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

DECLASSIFIED

MODEL TESTS OF WELD REINFORCEMENTS FOR THE HATCH CORNERS OF WELDED SHIPS

by

Commander G.L. Smith, USN, (Ret)

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~~RESTRICTED~~

November 1944

Report R-289

PERSONNEL

The idea of applying stresses near the corners of openings in ship plating to set up initial strains at critical points originated with Commander G.L. Smith, USN, (Ret), of the David Taylor Model Basin staff, who planned the tests and also wrote the report. The tests were carried out by personnel of the Structural Mechanics Section. Appendix 1 is the work of Commander H.M. Westergaard, USNR. Appendix 2 was written by A.R. Cohen, Chief Specialist (X) USNR, and B. Stiller, Specialist 1/c (X) USNR.

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"Model Tests of Weld Reinforcements for the Hatch Corners of Welded Ships," by Commander G.L. Smith, USN, (Ret), TMB RESTRICTED Report R-289, November 1944.

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RESTRICTED

MODEL TESTS OF WELD REINFORCEMENTS FOR THE HATCH CORNERS OF WELDED SHIPS

ABSTRACT

A preliminary report is made of tests with model plates to determine the effect of diagonal welded beads or straps applied to deck plating near the corners of hatch openings on ships. It was considered that by shrinking or compressing the material in this area the possibility of cracking under tensile load would be reduced.

The tests indicate that tensile strains can be introduced into the material at the corners of an opening in a plate to prevent a crack from starting at the corner under overall tensile load or to delay the starting of a crack at a sharp corner until the ultimate strength of the material has been reached.

Theoretical calculations show that the reinforcement derived from the pre-straining set up by welded beads is of the order of 7000 pounds per square inch. The welded bead is so small with respect to the area of the plate under tension that it cannot appreciably effect the ultimate strength of the material, but it does have the effect of increasing the elastic limit of the metal in the area around the corner from about 25,000 pounds per square inch to 32,000 pounds per square inch, an increase of 28 per cent.

INTRODUCTION

Many of the structural defects which have developed in welded ships during the past few years have taken the form of transverse or diagonal cracks starting at the corners of hatches and other similar openings in the strength deck. In some cases these cracks have carried around the structure and the ship has broken in two.

It is possible that low temperatures may have been a contributing cause in some of these failures, but whatever the cause, the problem has been a grave one and the necessity for a solution has been most pressing.

In an endeavor to account for these phenomena and to find a remedy, one of the exploratory investigations at the David Taylor Model Basin has taken the form of applying initial compression to the metal in the deck plating near the hatch corners. This is analogous to the initial compression applied to the tube of a built-up gun by shrinking on hoops or jackets around it.

Two methods were considered for accomplishing this:

1. Applying a strap of steel with a high elastic limit, such as special treatment steel, to the deck plating at each corner of the hatch or

other opening. Each strap would lie at an angle of about 30 degrees with the longitudinal axis of the ship, and would be welded to the deck plate only at its ends with welds of strength greater than that of the strap. The preloading would be accomplished by placing a sheet of heat-insulating material under the central portion of the strap, heating the strap to a predetermined temperature to make it longer than the corresponding length of deck plating under it, then welding the ends to the deck plate while the strap was still hot.

The initial tension set up in the strap would be controlled by the differential temperature. This tension would preferably be of such amount that when the tension in the deck plate at the corner, under fore-and-aft load, reached the elastic limit of the deck material, the material in the strap would reach its higher elastic limit at the same time.

2. Applying beads of weld metal in areas corresponding to the positions of the straps, heavy enough to set up large shrinkage stresses and to place the metal of the deck plating under the bead area in initial compression. It appeared that weld metal of relatively high yield strength would have to be used to prevent cracking of the weld metal before the plate metal reached its elastic limit.

As this method of applying a reinforcement by pre-stressing was quite new, and as no reference data were available, tests of relatively small models were initiated at the Taylor Model Basin to check the theory. It was decided to start with welded beads, as described in paragraph 2 preceding, because suitable material for making the straps was not available. Likewise, it was necessary to use the regular Grade EA electrodes for making the beads because no better metal for this purpose was available at the time. The angle selected for the beads was 30 degrees with the length of the model, representing the fore-and-aft axis of the ship, and the weld was placed at a distance from the opening which represented the hatch corner equal to the thickness of the deck plating. The length, width, depth, and other features of the welded beads were left to be determined as the tests proceeded.

TEST SPECIMENS AND PROCEDURE

Specimens were cut from medium steel plate for these tests. Openings of various shapes and dimensions were cut in these specimens to bring out the various conditions being explored. All specimens were pulled to failure in the 600,000-pound Baldwin Southwark testing machine at the Taylor Model Basin.

EXPLORATORY TESTS

Seven specimens, cut from 1/8-inch plate, were used in exploratory tests to develop the size of weld required and to determine which line of investigation would be most advantageous. Five of these, numbered 300, 301, 302, 304, and 305,* are shown before and after testing in the photographs, Figures 1 to 5. A rectangular opening was cut in each, and welds were applied near the corners of the openings in all specimens, except 300, as shown in the photographs and described in Table 1.

Of the two other 1/8-inch specimens, one, Specimen 306, was heated along the lines on which welds were applied in the others, in an effort to set up compressive strains in the plate without using welded beads. The other, Specimen 307, was reinforced at the corners of the opening by diagonal straps of furniture steel; this was perhaps not a good material for the purpose but it was the best that was available when the model was prepared. Specimens 306 and 307 are depicted in Figures 6 and 7 respectively, and are described in the sub-titles of the figures.

Specimen 312 was made up of two thicknesses of 1/4-inch plate held together by two slot welds, as shown in Figure 8. This model was designed to explore the possibility of welding through diagonal slots in a deck plate to a doubling plate underneath. The diagonal slots in the upper or deck plate were 5/16 inch wide and 2 inches long and the near side of each slot was 5/16 inch from the corner of the opening in the plate; the sides of the slots were parallel to each other, with no countersink or veeing. The deck plate was finally welded to the doubling plate underneath by filling the slots with weld metal.

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* Through an inadvertence, the number 303 was omitted from the series when marking the specimens.

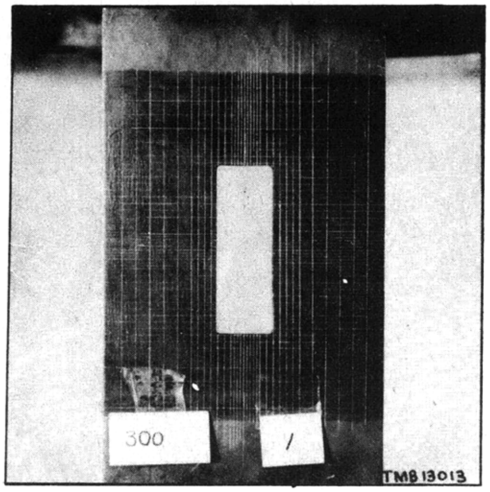


Figure 1a - Before Test

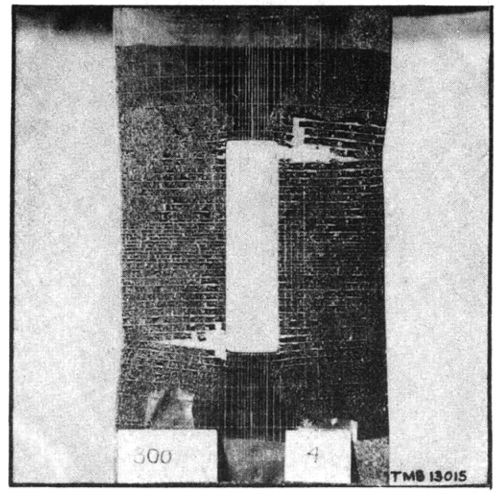


Figure 1b - After Test

Figure 1 - Exploratory Specimen 300

This specimen, 5 inches wide by 24 inches long, was cut from 1/8-inch plating of medium steel. The rectangular opening was 1 inch by 3 inches, with corners rounded to a radius of 1/16 inch. No reinforcement was applied.

The specimen was tested at a temperature of 80 degrees fahrenheit, to a maximum load of 31,400 pounds, corresponding to a mean stress in the net section abreast the opening of 62,800 pounds per square inch, at which load cracks developed at the upper right and lower left corners. Fracture was in the ductile mode.

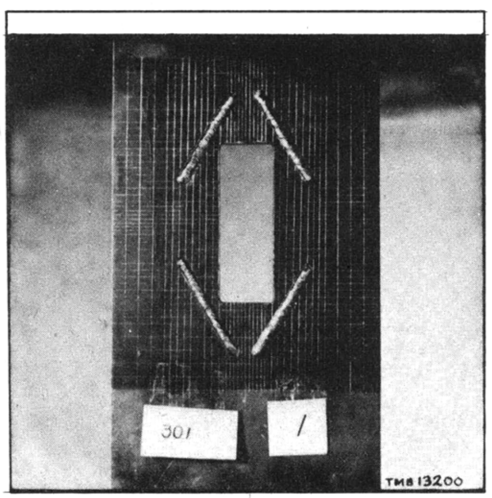


Figure 2a - Before Test

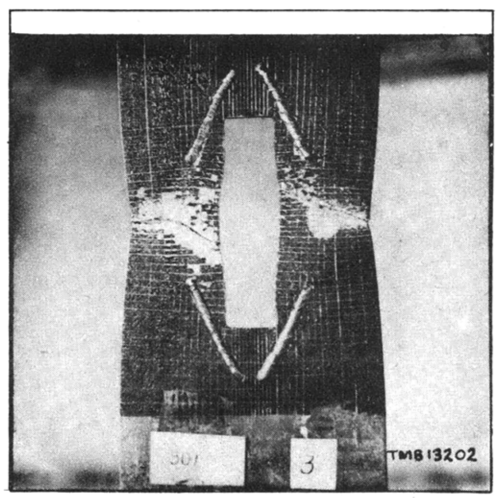


Figure 2b - After Test

Figure 2 - Exploratory Specimen 301

This specimen, 5 inches wide by 24 inches long, was cut from 1/8-inch plating of medium steel. The rectangular opening was 1 inch by 3 inches, with corners rounded to a radius of 1/16 inch. A welded bead 1/16 inch thick, 1/8 inch wide, and 2 inches long was applied 3/16 inch from each corner at an angle of 30 degrees to the centerline.

The specimen was tested at a temperature of 80 degrees fahrenheit, to a maximum load of 33,000 pounds, corresponding to a mean stress in the net section abreast the opening of 66,000 pounds per square inch, at which load it failed in the ductile mode, as shown in Figure 2b.

