SERIAL NO. **SSC-79**

FINAL REPORT
(Project SR-118)

on

CRACKING OF SIMPLE STRUCTURAL GEOMETRIES

by

S. T. CARPENTER and R. F. LINSENMEYER
Swarthmore College

for

SHIP STRUCTURE COMMITTEE

Convened by
The Secretary of the Treasury

Member Agencies—Ship Structure Committee

Bureau of Ships, Dept. of Navy
Military Sea Transportation Service, Dept. of Navy
United States Coast Guard, Treasury Dept.
Maritime Administration, Dept. of Commerce
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Address Correspondence To:

Secretary
Ship Structure Committee
U. S. Coast Guard Headquarters
Washington 25, D. C.

SERIAL NO. **SSC-79**
BuShips Project NS-731-034

JANUARY 31, 1955

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SECRETARY
SHIP STRUCTURE COMMITTEE
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WASHINGTON 25, D. C.

January 31, 1955

Dear Sir:

As part of its research program related to the improvement of hull structures of ships, the Ship Structure Committee has sponsored an investigation on the cracking of simple structural geometries at Swarthmore College. Herewith is a copy of the Final Report, SSC-79, of the investigation entitled "Cracking of Simple Structural Geometries" by S. T. Carpenter and R. F. Linsenmeyer.

Comments concerning this report are solicited and should be addressed to the Secretary, Ship Structure Committee.

This report is being distributed to those individuals and agencies associated with and interested in the work of the Ship Structure Committee.

Yours sincerely,

K K Cowart

K. K. COWART
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

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S. T. Carpenter and R. F. Linsenmeyer

under

Department of the Navy
Bureau of Ships
Contract NObs-50250

with

Swarthmore College

Bureau of Ships Project NS-731-034

for

SHIP STRUCTURE COMMITTEE

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CRACKING OF SIMPLE STRUCTURAL GEOMETRIES

ABSTRACT

This report presents the results of an investigation concerning the general subject of the cracking of simple structural geometries under tensile loading. A summary is given of the effects of edge notch geometry and the effects of interrupted longitudinal members which were previously reported in Progress Reports I and II of this project, whereas the effects of edge preparation, the effects of fastenings, and the effects of welded pads are reported in their entirety for the first time.

Part 1 encompasses the general subject of the effect of edge conditions and includes a summary of the effects of flame cut edge notches of various geometries, the effects of the transition details between the sheer strake and the fashion plate, and the effects of various practical procedures of plate edge preparation. For edge notched specimens small differences were noted in transition temperature, whereas marked differences were noted in the strength and energy absorbing capacities of specimens of the various types. The results of tests of specimens designed to simulate the transition detail between the sheer strake and fashion plate emphasize the necessity of providing as smooth a transition as practicable from one structural component to another if benefits such as lower transition temperature and higher strengths are to be obtained. The effects of plate edge preparation at room temperature were of

little significance to specimens tested at room temperature. However, large differences in tensile behavior, and particularly in energy absorbing capacity, were noted for various edge treatments at low temperatures.

Part 2 of this report is a summary of tests of interrupted longitudinal members. Transition temperature was the characteristic most notably varied by variations in the geometry of the free end details of the longitudinals. However, significant variations were shown in strength and energy absorbing capacity, and emphasis has been added to the importance of a smoothly curved ending.

Part 3 reports the tests on 3-in. wide by 40-in. long specimens having various fastening details at the mid section. The details included drilled, punched, punched and reamed holes, or studs which were manually welded, automatically welded, or driven into the plate by an explosive charge. No major differences were noted in unit tensile strength for the specimens tested. However, an appreciable loss in specimen ductility was discernible in processes involving punching or other processes which cold work localized areas.

The effect of welding fixtures in close proximity on plates subjected to tensile loading was investigated and reported in Part 4. The specimens were 10 in. wide and 40 in. long with 3-in. wide by 2-in. long pads of 3/4-in. steel which were welded all around with 5/16-in. fillets made using

E6010 electrodes. The results indicated that the distance between the two pads had little effect on tensile behavior.

INTRODUCTION

The subjects of interrupted longitudinal members and edge notch geometries have been published in separate progress reports[1,2]. The effect on cleavage fracture of edge preparation, fastenings, and welded pads, is reported herein for the first time. This final report presents only a summary of the data of the first two subjects as found necessary, while the last three subjects are fully reported. Since specimen designations have been changed since the first two progress reports, a cross reference list is given in the appendix.

The overall objective of the entire investigation was to obtain a better understanding of certain factors affecting the fracture of steel plates. The factors introduced in this study were mainly geometrical conditions due to fabrication procedures such as edge notching, various forms of terminations of welded free ended stiffeners and longitudinals, practical methods of preparing plate edges, weld proximities, and types of fasteners other than welding.

Much of this investigation will be of use to a ship designer. However, many of the findings will be of particular value to inspectors responsible for passing upon workmanship. Everyone involved in this type of investigation, or who may have an interest in the results, has always agreed that materials, basic geometric design, and methods of fabrication are the prime controllable features of welded structures if the best obtainable margin is to be provided to prevent cleavage fracture.

The project was a large one, and many of its parts may appear unrelated. The various parts, however, represent the first information available on many neglected aspects of the overall total fractural problem and in the present stage may be of great value in design and in indicating where more work could profitably be done. The overall goal of designing and building crack-proof welded structures may someday be reached when the minute details, workmanship, and materials meet certain known threshold limitations. Until that day occurs, full attention must be paid to the minute detail of ship design and construction; and lacking other evidence, it is hoped that this work will be a guide to common sense.

PART 1

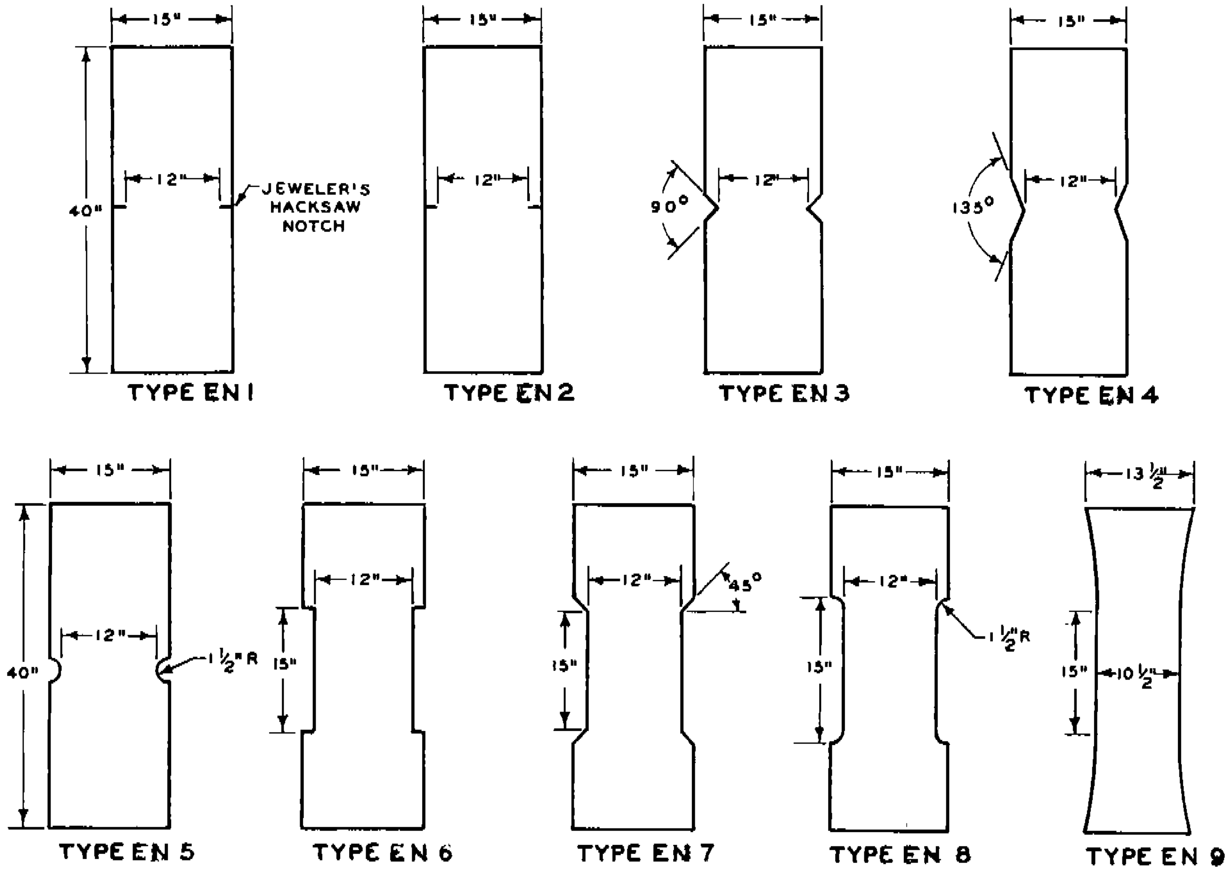
THE EFFECTS OF EDGE CONDITIONS

INTRODUCTION

Cleavage fracture has been shown to be influenced by edge notches which are either flame cut as a part of a fabrication technique or are inherent in the method by which plate edges are prepared. Fabricated notches of various geometric forms have previously been investigated and reported(1), whereas the effect of edge notches resulting from the method of edge preparation are reported for the first time.

In the investigation of flame cut edge notches, specimens as shown in Fig. 1-1 were utilized. It is to be particularly noted that tensile specimens of Types EN 1 to EN 5, inclusive, deal with edge notches at a single cross-section, whereas Types EN 6 to EN 8, inclusive, incorporated notch effects at two cross sections 15 in. apart. To form a basis for comparing the severity of notches, the Type EN 1 specimen had square notches produced by a jeweler's hack saw, and the Type EN 9 specimens had no edge notches other than those inherent in the flame cutting process.

A second series of specimen used in the study of edge conditions is shown in Fig. 1-2. These specimens, the EF series, were designed specifically to investigate the transition detail between the sheer strake and the fashion plate. Specimens of Type EN 9, having the same geometric form but without longitudinal



NOTE:

1. ALL SPECIMENS HAVE FLAME CUT EDGES AND NOTCHES EXCEPT TYPE I.
2. SPECIMENS WERE CUT FROM 3/4" DN STEEL PLATE WITH THE 40" DIMENSION IN THE DIRECTION OF ROLLING.

TYPES OF SPECIMENS

FIG. 1-1

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NOTE:

ALL EDGES FLAME-CUT

WELDS MADE USING E-6010 ROD

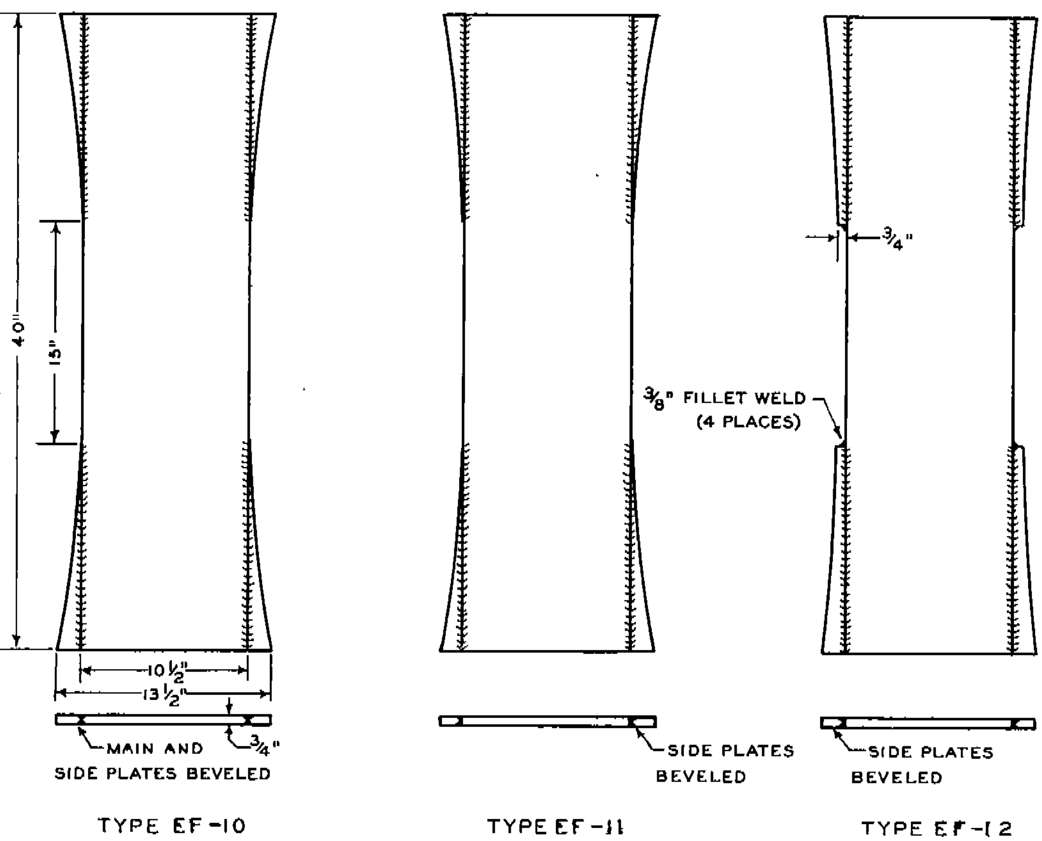


FIG. 1-2 SPECIMENS WITH LONGITUDINAL WELDMENT

weldments serve as a basis for comparison.

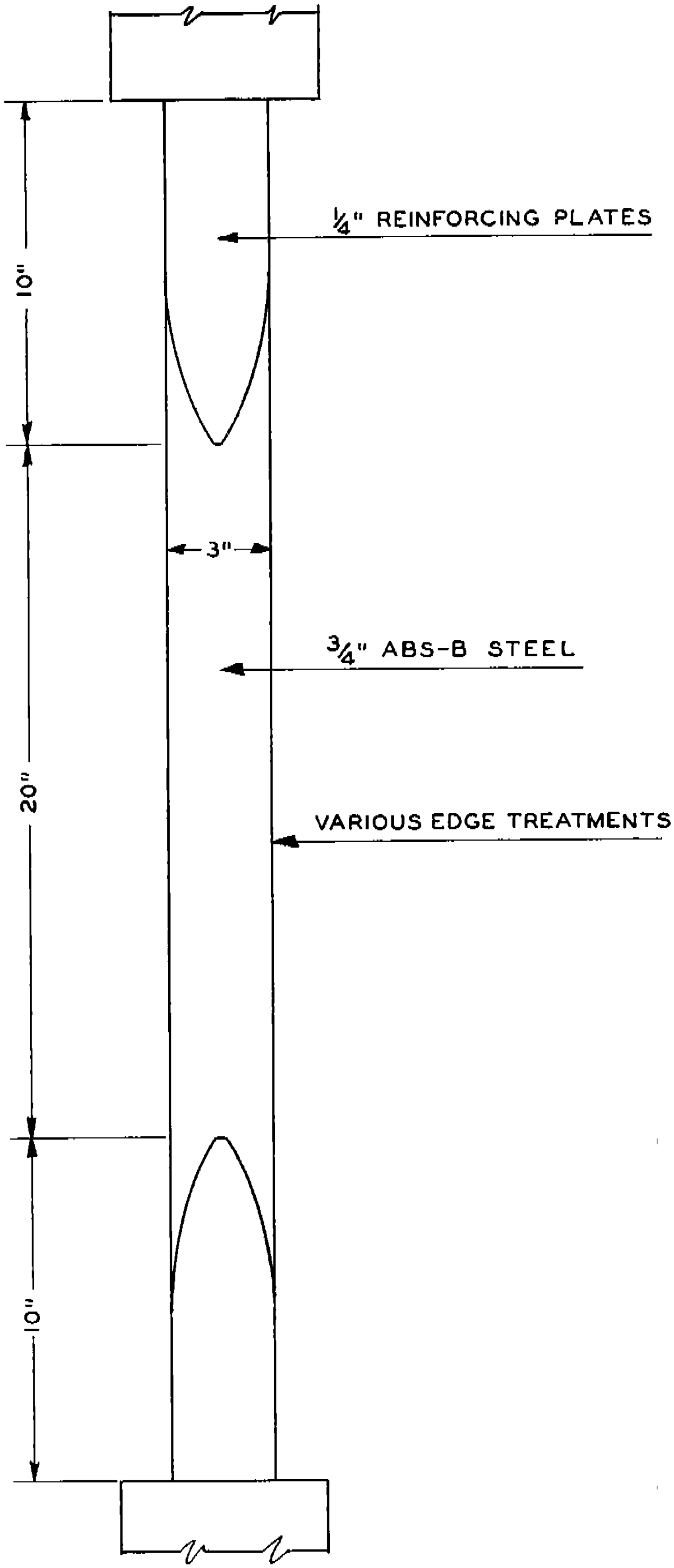
Plate edge preparation involves cutting and finishing by various methods. The methods investigated include machine and hand-guided flame cutting, shearing, and machining. Edge surface preparation may be such as to include three basic variables, namely, edge hardness by way of heat effects or by cold mechanical working, and edge notch effects. The basic specimen for these studies is shown in Fig. 1-3. The evaluation of the various methods has depended primarily upon tensile tests supplemented by bend tests and hardness surveys.

All specimens of this program were fabricated from either D_N steel or ABS-B steel of 3/4-in. thickness. The physical properties of these steels are given in the appendix.

TEST RESULTS FOR SPECIMENS WITH FLAME CUT NOTCHES

Test results are given in the form of load to visible crack, maximum load, unit stress at maximum load, energy to maximum load for both the cleavage and shear mode of fracture, as well as to the limit of load and elongation measurements for the shear mode, and character of the fracture as expressed by percentage of shear surfaces in fracture surfaces. The data are summarized in Table 1-I, and exhibited graphically in Figs. 1-4 to 1-8, inclusive. All load-elongation diagrams may be found in the First Progress Report.

<u>Visible Crack</u>. It was thought important to determine the



EDGE EFFECTS SPECIMEN

FIG. 1-3

TABLE 1-I

SUMMARY OF RESULTS OF EDGE NOTCHED WIDE PLATE D_N STEEL SERIES WITH NO WELDMENT

Type	Transition Temp, °F Based on Fracture Appearance	Ave. Load to Visible Crack		Ave. Max Load-kips		Ave. Energy to Max. Load--inch-kips 16 1/2" gage length		Ave. Energy to Max. Load--inch-kips 40" gage length		Remarks
		100% Shear Failures	0% Shear Failures	100% Shear Failures	0% Shear Failures	100% Shear Failures	0% Shear Failures	100% Shear Failures	0% Shear Failures	
EN 1	42	377(4)	374(3)	443(4)*	387(3)	242(4)	92(3)	420(4)	112(3)	Edges Burned Notches Jeweler's Hack Saw Cut
EN 2	39	373(3)	381(2)	448(3)	397(3)	230(3)	92(3)	410(3)	92(3)	Edges & Notches Burned
EN 3	53	371(2)	374(5)	455(2)	425(5)	255(2)	118(5)	432(2)	215(5)	Edges & Notches Burned
EN 4	48	381(3)	383(3)	508(2)	438(3)	295(2)	135(3)	558(2)	262(3)	Edges & Notches Burned
EN 5	25	416(4)	426(4)	590(4)	586(3)	658(3)	591(3)	1145(4)	1109(3)	Edges & Notches Burned
EN 6	42	368(4)	411(1)	502(4)	445(3)	510(4)	255(3)	791(4)	390(3)	Edges & Notches Burned
EN 7	52	371(5)	369(4)	508(5)	488(3)	425(5)	378(3)	742(5)	677(3)	Edges & Notches Burned

TABLE 1-I CONTINUED

Type	Transition Temp, °F Based on Fracture Appearance	Ave. Load to Visible Crack		Ave. Max Load-kips		Ave. Energy to Max. Load--inch-kips 16 1/2" gage length		Ave. Energy to Max. Load--inch-kips 40" gage length		Remarks
		100% Shear Failures	0% Shear Failures	100% Shear Failures	0% Shear Failures	100% Shear Failures	0% Shear Failures	100% Shear Failures	0% Shear Failures	
EN 8	42	415(3)	387(3)	563(3)	553(3)	951(3)	851(3)	1505(3)	1264(3)	Edges & Notches Burned
EN 9	25			580(2)	600(6)	2190(2)	1790(6)	3190(2)	2930(6)	Net Width 10 1/2"; Values Inflated to Correspond to 12" Net Width.

