NAVY DEPARTMENT
DAVID TAYLOR MODEL BASIN
WASHINGTON, D.C.

A BRIEF STUDY OF THE PLASTIC BEHAVIOR OF STEEL IN WAY OF THE TENSILE FRACTURES IN A GROUP OF PLATE SPECIMENS

by

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#53

July 1944

Report R-243

PERSONNEL

The tests described in this report were made by C.L. Pittiglio under the supervision of H.R. Thomas of the David Taylor Model Basin staff. The report was prepared by Captain W.P. Roop, USN.

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ABSTRACT

This report describes a short series of exploratory tests on a group of 24 plate specimens and simple model structures undertaken in an effort to learn more of the behavior of shipbuilding steel in the plastic range. Each of the specimens was provided with a "crack starter" in the form of a central hole with narrow transverse saw cuts on either side, and most of the specimens were fitted with what may be termed "crack stoppers" represented by rows of holes, riveted straps, or other similar devices applied in pairs abreast the holes.

The various specimens are illustrated by diagrams and photographs, their behavior under load is described, and a brief analysis of the test results is given.

It is concluded that relatively little is yet known of the behavior of steel in the plastic range, that comprehensive tests of this kind require larger-scale specimens, and that much more work is urgently needed.

INTRODUCTION

As a supplementary step to studies recently undertaken (1) (2)* at the David Taylor Model Basin, a further investigation has been made of the behavior of shipbuilding steel in the plastic or ductile range, where the conditions governing stress distribution are quite different from those prevailing in the elastic range. Before it finally ruptures, a piece of steel not uniformly stressed must go through a drastic adjustment to the loads placed upon it, in the course of which its ductility may be heavily drawn upon. In some cases, the actual ductility is not sufficient to prevent premature failure at a value of average stress over an extended section far below the ultimate value found in the standard tensile test. The conditions under which this occurs must be determined.

As a part of this task, a number of small plate specimens and simple model structures have been tested under conditions intended to simulate those prevailing in a large structure after rupture has begun. A group of these have been selected for description and discussion in the present report. It is to be understood that these tests were exploratory in nature, and that they do not represent a comprehensive and thoroughly systematic program of research.

The conditions under which these experiments were made differed from those of the usual tensile test on a plate specimen (3) in that internal transverse cuts were present from the beginning near the center of the specimen, so disposed as deliberately to start cracks which were then expected to spread gradually outward toward the edges of the specimen. In addition to these cuts, most of the specimens were

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* Numbers in parentheses indicate references on page 27 of this report.

perforated with rows of holes or were supplemented with bars or angles riveted on to simulate in a general way devices which might possibly be adopted on a ship to retard or stop cracks once started.

The various specimens, 24 in number, are illustrated and described, still and motion-picture photographs of the fractures are reproduced, and a brief analysis of the results is made.

GENERAL CONSIDERATIONS

Before proceeding to give these details, however, it may be well to set down a general statement showing why these tests are of so much importance at this time.

A new aspect of ship design is emerging from considerations growing in part out of recent failures in welded merchant vessels and in part from experience with fighting ships damaged in action but not lost. It has become apparent that the design procedure which has hitherto been developed for the single purpose of obtaining a ship structure capable of bearing an assigned static load may in some cases produce an inadequate result. In addition to its ability to bear its design load, a ship structure must also resist *damage.*

This means that a ship which has been subjected to excessive adverse conditions, such as overload, may yet be saved if its total loss can be deferred, either by abatement of the cause of damage or by the arrival of help.

One kind of damage is present in a greater or less degree in every steel ship when it is delivered to its operators. In spite of every effort, no new ship can be said to be perfect with respect to its material and workmanship; some of them fall far short of perfection. Even in the most nearly perfect ship structures, an inevitable series of more or less trivial accidents begin immediately when the vessel enters service. When the damage caused by these accidents can be repaired, it ordinarily is, but sometimes this must be deferred, and sometimes even the most skillful repair job fails to produce the equal of new work.

A valid and adequate design procedure must consider contingencies such as these as well as the load-bearing capacity of the vessel. It has been usual to do this by simple additions to the load-bearing capacity to provide a margin of strength, and there is no doubt that in most circumstances a ship's life is increased when its strength is increased relatively to its loads.

However, there are recent failures of ship structures which cannot be explained simply in terms of deficient strength since they have occurred in vessels of a design which was considered adequate and under loads which were not at all extreme. To make the failure more puzzling, many ships of the same design built at the same yards have withstood apparently greater loads without failure.

In this situation, the quality of ductility in the metal is known to play an important part; this is the capacity of the metal to yield or flow without breaking.

A more general word for this action is plasticity, a phenomenon which has received increasing study in recent years.

It was to investigate this phenomenon more fully, especially in an effort to find out how to stop a crack once started, that the present tests were planned.

TEST SPECIMENS

The tests were made on relatively thin plates, some of them 4 inches and others 5 inches wide, pulled in tension in the 600,000-pound testing machine at the Taylor Model Basin. All specimens except one were 1/8 inch thick, and 22 inches long including the portions held in the grips. Although this gave a width-thickness ratio of 32 or 40 across the section under test, it is recognized that the plate models were all too narrow to represent single strakes on a ship.

The general principle followed in laying out these specimens was to have a notch or "crack starter" at the center of a plate of uniform width, and then abreast this crack starter to drill two rows of holes or to attach two rows of bars of some kind, as described on page 4, that would act as "crack stoppers."

All specimens were of medium steel; the material chosen had a uniform intact coat of mill scale which served especially well to show the strain figures.

The construction details of the 24 specimens are shown in Figure 2.

CRACK STARTERS

A hole 5/16 inch in diameter was drilled through the center of each specimen. From this hole, two transverse cuts were made with a hack saw, one extending on each side of the hole. In Specimens 1 to 8, the total width of the section so removed was 5/8 inch; in later specimens the slots were longer and were made with the thinnest saw blades that could be obtained. The details are given in notes under the photographs shown later in the report.

The expectation was that a crack would start at a moderate load from each end of the saw cut, owing to the high stress concentration there. In point of fact, this did not occur in any case until the hole was well elongated and the slot had opened up to several times its initial width. At this stage the ends of the slot had become well rounded through the plastic flow of the metal there, as shown diagrammatically in Figure 1.

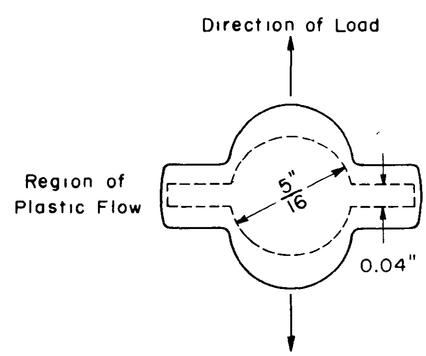

Figure 1 - Diagram Showing Widening of the Crack Starter in a Thin Plate Specimen

The original shape is shown in broken lines; the final shape in full lines. It is possible that many microscopic cracks appeared abreast the saw cut before one on each side began to enlarge and so to become visible to the eye.

CRACK STOPPERS

In one group of specimens, numbered 2 to 7, and in Specimen 10, the crack stoppers were two simple rows of drilled holes with varying spacing between the rows and in the rows,* as shown in Figure 2.

In Specimens 8 and 11, the two rows of drilled holes were filled with rivets, driven hot.

In Specimens 9 and 12, flat-bar straps were riveted over the holes on one side of the plate specimen to serve as a reinforcement in place of the metal cut out in the holes.

In Specimens 20 to 23 inclusive, angle bars were riveted to the plate through the two rows of holes; a pair of bars was thus attached to each side of the plate. The

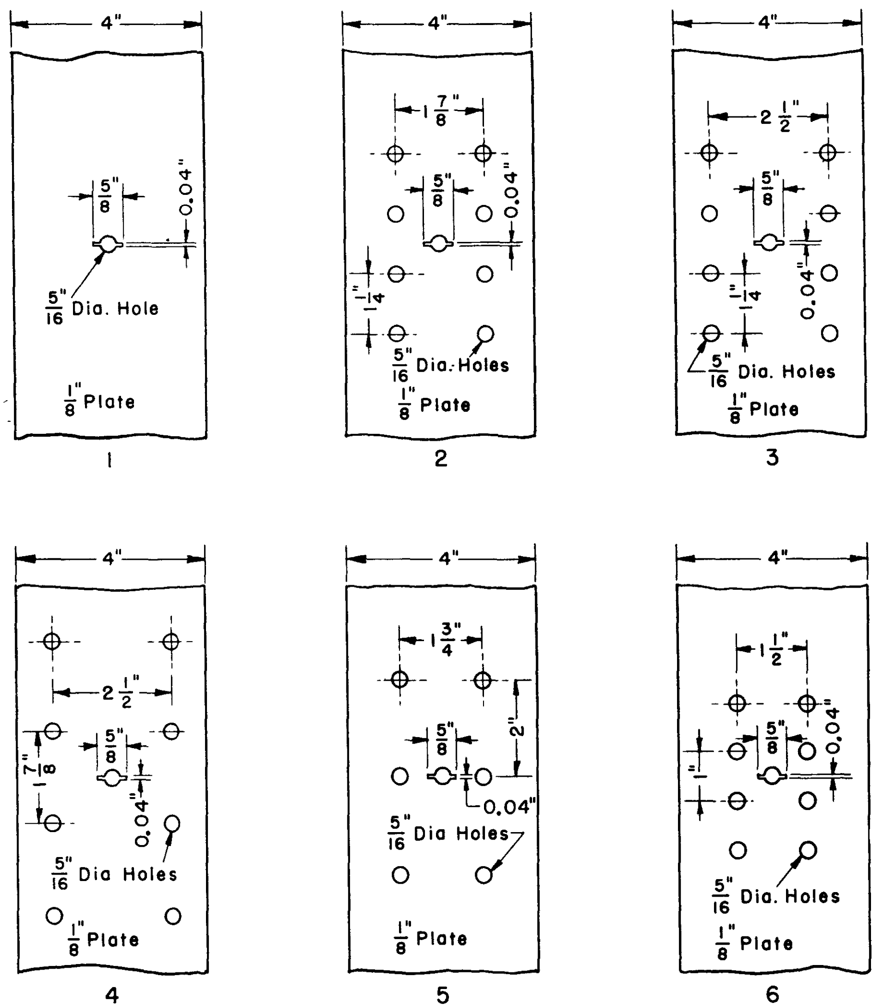

Figure 2 - Details of Test Specimens before Testing

* Any crack stoppers of this kind on a ship would have to be filled with hollow collapsible plugs which would render the plate normally watertight but which would offer little resistance to a change in shape of the holes.