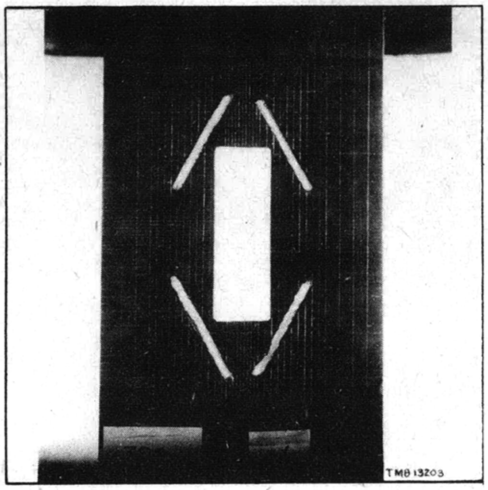


Figure 3a - Before Test

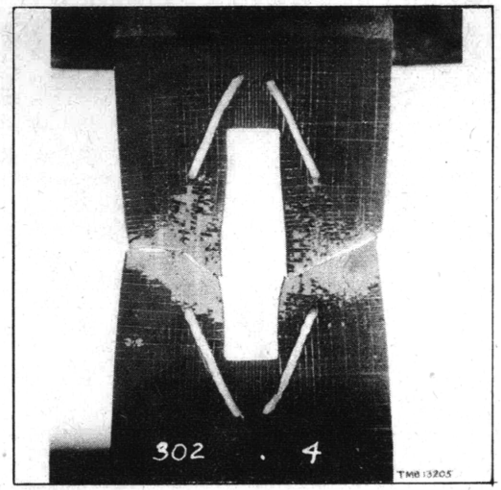


Figure 3b - After Test

Figure 3 - Exploratory Specimen 302

This specimen, 5 inches wide by 24 inches long, was cut from 1/8-inch plating of medium steel. The rectangular opening was 1 inch by 3 inches, with corners rounded to a radius of 1/16 inch. A welded bead 1/16 inch thick, 1/8 inch wide, and 2 inches long was applied 3/16 inch from each corner at an angle of 30 degrees to the centerline. This bead was then ground off to a thickness of 1/32 inch.

The specimen was tested at a temperature of 80 degrees fahrenheit to a maximum load of 32,500 pounds, corresponding to a mean stress in the net section abreast the opening of 65,600 pounds per square inch, at which load the plating failed in the ductile mode, as shown in Figure 3b.

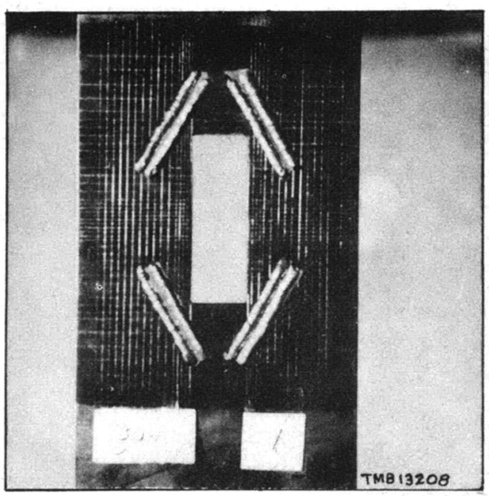


Figure 4a - Before Test

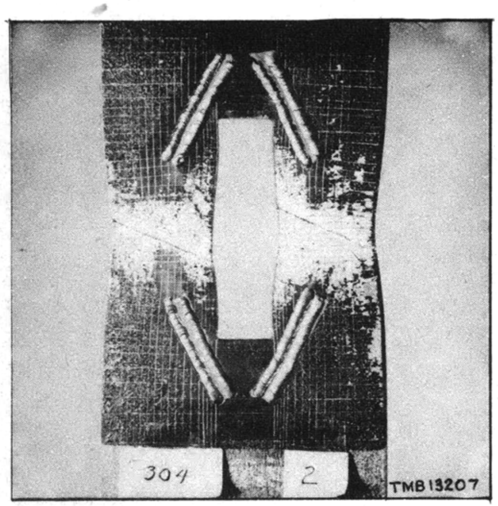


Figure 4b - After Test

Figure 4 - Exploratory Specimen 304

This specimen, 5 inches wide by 24 inches long, was cut from 1/8-inch plating of medium steel. The rectangular opening was 1 inch by 3 inches, with corners rounded to a radius of 1/16 inch. Two welded beads 1/16 inch thick, 1/8 inch wide, and 2 inches long were applied side-by-side and parallel to each other, 3/16 inch from each corner at an angle of 30 degrees to the centerline.

The specimen was tested at a temperature of 80 degrees fahrenheit to a maximum load of 33,000 pounds, corresponding to a mean stress of 66,000 pounds per square inch in the net section, at which load it failed in the auctile mode as shown in Figure 4b.

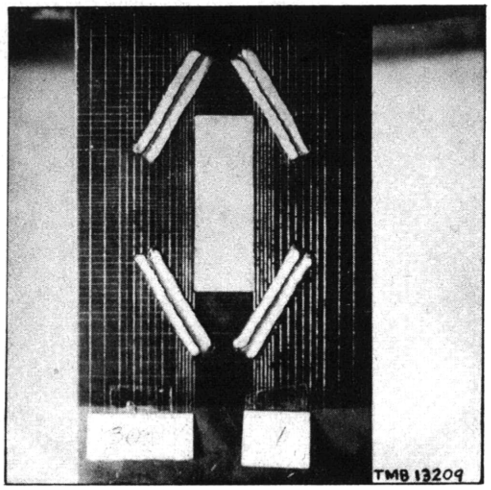


Figure 5a - Before Test

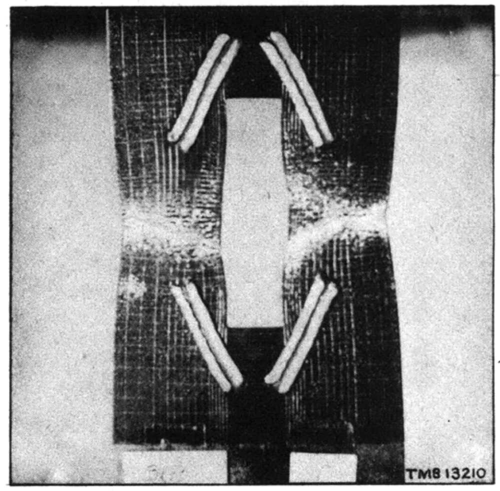


Figure 5b - After Test

Figure 5 - Exploratory Specimen 305

This specimen, 5 inches wide by 24 inches long, was cut from 1/8-inch plating of medium steel. The rectangular opening was 1 inch by 3 inches, with corners rounded to a radius of 1/16 inch. Two welded beads 1/16 inch thick, 1/8 inch wide, and 2 inches long were applied side-by-side and parallel to each other, 3/16 inch from each corner at an angle of 30 degrees to the centerline. These beads were then ground down to a thickness of 1/32 inch.

The specimen was tested at a temperature of 80 degrees fahrenheit to a maximum load of 33,000 pounds, corresponding to a mean stress of 66,000 pounds per square inch in the net section, at which load it failed in the ductile mode as shown in Figure 5b.

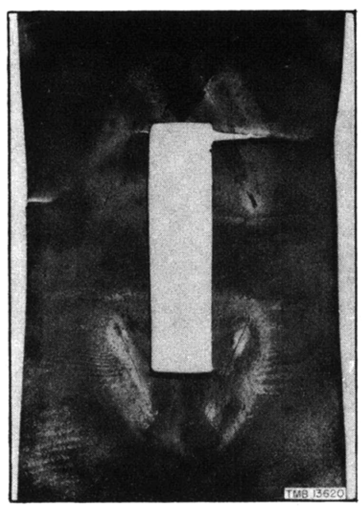


Figure 6 - Exploratory Specimen 306, after Failure

This specimen, 5 inches wide by 24 inches long, was cut from 1/8-inch plating of medium steel. The rectangular opening was 1 inch by 3 inches, with corners rounded to a radius of 1/16 inch. Heat was applied over areas corresponding to those covered by welded beads in the preceding exploratory specimens; see Figures 2 to 5 inclusive.

The specimen was tested at a temperature of 80 degrees fahrenheit to a maximum load of 32,000 pounds, corresponding to a mean stress of 64,000 pounds per square inch in the net section, at which load it failed in the ductile mode as shown in the photograph.

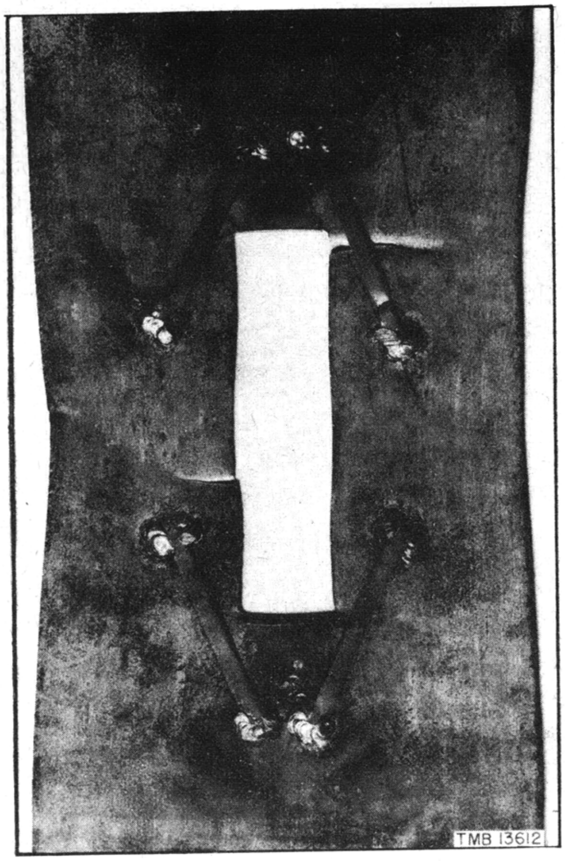


Figure 7 - Exploratory Specimen 307, after Failure

This specimen, 5 inches wide by 24 inches long, was cut from 1/8-inch plating of medium steel. The rectangular opening was 1 inch by 3 inches, with corners rounded to a radius of 1/16 inch. Straps of furniture steel, 3/16 inch by 1/16 inch by 2 inches, were welded to the plate 3/16 inch from the corners at 30 degrees to the centerline, as shown in the photograph. The straps were attached while hot.

The specimen was tested at a temperature of 80 degrees fahrenheit to a maximum load of 32,000 pounds, corresponding to a mean stress of 64,000 pounds per square inch in the net section, at which load it failed in the ductile mode as shown. One of the straps fractured before the plate.