*Numbers in parentheses indicate the number of tests included in the average.

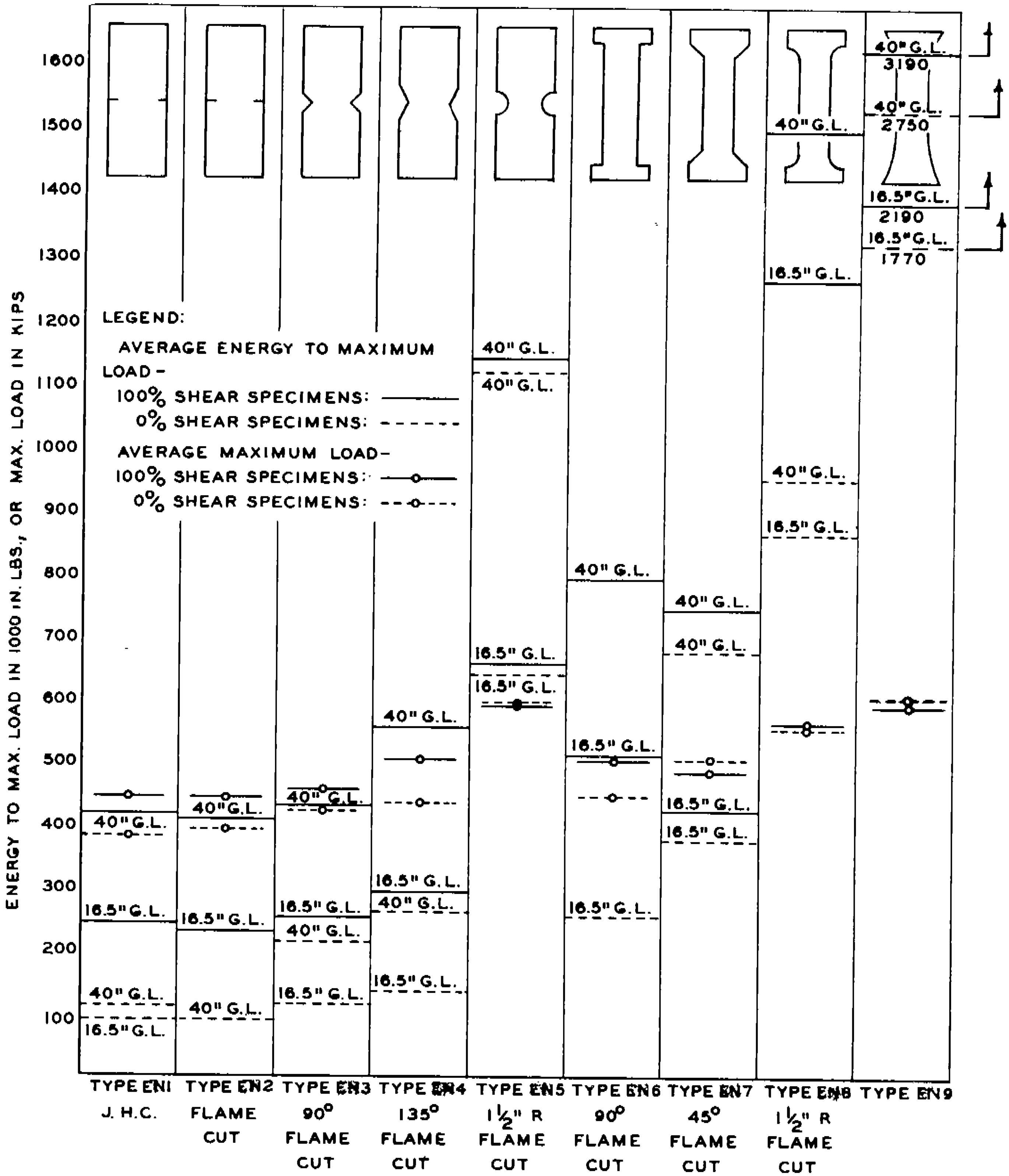


FIG. 1- 4 SUMMARY OF AVERAGE ENERGY AND LOAD VALUES

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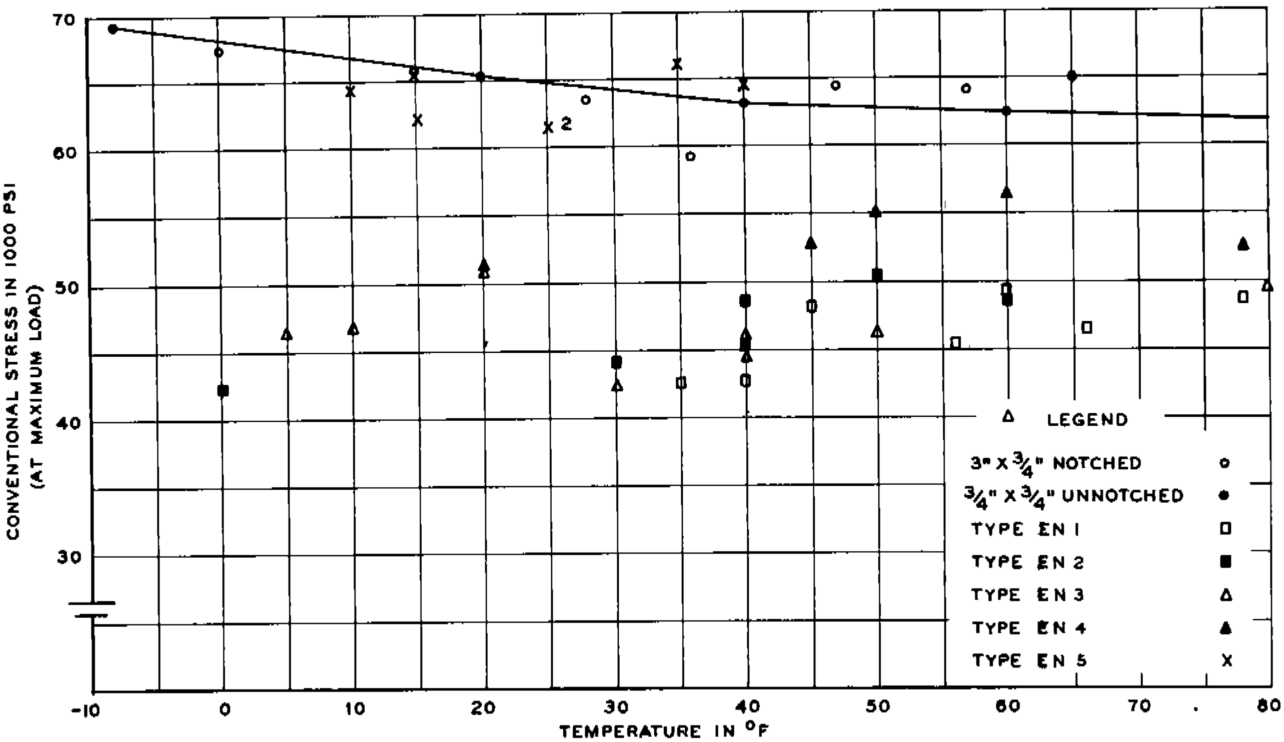

FIG. I- 5 RELATIONSHIPS BETWEEN ULTIMATE TENSILE STRENGTH AND TEMPERATURE

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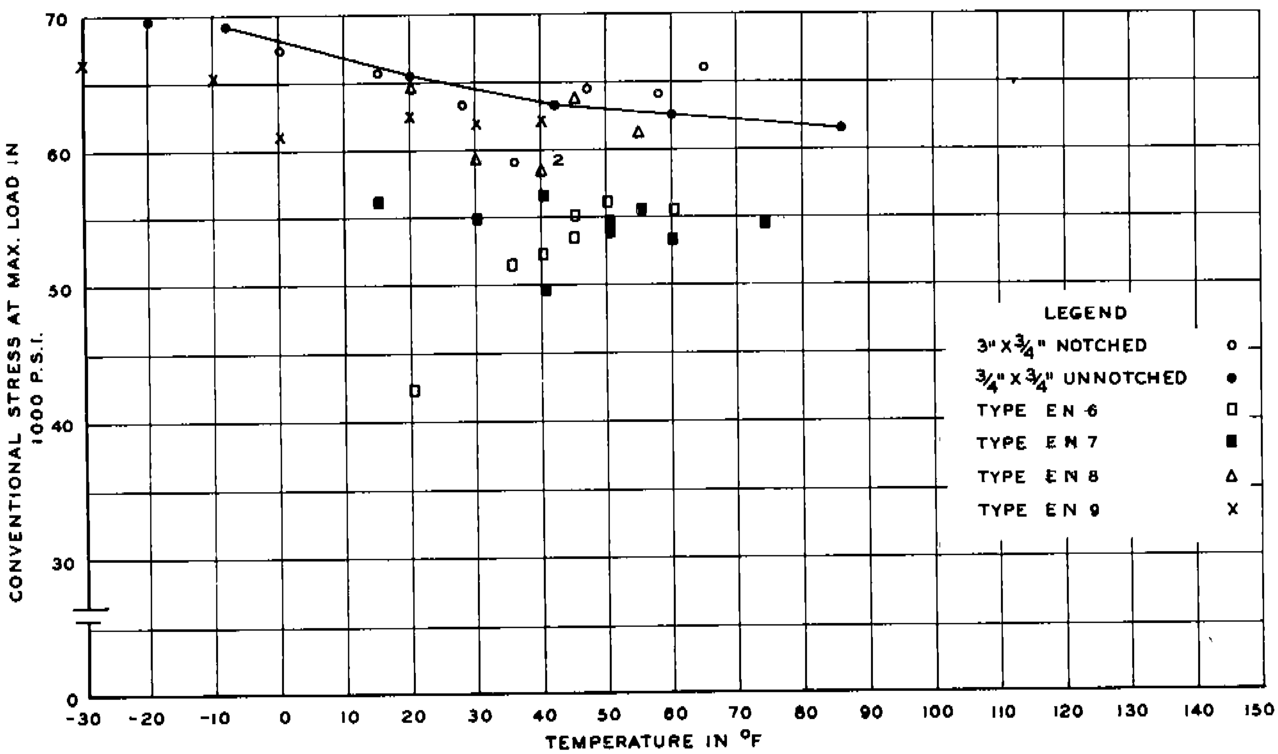

FIG. I- 6 RELATIONSHIPS BETWEEN ULTIMATE TENSILE STRENGTH AND TEMPERATURE

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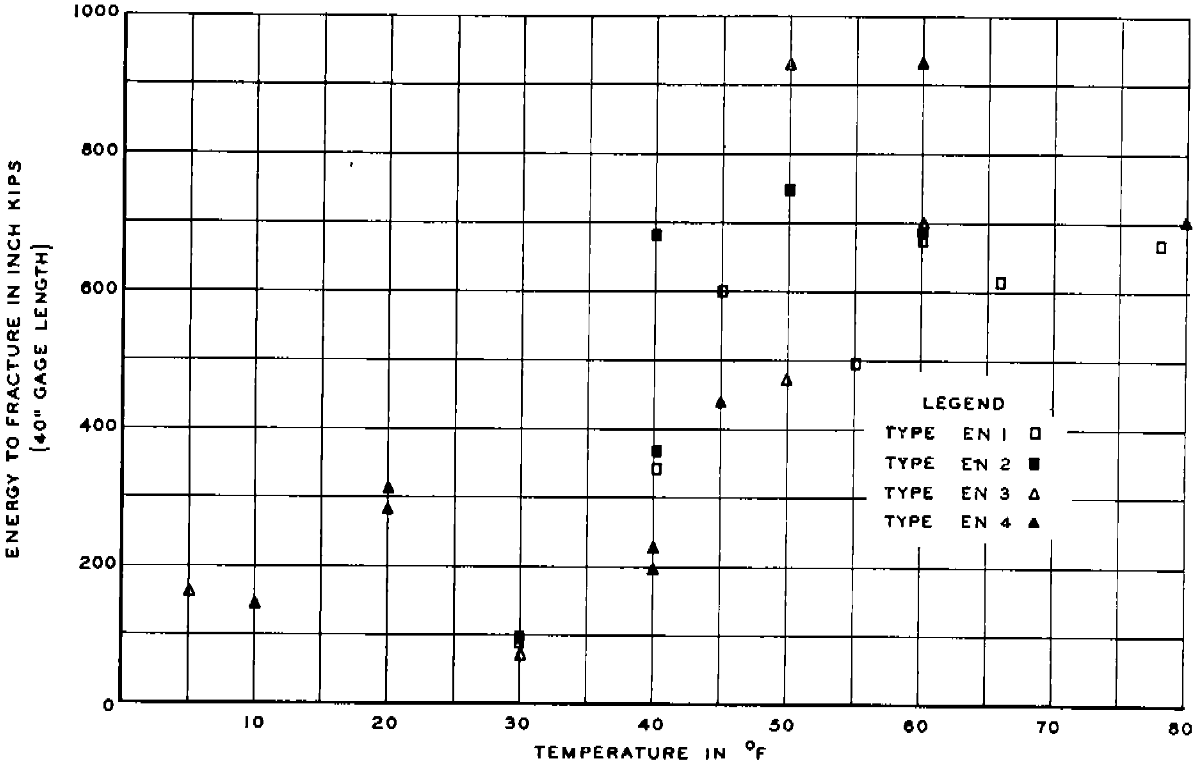

FIG. I-7 RELATIONSHIP BETWEEN ENERGY TO FRACTURE AND TEST TEMPERATURE OF NOTCHED EDGE SPECIMENS

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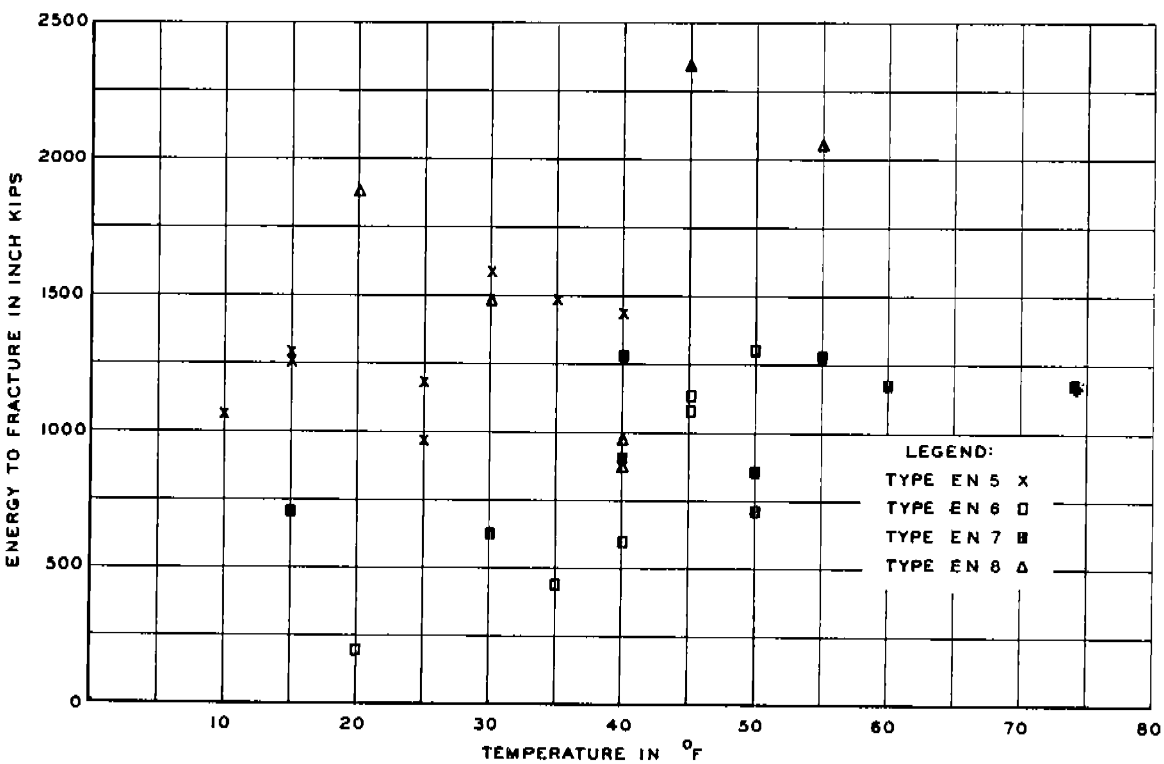

FIG. I-8 RELATIONSHIP BETWEEN ENERGY TO FRACTURE AND TEST TEMPERATURE OF NOTCHED EDGE SPECIMENS

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load at which a visible crack formed at root of notch. For Types EN 1 to EN 4, inclusive, the average loads to visible crack were practically the same. It is to be recalled that Type 1 had sharp jeweler's hack saw notches while others had flame cut notches. The investigators believe that the acuity of the visible crack controlled the action of the specimen rather than the initial notch geometry, since the stresses at visible crack appear to be independent of test temperature and the mode of the subsequent fracture. Type EN 5 with semi-circular notches, exhibited a slightly higher load to visible crack. As will be presented subsequently, Types EN 1 to EN 4, inclusive, had essentially the same transition temperatures.

Types EN 6 to EN 8, inclusive, with notching techniques and geometry similar to their counterparts of Types EN 2 to EN 5, inclusive, but with notches separated by 15 in., indicate parallel performance to visible crack.

Maximum Tensile Strength. Figure 1-4 summarizes maximum load values for the various types of specimens. (At top of figure is a pictorial guide for easy reference to determine geometric shape.) Types EN 1 to EN 5, inclusive, show a gradual improvement in maximum load for either shear or the cleavage mode of failure. The maximum loads for Type EN 1 with jeweler's hack saw notch are essentially equal to those of Type EN 2 with a flame cut notch, thus credence may be given to the assumption that notch acuity is regulated by the visible crack. A comparison of Types EN 3 and EN 4, which differ in only included angle of notch opening, shows a slight load margin in favor of Type EN 4. Type EN 5 with semi-circular notches has the highest load carrying capacity, and as will later be seen, provides the best performance in energy absorption of the Types EN 1 to EN 5, inclusive.