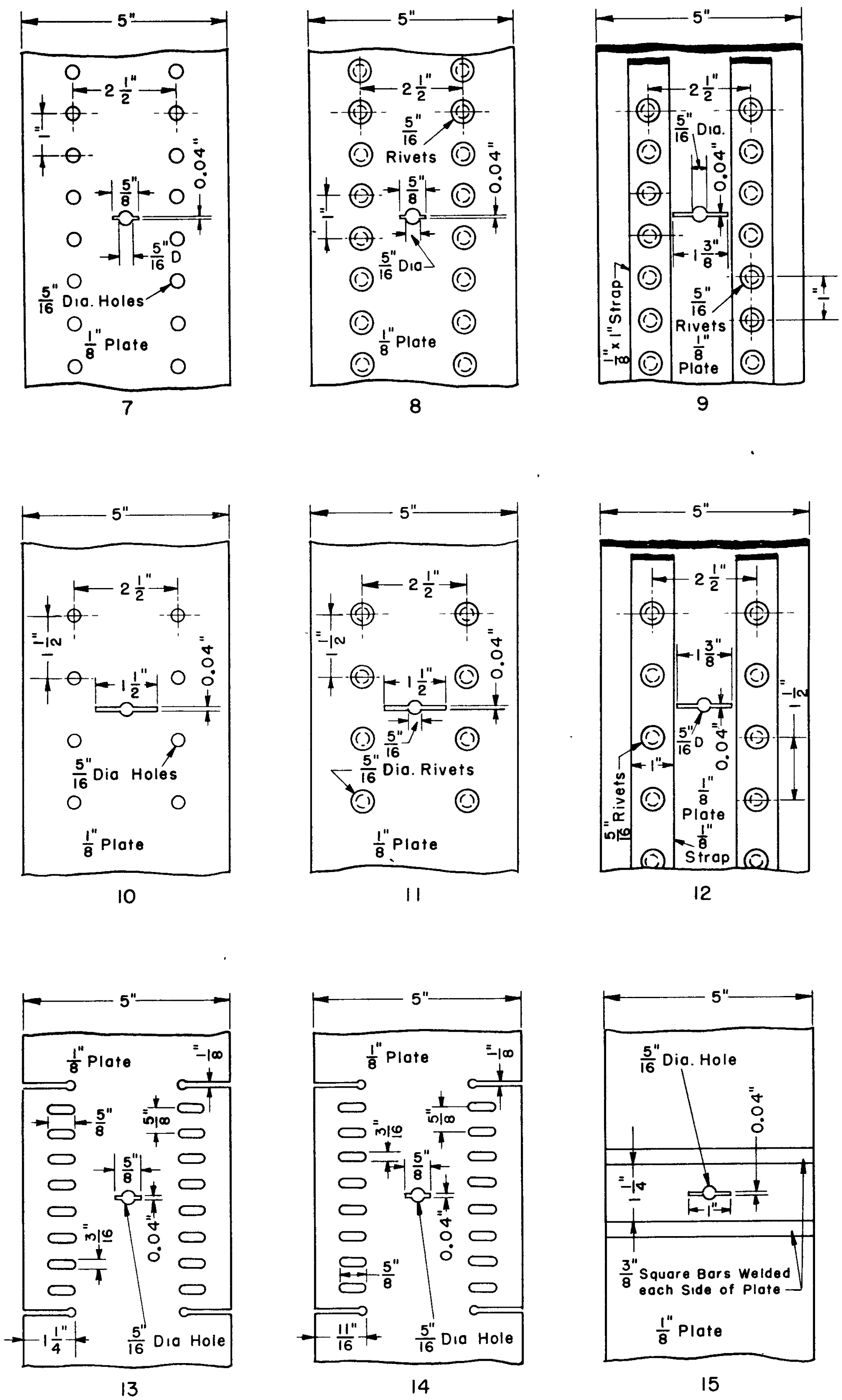

Figure 2 (continued)

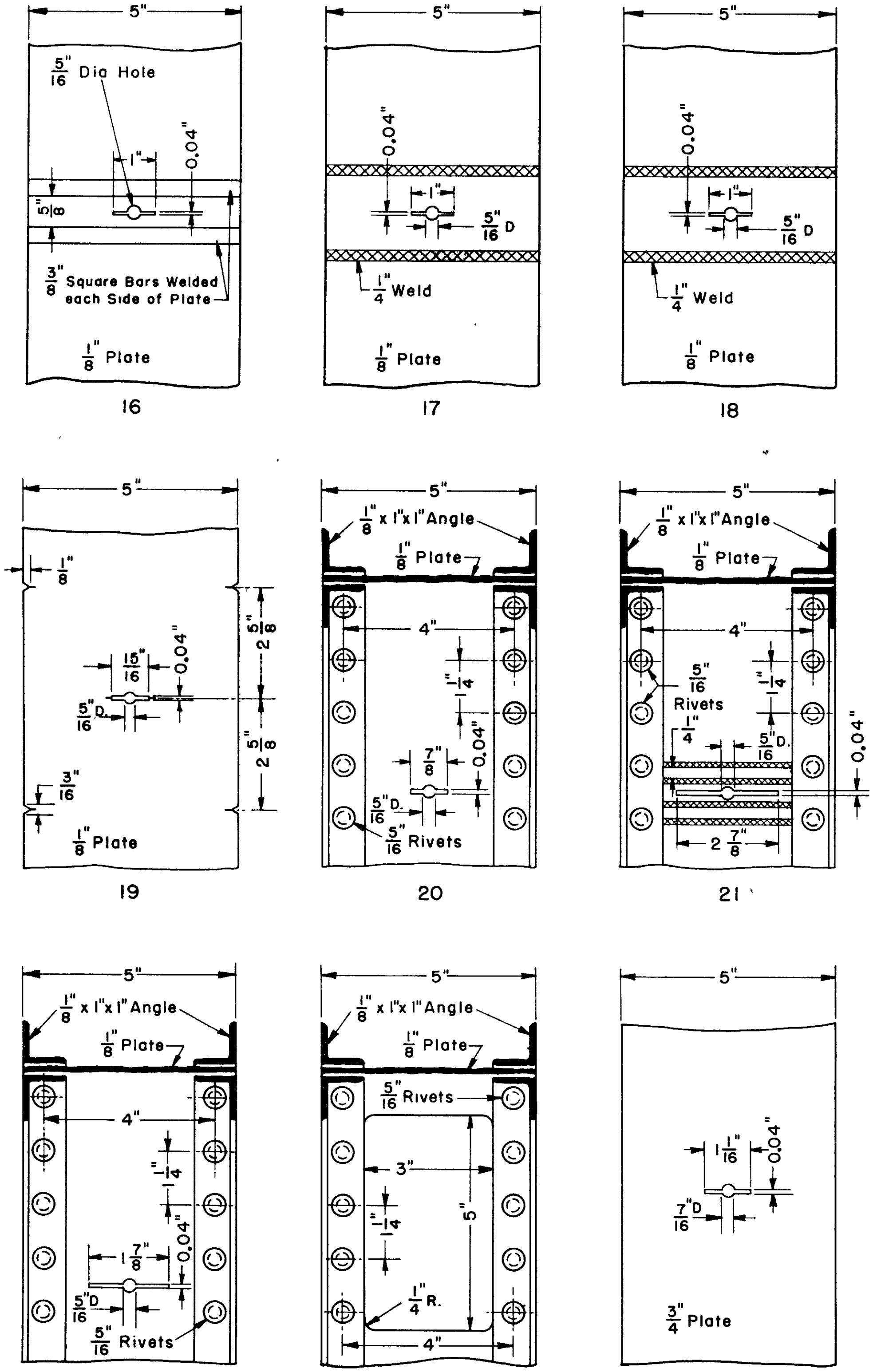

Figure 2 (continued)

ends of these bars were carried through to the grips, and so they shared the load directly. It was hoped that by using these bars lateral contraction or necking of the plate might be prevented.

In Specimens 13 and 14, two rows of elongated transverse slots were cut inside and along the two edges of the specimens, and four slots were cut in from the outer edges at the ends of the rows. It was thought possible that such a scheme might provide resistance to edge necking and so serve to give increased unit resistance in the remaining section.

Because the fractures in these specimens all failed to show the lack of elongation and the square, coarse fracture characteristic of so many of the failures on welded ship structures, a set of specimens was prepared for test in which the plate was prevented from contracting transversely abreast the crack starter by two or more reinforcing bars, welded across the plate, one on each side of the central hole. Specimens 15 and 16 were of this kind.

In the preparation of Specimens 17 and 18, strips 1 7/8 inch by 5 inches were cut from a plate which previously had been elongated plastically about 10 per cent and were welded between pieces of 1/8- by 5-inch plate. For Specimen 17, the inserted strip had been elongated in a direction perpendicular to the direction of loading in this test; for Specimen 18, the strip had been elongated in a direction parallel to the direction of loading in this test.

Specimen 19 had a slot 15/16 inch long, and 4 notches in the edges of the plate. The apices of the slot and of the notches were cut with a saw blade 0.015 inch thick, and part of the specimen was immersed in dry ice during the test.

In Specimen 21, two pairs of transverse welded bars were combined with two pairs of riveted angles.

The details of the various specimens may also be seen in photographs reproduced in later sections.

TEST PROCEDURE

The specimens were placed in the tension grips and pulled in the usual manner, except that the machine was stopped short of rupture in each case to show the nature of the fracture to better advantage. No observations or measurements were made in the elastic range.

As has been customary in many recent tests at the Taylor Model Basin, use was made of motion-picture photography to show the development of the strain lines and the cracks and the nature of the plastic flow. Samples of the motion-picture records are included as Figures 3a and 3b.

A pressure gage connected to the hydraulic system of the loading ram was placed in the field of view to give a correlation between the momentary load value and the condition of the specimen.