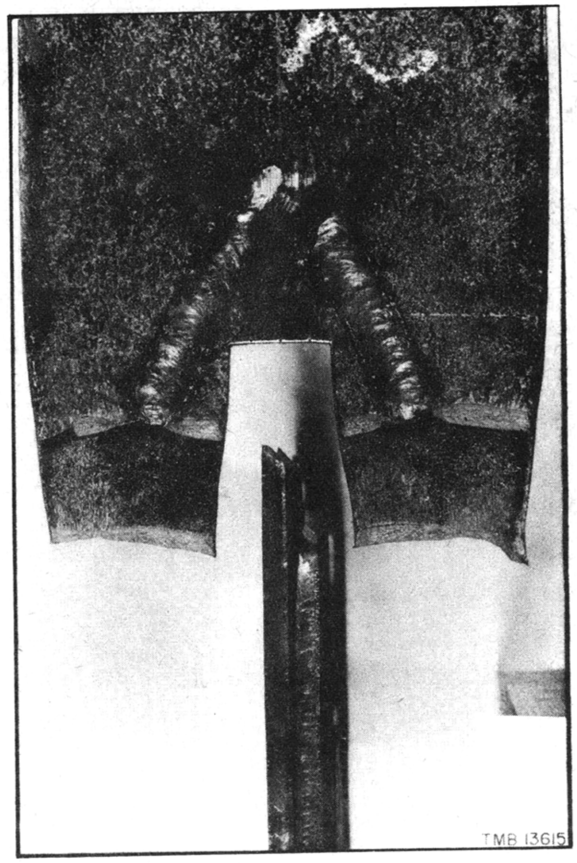


Figure 8 - Exploratory Specimen 312, after Failure

This specimen consisted of two medium steel plates 1/4 inch thick by 5 inches wide, with a 1-inch by 3-inch rectangular opening cut in each. The specimen was made up to represent a section of deck plating with a doubler plate underneath. Slots 5/16 inch by 2 inches were cut through the deck plate 5/16 inch from the corners of the opening and at a 30-degree angle to the centerline, and the two plates were welded together through these slots.

The specimen was tested at a temperature of 75 degrees fahrenheit, to a maximum load of 138,000 pounds, corresponding to a mean stress of 69,000 pounds per square inch in the net section, at which load it failed in the ductile mode, as shown in the photograph. The deck plate fractured across the ends of the weld beads, manifestly due to incomplete fusion of the weld metal with the plate metal at the ends of the slots.

TESTS OF THICK PLATES WITH PRE-STRESSING WELDS

Results of the exploratory tests on 1/8-inch plates showed that the use of welded beads near the corners of the openings gave definite promise of increased strength and freedom from cracking in those areas. Subsequent specimens were therefore all designed to have diagonal welded beads, except a few special and control specimens. Ten specimens were made much thicker; they were all cut from the same 3/4-inch plate. Three specimens were cut from 1/2-inch plate. The sizes, shapes, and positions of the openings and the welded beads are given in Table 2 and are shown in the photographs referenced in that table.

Specimen 309 was made up to match a model tested at the Taylor Model Basin in a previous series; it is listed in Table 2 as Specimen S. Like Specimen 309 of this pair, Specimen S was cooled to a relatively low temperature in an effort to produce definitely brittle failure. Comparing the results of the two tests, Specimen 309 with welded beads broke at 365,000 pounds while Specimen S without beads broke at 303,000 pounds. The difference, 62,000 pounds, is much greater than the computed strength of the welded beads, about 7500 pounds.

Specimens 310 and 311 were made up as a pair, with and without welded beads, to find the qualitative effect of these beads. They were both likewise cooled to about 72 degrees fahrenheit in an effort to induce brittle failure. For an analysis of the energy absorption of these two specimens, see Appendix 2.

Specimens 313 and 314 were provided with special openings and narrow slots, which the results of previous tests indicated might cause sharp cracks and brittle failures. Both of these specimens were cooled to 38 degrees fahrenheit.

The specimen with the welded beads developed slightly more tensile strength but failed at the corners.

This test showed that the welded beads were too small to compensate for the heavy stresses.

On the next pair of plates, Specimens 315 and 316, the welded beads were made larger. One plate was chilled, but both broke near the middle of the opening, showing that the previous small welded beads were not adequate.

In Specimens 317 and 318 the width was reduced to 10 inches because of the limited amount of 3/4-inch plate remaining. The welded beads on these plates were spaced from the corners a distance equal to 1 1/2 times the thickness of the plate. Both gave satisfactory results.

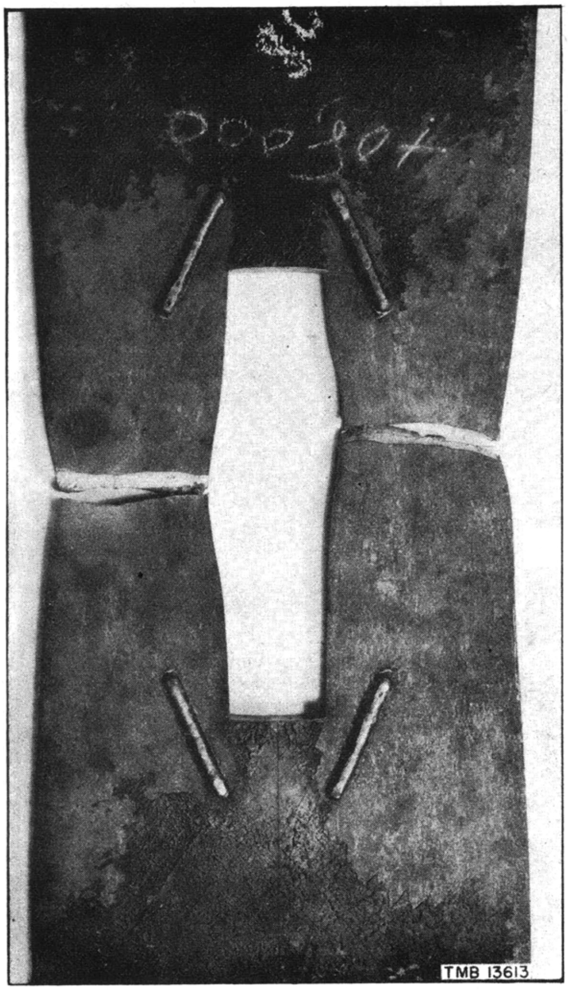


Figure 9 - Specimen 308

This specimen, 12 inches wide by 24 inches long, was cut from 3/4-inch plating of medium steel. The rectangular opening was 2.4 inches by 7.6 inches, with square corners. Welded beads 1/4 inch thick, 3/8 inch wide, and 3 inches long, were applied 3/4 inch from each corner at an angle of 30 degrees to the centerline.

The specimen was tested at a temperature of 79 degrees fahrenheit, to a maximum load of 408,000 pounds, corresponding to a mean stress of 55,800 pounds per square inch in the net section, at which load it failed in the ductile mode, as shown in the photograph.

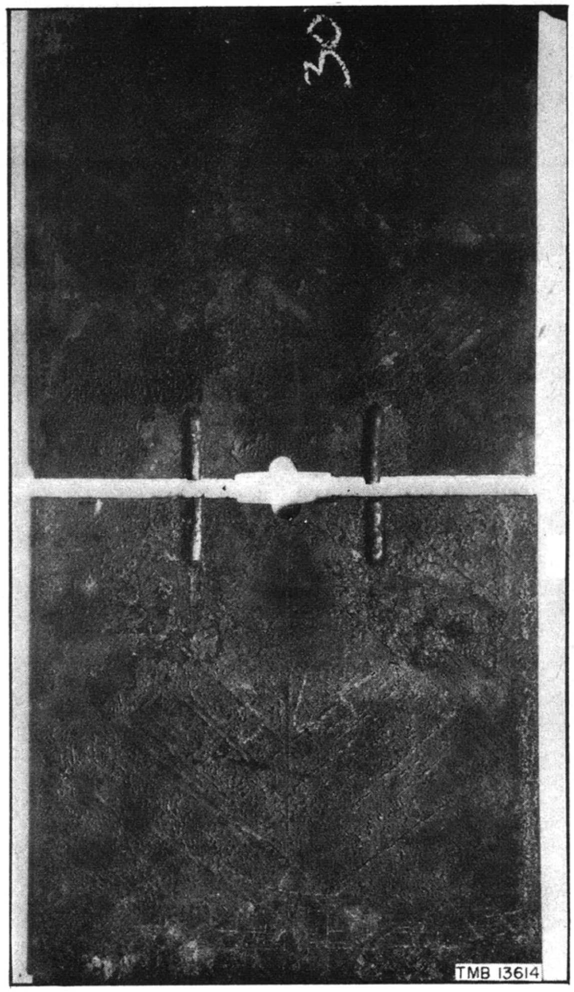


Figure 10 - Specimen 309

This specimen was 12 inches wide and 24 inches long, cut from 3/4-inch plating of medium steel. A circular opening 3/4 inch in diameter was drilled at its center, and lateral hacksaw cuts normal to the centerline of the plate extended the width of the opening to 2 3/8 inches. Welded beads 3 inches long, 1/4 inch thick, and 3/8 inch wide were applied 3/4 inch from the outer end of each saw cut, parallel to the centerline.

The specimen was tested at 75 degrees fahrenheit to a maximum load of 365,000 pounds, corresponding to a mean stress of 50,800 pounds per square inch in the net section, at which load it failed in the brittle mode as shown in the photograph.

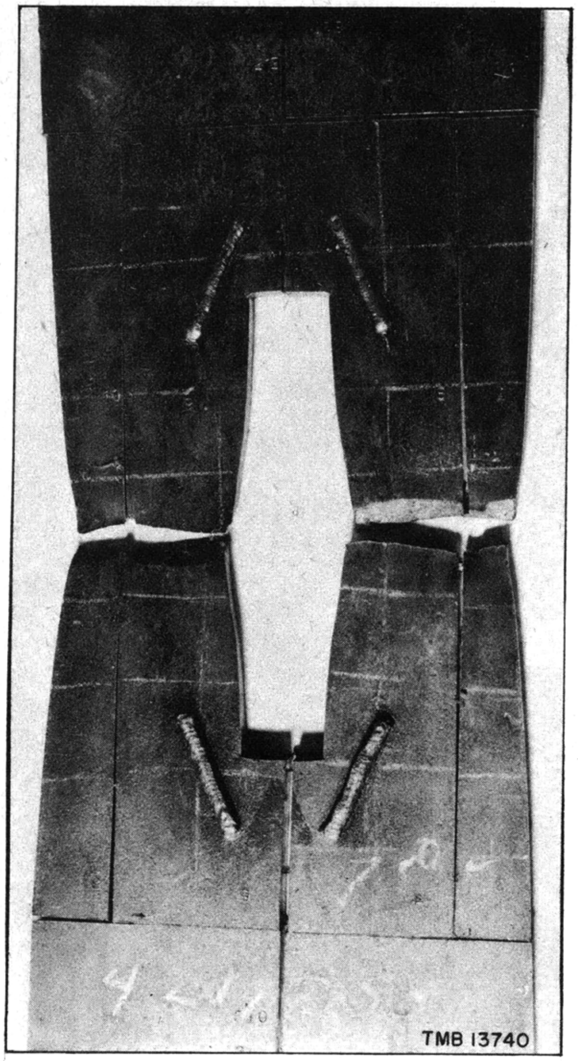


Figure 11 - Specimen 310

This specimen, 12 inches wide by 24 inches long, was cut from 3/4-inch plating of medium steel. The rectangular opening was 2 inches by 7.2 inches, with square corners. Welded beads 1/4 inch thick, 3/8 inch wide, and 3 inches long were applied 3/4 inch from each corner at an angle of 30 degrees to the centerline.