The Types EN 6 to EN 8, inclusive, with one-half notch profiles separated show some improvement in maximum load compared with Types EN 2 to EN 5, inclusive. Similar visible crack loads are shown by the two series, with Types EN 6 and EN 7 being about 10% better in maximum load capacity than Types EN 2, EN 3, and EN 4. EN 8 has about 5% less load capacity than Type EN 5. Increasing the angle of the edge notches improved the strength of specimens notched at mid length.

Type EN 0, an unnotched specimen, resisted the largest load, with Type EN 5 a close second. It thus appears that extremely sharp flame cut notches may lower the dependable load carrying capacity of a given specimen by as much as 30% or more if only the critically important cleavage mode of fracture is considered.

To clarify further the impairment of strength by notching, reference should be made to Figs. 1-5 and 1-6. In these figures the ordinate is in terms of lb. per sq. in. on the net section and the abscissa, the test temperature. To aid further in interpretation, tensile test data obtained on 3/4-in. square unnotched bars of D_N steel are plotted and connected with a solid line. This line may be termed the "par" line, representing strength of the metal under the most favorable conditions and thereby furnishing a quantitative basis for judging strength impairment due to notching and temperature. In addition, data have been plotted for 3-in. wide by 3/4-in. thick specimens of D_N steel with saw cut edge notches as obtained from a research report of the University of California. These latter data are useful in comparing strength of Type EN 1 (saw cut edge notches). The Type EN 1 specimen has a lower strength by virtue of its increased width, an expected event, as wider notched plates have been shown by many other investigations to have a lower strength.

As may be easily seen in Figs. 1-5 and 1-6, only Types EN 5 and EN 8 as well as EN 9 approach the "par" line for strength. These Types either have semi-circular notches or no geometrically prepared notches as for Type EN 9. While the strength of Type EN 9 should closely agree with the "par" line, it does not. The reason for this probably lies in the edge hardness due to flame cutting and the mild notches caused by hand guided flame cutting. A single specimen of Type EN 5 with semi-circular notch ground smooth did not fail at 616^k (testing machine capacity) at 0°F, 25° lower than transition temperature for Type EN 4. The impairment in strength for other notched types is clearly indicated. Designers must avoid sharp notched cut-outs and as in the best practice of this time use semi-circular or curved cut-outs and filleted transitions and then only when necessary.

Energy. The values of energy to maximum and fracture loadings are graphically summarized in Figs. 1-4, 1-7, and 1-8.

Many interesting energy comparisons may be made. First, the effects of separating the notches as in Types EN 6 to EN 8, inclusive, may be contrasted with Types EN 1 to EN 5, where the notches were at a single cross-section. This contrast indicates that separation improves energy values, primarily due to increased load values and the formation of two plastic zones instead of one as is the case of centrally notched Types. Second, the semi-circular notched Types EN 5 and EN 8 are much better than straight sided notches, since larger plastic zones are permitted to form. Third, energy absorption of all notched types is definitely inferior to the unnotched Type EN 9. This is similar to the statement concerning maximum loads; hence notching produces inhibitions on both strength and energy.

Transition Temperatures. Transition temperatures for all Types are summarized in Table 1-II. They have been determined as single values of temperature and as temperature ranges.

The basis for selecting single values of transition temperature is as follows: The mid value between maximum and minimum values of per cent of shear, or energy to maximum load,

TABLE 1-II

TRANSITION TEMPERATURES

°F

Type of Specimen	Based on Fracture Appearance		Based on Energy to Maximum Load		Based on Energy to Fracture	
	Single Pt.	Range	Single Pt.	Range	Single Pt.	Range
EN 1	42	45 to 60	45 or 57	45 to 60	38	30 to 45
EN 2	39	40 to 50	35	40 to 50	39	40 to 50
EN 3	53	50 to 60	48	50 to 60	46	50 to 60
EN 4	48	45 to 50	45	45 to 50	46	45 to 50
EN 5	25	25 to 30				
EN 6	42	40 to 45	40	40 to 50	42	40 to 50
EN 7	52	30 to 55	52	30 to 55	52	30 to 55
EN 8	42	40 to 45	42	40 to 45	42	40 to 45
EN 9	25	20 to 30				

or energy to fracture, where the latter quantities were separately plotted against temperature, was first located. An intersection of the mid value line with the curve in question determined the single value of temperature defined as transition temperature. Transition temperature ranges were determined as the temperature zone within which there was a likelihood of an abrupt change in energy level or a change in fracture from a shear to a cleavage mode.

In general, the transition temperatures and ranges for a given Type of specimen were about the same, regardless of whether they were based on fracture appearance, energy to maximum load, or energy to fracture. Minor variations of this occur particularly for Type EN 9 when the transition temperature was 10° to 12°F lower based on energy than when based on fracture appearance.

All types except EN 5 and EN 9 might be said, with small error, to have a transition temperature of about 45°F. The effect of the less severe notching of Type EN 5 is to lower the transition temperature to approximately that of the unnotched Type EN 0, 20° to 25°F.

Type EN 1 having notches produced by jeweler's hack saw cuts has essentially the same transition temperature as Type EN 2 with burned notches. The acuity of the notch is definitely different until the visible crack occurs at the notch. It may be postulated that the acuity of the visible crack is the controlling factor instead of the original notch. The visible crack should also establish the notch acuity for Types EN 5 and EN 9. This is apparently confirmed by their near equality in transition temperature. The fact that these types show a lower transition than the others may be due to the higher local strain in the region of the initial crack, thus shifting the transition downward.

TEST RESULTS FOR SPECIMENS HAVING LONGITUDINAL WELDMENTS

Ultimate Load. Welded specimens of Types EF 10 and EF 11 had the same external geometry as the specimens of the unwelded

Type EN 9 series. The results of the Type EN 9 series, unwelded and unnotched specimens, were used as a base of comparison for previously made edge notched specimens and hence are useful here for comparative purposes. The results for Type EN 9 for 10 1/2-in. wide specimens are plotted on Figs. 1-9 and 1-10. The maximum loads for specimens of the Types EF 10 and EF 11 series appear to be directly comparable to the maximum loads exhibited by specimens of the Type EN 9 series at the same test temperatures. The maximum tensile loads for specimens of each of these three series are plotted in Fig. 1-9. Plate beveling and longitudinal welding had little effect on strength when compared with the Type EN 9 series which had no weldment.

The 5/16-in. fillet welds and the 3/4-in. effects at the ends of the side plates of the EF 12 specimens had decidely detrimental effects on strength. Two specimens tested at 0°F and +15°F exhibited maximum loads which were approximately 100 kips lower than the EF 10 and EF 11 specimens tested at about the same temperatures.

The effects of plate beveling, which established the cross-sectional form of the longitudinal weldment, were apparently of little significance in limiting values of maximum load. Abrupt changes in external specimen geometry, however, combined with fillet welds at the point of offset, appeared to be more important factors in limiting the maximum load.

Energy to Maximum Load. Relationships between energy

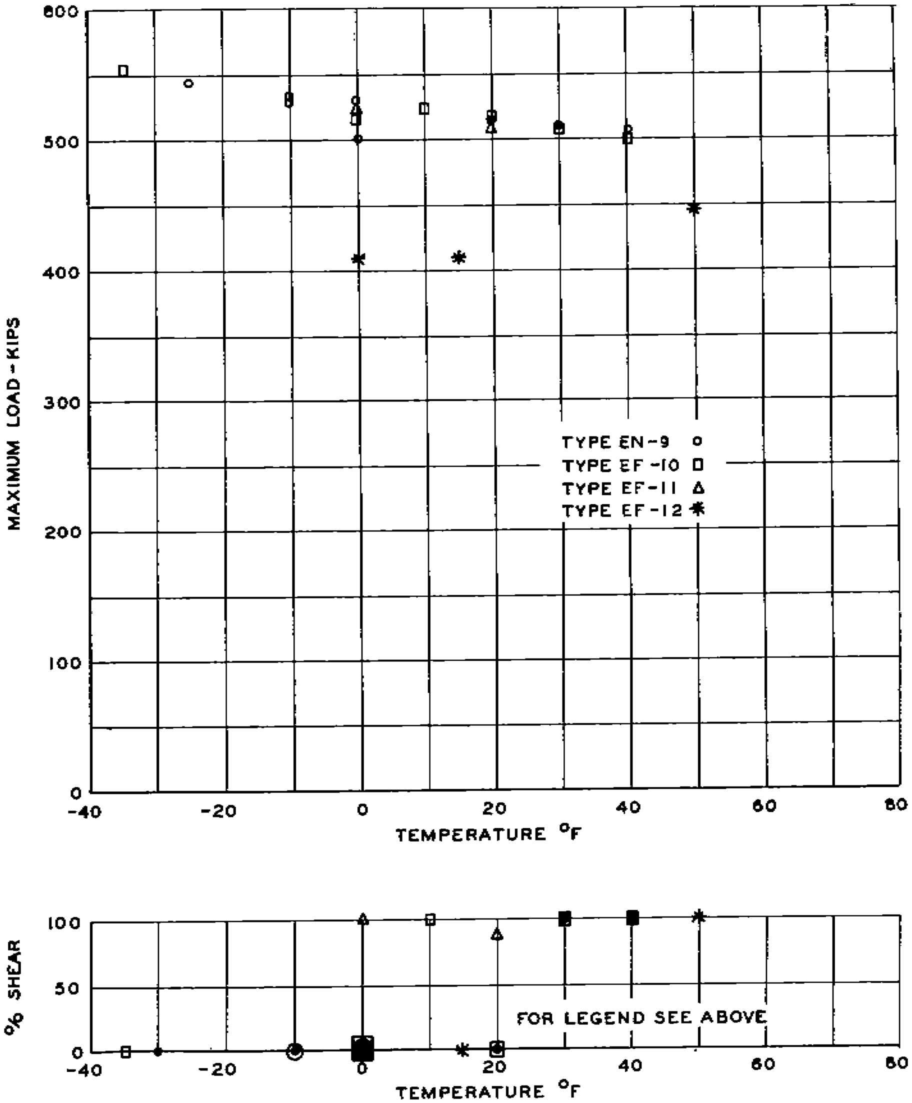

FIG. I -9 SUMMARY - MAXIMUM LOAD AND PERCENT SHEAR
VS. TEMPERATURE
TYPE EF SPECIMENS

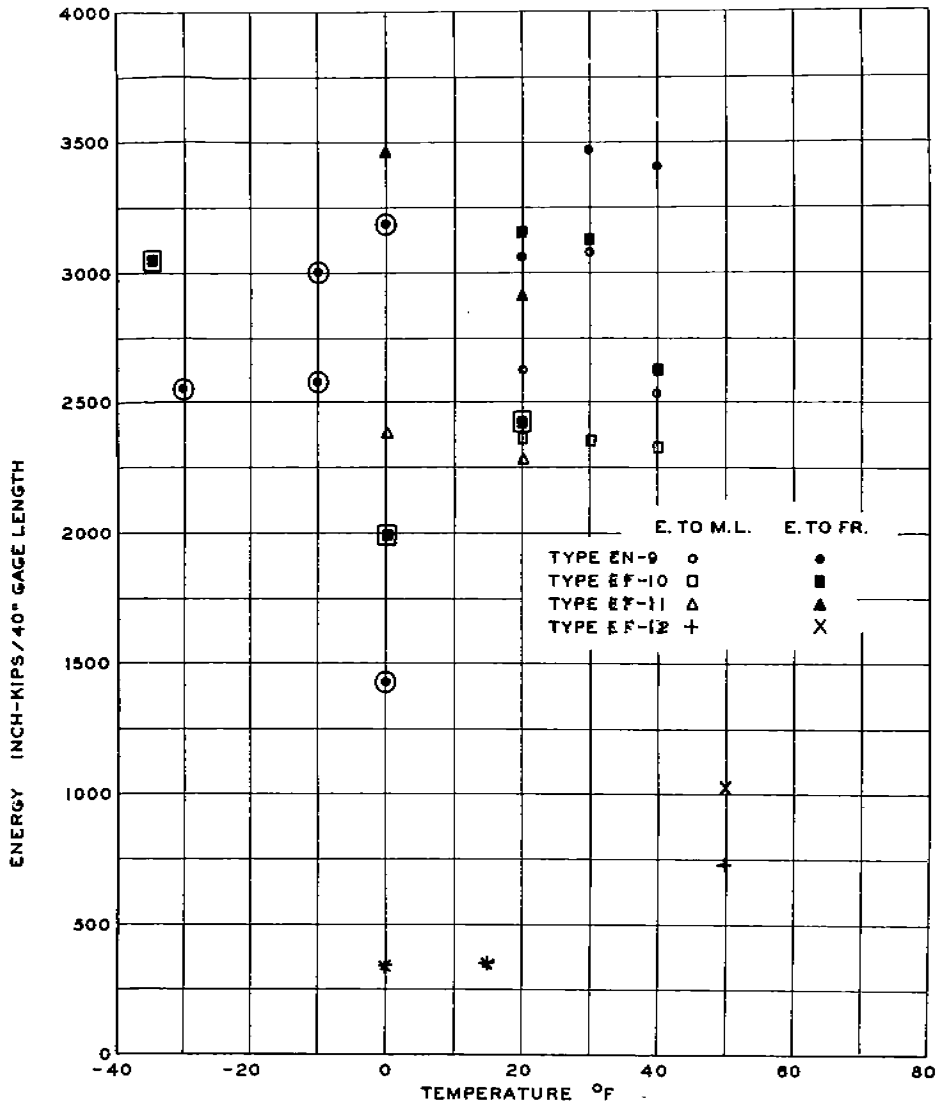

FIG. I-10 SUMMARY - ENERGIES TO MAXIMUM LOAD AND
FRACTURE VS. TEMPERATURE
TYPE EF SPECIMENS

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to maximum load, measured over the specimen length of 40 in., and test temperature for specimens of Types EF 10, EF 11, and EF 12 are shown in Fig. 1-10. The results for unwelded specimens of Type EN 9 having the same geometry as Types EF 10 and EF 11 are also plotted in Fig. 1-10. The scatter of the limited data makes the interpretation of the results difficult.

The energy to maximum load for welded specimens of Types EF 10 and EF 11 generally have slightly lower values at most test temperatures than the energies reported for unwelded Type EN 9. The exceptions occur at 0°F and at -35°F, where a single specimen of Type EF 10 with a cleavage fracture had an energy to maximum load which was higher than that for any other specimens.

Due to limited tests of Type EF 11, no conclusive comparisons can be made with Type EF 10. It appears, however, that the effects of welding and plate beveling reduces the energy absorbing capacity by only a small amount when results are compared with unwelded specimens of the same external geometry.

The three specimens of Type EF 12 with a 5/16-in. fillet weld and a 3/4-in. offset at the end of the side plates, had values of energy to maximum load which fell far below the energy values for the Types EF 10, EF 11, and EN 9, at the same test temperatures. The energy absorbing capacity of specimens of Type EF 12 appears to be about 20% of that of EF 10 and EF 11.

It is therefore apparent, given a free choice of details, that an abrupt change in geometry as exemplified by the details of Type EF 12 should be avoided. Type EF 12 is definitely inferior in both load and energy capacity.

Energy to Fracture. A graphical representation of values of energy to fracture of specimens of Types EF 10, EF 11, and EF 12, is given in Fig. 1-10. Energy to fracture values for the previously reported geometrically similar series of Type EN 9 is also shown.

Values of energy to fracture must be viewed considering the type of fracture, i.e., shear or cleavage. Specimens in shear always attain a higher energy value at fracture load than that at maximum load, while specimens failing in complete cleavage are assumed to have the same energy as at maximum load. The tenacity of the shear type of fracture is well known, and energy to fracture exemplifies this feature.

For Types EF 10, EF 11, and EN 9, it would appear that the energies to fracture are roughly equivalent at all test temperatures. In contrast, specimens of Type EF 12 exhibited energies to fracture which were less than 20% of the energy values for specimens of Types EF 10 and EF 11. As was the case with maximum load and energy to maximum load, external specimen geometry again seems to be the more important parameter in limiting the amount of energy absorbed to fracture.

Transition Temperatures. The criteria used to evaluate transition temperature for specimens of the EF series were based on fracture appearance, energy to maximum load, and energy to fracture. The estimated transition temperatures for each of the criteria are shown in Table 1-III.

The transition temperatures as represented by fracture appearance are the temperatures taken from sketched curves (not shown) of per cent shear vs. temperature based on data as shown in Fig. 1-9 and represent the temperature at which a 50% shear fracture would be expected.

Transition temperatures based on values of energy to maximum load or to fracture were taken from sketched curves of energies vs. temperatures based on data shown in Fig. 1-10. Transition temperatures represent the temperatures at the points on the sketched curves where the ordinates approximately represented the average of high and low values of energy.

The two tests of specimens of Type EF 11 at 0°F and +20°F indicated 100% shear fractures, thus making it impossible to evaluate the transition temperature for Type EF 11 except to state that it is lower than 0°F. Type EF 10 specimens indicated a transition temperature at about +25°F based on fracture appearance and +10°F based on energy.

The higher transition temperature for Type EF 10 may be attributed to a difference in severity of the weld notch at the end of the butt weld. For Type EF 10 the part of the butt

TABLE 1-III

Transition Temperatures
Type EF Specimens
D_N Steel

Type of Specimen	Transition Temperature, °F Based on Fracture Appearance	Based on Energy to Maximum Load	Based on Energy to Fracture
EN 9	25°	indeterminate	indeterminate
EF 10	25°	10°	15°
EF 11	lower than 0°	lower than 0°	lower than 0°
EF 12	35°	indeterminate	35°

weld lying in the main plate groove ends abruptly, whereas for Type EF 11, where only the side plate was beveled, a less severe weld notch was created. The fracture in all EF 10 specimens initiated through the weld termination; but for the two specimens of Type EF 11, fracture occurred above the termination for the test at +20°F and in the main plate, several inches below the termination of the test at 0°F. This change in location of fracture, coupled with the fact that both fractures were of the shear type, lends confirmation to the lesser severity of localized effects for EF 11.

Specimens of Type EF 12, due to the increased severity of localized effects at the offset, show a higher transition temperature than for EF 10 or EF 11. With only three tests of Type EF 12, it is possible to establish only an approximate value of the transition temperature at about 35°F.

EFFECTS OF EDGE PREPARATION

Introduction. Since this part of the report on edge conditions contains material which has not been previously reported by the investigators, a description of fabrication techniques and instrumentation is included with the discussion of test results.

The specific specimen types investigated are classified as follows:

Type	Edge Surface Preparation
EM	Machined in planer
ES	Sheared
EH	Hand guided flame cut
EG	Machine guided flame cut
EGG	Machine guided flame cut and lightly ground
EG-A	Carbon arc strikes on machine guided flame cut edges

The edge preparations introduce essentially three basic variables, i.e., heat effects, effects of cold mechanical working, and edge notch effects which may accompany either of the other two variables. To determine the relative effects of these variables, specimens with each of the edge treatments were tested in tension at room temperature, at -40°F, and at the lowest service temperature probably encountered by ships, 0°F. For each of these testing temperatures, the results of the tensile tests in terms of maximum loads, fracture loads, elongations, and energy absorptions were compared. As a further aid to the evaluation of the relative ductilities and notch effects of the edge treatments, bend tests were conducted for each of the edge types.