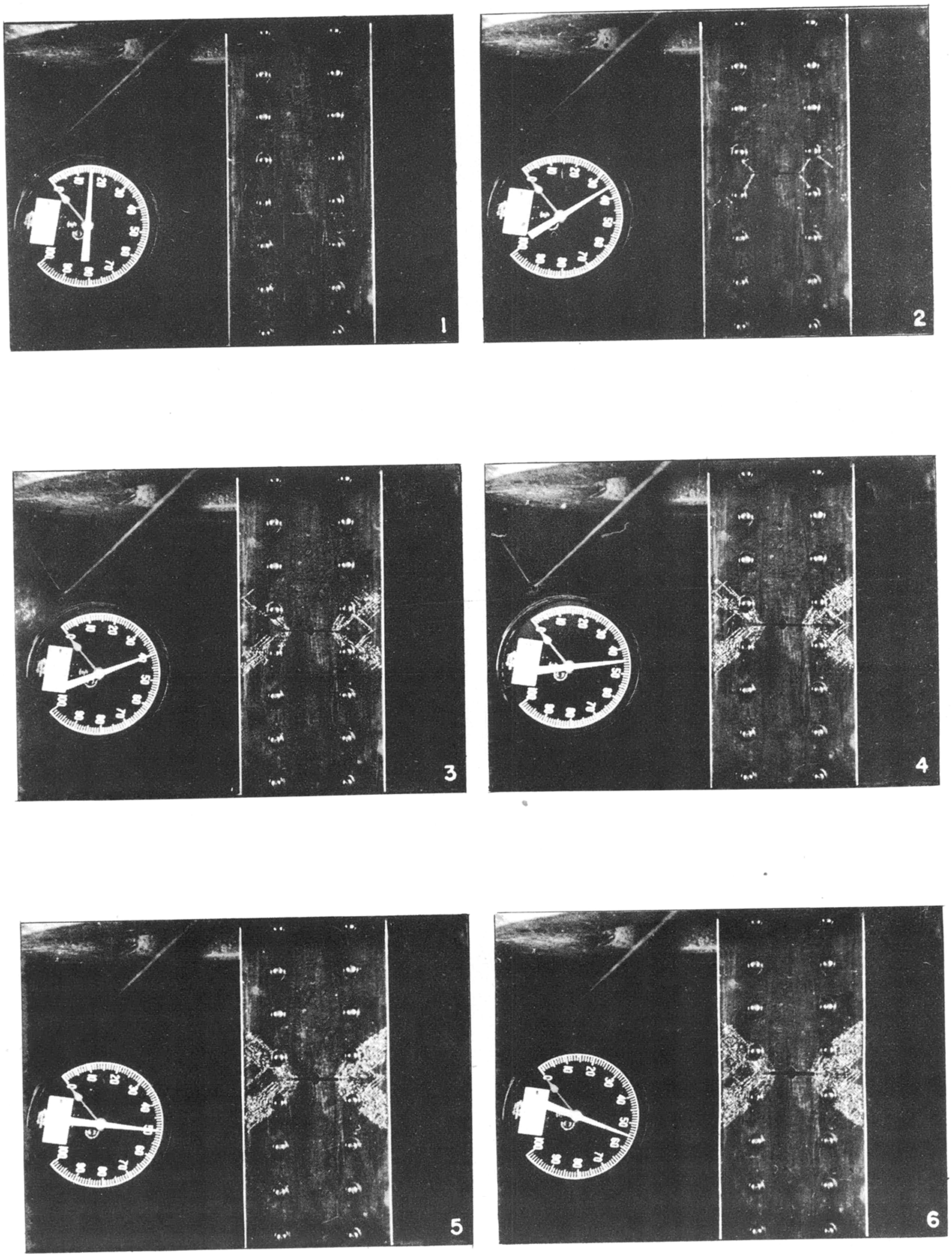

Figure 3a - Selected Frames from a Motion Picture of a Tensile Test

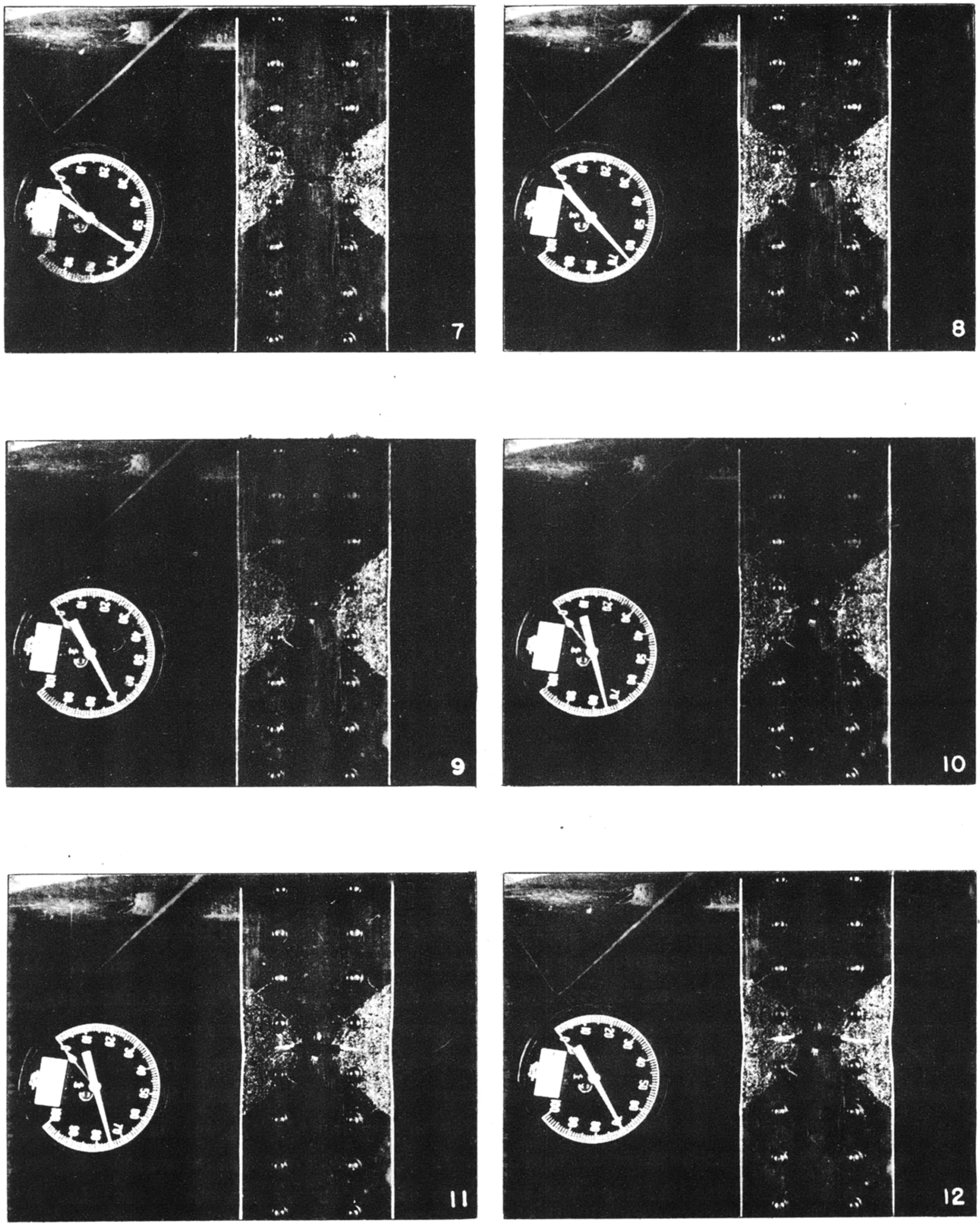

Figure 3b - Selected Frames from a Motion Picture of a Tensile Test

These 12 photographs were made during the test of Specimen 11, in which the crack-starter slot was 1 1/2 inch long, including the hole 5/16 inch in diameter.

In several cases, the crack starters were modified during the course of the tests to modify the plastic action and the fracture. Notes concerning this procedure will be found under the photographs for Specimen 9 in Figure 7 and Specimen 16 in Figure 13.

TEST RESULTS

The development of the strain figures was recorded by motion pictures, as shown in Figure 3. The first lines to appear in the strain figures in most of the specimens were diagonals from the ends of the saw cut; see Frames 2 and 3 of Figure 3a.

As the pulling was continued, the space between the diagonals filled in with strain lines, and the pattern was extended by the gradual appearance of other lines as the strain was increased; see the frames reproduced in Figure 3b, and other photographs given subsequently in the report.

As mentioned previously and as shown in Figures 3a and 3b, the metal around the notches at the saw cuts behaved in an entirely unexpected fashion. Instead of cracks appearing almost immediately in the regions of high concentration of stress at the square ends of the cuts, the saw cuts began to widen as the plastic range was reached. The transverse edges of the cuts remained sensibly parallel until the cuts opened out to several times their original width. The metal at the ends of the cuts or notches appeared to flow until it seemed that the corners of the cuts were, if anything, less sharp than when they had been originally made. Figure 1 illustrates this phenomenon.

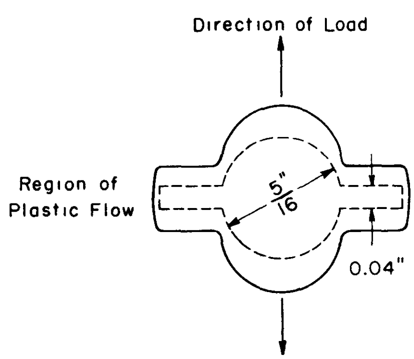

Figure 1 - Diagram Showing Widening of the Crack Starter in a Thin Plate Specimen

It has been suggested by some persons with whom this phenomenon has been discussed that, paradoxical as it may seem, transverse *compressive* strains may exist initially at the ends of the saw cuts, or that such *compressive* strains develop with the loading. However, it is difficult to believe that longitudinal compressive action could exist under the conditions shown in Frame 10 of Figure 3b.

The equalizing effect of the localized flow around the ends of the cuts was such that visible cracks did not begin to form until the *average* stress across the whole of the remaining section outboard of the cuts approached or even exceeded the yield strength of the metal as determined by a standard test specimen. At that time, necking at the edges of the specimen in line with the saw cuts had already appeared.

After the cracks appeared at the ends of the cuts, the strain figures remained unchanged, and further developments consisted mainly in widening of the cuts, extension of the cracks, and more pronounced necking at the edges.

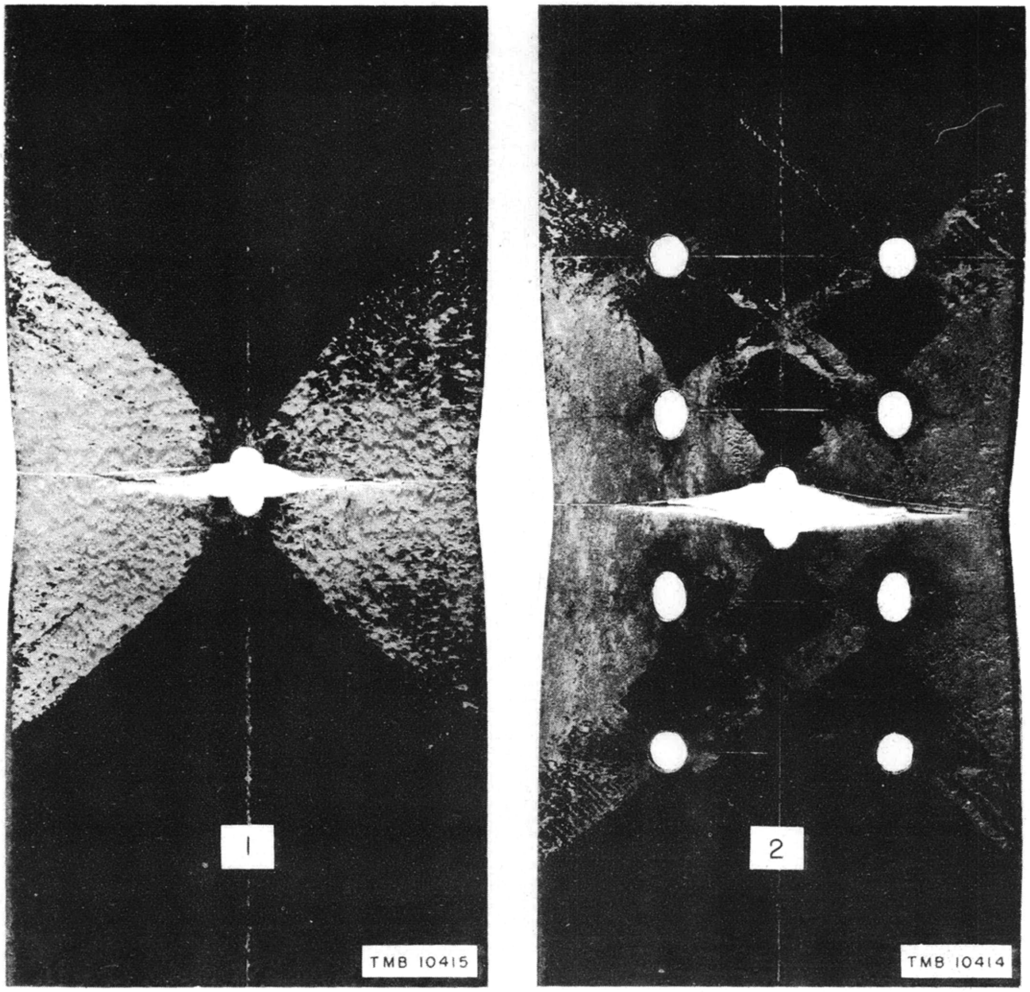

Figure 4 - Specimens 1 and 2 after Testing

Each specimen was 1/8 inch by 4 inches in section with a 5/8-inch slot at the center. Specimen 2 had two rows of 5/16-inch holes spaced 1 1/4 inch apart; the transverse spacing of the rows was 1 7/8 inch. Note the elongation and the transverse contraction of the holes in Specimen 2.