The specimen was tested at a temperature of 73 degrees fahrenheit to a maximum load of 421,000 pounds, corresponding to a mean stress of 56,200 pounds per square inch in the net section, at which load it failed in the ductile mode as shown in the photograph.

The specimen was cut up after the test to supply data for the calculation of energy absorption, given in Appendix 2.

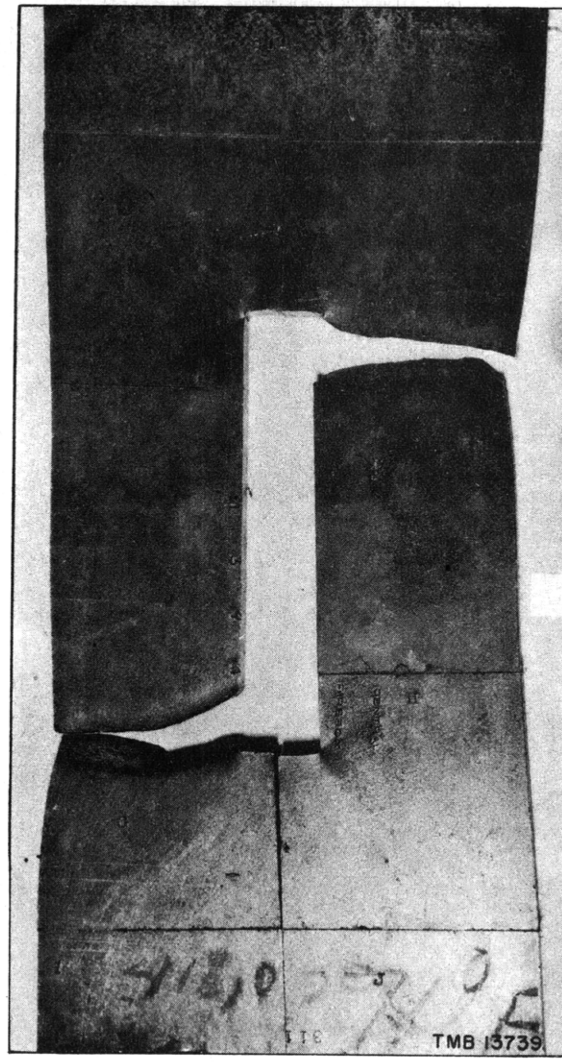


Figure 12 - Specimen 311

This specimen was identical with Specimen 310, Figure 11, except that welded beads were not applied. It was tested at 71 degrees fahrenheit to a maximum load of 418,000 pounds corresponding to a mean stress of 56,000 pounds per square inch in the net section, at which load it failed in the ductile mode. This specimen, like Specimen 310, was cut up after the test to supply data for the calculation of energy absorption given in Appendix 2.

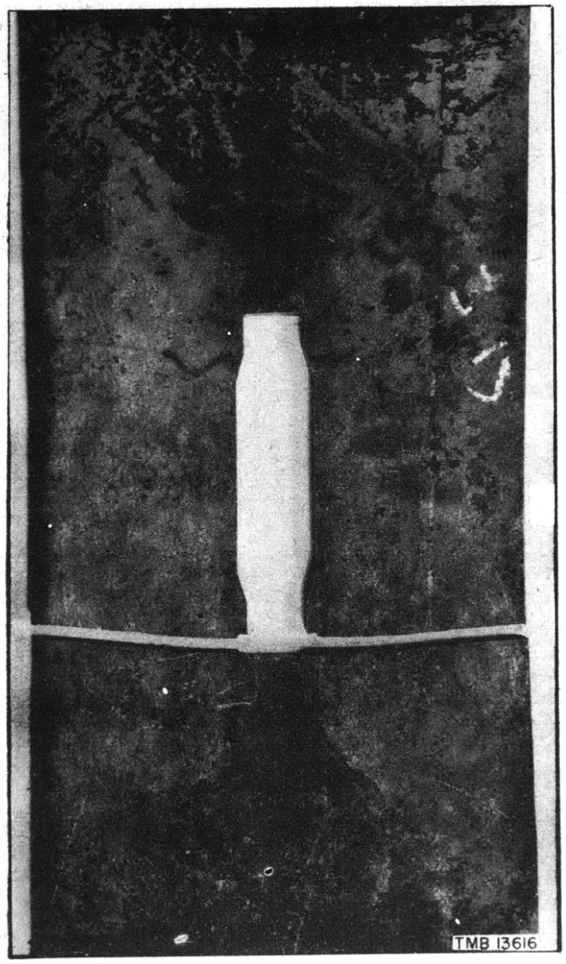


Figure 13 - Specimen 313

This specimen, 12 inches wide by 24 inches long, was cut from 3/4-inch plating of mild steel. The shape of the original opening can be reconstructed from the photograph. The length of the opening was 7.2 inches and its greatest width was 2 inches, tapering down to 1 1/2 inch at the ends, with transverse hacksaw cuts at one end increasing the width to 2 inches.

The specimen was tested at a temperature of 38 degrees fahrenheit to a maximum load of 387,000 pounds, corresponding to a mean stress of 51,500 pounds per square inch in the net section, at which load it failed in the brittle mode as shown.

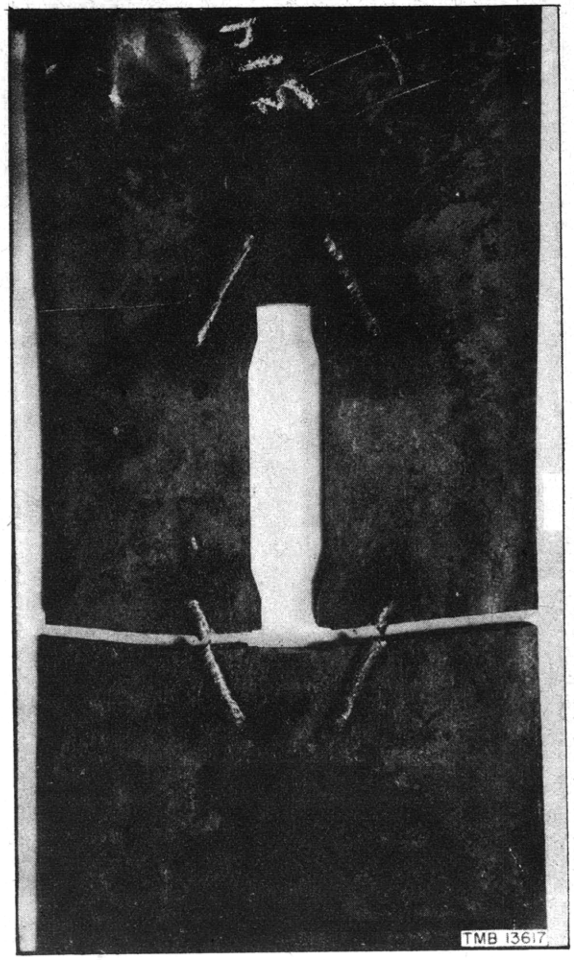


Figure 14 - Specimen 314

This specimen was identical with Specimen 313, Figure 13, except that welded beads 1/4 inch thick, 3/8 inch wide, and 3 inches long were applied 3/4 inch from each corner of the opening at an angle of 30 degrees to the centerline. It was tested at a temperature of 38 degrees fahrenheit to a maximum load of 399,000 pounds, corresponding to a mean stress of 53,200 pounds per square inch in the net section, at which load it failed in the brittle mode as shown.

The fracture at the upper left corner of the opening did not break the welded bead.

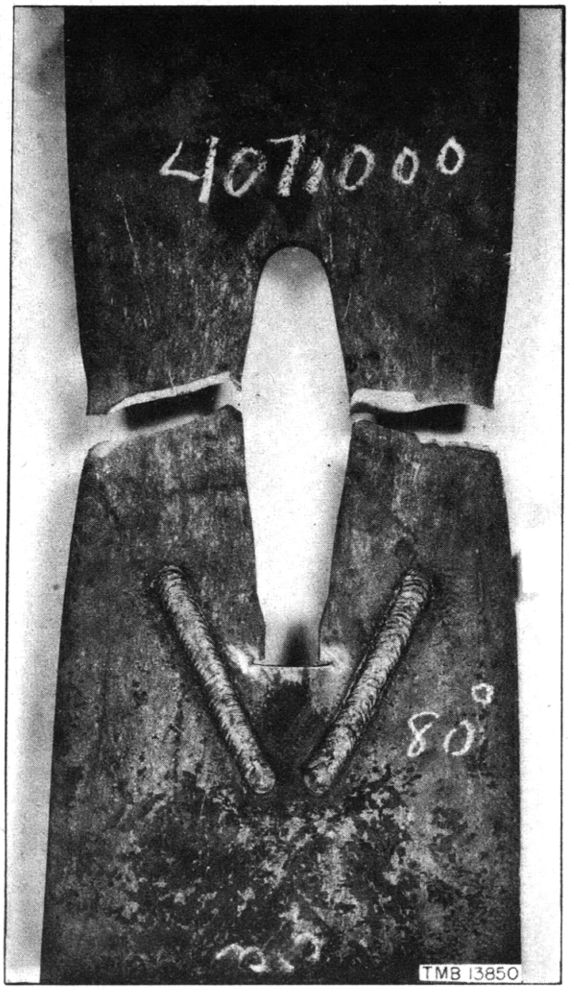


Figure 15 - Specimen 315

This specimen, 12 inches wide by 24 inches long, was cut from 3/4-inch plating of medium steel. The opening was rounded at one end and rectangular at the other, with transverse hacksaw cuts on each side of the rectangular end. Its length was 7.2 inches; its width was 2 inches for 5.7 inches of its length from its rounded end, tapering to 1.5 inch at the rectangular end, with transverse hacksaw cuts increasing the width to 2 inches. Welded beads 1/4 inch thick, 3/4 inch wide, and 6 inches long were applied 3/4 inch from each of the two notched corners at an angle of 30 degrees to the centerline.

The specimen was tested at a temperature of 82 degrees fahrenheit to a maximum load of 407,000 pounds, corresponding to a mean stress of 54,500 pounds per square inch in the net section, at which load it failed in the ductile mode as shown in the photograph.