Specimens with edges prepared by machining are to be referred to in this report as a standard of specimen behavior, since it is believed that this type of edge preparation does not introduce the variables mentioned to any great extent. Machine guided flame cuts introduce considerable heat effects with moderate edge notching resulting from the cutting irregularities. Hand guided flame cutting introduces heat effects with severe edge notching due to the more irregular surface resulting from this type of edge preparation. Machine guided flame cut surfaces may be improved in appearance by a light grinding which removes the mild edge grooving and part of the heat-affected zone. Edge shearing introduces mechanical working of the metal in the edge zones along with edge notches due to roughness. The carbon arc strikes introduce localized pitted areas of severe heat effects with microscopic cracks radiating from pitted area into the adjoining base plate.

Specimen Fabrication. The tensile specimens used were of 3/4-in. thick ABS-B steel, 3 in. wide, and having a 40-in. long test section for the tests made at room temperature, and a 20-in. long test section for tests conducted at temperatures lower than room temperature. The specimens are shown in Fig. 1-3.

The machined edge specimens, Type EM, were prepared by planing. Fig. 1-11 is a photograph of typical edge surface appearances for all specimen types.

The sheared edge specimens, Type ES, were prepared at the Sun Shipbuilding and Dry Dock Co., in Chester, Pennsylvania. The resulting edges were of a good quality in the opinion of the shipyard personnel. The specimens were aged for a period of approximately four weeks before testing.

The machine guided flame cut surfaces, Type EG, were prepared according to published recommendations of the Linde Air Products Co. The resulting edges exhibited only slight edge irregularities.

Specimens of Type EGG were prepared by machine guided flame cutting with the edge surfaces further prepared by a light grinding. The grinding was sufficiently deep to remove all surface grooves but did not extend deeply into the heat-affected zone. It is estimated that the maximum depth of grinding was 1/32 in. with the greater part to a lesser depth. Hardness tests also indicated that only a small part of the heat-affected zone was removed.

Specimens which had hand guided flame cut edges are designated as Type EH. The resulting edges were quite irregular, as can be seen in Fig. 1-11.

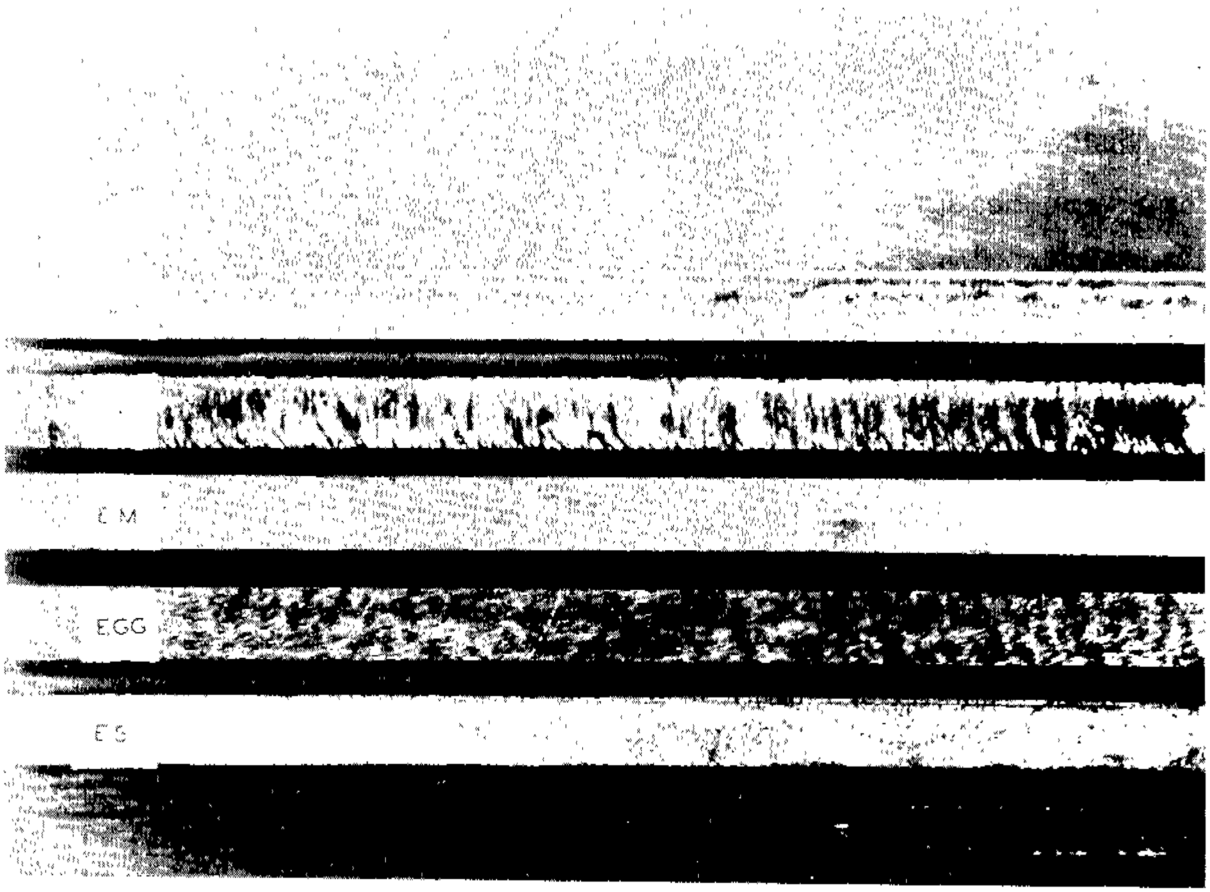


Fig. 1-11. Typical Edge Preparations
E Specimens

Following the preparation of the specimens, 1/4-in. reinforcing pads were attached to ends of the test sections with fillet welds. The assembly was then welded to the headers which fitted into the jaws of the testing machine.

Specimen Instrumentation and Testing. Specimen elongations were measured with a spool type extensometer sensitive to 0.005-in. The terminal points of the extensometer were located on the pulling heads which had a much greater cross-sectional area than the specimens themselves, making it possible to attribute all of the elongations registered on the extensometer to the test section of the specimens.

The testing machine employed for the program was a Baldwin machine with a 600,000-lb. capacity located in the Civil Engineering Department's Laboratories at Swarthmore College.

The specimens were tested at room temperature or were surrounded by an insulated temperature control chamber which was telescopic to permit it to follow the elongations of the specimens. The specimens were cooled to testing temperature by air which was circulated through a closed system consisting of the chamber, insulated hoses, and an insulated box containing dry ice. Three thermocouples were attached to each specimen, at the top, center, and bottom, which actuated the fan switches in the circulatory system. The temperatures were automatically recorded through the cooling period and testing.

The specimens were loaded slowly, and load, elongation, and temperature readings were taken simultaneously. The data were recorded and plotted as load vs. elongation curves. Energies to maximum load and to fracture were computed from the areas under the curves and are tabulated in Tables 1-IV and 1-V.

Specimens were tested at room temperature, at -40°F, and at 0°F, the latter temperature, in the opinion of the advisory committee, representing the lowest recorded service temperature at which ship fractures were known to occur.

Hardness Measurements. As a further aid to the evaluation of the effects of edge preparation, Rockwell hardness measurements were made on specimens having sheared, machine guided flame cut, machine guided flame cut and ground edges. Specimens were cut transversely across unstrained specimens, and hardness readings were taken from edge to edge at the mid-thickness of the plate. The values of Rockwell "B" hardness vs. distance from the edges are plotted in Fig. 1-12.

Hardness measurements on machined edge specimens Type EM indicated that the hardness was constant across the specimen at a value of B-70. Converting Rockwell "B" hardness of 70 to Brinell hardness and applying Dohmer's law to estimate tensile strength indicates that the tensile strength of ABS-B

TABLE 1-IV

EDGE EFFECTS PROGRAM--SUMMARY OF ROOM TEMPERATURE TESTS

Specimen Size: 3 in. by 3/4 in. by 40 in.

Speci-men	Edge Treatment	% Shear Fracture Surfaces	Maxi-mum Load Kips	Energy to Max. Load In-Kips	Elongation to Max. Load Inches	Frac-ture Load Kips	Energy to Fracture Load In-Kips	Elongation to Fracture Load Inches
EM-L 20	Machined	100	126.5		8.50	100		10.15
EG-L 16	Guided Burned	100	127.5		7.00	100		8.90
EGG-L 19	Guided Burned and Ground	100	125		6.00	100		7.25
EH-L 17	Hand Burned	100	125		6.00	22		7.10

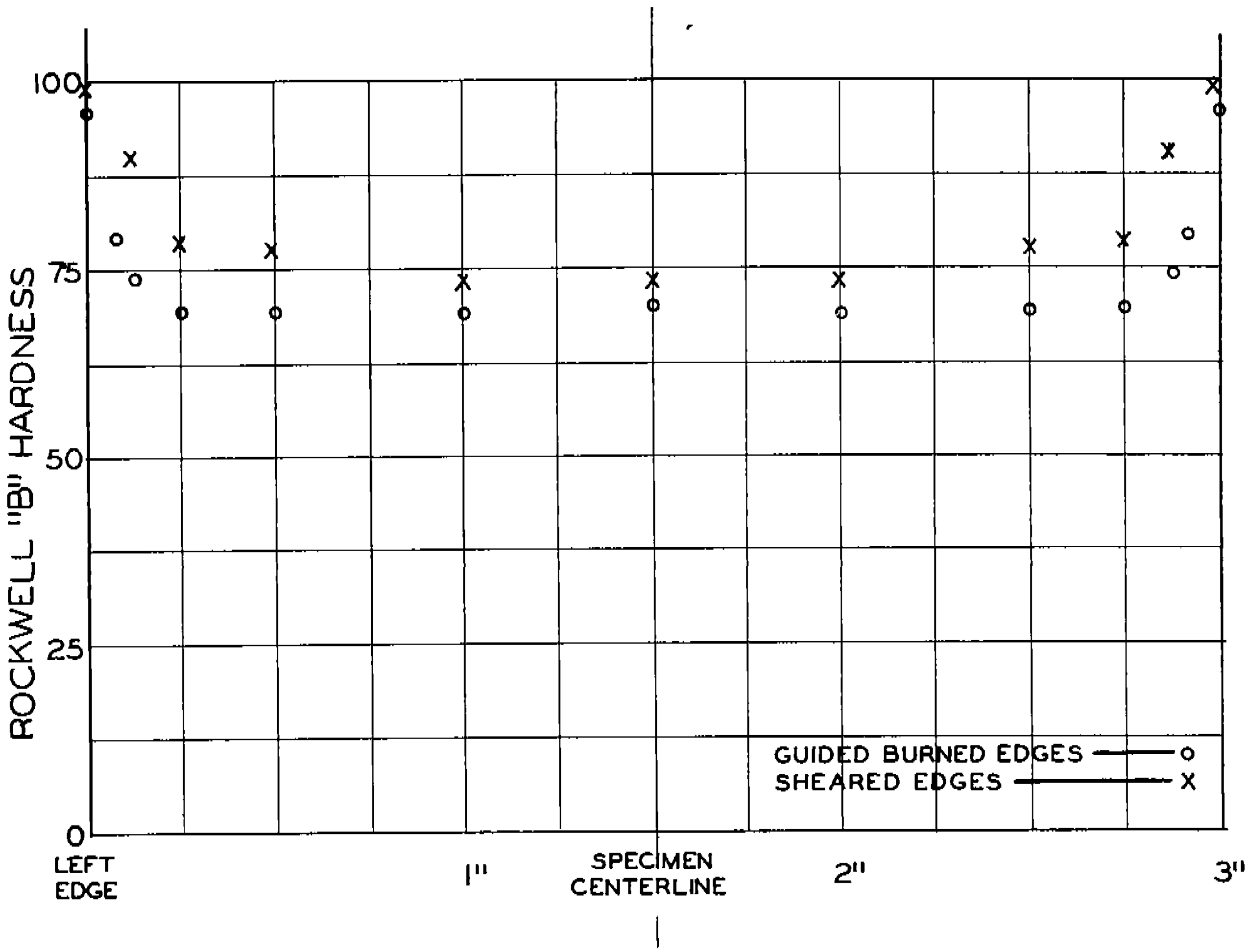
TABLE 1-V

SUMMARY OF TEST DATA FOR LOW TEMPERATURE TESTS

Specimen	Edge Treatment	°F	% Shear	Max. Load Kips	Energy to Max. Load In-Kips	Elong. to Max. Load Inches	Fracture Load Kips	Energy to Frac. Load In-Kips	Elong. to Frac. Load Inches	% Reduct. Thickness at Frac.	Fracture Origin
EM-M19	Machined	-40	70	156.0	627	4.500	130.0	787.5	5.570	27.9	Mid Width-1/3 Length
EM-M17	"	-40	50	160.7	492.5	3.500	139.0	787.5	5.370	25.4	Mid Width-1/3 Length
EM-M18	"	-60	0	163.0	-	2.850	163.0	-	2.850	4.5	At end reinforcement
EM-M29	"	-60	0	161.5	-	2.350	161.5	-	2.350	3.5	At end reinforcement
EG-M20	Guided-Burned	-40	0	150.0	452.5	3.500	150.0	452.5	3.500	8.9	Edge-1/3 Length
EG-M15	Guided-Burned	-40	0	136.0	115.0	1.025	136.0	115.0	1.025	2.8	" " "
EG-M22	Guided-Burned	-20	0	148.5	253.5	1.900	148.5	-	1.900	5.2	" " "
EG-M34	Guided-Burned	-40	0	166.0	-	2.935	166.0	-	2.935	3.22	At reinforcement
EG-M32	Guided-Burned	0	50	160.5	485.0	3.500	138.0	705.0	4.900	23.4	Edge-1/3 Length
EGG-M14	Guided-Ground	-40	50	161.5	570	4.000	135.0	672.5	4.700	26.9	Mid Width-Mid Length
EGG-M16	Guided-Ground	-40	50	157.5	477.5	3.500	135.0	602.5	4.330	26.9	Mid Width-Mid Length
EGG-M21	Guided-Ground	-40	0	153.0	-	2.925	153.0	-	2.925	3.6	At Reinforcement
EGG-M31	Guided-Ground	-60	0	154.0	-	1.650	154.0	-	1.650	2.1	At Reinforcement

TABLE 1-V CONTINUED

Speci-men	Edge Treatment	°F	% Shear	Max. Load Kips	Energy to Max. Load In-Kips	Elong. to Max. Load Inches	Frac-ture Load Kips	Energy to Frac. Load In-Kips	Elong. to Frac. Load Inches	% Reduct. Thickness at Frac.	Fracture Origin
EH-M11	Hand Burned	-40	0	144.5	147.0	1.125	144.0	147.5	1.125	2.8	Edge at 1/4 Length
EH-M13	Hand Burned	-40	0	137.5	92.5	0.860	137.5	92.5	0.860	2.1	Edge at 1/3 Length
EH-M12	Hand Burned	0	0	157.0	257.5	1.990	157.0	257.5	1.990	4.5	Edge at 1/4 Length
ES-M23	Sheared	-40	0	161.0	222.5	1.595	161.0	222.5	1.595	3.0	Edge-1/3 Length
ES-M24	"	0	0	153.5	180.0	1.420	153.5	180.0	1.420	3.1	Edge-1/3 Length
ES-M25	"	+20	0	155.5	-	2.300	155.5	-	2.300	6.4	Edge-1/3 Length



ROCKWELL HARDNESS
VS.
SPECIMEN WIDTH

NOTE: HARDNESS READINGS TAKEN ON SAWED SURFACE AT MIDTHICKNESS OF UNSTRAINED SPECIMENS.

FIG. 1-12

steel should be approximately 62,500 lb. per sq. in. which compares favorably with the coupon strength.

Specimens with machine guided flame cut edges, Type EG, exhibited edge hardness of B-90. The heat-affected zone apparently extends for a distance of somewhat less than 1/4 in. from the edge as the hardness values diminish rapidly to a value of B-70 at that distance.

Specimens having machine guided flame cut edges which were further prepared by light grinding, Type EGG, had an edge hardness of B-80, indicating that the heat-affected zone was only partially removed by the grinding. However, the edge hardness remaining in combination with smoother edge surfaces apparently had no detrimental effects on the tensile behavior of these specimens.

Sheared edge specimens, Type ES, had hardness values which exceeded those of flame cut specimens. The average hardness of the sheared edges was B-98. The effects of cold mechanical working of the edges during the shearing operation extended to a distance of approximately 1 in. into the virgin plate, leaving only the center 1 in. of width of the 3-in. wide specimen unaffected by the mechanical working. This cold working of the metal affected the load vs. elongation curves for sheared edge specimens. The curves lacked the characteristic upper and lower yield points as shown by the other specimens and departed gradually from the elastic tangent.

Fracture Origins. Methods used in cutting and preparing the edge surfaces of steel plates become critical when the resultant edge conditions provide the origins for initiation of cleavage fracture. The ideal edge condition would represent edge surfaces free of notches and with edge zones of the plate unchanged in hardness or physical properties as compared to the parent plate. In this investigation the ideal is closely represented by edges prepared by machining. All other methods of edge preparation depart from this ideal.

The methods of edge preparation were not critical at nominal room temperature (averaging 75°F), since all specimens fractured in the shear mode with the shearing action starting at the mid widths of the 3-in. wide specimens.

Tests at low temperature developed both shear and cleavage fractures. Only two types of edge preparations, machined and machine guided flame cut with subsequent grinding, permitted initiation of fracture in the shear mode at mid width; whereas all other edge surface preparations provided edge conditions for initiation of cleavage fracture. Although specimens having machined and machine guided flame cut edges, the latter with ground edges, separated first at mid width in the shear mode at low temperature, continued straining and the internal shear plane notches caused these specimens to fracture in the cleavage mode for about one-third of the specimen width.

The effects of edge preparation on fracture can usually be evaluated by the visual appearance of the fracture surface. The fracture initiations in specimens having sheared edges were apparently caused by the high edge hardness due to the cold working of the edges during the shearing operation, and particularly that part of the edge which was on the under side of the specimen during the shearing operation. At very low unit strains cracks opened along this edge, providing the fracture origins. It is possible that these cracks were microscopically present before the specimen was strained in tension. A close examination of the edge photograph of Fig. 1-13 shows these cracks at approximately 10% strain. At the fractured cross-section the small shear lips caused by the shearing operation also serve as triggers for the cleavage fractures. These small shear lips can be seen at the upper right and lower left of the photograph of the fracture cross-section of Fig. 1-13.