Specimens 2, 3, 4, 5, 6, and 7 differed among themselves only with respect to the spacing of the rows of holes and the spacing in the rows; in all of them, the cut was widely opened before the cracks at the ends began to form.* The stress at which this happened, averaged by dividing the gross load by the section outboard of the slot, was from 43 to 49 kips per square inch, except for Specimen 5 in which two of the holes were directly opposite the ends of the saw cuts; in this specimen, the cracks did not start until the average stress reached 58 kips per square inch. This is commented upon at some length in a subsequent paragraph.

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* These comments refer to the visible cracks only.

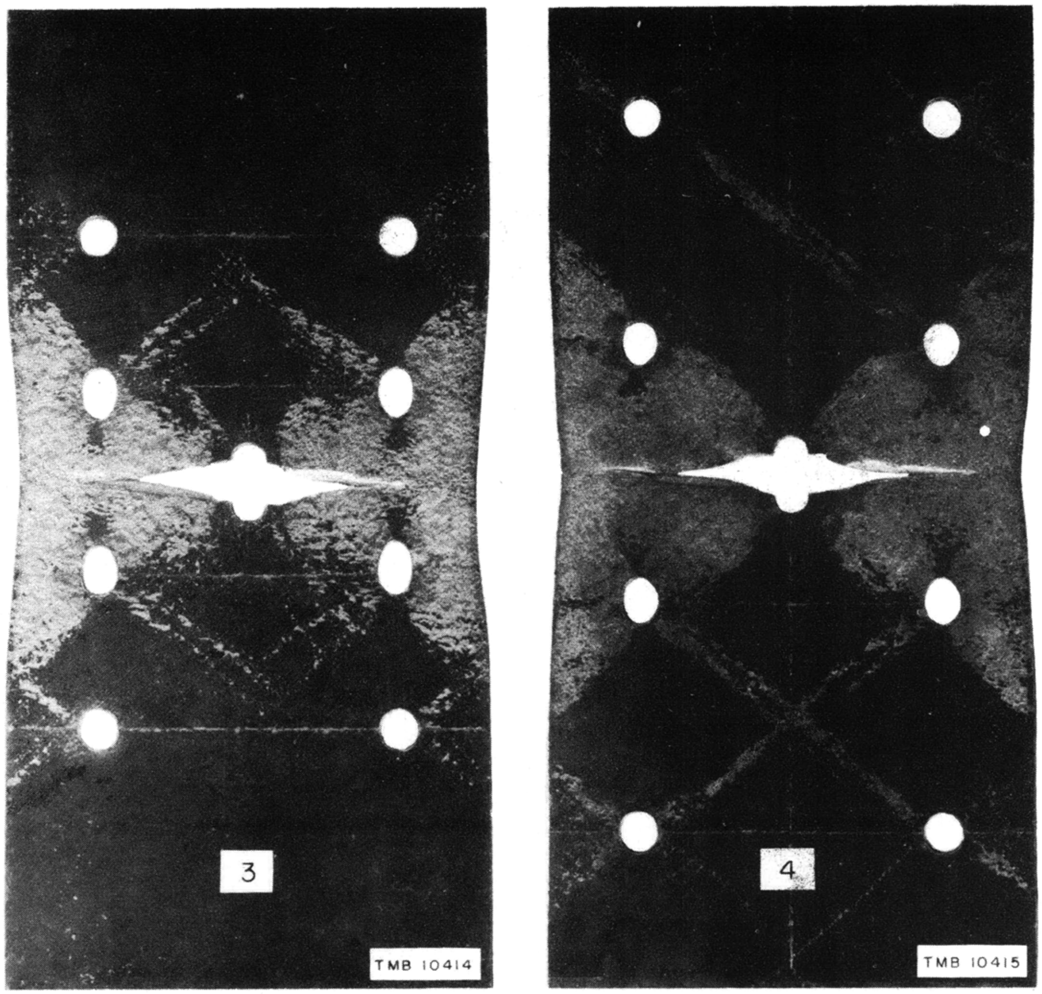

Figure 5 - Specimens 3 and 4 after Testing

Each specimen was 1/8 inch by 4 inches in section with a 5/8-inch slot at the center. Specimen 3 had two rows of 5/16-inch holes spaced 1 1/4 inch apart; the spacing of the rows was 2 1/2 inches. Specimen 4 had two rows of 5/16-inch holes spaced 1 7/8 inch apart; the spacing of the rows was 2 1/2 inches. The elongation and transverse contraction of the holes near the slot is quite pronounced here, as is the necking of the entire specimen in way of the crack starter.

In the case of Specimen 3, the *load* increased slightly after the crack had started, and the stress in the remaining metal rose to a maximum of 54 kips per square inch. In the others, the load diminished as the crack extended, in such a way that the average stress over the remaining section held at the same value with little variation.

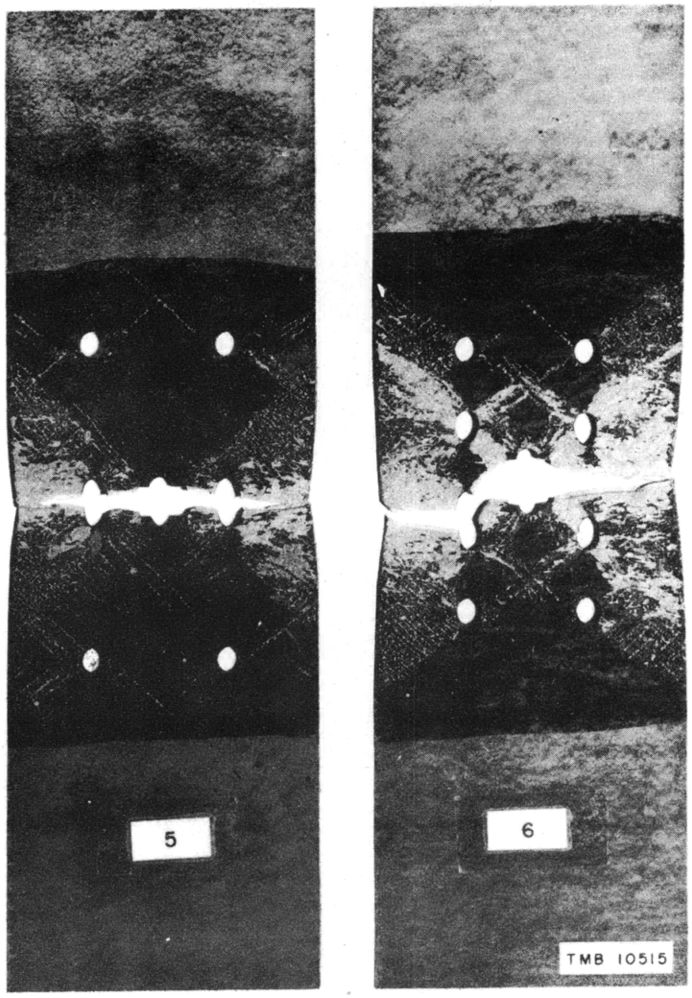

Figure 6 - Specimens 5 and 6 after Testing

Each specimen was 1/8 inch by 4 inches in section with a 5/8-inch slot at the center. Specimen 5 had two rows of 5/16-inch holes spaced 2 inches apart; the spacing of the rows was 1 3/4 inch. Note that for this specimen two of the holes were directly opposite the slot.

Specimen 6 had two rows of 5/16-inch holes spaced 1 inch apart; the spacing of the rows was 1 1/2 inch.

The cracks hesitated but did not stop at the holes opposite or near the crack starter.

In Specimen 5, the crack led directly into the opposite pair of holes, and the area of these might be combined with that of the crack in inferring the stress. However, as previously mentioned, this method leads to a value of 58 kips per square inch, whereas if the holes are disregarded in Specimen 5 as in Specimens 2 and 4, the stress in the remaining metal during the advance of the crack is found to be about 47 kips per square inch, as before. This indicates that the holes had about the same effect regardless of whether the crack passed through a hole or between holes.