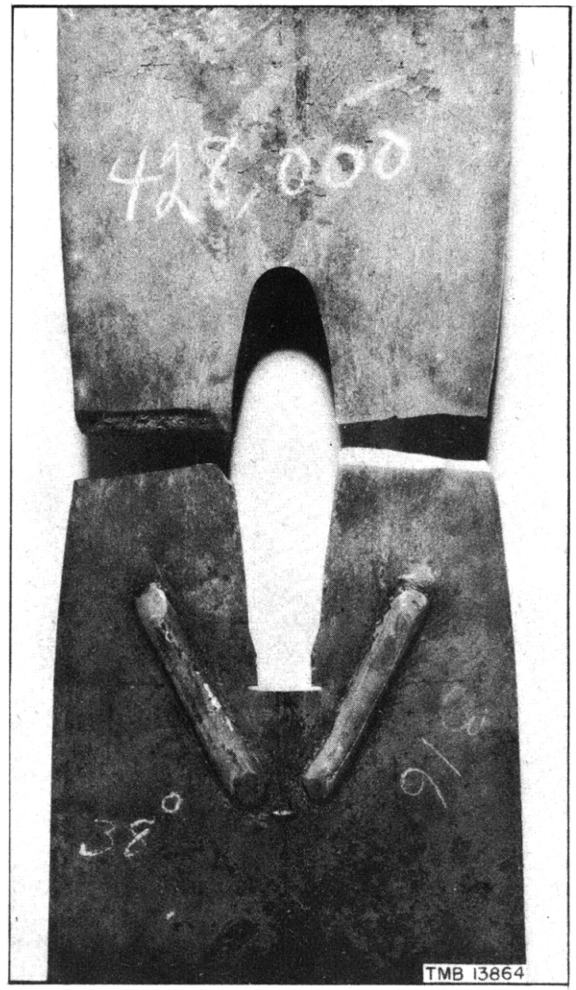


Figure 16 - Specimen 316

This specimen was identical with Specimen 315, Figure 15, except for the fact that the welded beads which were originally somewhat thicker, were ground down to a thickness of 1/4 inch.

The specimen was chilled to a temperature of 38 degrees fahrenheit, and tested to a maximum load of 428,000 pounds, corresponding to a mean stress of 57,000 pounds per square inch in the net section, at which load it failed in the ductile mode, as shown in the photograph.

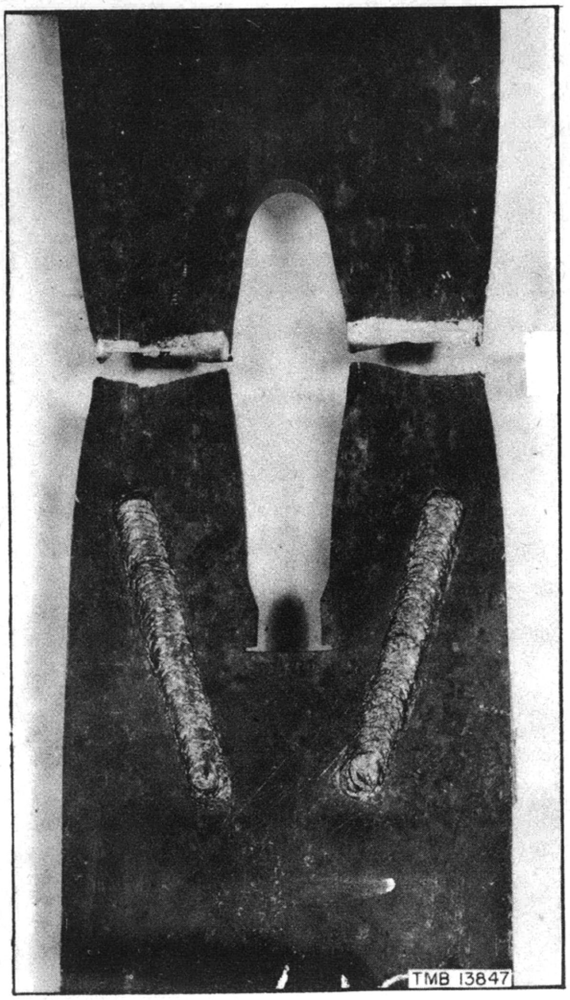


Figure 17 - Specimen 317

This specimen was 10 inches wide by 24 inches long, cut from 3/4-inch plating of medium steel. The opening was like those in Specimens 315 and 316, Figures 15 and 16. Welded beads 1/4 inch thick, 3/4 inch wide, and 6 1/2 inches long were applied 1 1/8 inch from each of the notched corners at an angle of 20 degrees to the centerline.

The specimen was chilled to a temperature of 38 degrees fahrenheit, like Specimen 316, and tested to a maximum load of 328,000 pounds, corresponding to a mean stress of 56,200 pounds per square inch in the net section, at which load it failed in the ductile mode, as shown in the photograph.

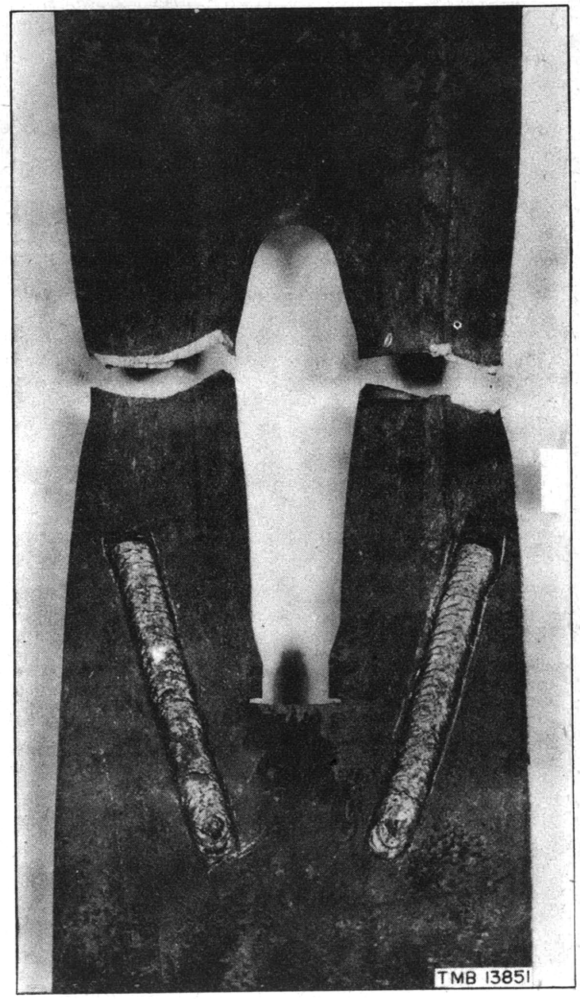


Figure 18 - Specimen 318

This specimen was identical with Specimen 317, Figure 17, except that instead of two welded beads 1/4 inch thick on one side of the plating, four welded beads 1/8 inch thick were applied, two on the front and two directly opposite on the back.

This specimen was tested at a temperature of 72 degrees fahrenheit to a maximum load of 328,000 pounds, corresponding to a mean stress of 56,200 pounds per square inch in the net section, at which load it failed in the ductile mode, as shown in the photograph.

TESTS OF THICK BUILT-UP PLATES

Specimens 319, 320, and 321 were made up as special models at the suggestion of the Director of the Technical Division of the Unites States Maritime Commission to represent more nearly the conditions which would exist in the actual strength deck of a ship. Each model was assembled by using two long strips for the sides and by welding in two short strips at the ends, leaving the hatch opening between the latter strips. In this manner there was a longitudinal weld beyond each of the four corners of the opening. The diagonal welded beads were then applied over the longitudinal welds, as indicated on the photographs, Figures 19, 20, and 21 and in Table 3.

The tests on some of the specimens indicated a possible lack of uniformity in the distribution of the testing-machine loads, as applied across the width of the intact plate in the model. Specimen 321 was therefore fitted with eight metalectric strain gages, four on each side of the plate underneath the upper loading head. The gages were placed as shown in the diagram with Figure 22.

During the pulling of Specimen 321 it was noted that the strains were localized off the middle of the 6-inch by 12-inch opening, with little evidence of any excessive strains in line with the welded beads. This shows the decidedly greater effectiveness of the welded beads in pairs over single beads.

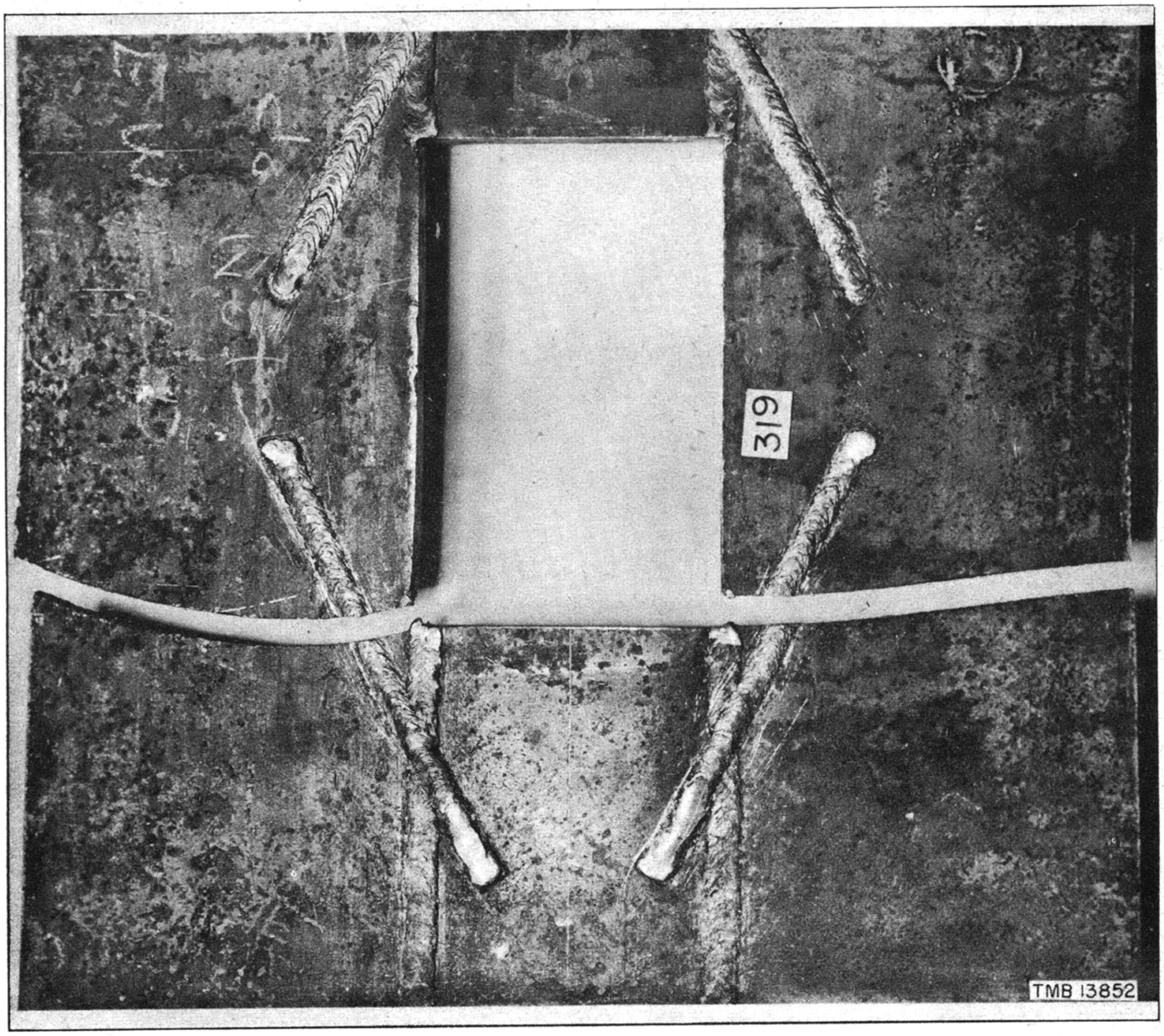


Figure 19 - Specimen 319

This specimen was 22 inches wide by 24 inches long, built up of 1/2-inch plating of medium steel. Two plates, 6 inches wide by 8 inches long, separated by a space 6 inches by 8 inches, were welded between two side plates 8 inches by 24 inches, leaving a 6- by 8-inch opening in the assembly. Welded beads 8 inches long, 1/2 inch wide, and 1/8 inch thick were deposited in one pass 1 inch from each corner at an angle of 30 degrees to the centerline.