The method of hand guided flame cutting edges develops a fairly rough edge surface (See Fig. 1-14), having an edge hardness considerably greater than that for the machined plate. The combination of roughness and hardness appears to be the cause of fracture. In all cases a crack developed at the root of one of the edge grooves and provided the notch required to trigger the fracture. The cleavage fractures began on the edge at the mid thickness of the plate at a

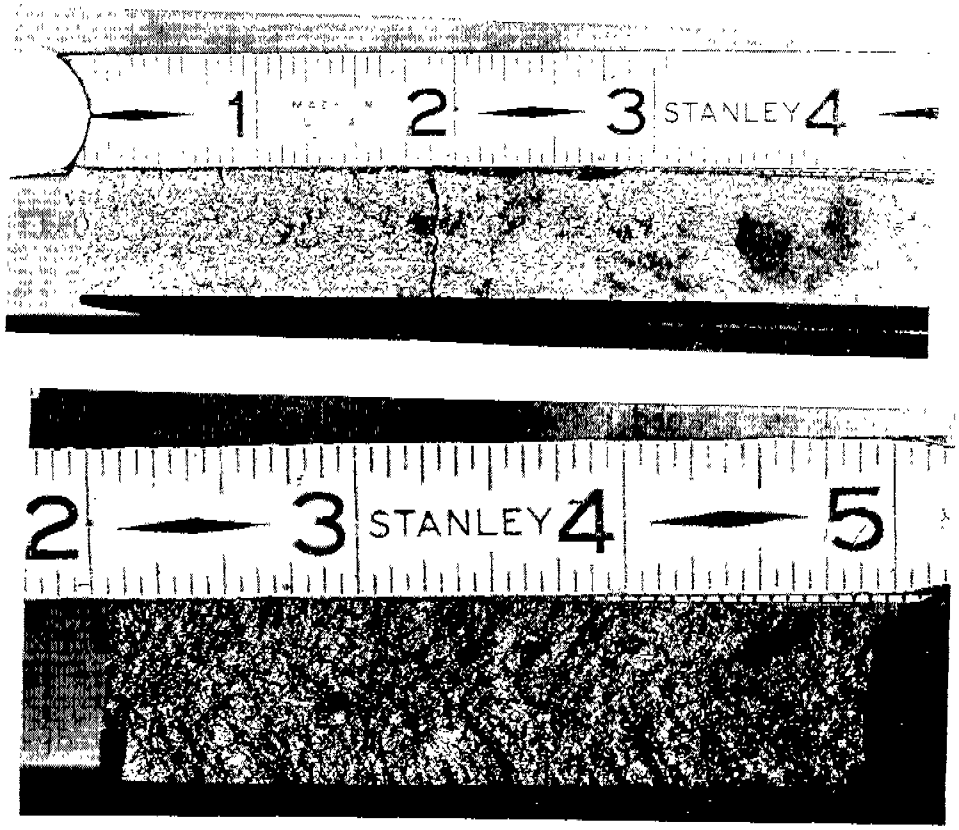


Fig. 1-13. Edge and Fracture Views. Sheared Edge Specimen

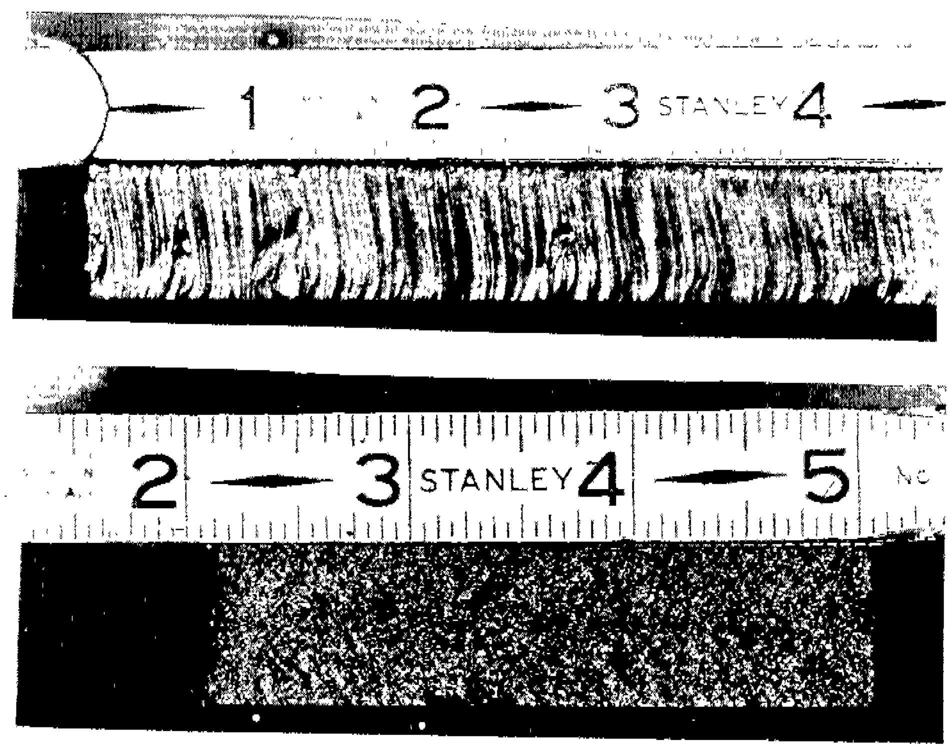


Fig. 1-14. Edge and Fracture Views. Hand Guided Flame Cut Specimen

crack and progressed rapidly across the plate.

Machine guided flame cutting results in a more regular edge surface than hand guided flame cutting; but small grooves on edge surfaces were still present, as can be seen in Fig. 1-15. For each instance of low temperature fracture, the fracture origin could be traced to an edge groove. Cleavage fractures initiated from a crack at the mid thickness of the plate at an edge groove.

Further preparing of initially machine guided flame cut edges by grinding results in edges essentially free of macroscopic external notches but retaining some of the edge hardness imparted by the flame cutting operation. The edge conditions were not serious enough in all cases of low temperature tests to cause the fracture to initiate at the edges. The specimen behavior was similar to the behavior of machined edge specimens. A typical photograph is shown in Fig. 1-16.

Machined edge specimens, when tested at low or high temperatures, apparently show no initial effects due to edge preparation. The fractures initiated at the mid width of the specimens in the form of shear planes at both high and low temperature, but at low temperature the ends of the shear planes apparently provided the trigger producing cleavage fracture over approximately one-third of the plate width. Edge and fracture views are shown in Fig. 1-17.

The specimens of the sheared edge series, Type ES, all

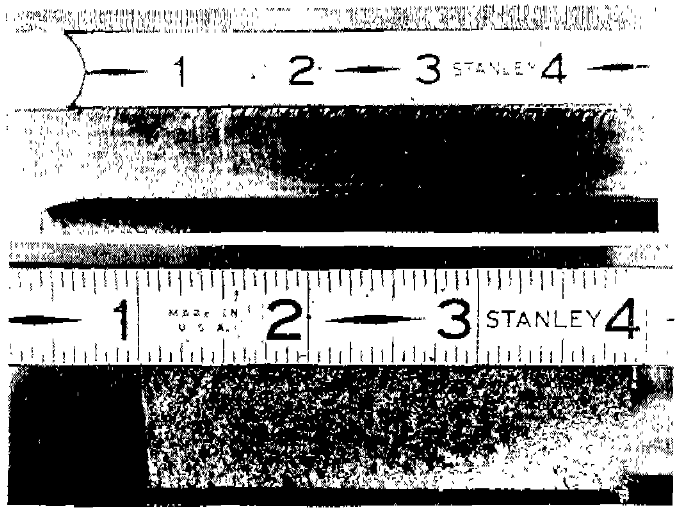


Fig. 1-15. Edge and Fracture Views
Guided Flame Cut Specimen

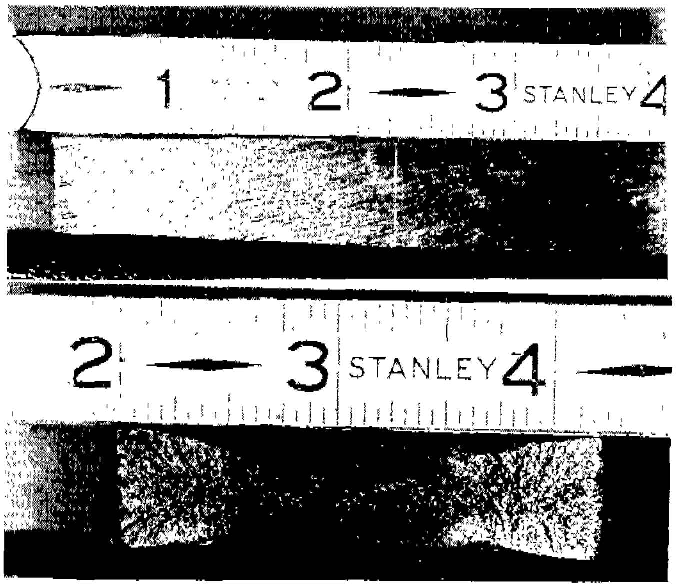


Fig. 1-16. Edge and Fracture Views
Guided Flame Cut and Ground Edge Specimen

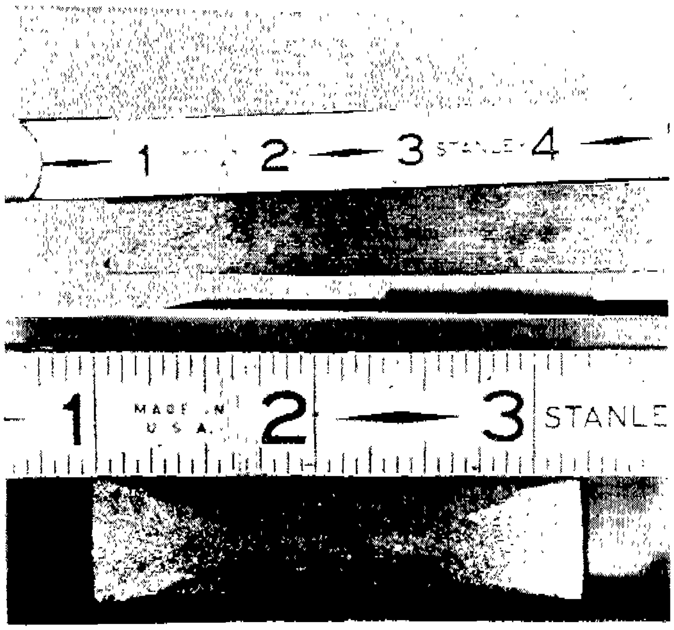


Fig. 1-17. Edge and Fracture Views
Machined Edge Specimen

exhibited fracture origins at the corner of the specimen edge which was on the under side of the shear blade. As was previously stated, this work hardened edge was subjected to severe cracking with very low unit strains as shown in Fig. 1-13. In an attempt to improve the tensile behavior of sheared edge specimens, this corner was ground to a radius of approximately 1/8 in. on a single specimen, and the specimen tested at 0°F. The results may be compared with those for a sheared edge specimen tested at the same temperature. Although both specimens fractured in the cleavage mode, an improvement was noted for the ground specimen in tensile characteristics over its counterpart with no further edge preparation. Visible cracks did not appear during the test on the corner which was ground; however, the cleavage fracture apparently started at this corner. The comparative results of the two tests at 0°F are given below:

Specimen	Maximum Load	Elongation	Thickness Reduction
With corner grinding	164.5 k	2.95 in.	8.05%
Without corner grinding	153.5 k	1.42 in.	2.10%

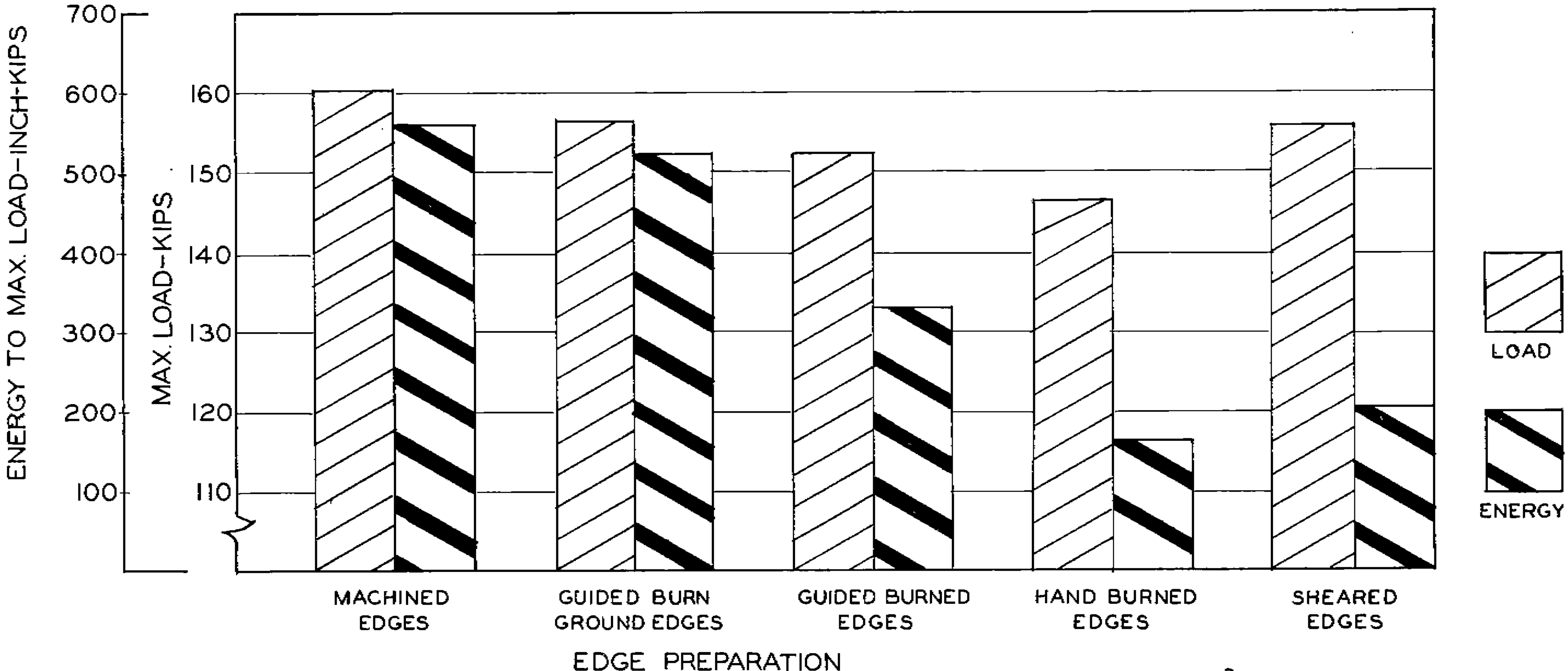
A similar attempt was made to improve the tensile behavior of machine guided flame cut specimens by grinding a 1/8-in. radius on the corners which were on the under side of the torch during the cutting operation. A single specimen prepared in this manner was tested at 0°F, and the results compared with those of a specimen which had no further preparation of the edge. Both specimens fractured partially in the shear mode with no discernible improvement noted for the 1/8-in. radius ground corner as shown:

Specimen	Maximum Load	Elongation	Thickness Reduction
With corner grinding	159.5	4.80	23.6%
Without corner grinding	160.5	4.90	23.4%

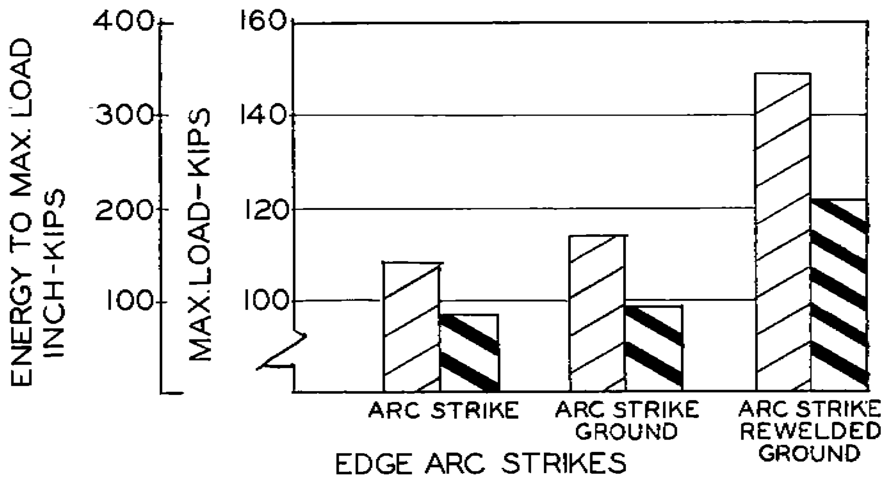
DISCUSSION OF TEST RESULTS

Room temperature tests of specimens with all edge preparations investigated in this study showed little variation in tensile characteristics as shown in Table 1-IV. This discussion, therefore, will be concerned primarily with the results of tests at temperatures lower than 72°F.

Specimens with machined edges, which should represent the optimum in specimen behavior, were tested at -40°F and at -60°F. At -40°F the average maximum load for two specimens was 158.3 kips; energy to maximum load, 560 in.-kips; energy to fracture load of 787.5 in.-kips; and a total elongation of 5.47 in. The average load and energy summaries for all edge types are shown in Fig. 1-18. The specimens fractured partially in the shear mode at this temperature. An attempt was made to obtain a complete cleavage fracture with this type of specimen by testing at -60°F, but in two attempts the specimen fractured through the toe of the fillet weld at the end of one of the reinforcing pads, a fracture which could



SPECIMENS 3" X 3/4" X 20"



SUMMARY: AVERAGE MAXIMUM LOAD, AND ENERGY TO MAXIMUM LOAD FOR LOW TEMPERATURE TESTS OF VARIOUS EDGE PREPARATIONS.

FIG. 1-18

SWARTHMORE COLLEGE

not be attributed to the effects of edge preparation. Of all edge preparations the machined edge specimens exhibited the greatest amount of ductility as measured by specimen elongation and per cent reduction of thickness at the fracture.

Following closely in tensile characteristics were specimens which were machine guided flame cut with the edges further prepared by light grinding, Type EGG. As was previously mentioned, this method of edge preparation was effective in removing all visible edge grooves but not the hardened edge zones. Of three specimens tested at -40°F, two fractured through the test section with an average maximum load of 156.5 kips. The average energy to maximum load for these specimens was 524 in.-kips, energy to fracture load of 637.5 in.-kips, and average total elongation of 4.5 inches. The specimens fractured partially in the shear mode with the shear plane providing the notch for subsequent cleavage fracture of the remainder of the cross-section. One test at -40°F and one at -60°F fractured through the fillet weld at the ends of reinforcing pads, fractures which could not be attributed to edge preparation effects. For the limited tests made, the machine guided flame cut edge with subsequent grinding appeared to have no serious detrimental effects on tensile behavior other than a small loss in ductility when the results are compared with those of machined edges.

Machine guided flame cut specimens without grinding, Type EG, showed more scatter of data, an indication of the variable nature of edges prepared by this method. Visible differences could be noted in specimen edges of this group with no two specimens showing the same edge grooving due to the flame cutting. Cold temperature tests were made at 0°F, -20°F, and -40°F. Two specimens of the three tested at -40°F fractured in the cleavage mode with the fractures originating at edge grooves. A wide spread existed between the results for these tests, so that an average of the tensile values is not particularly meaningful. However, the better of the two specimens approached the machined specimen in tensile behavior, and the other approached the poorer of the hand guided flame cut specimens. A third test of this type of edge preparation at -40°F reached a maximum load of 166 kips higher than the maximum load of any other specimen tested in this program before it fractured at the fillet weld at the reinforcing pad. A visual examination of the edge of this specimen indicated that it was comparatively free of edge grooving. A single specimen tested at -20°F exhibited characteristics which were midway between the low and high values of the tests at -40°F. At 0°F a single specimen fractured partially in the shear mode at a maximum load of 160.5 kips; energy to maximum load of 485 in.-kips; energy to fracture of 705 in.-kips; and total elongation of 4.9 in.

Specimens having hand guided flame cut edges, Type EH, were tested at 0° and -40°F. Two tests were conducted at the colder temperature with the following averages: maximum load, 140 kips; energy to maximum load, 119.2 in.-kips; elongation to maximum load, 2.29 in. Both specimens fractured in the cleavage mode with the fracture initiating at one of the edge grooves. The specimen tested at the 0°F fractured in the cleavage mode at a maximum load of 157.0 kips, energy to maximum load of 257.5 in.-kips, and elongation of 1.99 in.