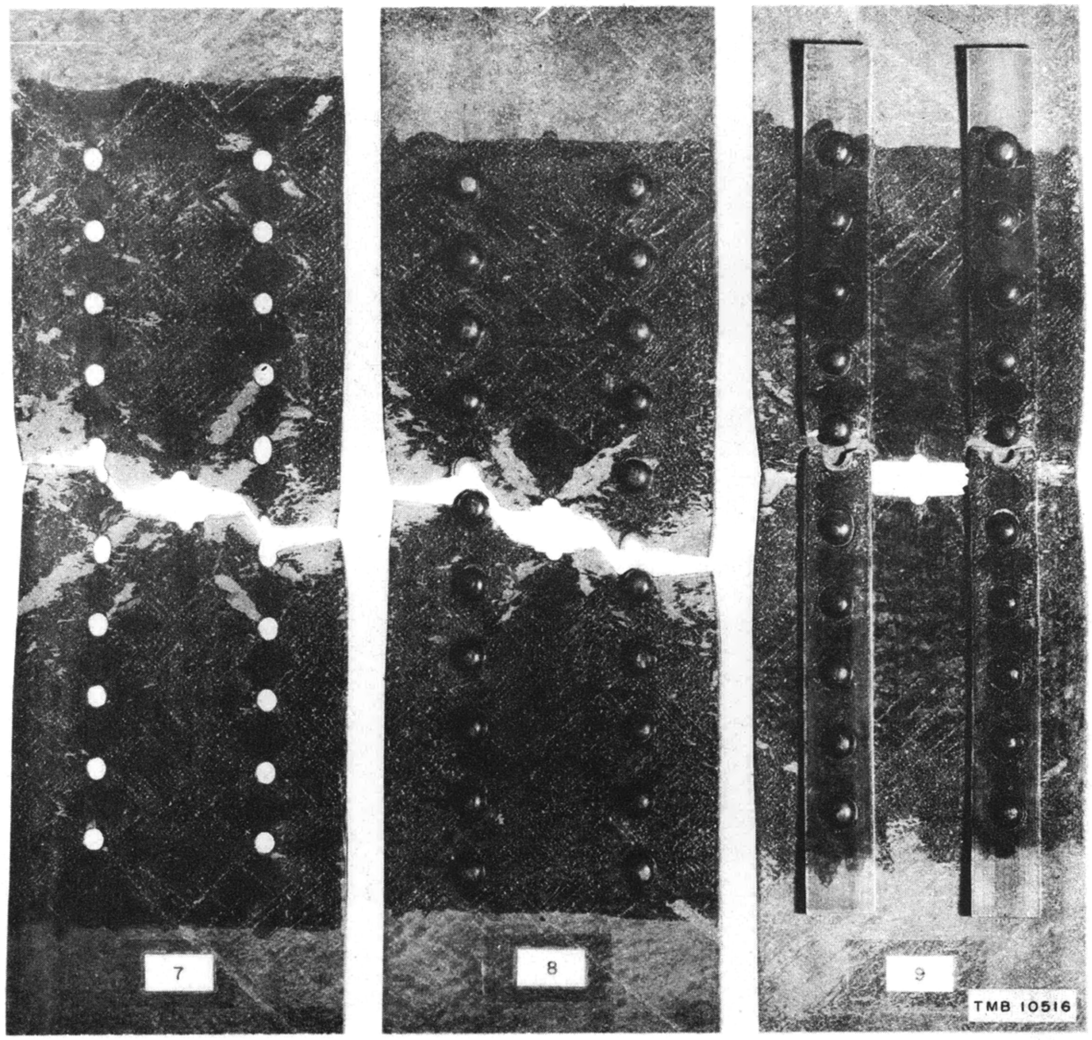

Figure 7 - Specimens 7, 8, and 9 with Holes Open, Filled, and Strapped

Each specimen was 1/8 inch by 5 inches in section with a 5/8-inch slot at the center. All specimens had two rows of 5/16-inch holes spaced 1 inch apart; the spacing of the rows was 2 1/2 inches.

Specimen 7 was tested with open holes; Specimen 8 had 5/16-inch rivets driven hot in all holes; Specimen 9 was reinforced by two 1/8- by 1-inch straps hot-riveted to the plate.

The slot in Specimen 9 was 5/8 inch long initially; it was lengthened to 1 3/8 inch after the test was started, to prevent failure of the plate outside of the straps.

Note the diamond-shaped unstrained areas between the holes in the longitudinal rows in Specimen 7. The rivets in the holes of Specimen 8 prevented transverse contraction of the holes and so concentrated the plastic flow and the necking to a relatively restricted area abreast the crack starter. In Specimen 9, some concentration of strain occurred around the ends of the straps.

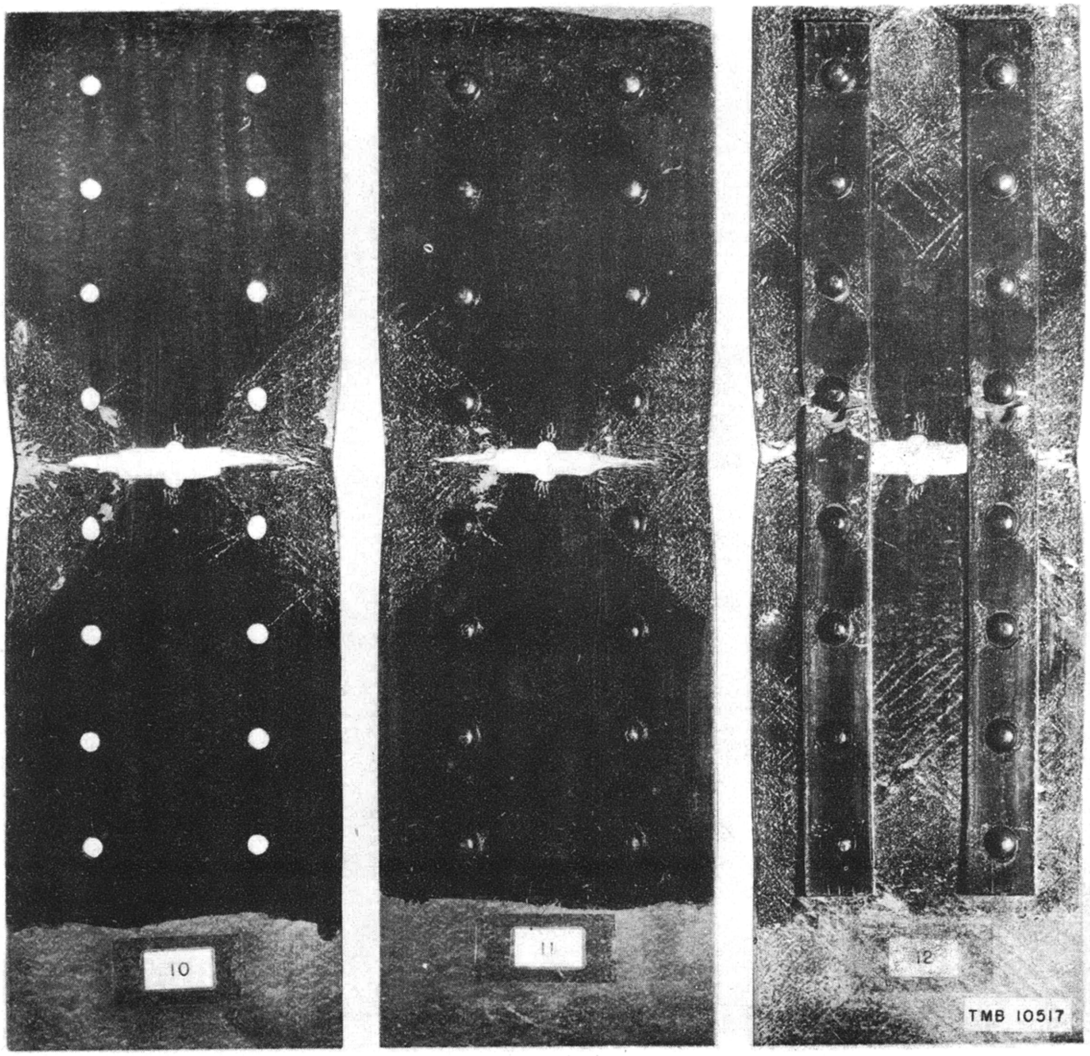

Figure 8 - Specimens 10, 11, and 12 with Holes Open, Filled, and Strapped

Each specimen was 1/8 inch by 5 inches in section and had two rows of 5/16-inch holes spaced 1 1/2 inch apart; the spacing of the rows was 2 1/2 inches. In these specimens, the total width of the slot was 1 1/2 inch, except in Specimen 12 where it was only 1 3/8 inch. In other respects, these specimens are similar to those shown in Figure 7.

In Specimens 10 and 11, the long slot limited the plastic flow to two relatively small areas abreast the crack starter.

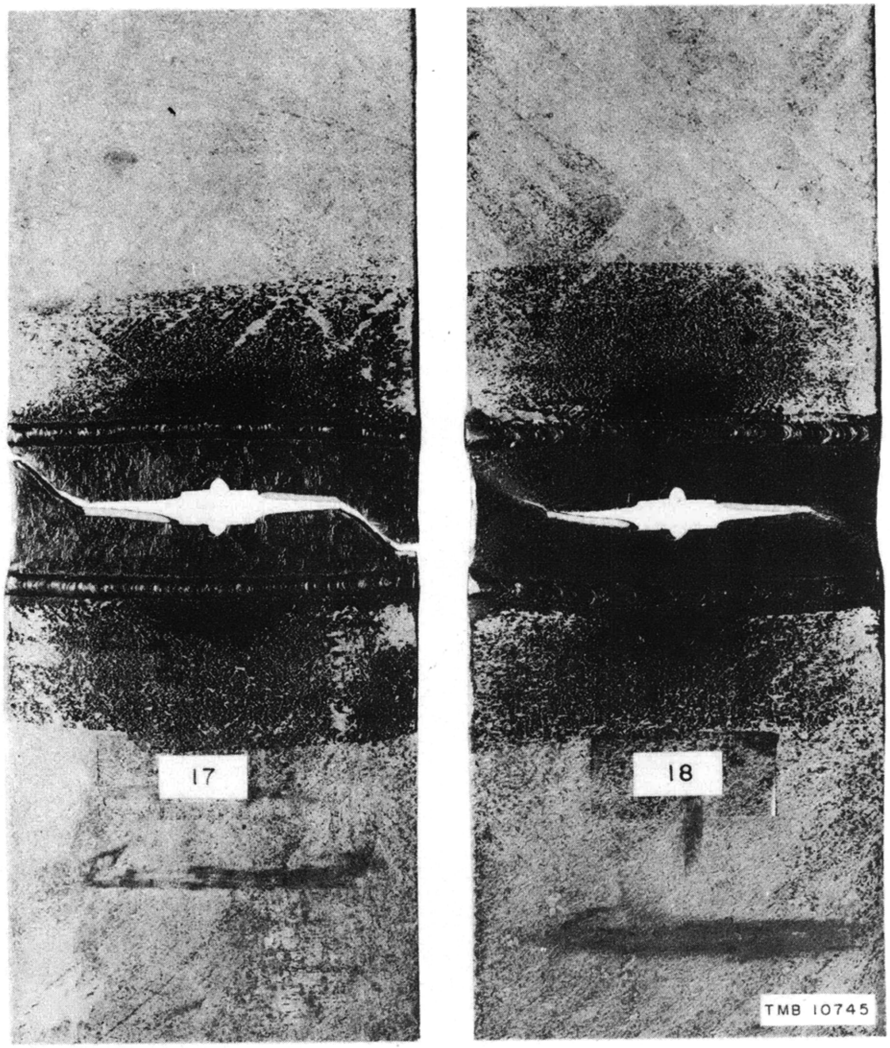

Figure 9 - Specimens 17 and 18 with Prestressed Test Sections Welded in Place

Each specimen was 1/8 inch by 5 inches in section with a 1-inch slot at the center. In the preparation of Specimens 17 and 18, strips 1 7/8 by 5 inches were cut from a plate which previously had been elongated plastically about 10 per cent and were welded between pieces of 1/8- by 5-inch plate. For Specimen 17, the inserted strip had been elongated in a direction perpendicular to the direction of loading in this test; for Specimen 18, the strip had been elongated in a direction parallel to the direction of loading in this test.

The transverse welding beads offered some degree of transverse constraint, as shown by the limited area in which necking occurred.

Specimens 13 and 14 yielded no significant data. Specimens 15 and 16 will be illustrated and analyzed in a subsequent section.

Specimens 17 and 18 behaved in much the same way as if they had consisted of intact pieces of virgin metal.