The specimen was tested at a temperature of 60 degrees fahrenheit to a maximum load of 423,000 pounds, corresponding to a mean stress of 53,000 pounds per square inch in the net section, at which load it failed in the brittle mode as shown in the photograph.

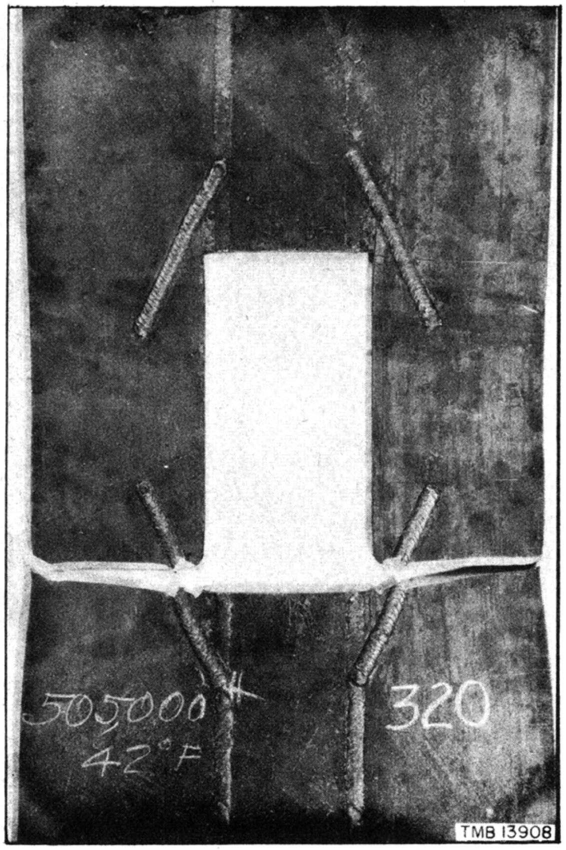


Figure 20 - Specimen 320

This specimen was 24 inches wide by 36 inches long, built up of 1/2-inch plating of mild steel. It was similar to Specimen 319, Figure 19, except that the longitudinal welds were offset from the corners, leaving an opening 8 inches by 12 inches. Two-pass welded beads 8 inches long, 1/4 inch thick, and 3/4 inch wide were applied 3/4 inch from each corner.

The specimen was tested at a temperature of 42 degrees fahrenheit to a maximum load of 505,000 pounds, corresponding to a mean stress of 63,100 pounds per square inch in the net section, at which load it failed in the ductile mode, as shown in the photograph.

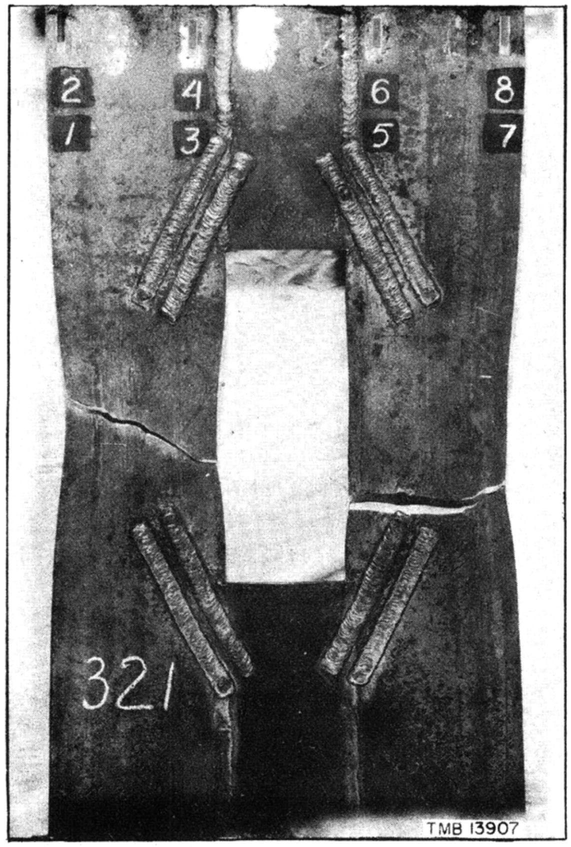


Figure 21 - Specimen 321

This specimen was 22 inches wide and 36 inches long, built up of 1/2-inch plating of medium steel. The side plates were 8 inches wide. Two plates, 6 inches wide by 12 inches long, were welded between the ends of the side plates, leaving a 6- by 12-inch opening. Two parallel welded beads 8 inches long, 1/4 inch thick, and 3/4 inch wide, deposited 1/2 inch apart, were applied 3/4 inch from each corner at an angle of 30 degrees to the centerline.

The specimen was tested at a temperature of 50 degrees fahrenheit to a maximum load of 503,000 pounds, corresponding to a mean stress of 62,900 pounds per square inch in the net section, at which load it failed in the ductile mode, as shown in the photograph.

Four metalectric strain gages were attached to the front and four to the back of the specimen, as shown in the photograph and in Figure 22, to check the distribution of load for uniformity. The data thus obtained are plotted in Figure 22.

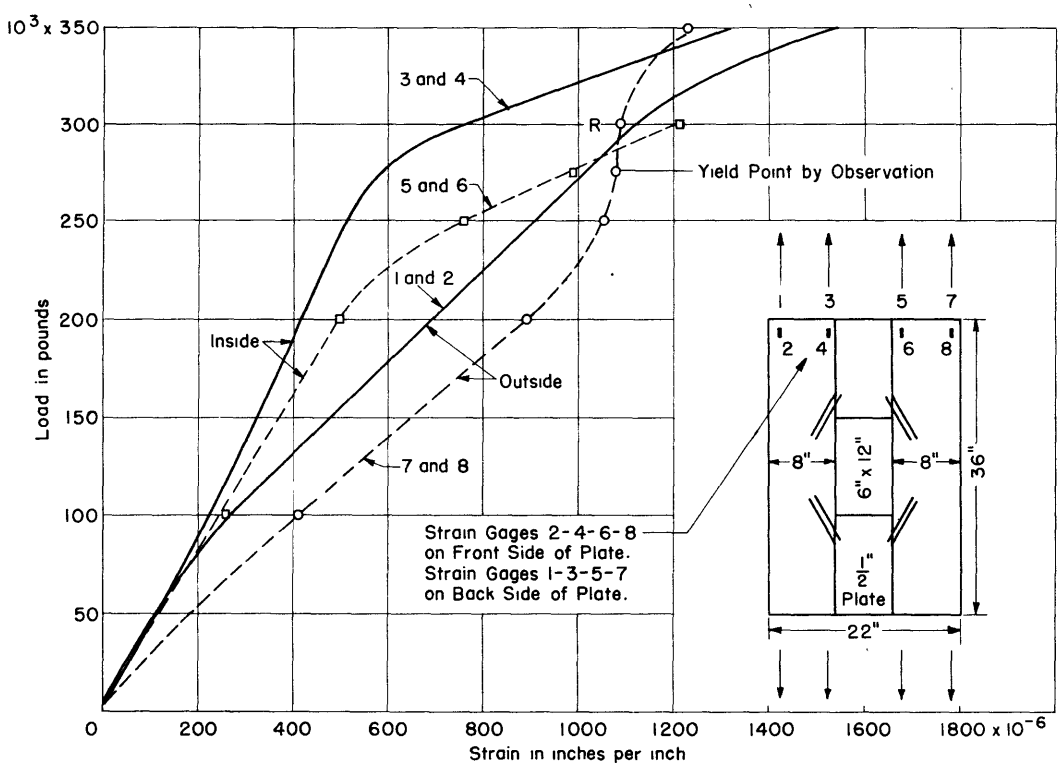


Figure 22 - Stress-Strain Curves Showing Distribution of Load in Specimen 321

At point R the load became fairly uniform across the plate. The stresses were slightly above the yield point, showing fairly uniform distribution across the plate.

TEST RESULTS

The results of the tests of the seven exploratory specimens, 300, 301, 302, 304, 305, 306, and 312, are shown by the photographs in Figures 1 to 7, inclusive, and in the legends below them. For easier comparison they are listed in Table 1.

Figures 8 to 19, inclusive, and Table 2, give the results of tests of the twelve specimens of 3/4-inch plating, and Figures 20, 21, and 22, and Table 3, give those for three specimens built up of 1/2-inch plating.

TABLE 1

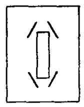
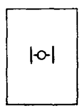
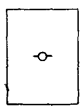
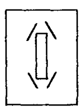
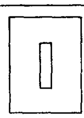
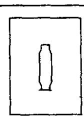
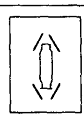
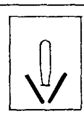
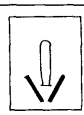
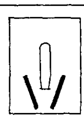
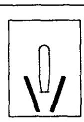
Characteristics of Exploratory Specimens and Results of Tensile Tests

All specimens were single thicknesses of 1/8-inch medium steel plating, with the exception of Specimen 312 which consisted of two 1/4-inch thicknesses welded together through slots near the corners of the opening. Each specimen had an opening 1 inch by 3 inches, with corners rounded on a 1/16-inch radius except Specimen 312, which had sharp corners. Pre-stressing treatment was applied over areas 2 inches long and of various widths at an angle of 30 degrees to the centerline.

