in thickness toward the interior of the wedge. The loss of width parallel to y was barely discernible.

The test was now continued by pulling the crack open in increments, so as to extend it in the y-direction. Load was released after each increment. The elongation was in all cases gradual, but after each release the next succeeding load rose to a higher maximum. When this was divided by the steadily decreasing remaining area it was found that the average plastic stress on the remaining section rose to higher values as the crack advanced, attaining at the end a value of about 45 kips per square inch. This was well above the coupon yield point, but lower than the value found in thinner specimens of similar material. The test was stopped when the remaining section had been reduced to about half that of the intact plate.

The surface of initial fracture had the characteristic appearance of brittleness at each of the two ends of the notch. At one end the brittle area had an oval boundary, and at its outboard end, where another pair of

Lüders' lines originated, the shift to ductile mode was accompanied by shift of the fracture surface to the form of a single diagonal rupture plane. At the other end the brittle parting was limited to a small triangle, confined between the walls of a V-shaped ductile-fracture surface.

SPECIMEN 1

The mean stress required to produce the pre-strain of about 1 per cent was 33 kips per square inch. After the preparatory operations already described, load was applied at the rate of 8 kips per second. At a mean stress of 29 kips per square inch on the remaining area failure occurred with all symptoms of complete brittleness.

SPECIMEN 3

The rupture in this case occurred with little elongation, but the fracture showed none of the surface symptoms of brittleness in the material. The average stress at which initial rupture occurred was about the same as in Specimen 2.

The crack originated abruptly on one side of the notch, and almost immediately thereafter on the other side; in both cases it progressed quickly for a short distance and then stopped. The fracture surfaces to this point showed brittle mode. After a brief pause the cracks proceeded toward the edges of the plate on both sides, with fracture surfaces thereafter showing indications of ductile action.

A motion-picture record was obtained of this process, and it is expected that its analysis will yield more detailed information.

In any case the failure was in the brittle mode only at its inception; after a short preliminary action it shifted to ductile mode, although the overall elongation was small compared with that in Specimen 2.

The phenomenon of failure with small elongation and low energy absorption, caused by the state of stress in the metal rather than by any inherent quality in the metal or in its crystal structure, may be described as "geometrical brittleness."

TESTS AT THE UNIVERSITY OF CALIFORNIA

A test was made as nearly as possible identical with that on Talbot Specimen 1 with the single difference that the operation of strain age-embrittlement was replaced by a welding operation. Two longitudinal butt welds were run at 10 inches distance from the centerline, one on each side. The slot was then cut to a distance of 2 inches from each weld. Without further treatment the plate was pulled at the temperature of melting ice.

Brittle fracture occurred at a mean stress on the remaining section of 35 kips per square inch.

COMMENT

The only conclusion definitely suggested by the tests thus described is that melting ice on the notched specimen causes brittle failure. The effects of longitudinal welds, of strain age-embrittlement, and of transverse constraint by high width all require additional tests before any conclusion about them can be drawn.

However, fractures brittle in the beginning, but in which a shift to the ductile mode occurred during advance of the crack, have frequently occurred in these and other tests. From a careful study of the appearance of the surfaces of such fractures, some conclusions may be sketched as follows.

The process leading up to the occurrence of initially brittle fracture depends on the presence of both of two conditions: the inhibition of ductile response of the metal to load put upon it, and the concentration of stress in a ratio high enough, at least over a small region, to reach the intensity needed to cause rupture. The material has a strong tendency to ductile action, and it will flow, if it can, so as to smooth out the concentrations. Only when this is prevented, either by loss of ductility in the metal itself, by the geometry of the case, or by other circumstances, will the process of adaptation fail. Without the presence of the stress-raiser adaptation will not even be needed; the plastic flow will be widespread and the energy absorption very great.

After the crack has been established the acute concentration must continue to exist and it cannot be effaced by the action of ductility alone. There has been some disposition to think that such a natural stress-raiser is more effective in causing propagation of the crack than an artificial one is in starting it. This is not confirmed by the test, since in Specimen 2 a higher value of average stress is needed to continue the progress of the crack than to start it. It appears that the crystal structure of the metal has a greater significance in this connection than the geometry.

The inhibition of ductility may not necessarily continue, however, and it is in fact often observed that a fracture which begins in brittle mode may shift to ductile mode as it progresses. If by the changing geometry caused by advance of the crack the near-equality of tensile components, or the "triaxility," is reduced, the ratio of shear to tensile stress will rise and plastic flow will be favored. Or if the extension of a crack brings it into a region of low average stress it may happen that its progress may be altogether stopped.

In fact this is exactly what happens in a great many cases during welded assembly of a ship; the cracks are of limited extent and they are simply welded up with whatever modified procedure may be appropriate. The occurrence of cracks during welding is strongly affected by the transitory phases of the geometry and history of the situation. Once such cracks are eliminated and an intact completed structure is obtained the phenomenon of cracking is to be considered from an entirely new viewpoint. Only the exceptional case of very extensive fracture or of cracking in service comes at all into notice in connection with the present tests.

It has been suggested that benefit might be had in such cases by providing features of design which would retard or stop the progress of a crack. Such an effect has been observed in service on ships with riveted seams which served to stop a crack which otherwise might have continued to a point of complete parting of the members. Laboratory tests on small specimens have offered some confirmation of this possibility, and further work on plates 3/4 by 72 inches would be useful.

Even more important, however, is the need for some systematic information on the conditions governing plastic flow. When may it form a necessary condition prior to rupture, and when may rupture occur with no plastic flow whatever, as it appears to do in many ship fractures?

RECOMMENDATION

It is proposed to continue this work in three series of tests.

1. In specimens 3/4 inch by 12 inches in width, with centerline notches. In this series of smaller specimens the limits of embrittling action are to be explored along the following lines:

   a. By uniform pre-straining and aging in different steels.

   b. By various degrees of severity of notching, including the notch effects of welds.

   c. By low temperature.

2. In specimens 3/4 inch by 72 inches, with centerline notches, as needed to confirm on this large scale the limits of embrittling action as found on 12-inch specimens.

3. In specimens of tubular form provided with notches.

It is intended by these tests to disentangle the overlapping effects of history, geometry, and temperature in causing brittle fracture, and so to clarify the conditions necessary for increasing the capacity of ship structure for absorbing energy and withstanding damage.

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