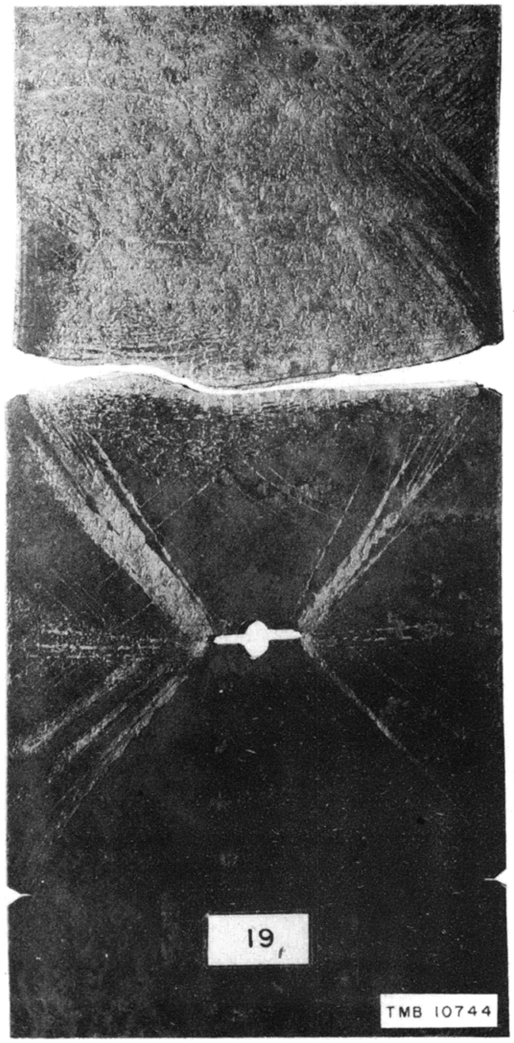

Figure 10 - Specimen 19 after Testing

This specimen was 1/8 inch by 5 inches in section with a slot 15/16 inch long and 4 notches in the edges of the plate. The apices of the slot and of the notches were cut with a saw blade 0.015 inch thick.

This specimen was tested with the lower part, between the edge notches, held at a low temperature by immersion in a bath of acetone and dry ice. Under these conditions, by far the greater part of the plastic flow occurred in the portion of the specimen which was near normal temperature, so much so that the fracture took place across a section notably greater than the section of minimum area.

Specimen 19, as shown in Figure 10, failed by tearing through the edge-notches in the uncooled section. The slot was at an intermediate temperature; it was widened, but no crack started there. The cold notches were unaltered by the test, and the adjoining metal showed no strain lines.

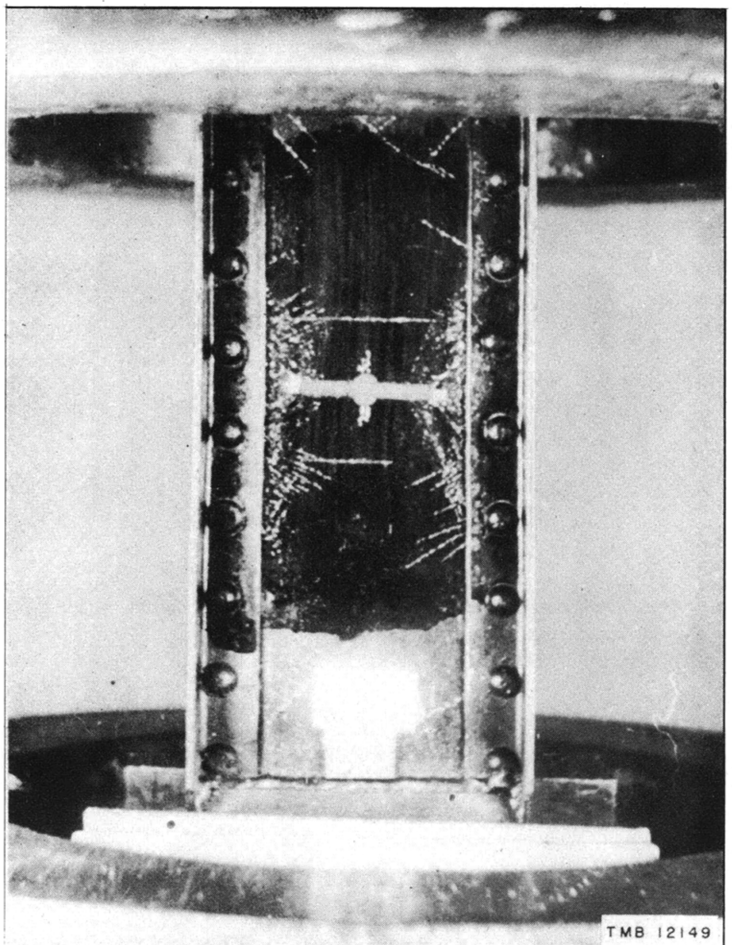

Figure 11 - Specimen 22 during Test, with Crack Starting to Develop

This specimen was made up with a 1/8- by 5-inch plate to which two pairs of 1- by 1- by 1/8-inch angles were riveted along the edges.

The crack can be seen just starting at the ends of the saw cut. Note the width of the cut at this stage of the test.

Specimens 20 to 23, shown in Figure 2, were laid out to afford edge support to the plate such as might be expected to restrain edge-necking. However, restraint did not occur to any great extent; the rivets joining the angles to the plate did not affect the behavior of either of the joined members much, and both plate and angles appeared to fail very much as they would have done under the same tensions if they had not been joined by the rivets. Figure 11 shows Specimen 22 under test. The angles were more and more heavily loaded as the crack in the plate advanced, and eventually they started to fail through rivet holes in the faying flanges; however, this occurred only after rather complete failure in the plate. The angles thus afforded a certain reserve of strength in the assembly.

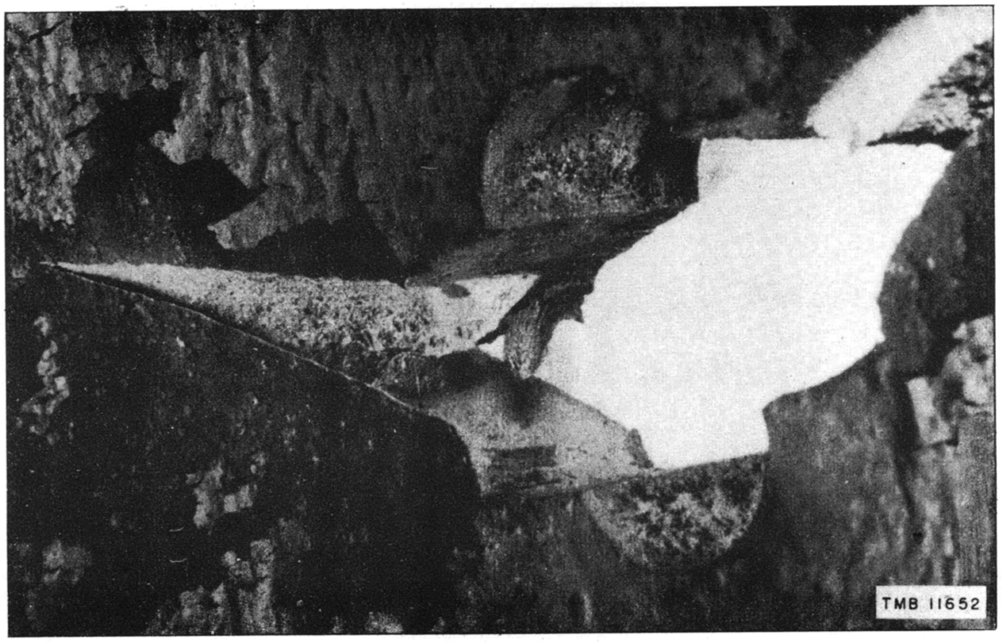

Figure 12a

Figure 12b

Figure 12 - Specimen 24 after Test

This was a 3/4- by 5-inch plate which failed in much the same manner as the others. Note the necking in width.

Specimen 24 was made up with 3/4-inch plate so that it had 6 times the thickness of the others. It was intended as a test of the effect of absolute thickness. The nature of the failure, with its 45-degree shear fractures as shown in Figure 12b, did not differ notably from that in thin specimens. This was perhaps affected by the fact that the plate was quite narrow in proportion to its thickness, and considerable necking in width took place.

ANALYSIS OF TEST DATA

In Specimen 7, Figure 7, the effects of flanking rows of open holes are shown. The elongation of the holes visibly relieves the metal between the holes from heavy plastic working, as shown by the unstrained patches which show in the spaces adjoining the elongated holes.

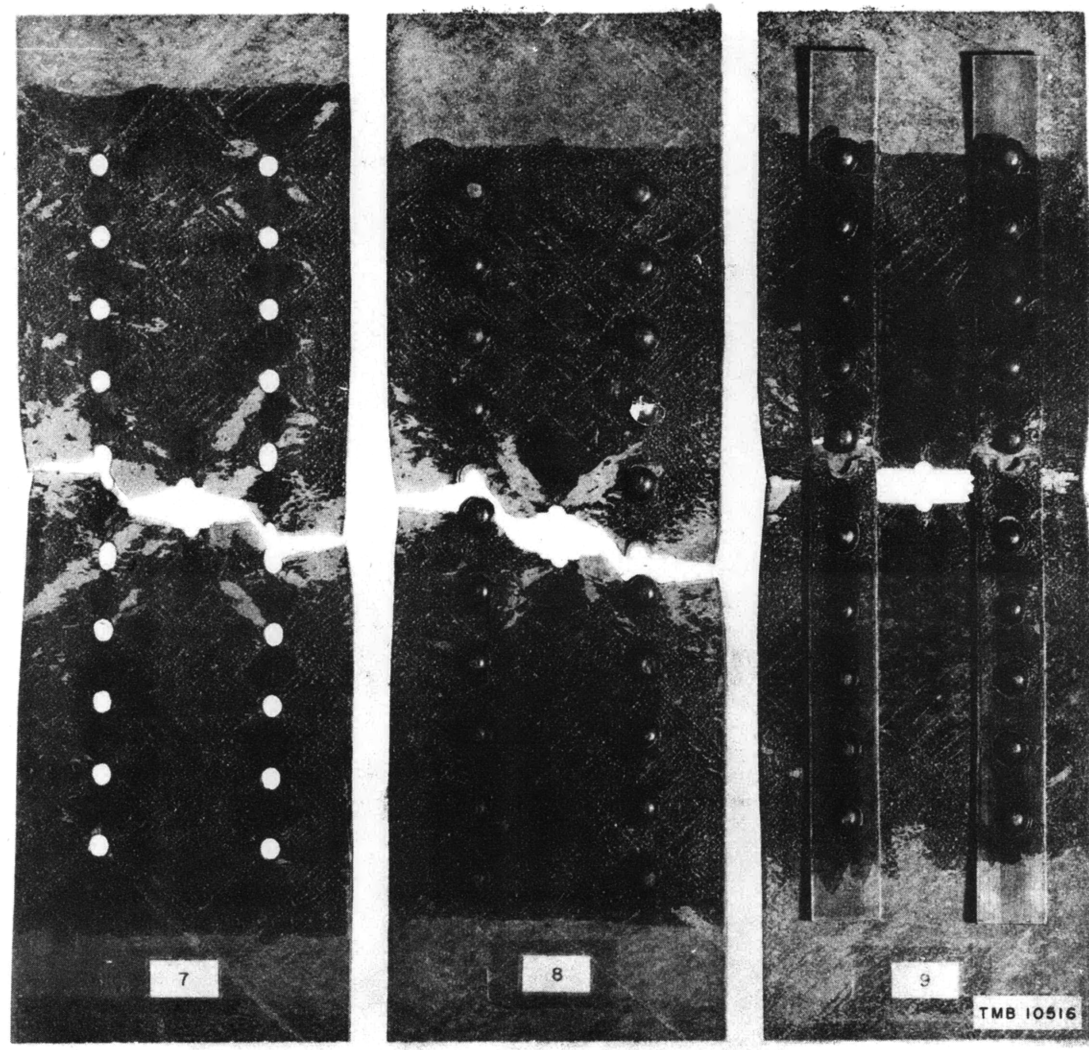

Figure 7 - Specimens 7, 8, and 9 with Holes Open, Filled, and Strapped

These diamond-shaped areas between the holes, which show clearly everywhere except where the crack has passed, are in some degree unfavorable to crack propagation, hardly less so, in fact, than the holes themselves. In this case, the cracks sought the holes rather than to pass between them, but this diversion of the course of advance of the crack did not suffice to cause notable increase in the load-carrying capacity of the remaining section of the ruptured specimen.