Specimen	See Figure	Method of Pre-Stressing	Test Temp. degrees F	Maximum Load pounds	Mean Stress lb/in^2	Mode of Failure	Remarks
300	1	None	80	31,400	62,800	Ductile	
301	2	Welds 1/16 in. thick, 1/8 in. wide, 3/16 in. from corners.	80	33,000	66,000	Ductile	
302	3	Welds 1/32 in. thick, 1/8 in. wide, 3/16 in. from corners.	80	32,500	65,600	Ductile	
304	4	2 weld beads 1/16 in. thick, 1/8 in. wide, 3/16 in. from corners.	80	33,000	66,000	Ductile	
305	5	2 weld beads 1/32 in. thick, 1/8 in. wide, 3/16 in. from corners.	80	33,000	66,000	Ductile	
306	6	Heat applied over areas covered by welds in other specimens.	80	32,000	64,000	Ductile	
307	7	1/8-in. x 1/16-in. straps in tension in place of weld beads.	80	32,000	64,000	Ductile	Straps were furniture steel. One failed before plate cracked.
312	8	Weld deposited in slot 5/16 in. wide filling slot and projecting slightly above deck plate.	75	138,000	69,000	Ductile	

TABLE 2

Characteristics of Specimens 3/4 Inch Thick, and Results of Tensile Tests

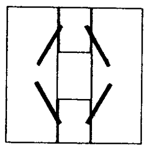
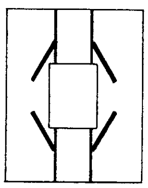
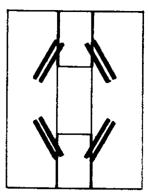
Specimen	See Figure	Configuration	Method of Pre-Stressing	Test Temp. degrees F	Maximum Load pounds	Mean Stress lb/in²	Mode of Failure	Remarks
308	9		Welds 1/4 in. thick, 3/8 in. wide, 3 in. long, 3/4 in. from corners at 30° to centerline.	79	408,000	55,800	Ductile	12 inches wide.
309	10		Welds 1/4 in. thick, 3/8 in. wide, 3 in. long, 3/4 in. from ends of slot, parallel to centerline.	75	365,000	50,800	Brittle	Paired specimens, 12 inches wide, one with and one without welded beads.
S*			None	75	303,000	42,100	Brittle	
310	11		Welds 1/4 in. thick, 3/8 in. wide, 3 in. long, 3/4 in. from corners, at 30° to centerline.	73	421,000	56,200	Ductile	Paired specimens, 12 inches wide, one with and one without welded beads.
311	12		None	71	418,000	56,000	Ductile	
313	13		None	38	387,000	51,500	Brittle	Paired specimens, 12 inches wide, with special slots to encourage brittle failures, one specimen with and one without welded beads.
314	14		Welds 1/4 in. thick, 3/8 in. wide, 3 in. long, 3/4 in. from corners at 30° to centerline.	38	399,000	53,200	Brittle	
315	15		Welds 1/4 in. thick, 3/4 in. wide, 6 in. long, 3/4 in. from ends of saw cuts at 30° to centerline.	82	407,000	54,500	Ductile	Paired specimens, 12 inches wide, one tested at room temperature, and one chilled.
316	16		Welds 1/4 in. thick, 3/4 in. wide, 6 in. long, 3/4 in. from ends of saw cuts at 30° to centerline.	38	428,000	57,000	Ductile	
317	17		Welds 1/4 in. thick, 3/4 in. wide, 6 1/2 in. long, 1 1/8 in. from ends of saw cuts at 20° to centerline.	38	328,000	56,200	Ductile	Paired specimens, 10 inches wide. The amount of weld metal was the same in both, but was deposited on one side of Specimen 317, and divided between front and back of Specimen 318.
318	18		Welds 1/8 in. thick, 3/4 in. wide, 6 1/2 in. long, 1 1/8 in. from ends of saw cuts, on front and back, at 20° to centerline.	72	328,000	56,200	Ductile	

* This specimen was part of an earlier series tested at the Taylor Model Basin.

TABLE 3

Characteristics of Built-Up Specimens 1/2 Inch Thick, and Results of Tensile Tests

Weld beads 8 inches long were deposited at 30 degrees to the centerline on all specimens.

Specimen	See Figure	Configuration	Method of Pre-Stressing	Test Temp. degrees F	Maximum Load pounds	Mean Stress lb/in^2	Mode of Failure
319	19		1 weld bead 1/8 in. thick, 1/2 in. wide, 1 in. from corner, deposited in 1 pass.	60	423,000	53,000	Brittle
320	20		1 weld bead 1/4 in. thick, 3/4 in. wide, 3/4 in. from corner, deposited in 2 passes.	42	505,000	63,100	Ductile
321	21		2 weld beads 1/4 in. thick, 3/4 in. wide, 1/2 in. apart, 3/4 in. from corner, deposited in 2 passes.	50	503,000	62,900	Ductile

DISCUSSION OF RESULTS

As was the case with small model tests of this kind made and described recently in another Taylor Model Basin report, the models were all too narrow to give an adequate representation of the structure of a ship's strength deck. However, neither the thickness nor the width of the larger specimen could have been increased appreciably without exceeding the maximum load on the testing machine, especially in view of the possible increased strength to be found in the various models.

A welding material superior to the standard Grade EA electrode in yield strength and ductility would undoubtedly have produced some improvement, but in view of the generally excellent performance of the welded beads on these specimens, this feature is probably of secondary importance. When a pre-stressing weld is made to full scale on a ship, it is proposed that the beads run lengthwise of the weld area, about as shown for the double beads in Figures 4 and 5. Two or more beads would be laid at each corner and would be of varying lengths to avoid a sudden termination of shrinkage strains.

As the thickness of the 1/4-inch, 1/2-inch, and 3/4-inch specimens lies in the region where the size and scale effect is still indeterminate, too much reliance should not be placed upon the performance of these models as affording predictions of full-scale performance with plates of 7/8-inch or greater thickness on a ship.

Despite these various shortcomings, the tests show unmistakable evidence of considerable advantage in the use of welded beads for pre-stressing ship material, in locations where cracks may normally be expected under severe service. It is rather surprising to note that this advantage is much greater than would be expected from any increased strength due to the welded bead itself.

In this connection there is included in Appendix 1 a mathematical analysis of the general problem presented in the introduction, which was prepared by Comdr. H.M. Westergaard, USNR, who was on temporary duty at the Taylor Model Basin during most of the period when these tests were being made. This analysis shows that the advantage to be gained by introducing initial compressive strains can be computed with the formulas given in his analysis.

Although the capacity of the ship material for absorbing energy is not a primary consideration here, as it would be were the material to be used as part of a structure to protect against underwater explosions, the capacity of the assembly to absorb energy is nevertheless considered a definite indication of its ability to resist rupture and fracture.

An analysis of the increased ability of a structure pre-stressed with welded beads to absorb energy has been made by Messrs. Cohen and Stiller of the Taylor Model Basin staff. This analysis, quoted as Appendix 2, indicates that of the two comparison specimens, Numbers 310 and 311, the specimen with the welded beads absorbed about 35 per cent more energy before fracture than that without the beads. In this case there was no appreciable difference in yield strength or ultimate load, although the difference shown in the photographs is striking. ~~It is probable that a similar analysis of Specimens 313 and 314 would show a still greater difference in the energy absorbed, due to the heavier welds applied to the corners.~~

APPENDIX 1

STOPPING A CRACK BY LOCKED-UP STRESS

STATEMENT OF THE PROBLEM

Commander G.L. Smith, USN, (Ret), David Taylor Model Basin, has proved by tests that the ultimate average tensile stress s_u on the gross cross section of a plate like that shown in Figure 23, in which a stress raiser such as the slit 1-2 is present, can be increased appreciably by placing beads of weld along lines such as 3-4 and 5-6 in the figure. The beads of weld and immediately adjacent narrow regions of the plate will be in tension after cooling. The effect on the remaining portion of the plate is essentially that of applying four forces P at the ends of the weld, as indicated in Figure 23. The forces P can be assumed to remain practically constant; the stresses that they create are locked-up stresses.

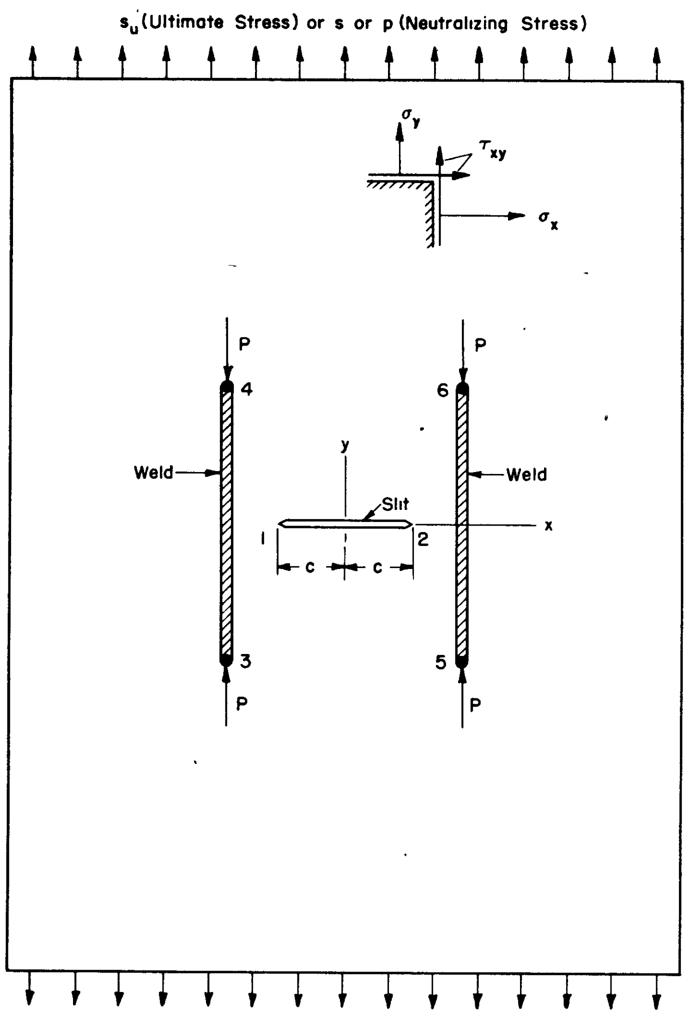


Figure 23 - Plate with Slit and Beads of Weld

Without the tension s the forces P create stress concentration in compression at the ends of the slit; but, vice versa, without the forces P, the tension s creates stress concentration in tension at the ends of the slit. With the forces P present to begin with, and with the tension s increasing gradually from zero, when s reaches a particular value p, the stress concentrations in tension and in compression will neutralize each other, leaving only moderate stresses on the cross section along the plane of the slit.

As the tensile stress s is increased beyond the neutralizing value p, the excess $s-p$ will produce stress concentration in tension. Since the initial pattern of stress concentration in tension and that in compression are essentially alike though of opposite sign, it is reasonable to assume that the excess $s-p$ will be a proper measure of the approach toward failure; accordingly one may assume that the ultimate stress s_u on the gross section may be expressed approximately for the formula

$$s_u = s_0 + p \qquad [1]$$

in which s_0 is the ultimate stress without the benefit of the locked-up stresses. Thus the neutralizing stress p will serve as an estimate of the gain of strength obtained by the locked-up stresses.

While the value of s_u may be in the plastic range, it can be assumed that the neutralizing stress p is in the elastic range. The determination of p thus is a problem of elasticity. Results of a solution of this problem are stated in the next section; thereafter an example is discussed; the derivations are presented last.

The slit may be interpreted as a crack.

FORMULA FOR THE NEUTRALIZING STRESS

The important features of the locked-up stress are defined by stating the compressive stresses q that would exist across the plane of the slit between the ends of the slit, if the slit had not been cut. Since the stress patterns can be assumed to be symmetrical with respect to both axes x and y in Figure 23, no shearing stresses are assumed to accompany q on the plane of the slit. Furthermore, the pressure q may be stated with adequate approximation in the form

$$q = q_0 + q_2\left(\frac{x}{c}\right)^2 + q_4\left(\frac{x}{c}\right)^4 + \ldots + q_{2n}\left(\frac{x}{c}\right)^{2n} \qquad [2]$$

in which q_0, q_2, $\cdots$ q_{2n} are constants and c one-half the length of the slit. If a diagram for q is known from experiments, the values of the coefficients q_0, q_2 $\cdots$ can be fitted to the case.