Specimens having sheared edges were particularly susceptible to edge cracking at relatively low unit strains. For the 3-in. wide specimens used in this program, the cold mechanical working of the specimen in the shearing operation affected the entire cross-section as indicated by the hardness survey of the cross-section, Fig. 1-12. As a result of the mechanical working, the average maximum load for these specimens was relatively high, 156.0 kips, close to the average value for the Type EGG specimens. The ductility as reflected by average energy absorption was low, 201.2 in.-kips, slightly better than the Type EH specimens. Opportunities for initiation of cleavage fracture were numerous through the edge cracks developed at low strains.

Closely related to the study of edge preparation effects was the brief study made of carbon arc strikes on the edges of 3-in. wide specimens. The microscopic cracks and localized hardness caused by the arc strikes were particularly detrimental to strength and energy absorption. Fig. 1-19 is a microphotograph

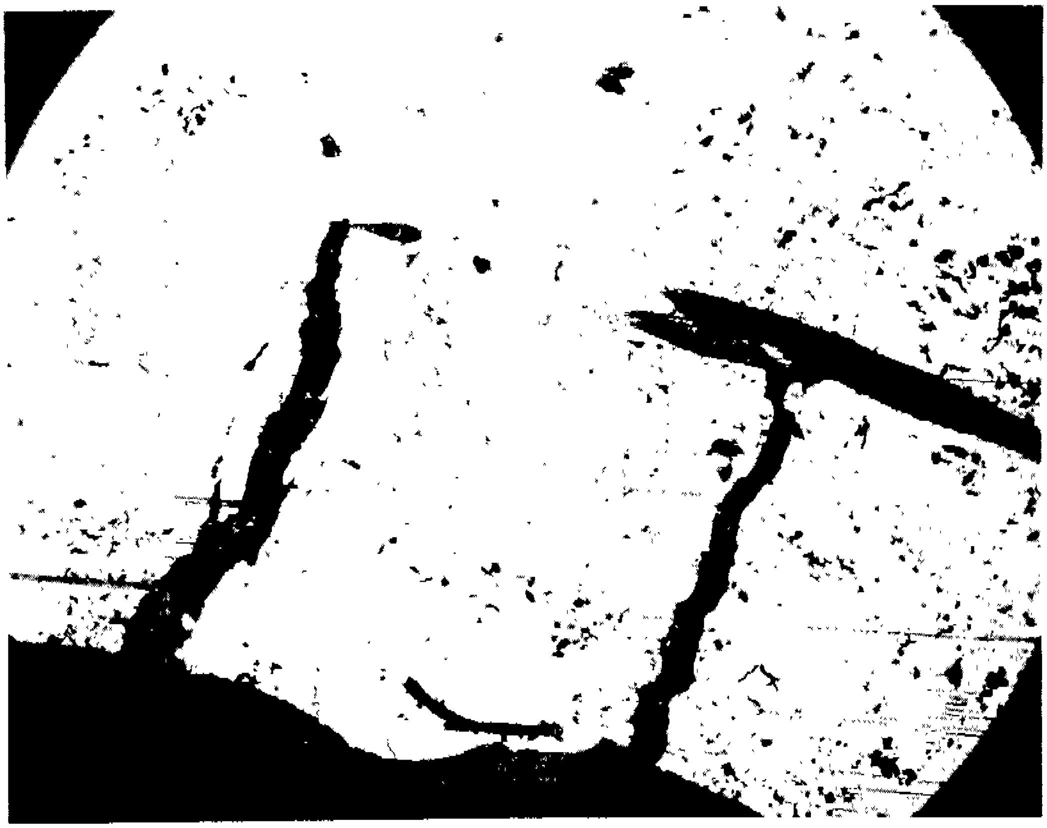


Fig. 1-19. Micro-Photograph of a Carbon Arc Strike.

of cracks from a carbon arc strike which had been slightly strained to open the cracks. The tensile test results for the specimens are given in Table 1-VI and shown graphically in Fig. 1-18. The specimen with arc strikes fractured at a stress slightly above the yield point stress for ABS-B steel. A light grinding of the arc strike areas did not materially improve results as shown by the second test in Table 1-VI. Chipping of the arc strike followed by rewelding and grinding effectively repaired the edge. This specimen, the third in Table 1-VI, had tensile characteristics similar to the Type EG specimen at the same test temperature.

TABLE 1-VI

DATA SUMMARY--ARC STRIKE SPECIMENS

Specimen	Edge Treatment	°F	% Shear	Maximum Load Kips	Energy to Maximum Load Inch Kips	Elongation to Maximum Load In.
EG-A-M36	Guided Burned	0	0	108.5	43.8	0.475
EG-AG-M35	Guided Burned Arc Strike Ground	0	0	113	49.5	0.560
EG-AW-M33	Guided Burned Arc Strike Rewelded	0	0	149	204.0	1.87

Bend Tests. As an aid to the evaluation of the edge preparations investigated, bend tests at room temperature were made of specimens having machined edges, sawed edges, sheared edges, machine guided burned edges, machine guided burned and ground edges, and hand burned edges. The specimens were 3/4 in. by 5/8 in., and 12 in. long, and were prepared from plate N of ABS-B steel. The prepared edges, 3/4 in. wide, the thickness of test plates, were on the tension side of the bend. Figures 1-20 through 1-22 are photographs of the bend specimens.

The sawed edge specimen and the machined edge specimen were bent through an angle of 180° without cracking. The sawed edge had slight irregularities of about the same order as the machine guided burned specimen. (See Fig. 1-11.)

The machine guided burned edge, and hand guided burned edge, did not show signs of cracking at a bend of 90°. At the 180° bend, however, small cracks were visible on the edges. (See Fig. 1-20.) Each crack apparently originated at the root of one of the edge irregularities. Smaller cracks also appeared on the sharp corners which were on the under side during the flame cutting operation.

The specimen with the machine guided burned edge which was further prepared by light grinding had a Rockwell "B" hardness of 80, indicating that this type of edge preparation did not remove all of the heat-affected zone. The specimen was bent through a 180° angle without showing signs of cracking. (See Fig. 1-20.)

The sheared edge specimen began to show cracks shortly after the bending operation was started. At an angle of 60°

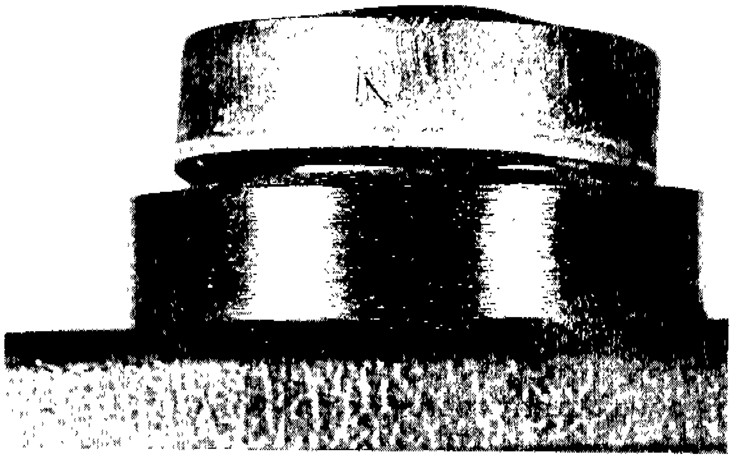


Fig. 1-20. Bend Tests, Types EG and EGG

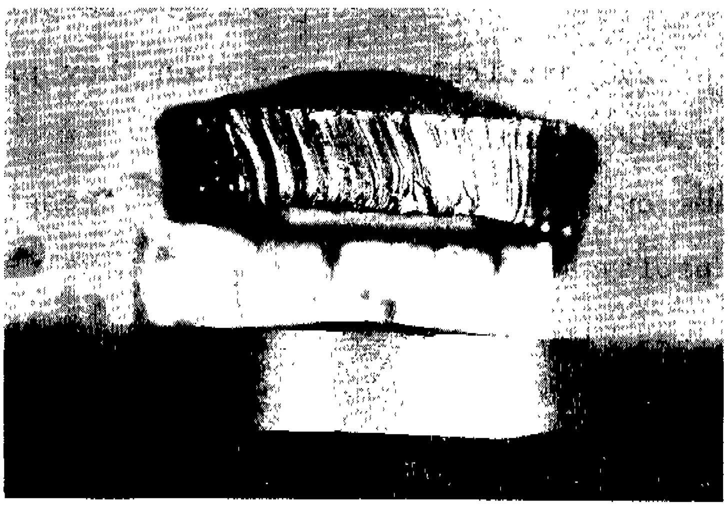


Fig. 1-21. Bend Tests, Types EN and EM

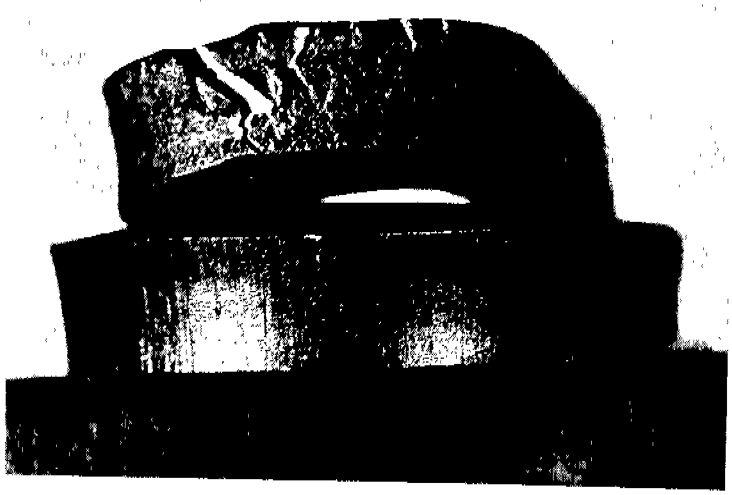


Fig. 1-22. Bend Tests, Type ES

cracks were well defined, and at 180° the specimen was almost completely fractured. (See Fig. 1-22.) The cracks originated at the sharp corner or lip of the plate which was on the under side of the specimen during the shearing operation.

SUMMARY STATEMENTS

The edge conditions considered in Part 1 of this report were primarily of two general categories: flame cut edge notches of various geometric configurations, and edge notches resulting from the method by which plate edges might be prepared. Edge conditions deserve critical analysis when they prove to be the source of cleavage fractures.

(1) Flame cut edge notching impaired strength and energy absorbing capacity as compared with similar values for unnotched plates. Notches with semi-circular geometry were best.

(2) There are no wide variations in transition temperature for the flame cut edge notched specimens used. The controlling notch acuity is apparently the small cracks appearing at the notch before fracture. Improvement in transition temperature is evident for semi-circular notches only.

(3) The transition detail between the sheer strake and the fashion plate should be made as smooth as possible.

(4) At high temperatures permitting shear failure, the method of edge preparation is of little consequence. At low temperatures, however, the method of edge preparation is

significant in determining the character of the fracture surfaces and the location at which the fracture chooses to originate.

(5) Of the two conditions introduced by flame cut methods of edge preparation--edge roughness and edge hardness--edge roughness is more seriously detrimental to tensile behavior. Fractures choose an edge notch as provided by conditions of preparation for their points of origin if such a notch is available, whereas they appear indifferent to mild edge hardness.

(6) Shearing, as a method of edge preparation, introduces conditions favorable to cleavage fracture from the edges. Sheared edges can be substantially improved by grinding off the shear lip produced by the shearing process.

(7) Carbon arc strikes on plate edges provide conditions favorable to cleavage fracture at low loads. The effect of these arc strikes can apparently be removed by chipping out the damaged area, rewelding, and grinding flush.

(8) The quality of edge preparation can be relatively determined by bend tests at room temperature. Specimens which crack on the edge surface in the bend test at room temperature will fracture in the cleavage mode at low temperature, with the fracture originating at an edge. Bend test specimens which do not crack at room temperature may or may not fracture from the edge at low temperatures.

PART 2

INTERRUPTED LONGITUDINAL MEMBERS

INTRODUCTION

Reports of fractures in welded ships indicate that many of the fracture origins were in the immediate vicinity of interrupted longitudinal members. Classifications of these welded discontinuities have included abrupt termination of stiffeners, longitudinals, and bilge keel endings. Fractures have been initiated by notch effects attributed to structural geometry, welding defects, or a combination of the two.

The purpose of the program outlined in this report has been to evaluate the efficacy of certain welded structural details as to tensile strength, energy absorption, and transition temperature. The welded specimens were intended to simulate existing ship details or possible modifications of present practice.

Specimens of Type L, Fig. 2-1, represent details similar to those found at the free ends of welded components, such as stiffeners, interrupted longitudinals, and the bilge keel endings.

The specimens were prepared by flame cutting and connected by welding. Both the flame cutting and welding techniques utilized in specimen fabrication represent the quality of workmanship to be expected in average shipyard practice. Machine guided flame cutting was employed on all

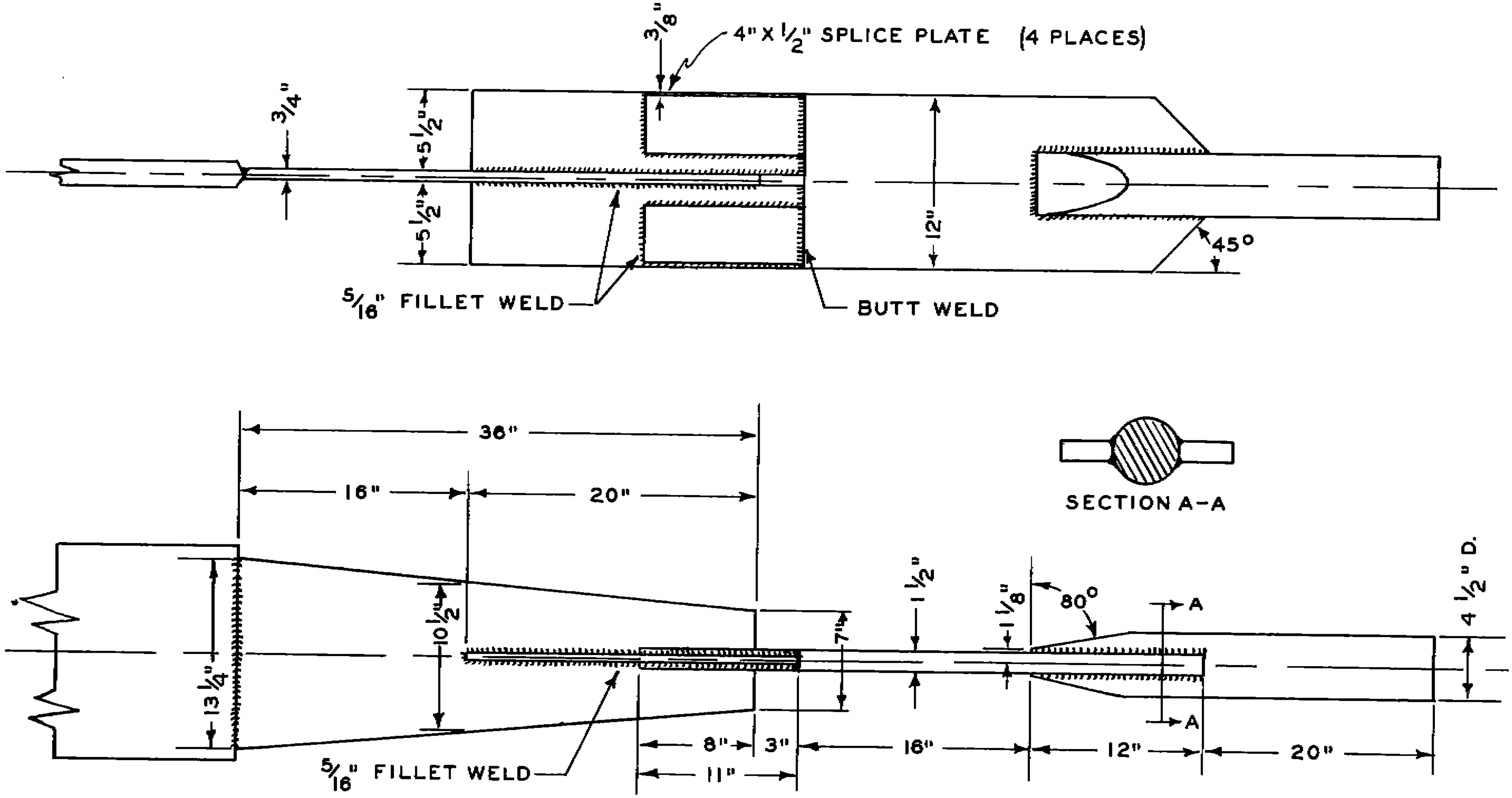


FIG. 2-1

TYPE L-1

SPECIMEN ARRANGEMENT

NOTE:

ALL EDGES FLAME-CUT

WELDS MADE USING E-6010 ROD

SCALE: 3/32" = 1"

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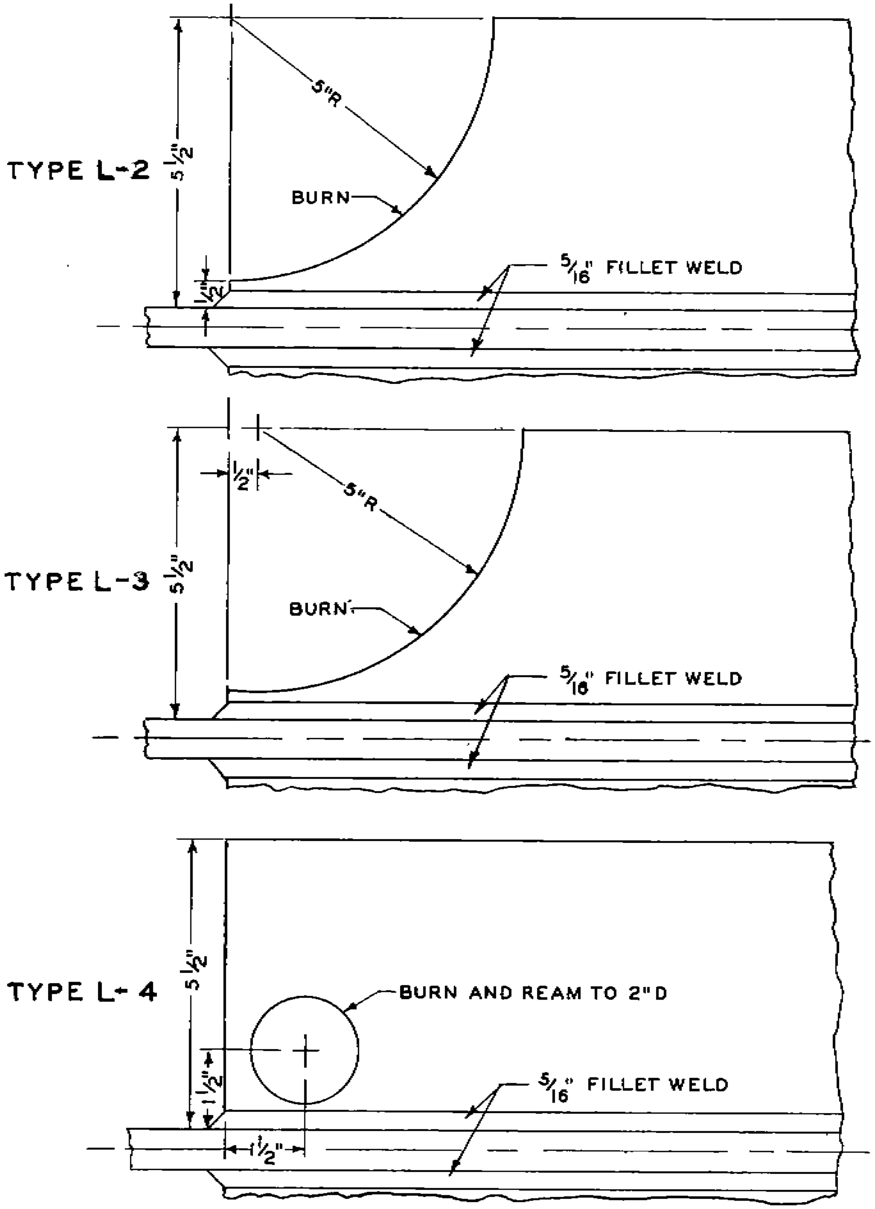
straight cuts, while radius cuts were hand guided. All welds were made manually using E6010 electrodes.