An index of the history of the plastic action during the test is found in the strain figures at sections distant from the slot. The strain lines in this specimen are distributed quite uniformly from end to end of the extent of the rows of holes. This did not occur in Specimen 1 where the holes were not present, and the highly strained area was rather closely confined to the vicinity of the slot. The presence of the holes thus increases the overall elongation of the specimen without reducing its load-bearing capacity.

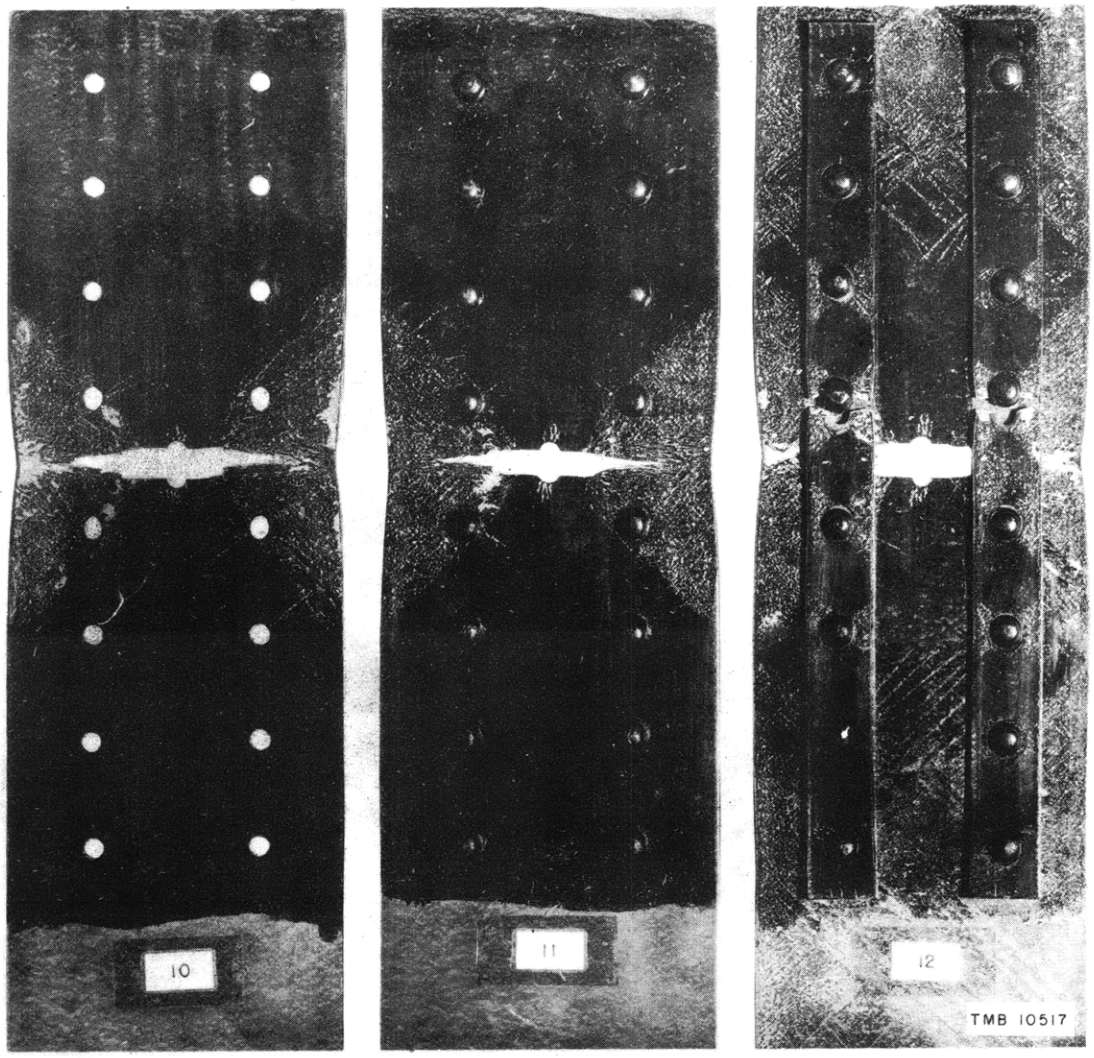

Figure 8 - Specimens 10, 11, and 12 with Holes Open, Filled, and Strapped

In Specimens 7 to 12 inclusive, shown in Figures 7 and 8, two series of three specimens each are seen; in the second series, the spacing of the holes is greater than in the first. The effect of the holes in providing areas of lightly strained metal is seen to be nullified when they are filled with rivets, but when a strap is added, a real crack-stopping effect is achieved. On this, however, some comment is needed.

In Specimen 7, the crack has turned aside to avoid the lightly strained spaces between the holes and to follow a longer path in the metal which leads to the edge of the plate through a hole. The well developed strain figures at a distance from the crack show that the margin by which the action in the rupture section exceeded in intensity that at other sections was not very great. In Specimen 8, the conditions are similar except that no lightly strained areas appear between the holes. The fact that the rivets prevented the holes from contracting transversely is probably responsible for this difference.

In Specimen 9, Figure 7, the plastic straining at the strap ends exceeded that at the cut so that it was necessary to widen the cut to prevent failure at one end of the straps. In this case, and in Specimens 10 to 12, Figure 8, in which the cut reduced the section by the same amount, the crack progressed straight across to the edges.

In Specimens 10 and 11, the strain figures show that elongation was rather closely confined to the immediate vicinity of the slot. This may be attributed to the wider spacing of the holes and especially to the greater width of the slot as compared with Specimen 7.

The crack-stopping effect in Specimens 9 and 12 is shown by two features of the photographs, Figures 7 and 8.

(a) Immediately above and below, adjoining the slot, are large patches of unstrained metal, but the straining at a distance from the slot is widespread and fairly intense. The straining action is more uniform and less localized than in Specimens 10 and 11. This shows that even with the slot extended to the inboard edges of the straps, the straps had a sufficiently strong reinforcing effect to develop the strength of the unstrapped plate at a distance from the slot to a value comparable with that of a similar area of metal including straps at the slot. The straps therefore substantially neutralized whatever effects of concentration might exist about the cracks spreading out from the slot.

(b) The original slot has opened up by an amount which greatly exceeds the gap at the ruptured section of the straps. In fact, during the test, there was a moment at which the cut had widened to several times its original opening, and the straps had been well loaded in consequence, though actual rupture had not yet occurred. If the load had not been increased above its value at that moment, ultimate rupture would not have occurred at all.

ANALYSIS OF MOTION PICTURES

Careful study, from frame to frame, of the motion pictures of Specimens 7 to 12 reveals additional details of interest. In particular, the actions which follow so closely on each other in the actual test as to escape direct observation are here spread out in time, and as a result it appears that the process is not continuous, but rather that it advances by transitions from one stage to the next.

The first appearance of strain lines occurs well below the ultimate load in the specimens with open holes and at about the same stage when the holes are filled with rivets. When straps are present, the facts are less clear, but it is certain that the strain figures are slower in appearing than when the straps are absent. This shows that large plastic deformations in the plate are not necessary to get an appreciable amount of load in the straps. This is decidedly not true, however, with respect to the first appearance of the crack. This does not occur until the load is at or near its maximum.

A small margin of strength appears to exist in Specimens 7 and 10 in which the crack started at somewhat less than the maximum total load. The same cannot be said, however, for the riveted specimens, whether strapped or unstrapped. In these cases, the loads at which the crack started and at which rupture became complete differed little from the maximum load. The benefit obtained from the riveted straps consisted rather in adding to the plastic resilience of the specimens. Even after the slots had opened up wide and the cracks had definitely appeared in the plate, the straps still hung on. Though the load dropped off as the remaining section of metal diminished, a definite margin of time and of elongation was present. If the same effects could be obtained in a service structure, a reduction of service load might be made during this margin of time, and complete fracture might be prevented.

TRANSVERSE CONSTRAINT AND BRITTLE FRACTURE

In all specimens up to and including Specimen 14, the only constraint against transverse contraction lay in the width of the section which had a width-thickness ratio of from 27 to 35 outside the cut. This is by no means large for a ship plate. The fractures in all cases were of the ductile or shear type characterized by fine grain, necking, and oblique parting surfaces, advancing gradually across the width of the plate by tearing action.

This does not reproduce the loading conditions in a ship's deck with welded seams where contraction in width of any strake is prevented by its firm attachment to the adjoining strakes.

In an effort to simulate this transverse constraint in a single plate, heavy transverse members were welded to two specimens, adjoining the crack starters, as illustrated in Figure 13. In Specimen 15, the spacing of these transverses was only about one-fourth the plate width. The nature of the failure in this specimen was almost identical with that in Specimen 1, except that the necking in width was confined to the length between the transverses. In Specimen 16, the transverses were more closely spaced and the failure was more abrupt, with less opening of the cut; the necking in width was reduced between the transverses, but the maximum load was enough higher than in Specimen 15, 34,000 pounds as compared to 27,600 pounds, to cause a definite reduction in width in the uncut sections beyond the transverses.

Even in Specimen 16, however, the fracture was fine-grained, the necking in thickness was pronounced, and the parting surfaces were oblique.

In no case among Specimens 1 to 24 was there any indication of true brittleness of the sort designated as cohesive fracture which is characterized by coarse grain, no elongation, and parting normal to the plate surfaces. An example of fracture of this kind is given in Figure 14 to show the results obtained in a test of a similar general nature but in which the metal had an absolute thickness 5 times the value in Specimens 1 to 23.