The formula for p is stated in terms of the coefficients q_0, q_2,··· The formula is

$$p = q_0 + \frac{1}{2} q_2 + \frac{1 \times 3}{2 \times 4} q_4 + \frac{1 \times 3 \times 5}{2 \times 4 \times 6} q_6 + \ldots + \frac{1 \times 3 \times 5 \ldots (2n-1)}{2 \times 4 \times 6 \ldots 2n} q_{2n} \quad [3]$$

Formulas [2] and [3] are applicable regardless of whether only the four forces P or a greater number of such symmetrically arranged forces are produced by the welds.

EXAMPLE

Assume that $q = 0.2k$ at $x = 0$; $q = 0.5k$ at $x = 0.5c$; and $q = k$ at $x = c$ at the end of the slit. Assume further that it is sufficient to include the first three terms on the right side of [2]. Then

$$q = q_0 + q_2\left(\frac{x}{c}\right)^2 + q_4\left(\frac{x}{c}\right)^4 \quad [4]$$

and

$$\left.\begin{aligned} q_0 &= 0.2k \\ q_0 + \frac{1}{4} q_2 + \frac{1}{16} q_4 &= 0.5k \\ q_0 + q_2 + q_4 &= k \end{aligned}\right\} \quad [5]$$

Solution of [5] gives

$$q_0 = \frac{1}{5} k, \qquad q_2 = \frac{4}{3} k, \qquad \text{and} \qquad q_4 = -\frac{8}{15} k \quad [6]$$

The corresponding value of the neutralizing stress is, according to [3],

$$p = \left(\frac{1}{5} + \frac{1}{2} \times \frac{4}{3} - \frac{3}{8} \times \frac{8}{15}\right) k = \frac{2}{3} k \quad [7]$$

so that, for example, k = 10,500 pounds per square inch would give p = 7000 pounds per square inch as the gain due to the locked-up stresses.

The example will serve to illustrate a further possible gain; namely, by an extension of the slit by cracks forming at the ends and reaching the points $x = c_1$ and $x = -c_1$. If [4] still applies, with c_1 replacing c, q_2 and q_4 will be replaced by $q_2(c_1/c)^2$ and $q_4(c_1/c)^4$ respectively, and [7] will be replaced by

$$p = \left[\frac{1}{5} + \frac{2}{3}\left(\frac{c_1}{c}\right)^2 - \frac{1}{5}\left(\frac{c_1}{c}\right)^4\right] k \quad [8]$$

This stress p obtains a maximum when $c_1 = c\sqrt{5/3}$. The maximum is

$$p_{\max} = \frac{34}{45}\,k = 0.756\,k \qquad [9]$$

which represents a further gain.

DERIVATIONS

Equation [3] can be derived by a method of analysis which is explained elsewhere.* The normal stresses and the shearing stress (in the directions indicated in the upper part of Figure 23) are stated in the form

$$\sigma_x = \operatorname{Re} Z - y \operatorname{Im} Z' + \sigma_0 \qquad [10]$$

$$\sigma_y = \operatorname{Re} Z + y \operatorname{Im} Z' \qquad [11]$$

$$\tau_{xy} = -y \operatorname{Re} Z' \qquad [12]$$

in which Z is an analytic function of the complex variable $z = x + iy$; $Z' = dZ/dz$; σ_0 is a constant; and the symbols Re and Im stand for "the real part of" and the "imaginary part of" respectively. Stresses defined by [10] to [12] obey the laws of elasticity.

The load to consider in selecting the function Z in [10] to [12] consists of a tension q pulling the upper and lower sides of the slit together; and a tension p applied at the upper and lower ends of the plate. When the tension q is superposed on the locked-up compression q existing after the placing of the welds but before the cutting of the slit, the result is that the sides of the slit become unloaded as they are in fact. The tension p is to be chosen so that the combination of the tensile loads p and q produce no stress concentration at the ends of the slit. Then the resultant system of stresses in the whole plate will be obtained by superposition of two systems: one is the locked-up stresses existing before the cutting of the slit but after the placing of the welds; the other is the system created by the tensile loads p and q and expressed through [10] to [12] with a proper choice of Z and σ_0.

If the distributed tensile load q were replaced by two equal and opposite concentrated forces Q applied at $x = u$ and pulling the sides of the slit together, the function Z would assume the following form, which is obtained by a minor modification of Equation [40] in Reference*:

$$Z_1 = \frac{Q}{\pi}\,\frac{\sqrt{z^2 - c^2}}{(z-u)\sqrt{c^2 - u^2}} \qquad [13]$$

* See "Bearing Pressures and Cracks," by H.M. Westergaard, Journal of Applied Mechanics, Transactions, American Society of Mechanical Engineers, June 1939, pp. A-49 to A-53.

Equation [13] is verified by noting that in the immediate vicinity of the singularity at $z = u$, the dominant part of Z_1 becomes

$$Z_2 = \frac{iQ}{\pi(z-u)} \qquad [14]$$

which, according to Equation [17] in the reference cited on page 25, represents Boussinesq's problem in the case of two dimensions. Furthermore $Z_1 = 0$ at $z = \pm c$, and Z_1 converges toward a constant when z becomes great.

In the case at hand Q in [13] will be replaced by $q\,du$, and the expression is to be integrated over the length of the slit with q interpreted as a function of u. This leads to the following formula which still requires verification:

$$Z = \frac{\sqrt{z^2 - c^2}}{\pi} \int_{-c}^{c} \frac{q\,du}{(z-u)\sqrt{c^2 - u^2}} \qquad [15]$$

It will be sufficient to investigate Z in [15] for the case in which q consists of the last term in [2] only. Then

$$q = q_{2n}\left(\frac{u}{c}\right)^{2n} \qquad [16]$$

and, by [15],

$$Z = \frac{q_{2n}\sqrt{z^2 - c^2}}{\pi c^{2n}} \int_{-c}^{c} \frac{u^{2n}\,du}{(z-u)\sqrt{c^2 - u^2}} \qquad [17]$$

Equation [17] gives

$$Z = q_{2n}\left(\frac{z}{c}\right)^{2n}\left[1 - W\sqrt{1 - \left(\frac{c}{z}\right)^2}\,\right] \qquad [18]$$

in which

$$W = 1 + \frac{1}{2}\left(\frac{c}{z}\right)^2 + \frac{1\times 3}{2\times 4}\left(\frac{c}{z}\right)^4 + \ldots + \frac{1\times 3\times 5\ldots(2n-3)}{2\times 4\times 6\ldots(2n-2)}\left(\frac{c}{z}\right)^{2n-2} \qquad [19]$$

At the end of the slit, at $z = \pm c$, Equations [11], [18], and [19] give $\sigma_y = Z = q_{2n}$, so that when the locked-up stress is superposed, the resultant σ_y becomes zero.

When $x^2 + y^2 > c^2$, Equation [19] may be restated as the convergent series

$$W = \frac{1}{\sqrt{1 - \left(\frac{c}{z}\right)^2}} - \frac{1\times 3\ldots(2n-1)}{2\times 4\ldots 2n}\left(\frac{c}{z}\right)^{2n}\left[1 + \frac{2n+1}{2n+2}\left(\frac{c}{z}\right)^2 + \frac{(2n+1)(2n+3)}{(2n+2)(2n+4)}\left(\frac{c}{z}\right)^4 + \ldots\right] \qquad [20]$$

which, substituted, in [18], gives

$$Z = \frac{1 \times 3 \ldots (2n-1)}{2 \times 4 \ldots 2n} q_n \sqrt{1 - \left(\frac{c}{z}\right)^2} \left[1 + \frac{2n+1}{2n+2}\left(\frac{c}{z}\right)^2 + \frac{(2n+1)(2n+3)}{(2n+2)(2n+4)}\left(\frac{c}{z}\right)^4 + \ldots\right] \quad [21]$$

When z becomes great compared with c, Z converges toward the value

$$p = \frac{1 \times 3 \ldots (2n-1)}{2 \times 4 \ldots 2n} q_n \quad [22]$$

and yZ' converges toward zero. Furthermore, if σ_0 is chosen equal to $-p$, in accordance with [10] to [12], σ_x will converge toward zero, σ_y toward p, and τ_{xy} toward zero. This verifies the last term in [3] and therefore the whole formula.

CONCLUSION

In the case illustrated in Figure 23 the value of p in Equation [3] furnishes a suitable estimate of the gain due to the locked-up stresses.

APPENDIX 2

CALCULATION OF ENERGY ABSORPTION OF TWO 0.750 INCH THICK STEEL PLATES

Two 0.750 inch thick notched steel Specimens 310 and 311 were prepared as in Figure 24. They differed only in that Specimen 310 had the deposits of weld metal indicated in Figure 24, while Specimen 311 did not. Tensile test heads were welded to both specimens and each was subjected to tensile loading. Upon completion of the tests, the test heads were cut away.

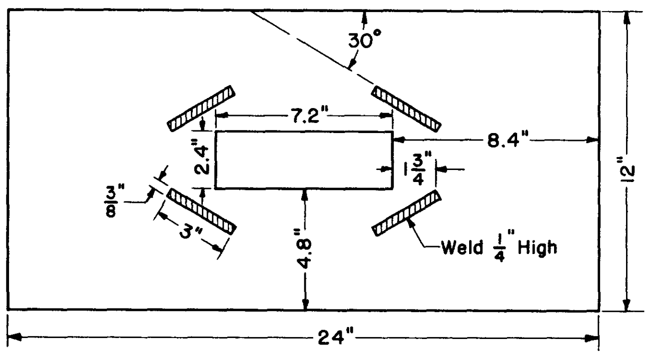


Figure 24 - Configuration of Specimen 310

Chemical analysis of the material indicates that it is very similar to Navy Specifications 48-S-5 medium steel plate.

Energy absorption was calculated for each of the plates in accordance with the thinning-strain technique based on the octahedral shearing stress-strain relations of the material.

Results of the energy calculations are given in Table 4.

TABLE 4

Calculated Energy Absorption of Specimens 310 and 311

Specimen	Original Thickness inches	Yield Load lb/in^2	Ultimate Load lb/in^2	Test Temp. degrees F.	Approximate Energy Absorbed inch-pounds
310	0.750	240,000	421,000	73	1,540,000
311	0.750	260,000	418,000	71	1,140,000

Although tensile loading of Specimens 310 and 311 revealed no differences in yield and ultimate loads, the energy-absorption values indicate

$$\frac{\text{Energy of 310}}{\text{Energy of 311}} = 1.35$$

Thus there was a marked difference in the behavior of the two plates, even though this was not indicated by the critical load values of the tests.

A more complete description of the tests and energy calculations is planned in a future Taylor Model Basin Report.