General Program. The specimens, while intended to simulate ship details, were of necessity simplified to a symmetical form convenient for tensile testing. This procedure has probably tended to oversimplify the general conditions found on ships, but the specimens are thought to duplicate the critical conditions representing structural and welding notch effects.

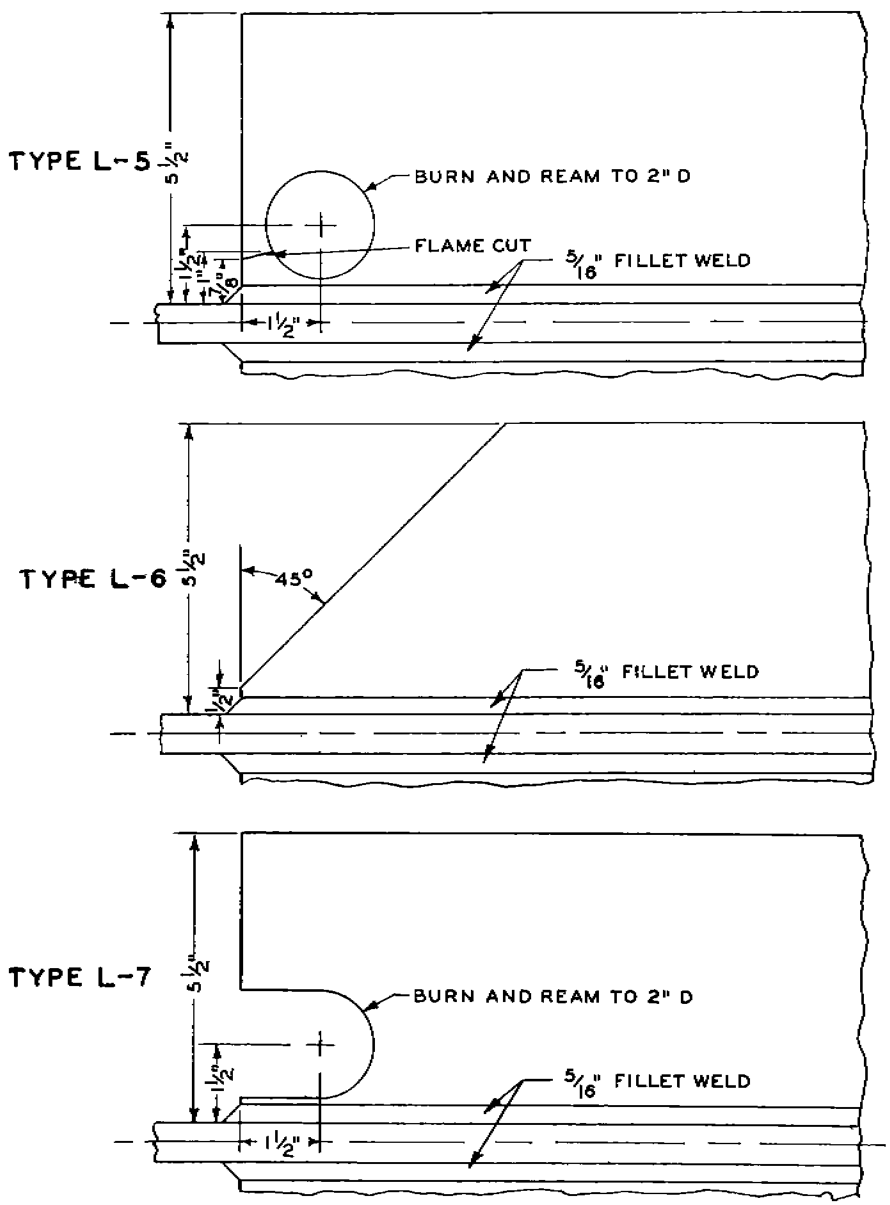
The purpose of tests of Type L specimens was to ascertain the effects on fracture of certain details and geometry occurring at the ends of abruptly terminated welded structural members. Specimens in this category represent free ended stiffeners, interrupted longitudinals, and bilge keel endings. The scope of the Type L specimens was limited to end variations found either to be actually in service or to certain variations which held promise of practical adaptability for modifying ships now in service or in new designs.

The general design of the Type L specimens finally adopted is given in Figs. 2-1 to 2-3, inclusive. Fig. 2-1 signifies the typical specimen and loading arrangement for all end variations but specifically shows the flat bar end condition termed Type L-1, where the flat bars are square ended. The tensile loading was applied through the flat bars at one end and through the main plates at the other end.



NOTE: ALL EDGES FLAME-CUT ... WELDS MADE USING E-6010 ROD

FIG. 2-2 END DETAIL VARIATIONS FOR TYPE "L" SPECIMENS



NOTE: ALL EDGES FLAME-CUT ... WELDS MADE USING E-6010 ROD

FIG. 2-3 END DETAIL VARIATIONS FOR TYPE "L" SPECIMENS

The tapered 3/4-in. thick main plate provided a reduced width and area to assure that a large part of the load introduced through the flat bars would be retained by the bars until the free ends, thus providing for a localization of strain on the end weld.

A single specimen intended to simulate a bilge keel ending detail was designed. A 3/4-in. main plate of ABS-B steel was cut to the same geometry as the main plates of the Type L specimens as previously described. The 1/2-in. side bars, however, were replaced by structural Tee sections which were modified to meet the requirements of the specimen design. The Tee sections were cut from a standard 12-in. I-beam weighing 50 lb. per ft. The resulting Tee sections had flange widths of 5.477 in. and depths of 6 in. The flange widths of the Tees were reduced to 4 in., and the ends were cut back on a 5-in. radius.

EXPLORATORY TESTS

Type XL Specimens. The photographs of Figs. 2-4 through 2-10 represent one-half scale models of the full size Type L specimens. One each of each Type was made and loaded until a well defined scaling pattern appeared. The scaling pattern was most valuable in interpretation of full-size tests with regard to stress transfer and stress direction in the flat bar terminations.

Fig. 2-4. Scaling Pattern of Specimen XL-1

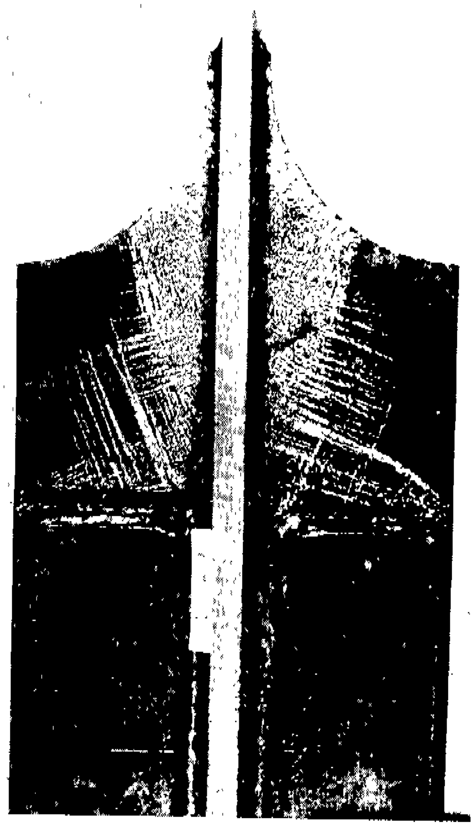


Fig. 2-5. Scaling Pattern of Specimen XL-2

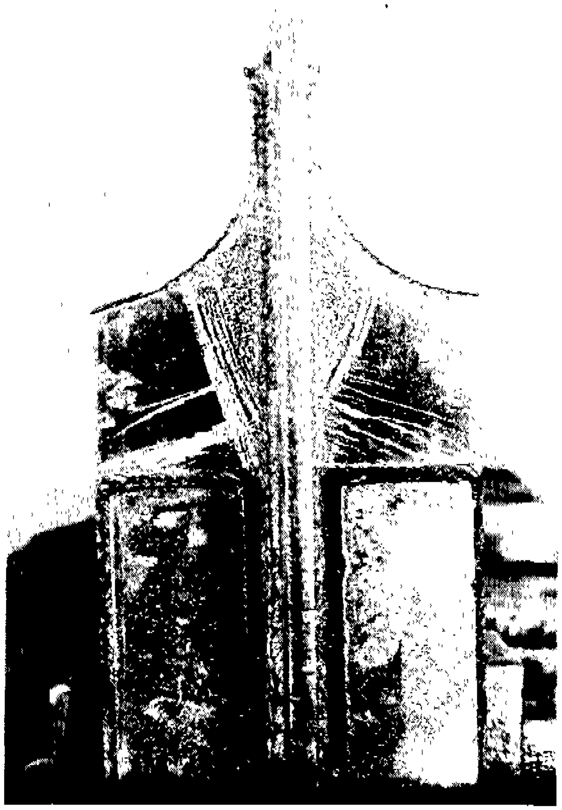


Fig. 2-6. Scaling Pattern of Specimen XL-3

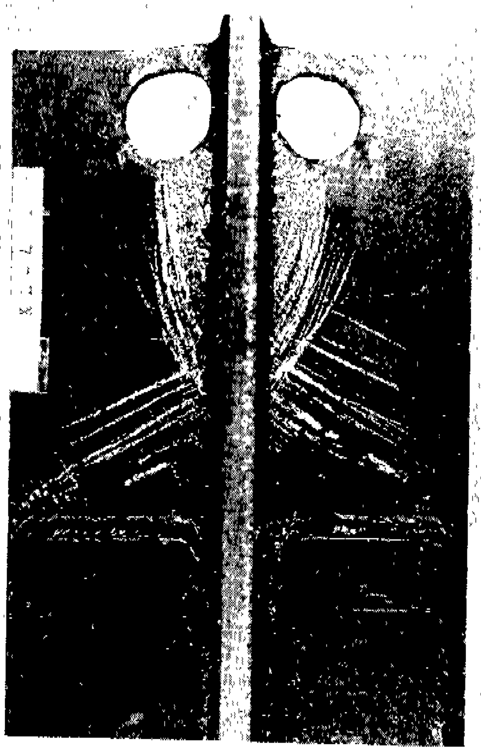


Fig. 2-7. Scaling Pattern of Specimen XL-4.

Fig. 2-8. Scaling Pattern of Specimen XL-5.

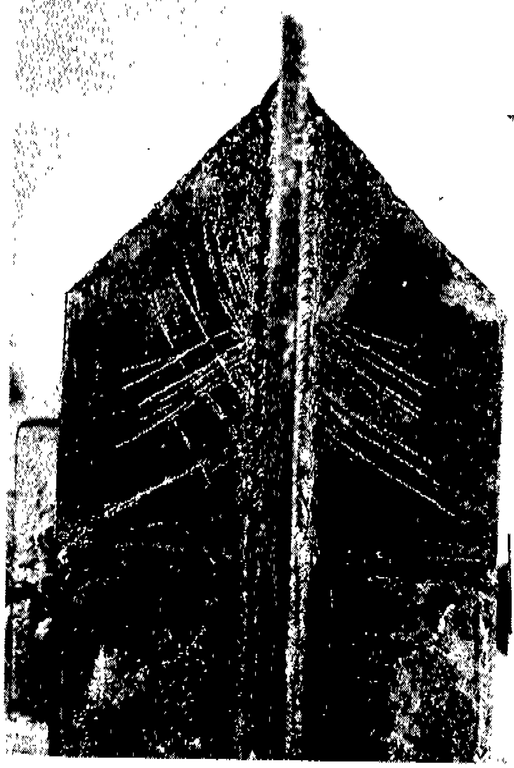


Fig. 2-9. Scaling Pattern of Specimen XL-6.

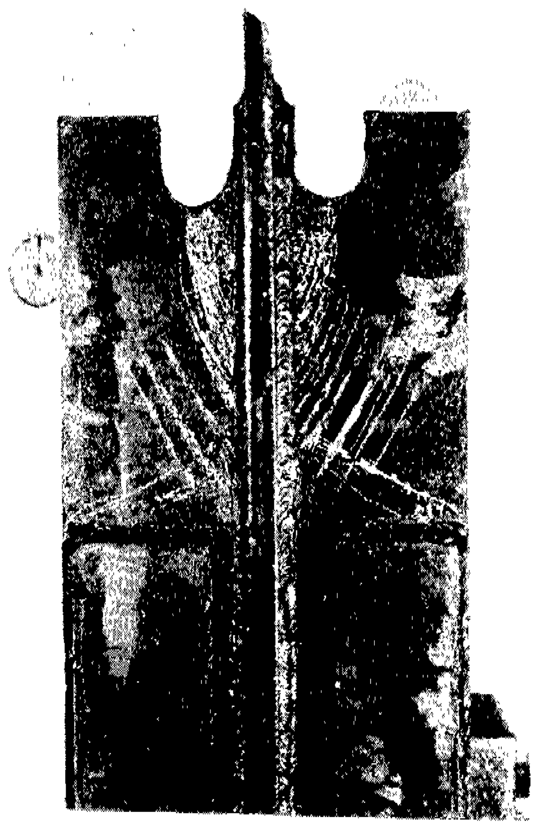


Fig. 2-10. Scaling Pattern of Specimen XL-7.

The photographs are presented at this point merely for the purpose of clarifying of the end conditions investigated and as supplementary to the line drawings of Figs. 2-1 and 2-3. The exploratory tests will again be referred to when discussing the results of full-scale tests.

Materials. The properties of the materials used for specimen fabrication can be found in Appendix B. Table 2-I is an outline of the materials combinations used for all L Type specimens.

OVERALL DISCUSSION

To assist in giving an overall view of the physical response of the Type L specimens, Table 2-II provides in summary form values of average maximum load, average energies to maximum load, and transition temperature. The average loads and energies are given separately for specimens failing in 100% shear and 0% shear. The transition temperatures given are based almost entirely on appearance of fracture. For most types the establishment of transition temperatures from energy curves was limited by too few data.

Transition temperature is the most discriminating characteristic for evaluating the geometry of the flat bar end conditions. The range of transition temperatures summarized in Table 2-II emphasizes the importance of choosing the most favorable end contour on the flat bars, which were

TABLE 2-I

CLASSIFICATION OF L TYPE TEST SPECIMENS

Type of Speci-mens	Specimen Geom. Shown in Figure	No. of Specimens Tested	Combinations of Types of Steel: Main Plate 3/4 in. thick	Combinations of Types of Steel: Flat Bars 1/2 in. thick	Remarks
L1	2	4	D_N	D_N	Square ended cut-offs on flat bars
L1	2	1	D_N	D'_N	" " " " " "
L1	3	7	ABS-B	D_N	" " " " " "
L1	3	2	ABS-B	D'_N	" " " " " "
L2	2 and 4	3	D_N	D_N	End of flat bars cut to 5" radius
L2	3 and 4	3	ABS-B	D_N	" " " " " " " "
L2	3 and 4	1	ABS-B	D'_N	" " " " " " " "
L3	3 and 5	5	ABS-B	D'_N	Modified type Z-B (see sketch)
L4	2 and 4	2	D_N	D_N	Square flat bar cut off, 2" burned hole
L5	2 and 4	3	D_N	D_N	" " " " " " " " with relief
L5	3 and 4	3	ABS-B	D_N	Square flat bar cut off, 2" burned hole with relief
L5	3 and 4	2	ABS-B	D'_N	Square flat bar cut off, 2" burned hole with relief
L6	3 and 5	3	ABS-B	D_N	45° cut off on flat bars
L6	3 and 5	2	ABS-B	D'_N	" " " " " "
L7	3 and 5	5	ABS-B	D_N	U-shaped cutout (see sketch)
L7	3 and 5	1	ABS-B	D'_N	" " " " "
L8	6		ABS-B	tee bar ASTM-A7	Simulating bilge keel ending

TABLE 2-II

SUMMARY OF TEST RESULTS--TYPE L SPECIMENS

Type of Speci-men	3/4-in. Main Plate	1/2-in. Flat Bars	Average Maximum Loads, kips: 100% Shear Fractures	Average Maximum Loads, kips: 0% Shear Fractures	Average Energy* to Max. Load, in.-kips: 100% Shear Fractures	Average Energy* to Max. Load, in.-kips: 0% Shear Fractures	Transition Temperature, °F: Based on Fracture Appearance	Transition Temperature, °F: Based on Energy to Max. Load
L1	D_N	D_N	517 (2)	522 (1)	1190 (2)	518 (1)	0°	-4°
L1	D_N	D'_N		485 (1)		500 (1)		
L1	ABS-B	D_N	485 (2)	475 (5)	857 (2)	616 (5)	+30°	-8°
L1	ABS-B	D'_N		464 (2)		465 (2)		
L2	D_N	D_N	533 (2)	529 (1)	1352 (2)	890 (1)	-30°	
L2	ABS-B	D_N	492 (1)	503 (3)	985 (1)	1040 (3)	+10°	
L2	ABS-B	D'_N		463 (1)		392 (1)		
L3	ABS-B	D'_N	505[2] (1)	504 (4)	1195[2] (1)	899 (4)	+25° approx.	
L4	D_N	D_N	524 (1)	504 (1)	1165 (1)	728 (1)	-10°	(Not ascertainable)
L5	D_N	D_N	523 (2)	536 (1)	1255 (2)	995 (1)	-26°	
L5	ABS-B	D_N		494 (3)		893 (3) above	+20°	
L5	ABS-B	D'_N		477 (1)		482 (1)	+30° approx.	
L6	ABS-B	D_N		460 (3)		472 (3) above	+20°	
L6	ABS-B	D'_N		473 (2)		486 (2) above	+40°	
L7	ABS-B	D_N	498 (1)	489 (4)	1032 (1)	748 (4)	+10°	
L7	ABS-B	D'_N		500[1] (1)		1040[1] (1) above	+30°	

*D_N Specimens 40 in. long
ABS-B Specimens 36 in. long

1) 5% shear
2) 90% shear

Numbers in parentheses indicate the number of specimens averaged.

intended to simulate interrupted longitudinals and stiffeners.

The exploratory program, which disclosed strain patterns and stress directions, indicates that through changing the end geometry the direction of stress on the end weld relative to the main plate can be altered. The endings investigated disclosed that the direction of principal stress can be changed from approximately a right angle to the face of the main plate in the case of the square cut-off, to 45° for the 45° cut-off, and to a direction parallel to the main plate with a curved ending. It is thought that this change in direction is one factor in establishing conditions for fracture in the weld and the plate directly beneath the weld.