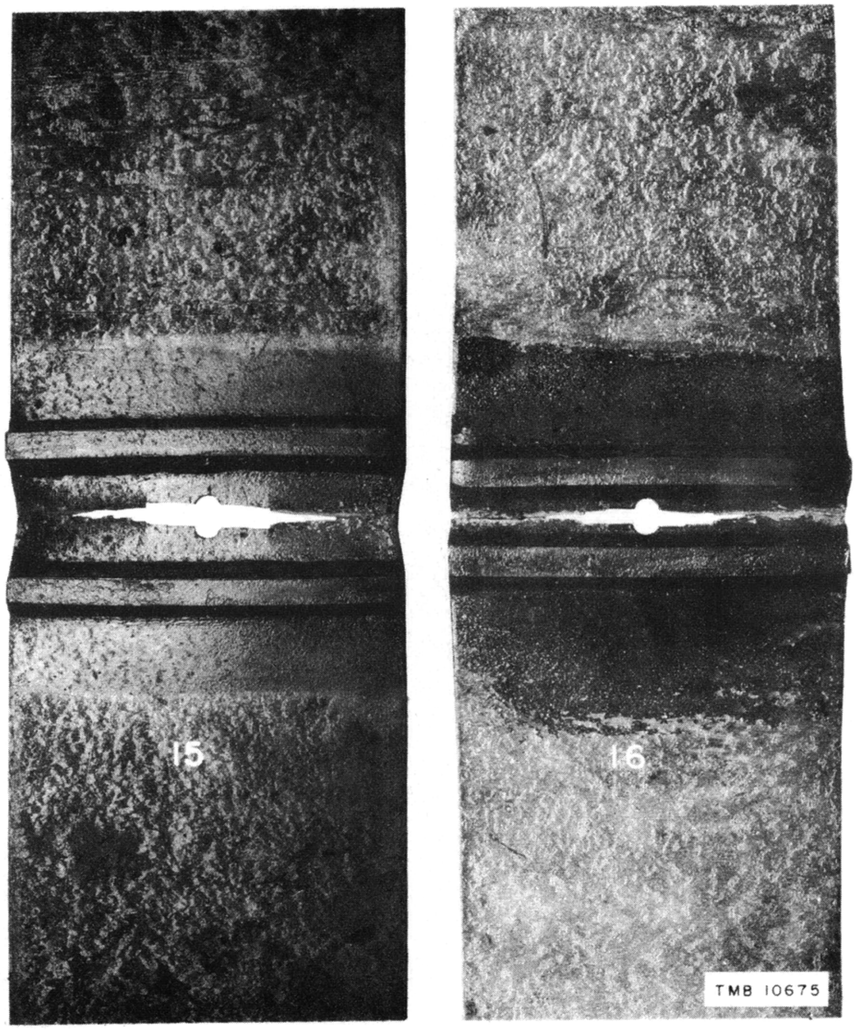

Figure 13 - Specimens 15 and 16 after Testing

Each specimen was 1/8 inch by 5 inches in section with a 1 5/8-inch slot at the center. Bars 3/8 inch square were welded on both sides of the plate and on each side of the slot. The spacing between bars was 1 1/4 inch for Specimen 15 and 5/8 inch for Specimen 16.

Specimen 16 was first pulled with a slot 1 inch wide, but this was widened after it was found that the rupture would otherwise have occurred outside the space enclosed by the transverse bars, as shown by the incipient necking there.

In Specimen 15, there was still considerable necking between the bars in spite of the transverse constraint. In Specimen 16, the necking between the bars was reduced to a purely local effect.

As explained in a preceding section, no attempt was made to gather data on elongation such as would be necessary for finding the energy absorbed in the specimens. However, it is believed that the capacity of specimens of this sort for absorbing energy is their most important feature, and that its measurement, in the more careful and larger-scale tests expected to follow these, is essential.

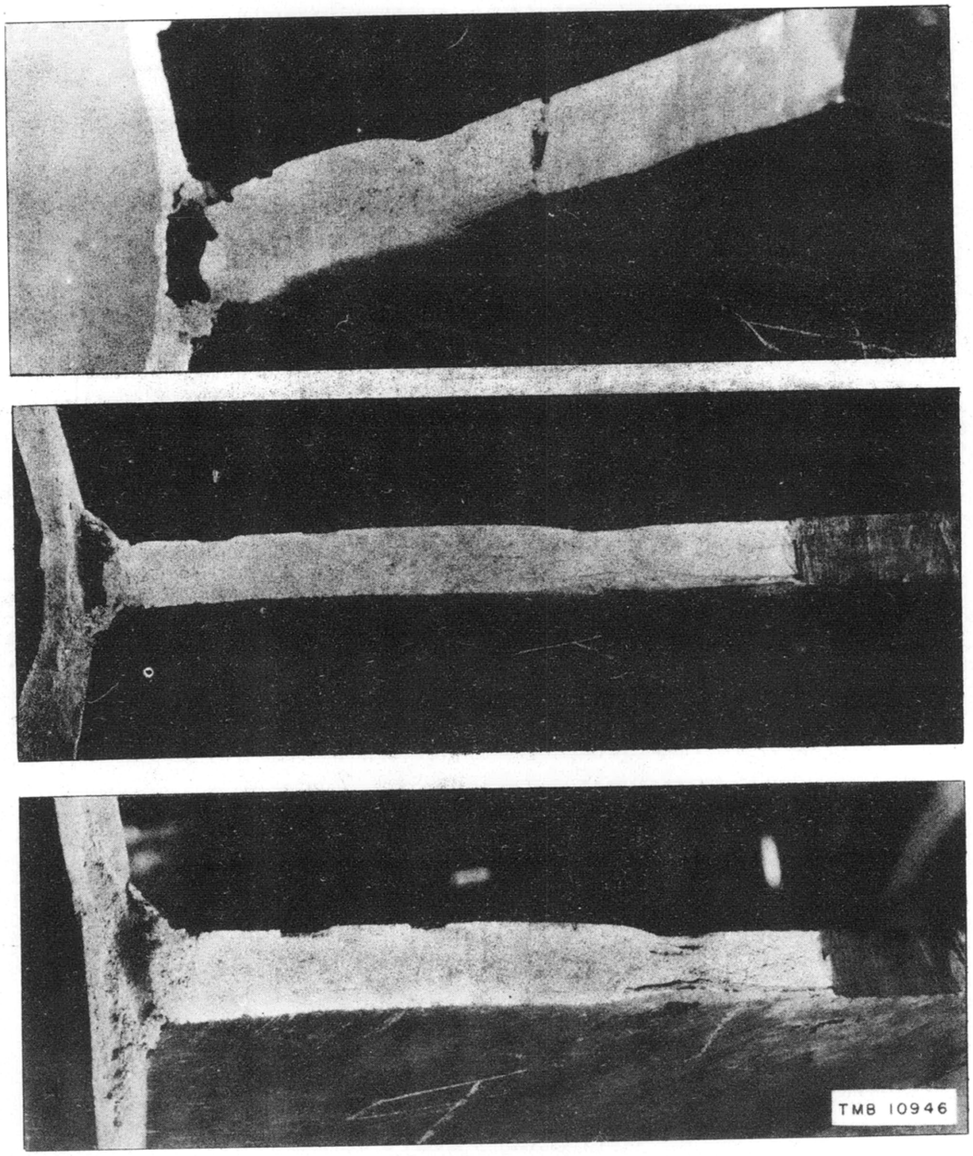

Figure 14 - Comparison of Cohesive and Ductile Fracture in a Plate 5/8 Inch Thick

These are three different views of a fracture which proceeded from the edge of the saw cut at the right toward the welded flange member at the left.

The oval boundary of the area of cohesive fracture is clearly marked. Within this area, the fracture is coarse, square, and without reduction in thickness; outside this area, the fracture is fine-grained, oblique, and shows reduction in thickness.

TENTATIVE CONCLUSIONS

These tests serve mainly to demonstrate that knowledge of the behavior of steel as it approaches and reaches rupture is very imperfect. The enormous elongations which occurred at the ends of the narrow saw cuts before a crack was formed and the high values of stress in the remaining section during the progress of the rupture were unexpected.

The low rate at which the fracture progressed across the strapped specimens, the margin of elongation, and hence of capacity for energy absorption are noteworthy.

However, these experiments with specimens 1/8 inch by 4 or 5 inches, though suggestive with respect to possibilities for barriers to crack-propagation, are not conclusive. Even in the case where the nearest approach to brittle failure was reached, as in Specimen 16, the fracture was still not of true brittle mode. The question as to what causes brittle failure and how it may be prevented from advancing across the tension flange of a thin-walled girder is still not answered by these tests. While these limited tests are by no means conclusive, there is strong suggestion of a scale effect in thickness for plate specimens of this kind when tested in tension.

In wide plates, there is known to be a lateral constraint with the resultant establishment of biaxial stresses when the plate is loaded in tension to the point where edge contraction begins. In wide plates which are also thick, and which are loaded in the same manner, there are presumably triaxial tensile stresses which may become very high if the plates are thicker than some limiting value, now unknown. It may be expected that under these conditions a tensile fracture will start at the mid-thickness of the plate, at average stresses which may not be excessively high, and that a brittle type of cohesive fracture may be the result. In following up these suggested ideas, the effects of thickness and of absolute dimensions on tensile specimens are being investigated separately at the Taylor Model Basin, and in due course, additional reports on this subject may be expected.

RECOMMENDATIONS

It is recommended:

1. That tests similar to those here described be made with much thicker plates in similar width-thickness ratios. If possible, the load should be released at intervals after the crack starts its advance, to permit careful observation both of the remaining section and of the average stress needed to start it on a further advance, at a series of stages in the process. Control assemblies like Specimens 1 and 10 are suggested, followed by specimens with light, free-ended, double-riveted straps. The metal of the plate between the two rows of rivets in each strap should in at least one case be left intact, in another slotted longitudinally. Transverse constraint, as in Specimen 16, should be applied at least to part of these heavy flat specimens.

2. That in any case, tests on flat specimens be supplemented by tests on heavy cylinders loaded by internal fluid pressure in combination with axial tension. In addition to tests already planned for such specimens, other tests with crack barrier features should be included. Only in this way has an adequate degree of transverse restraint been obtained in the tests hitherto made.

3. That in the tests with large specimens, which can be made only with the expenditure of considerable time and labor, the extra expense needed for an unhurried and adequate collection of data be undertaken. In particular, it is hoped that some data on energy absorption can be obtained.

REFERENCES

(1) BuShips letter QP/W and C-(4)-(6)(692) of 18 May 1943 authorized an extensive series of tests on welded and riveted ship plate specimens under Welding Test 306, Research Symbol D233.

(2) "The Brittle Failure of Medium Steel in Ship Structures," by Captain W.P. Roop, USN, TMB CONFIDENTIAL Report R-207, October 1943.

(3) "Tests of Joints in Wide Plates," by W.M. Wilson, J. Mather, and C.O. Harris, Bulletin 239, Engineering Experiment Station, University of Illinois, November 1931.