Simultaneously with the limiting of stress direction, the end contours of the flat bars limit the total force acting on the end welds. The cutting away of material reduces the load carrying ability of the flat bar in the critical region at the fractured cross-section. This second effect is integrated with the stress direction; i.e., with a reduced flat bar cross-section of a given contour, stress direction and magnitude may be controlled. A favorable combination will lower transition temperature, as evidenced by the results for Type L-2, and increase the expectancy of ductile action in the main plate.

For reasons stated before, the Type L-1 (square cut-off flat bars) was made the base for comparison purposes. For main plates of D_N steel end modifications of Types L-2, L-4, and L-5 resulted in lower transition temperatures than for L-1. The radius contour of Type L-2 depressed the transition temperature by the greatest amount. Although the radius contour of Type L-2 was the most beneficial, the Type L-4 flat bar termination with flame cut hole was essentially equal to Type L-2 in depressing transition temperature.

For specimens using main plates of ABS-B steel, benefits in the way of lower transition temperature are shown for Types L-2 and L-7. Type L-5 was equal to Type L-1, whereas Type L-2 was only slightly beneficial in lowering transition temperature. Type L-6, with flat bars cut off at 45°, contrary to normal expectations, had a higher transition temperature than the square cut-off of series L-1. It should be noted that the transition temperatures of all specimens using ABS-B steel were higher than those of D_N steel for all end variations where duplicating tests were made.

The Type L-3 specimens, with end contour cut to a radius with a slightly upturned end, were expected to be as good relative to transition temperature as Type L-2 where the upturned end was eliminated. Limited tests did not confirm this opinion. However, the differences in transition temperature may be due to the D'_N flat bars used in all L-3 specimens.

In comparing the transition temperatures of Types L-4 and L-5 with 2-in. diameter burned holes, having main plates of D_N steel, the straight cut from end of flat bar to the circular hole as in Type L-5 was beneficial in lowering transition temperature. For ABS-B steel plates no direct comparisons between the two types were possible due to lack of tests of Type L-4. Comparing the results of L-5 with Type L-1 with ABS-B steel it appears that no definite benefits accrue. Thus for D_N steel the detail of L-5 appears beneficial, and for ABS-B steel it does not.

The effects of various flat bar ends on maximum load (see Table 2-II) and the graphical summaries of Figs. 2-11 and 2-12 permit certain generalizations to be made.

First, the maximum load, within the limits of reliability of test results, does not appear to be significantly affected by the end contours, although there is an indication that the end radius of Type L-2 is better than square cut-offs in this respect. Since Type L-2 is definitely preferential to L-1 with respect to transition temperature, its improved load performance also provides a sound reason for favoring this detail.

Second, the average maximum loads, in general, are nearly alike for either cleavage failures or shear failures for a given type of specimen and kind of steel. Average loads as high, or often higher, for cleavage failure than

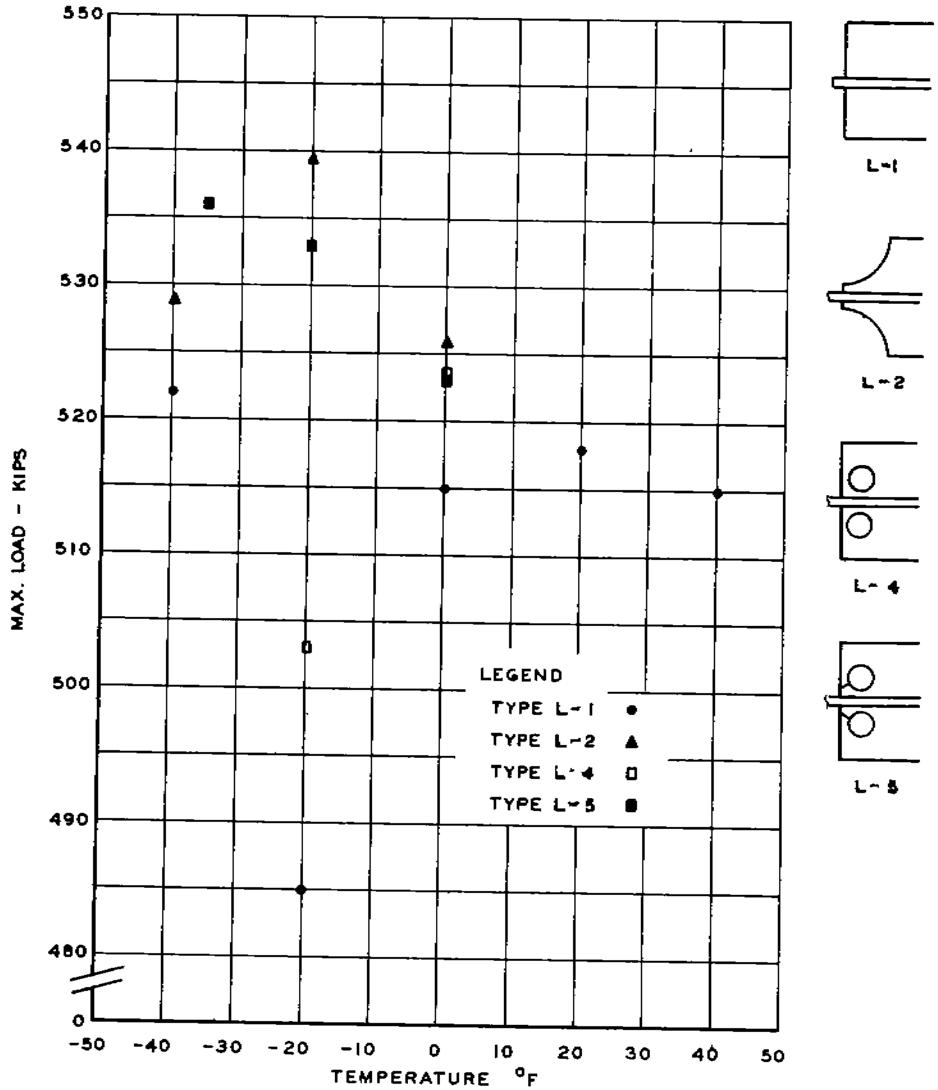


FIG. 2-11. SUMMARY - MAXIMUM LOAD VS. TEMPERATURE
TYPE L SPECIMENS - DN STEEL
GAGE LENGTH 40"

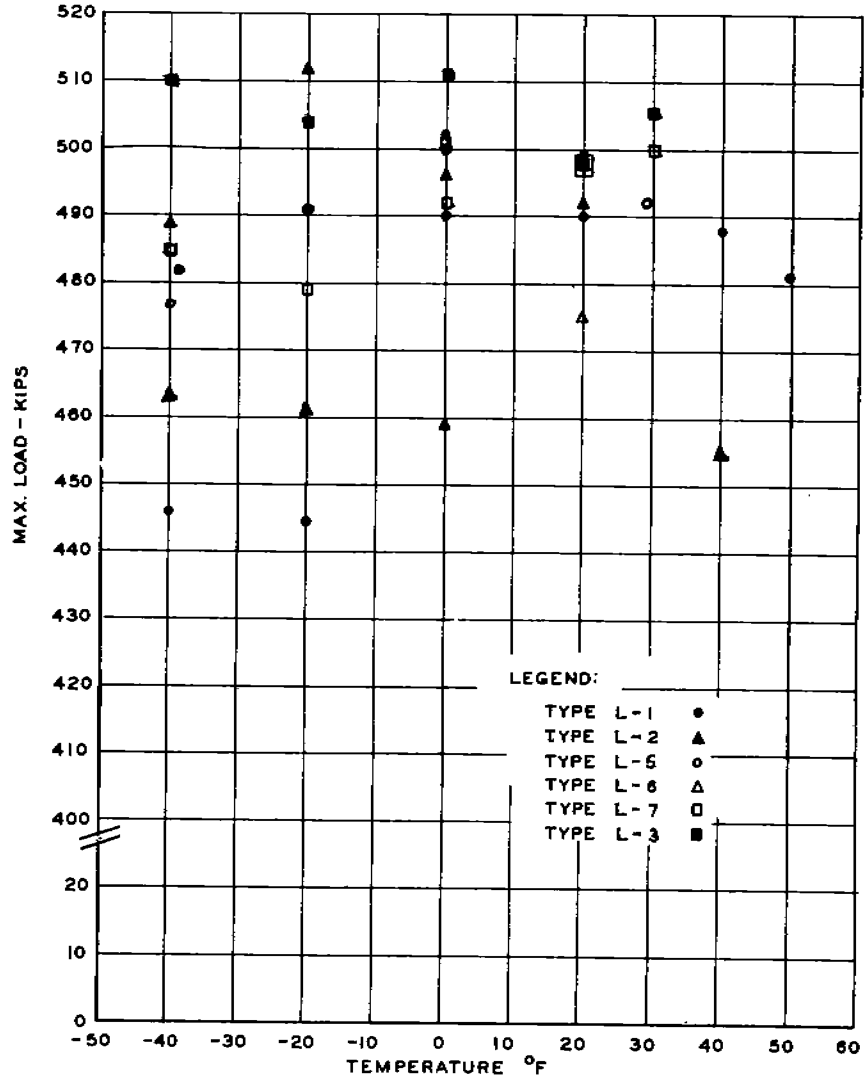


FIG. 2-12. SUMMARY - MAXIMUM LOAD VS. TEMPERATURE
TYPE L SPECIMENS - ABS-B STEEL
GAGE LENGTH 36"

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for shear failure are not a new finding and have been reported before by this laboratory. A close examination of the maximum load tabulations for varying temperatures (plotted in Figs. 2-11 and 2-12) reveals much scatter in loads for both the shear and cleavage modes. In general, the low load values for the cleavage mode occurred at a temperature 20° to 30°F lower than the transition.

The energies to maximum load are summarized in Table 2-II and shown in Figs. 2-13 and 2-14. For D_N steel plates, Type L-2 (radius cut ending) shows the highest energy values. This, along with the favorable trends in transition temperature and load capacity, adds further evidence to the suitability of the L-2 form. Again L-5 runs a close second to L-2.

Energies to maximum load remain high for cleavage fracture at 20°F to 30°F below the transition from shear to cleavage fracture. Evidence of this may be noted for each type of specimen. The average energies for the cleavage mode are perhaps meaningless unless each test is viewed separately. As a practical matter of selecting a transition temperature based on energy, one finds that these high values act to lower the transition temperature from that based on fracture appearance. For the square ended Type L-1 of D_N steel, the transition temperature so determined is 4°F lower and for the ABS-B steel, 38°F lower than values based on fracture appearance. Thus, on an energy basis the ABS-B steel would have a 4°F lower

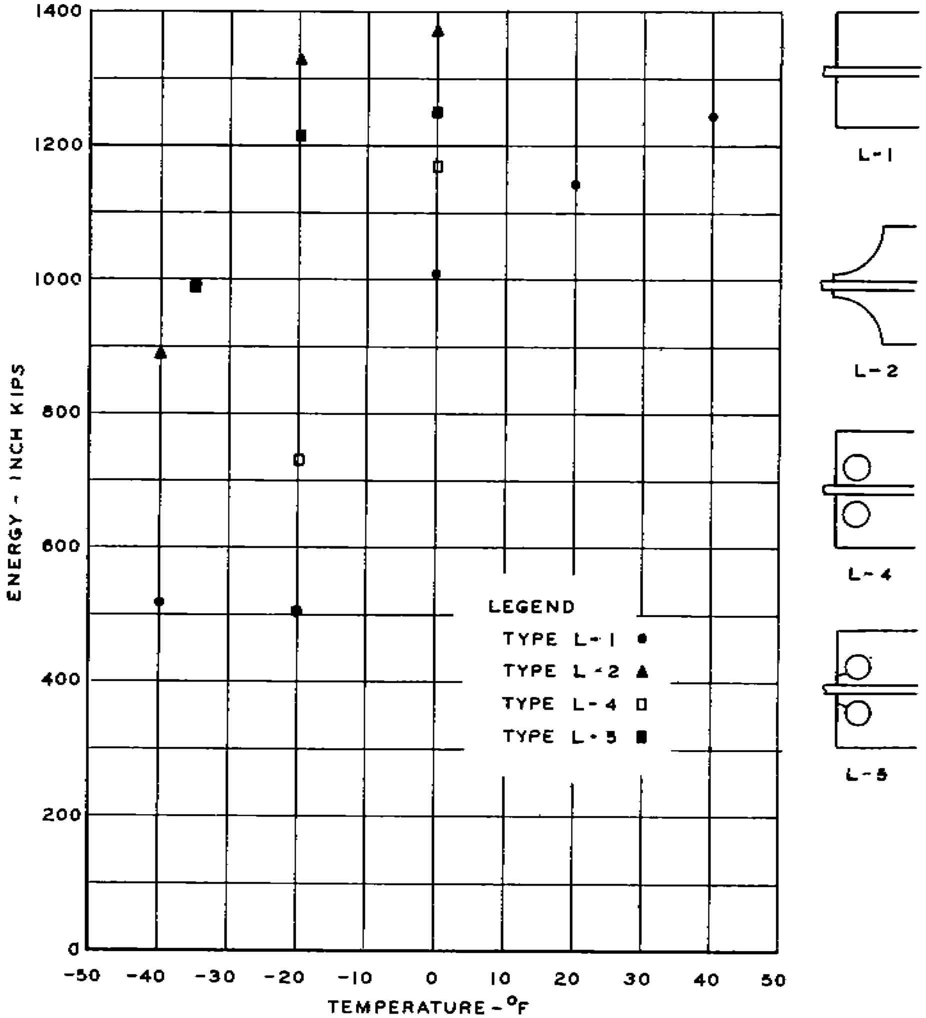

FIG.2-13 SUMMARY - ENERGY TO MAXIMUM LOAD VS. TEMPERATURE
TYPE L SPECIMENS - DN STEEL
GAGE LENGTH 40"

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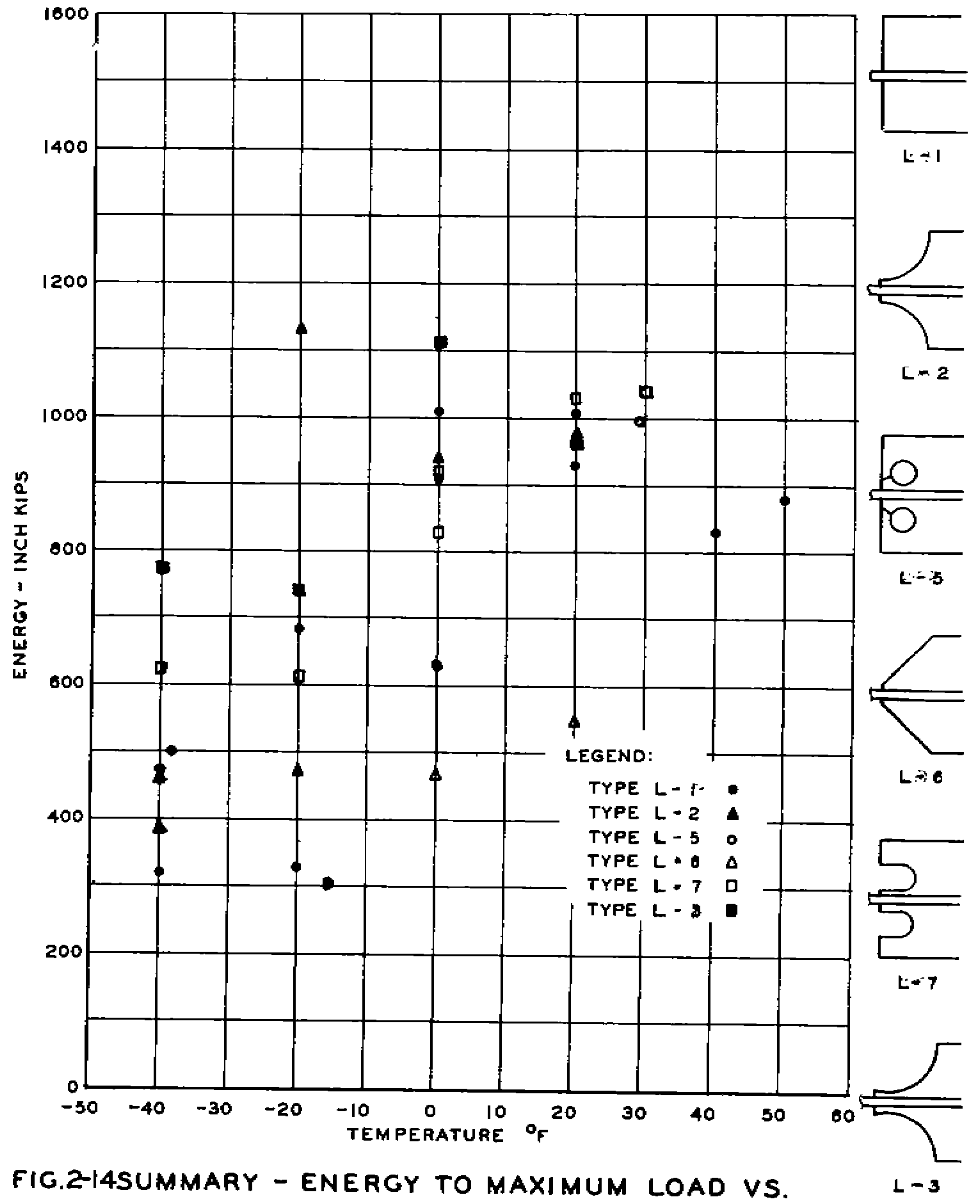

FIG.2-14 SUMMARY - ENERGY TO MAXIMUM LOAD VS. TEMPERATURE
TYPE L SPECIMENS - ABS-B STEEL
GAGE LENGTH 36"

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transition temperature than the D_N steel, whereas the ABS-B steel had a transition temperature 30°F higher than D_N steel based on fracture appearance. This is an anomaly that cannot be further investigated for other types because of limited data.

SUMMARY STATEMENTS

It often appears warranted to limit the reliability and applicability of test results by qualifying statements. If that were to be done here, it would be essential to note: (a) that the main plates of all specimens were narrow relative to the details; (b) that the edges of the main plate, representing a hull or bulkhead plate were free from lateral restraint; and (c) that limited tests were made as dictated by economy and available steel. All of these reservations would make certain conclusions relative to full-size ship details uncertain. However, since all of these conditions were appropriately noted when establishing this investigation, it is hoped that this work may point out the direction that future work should take or that the present data may be utilized in at least a qualitative manner for guiding immediate practical considerations where geometrical notches are involved.

(1) Test results confirm the long standing belief that abrupt changes in structural geometry can have only detrimental effects. While abrupt changes in structural geometry

are critical, as has been clearly demonstrated by a large number of actual casualties, little has been known about the actual relief that could be furnished by modifications in geometry. The test results indicate that anything short of the most practical smooth structural transition from one structural component to another impairs load capacity, energy absorption, and raises transition temperature.

(2) The structural notch effect of abrupt or gradually faired terminations of structural components, as exemplified by free ended longitudinals or stiffeners, is a result of the compounding of concentrations of stress and the direction of that stress at the termination. Favorable combinations of this compound effect tend to eliminate the structural notch. A favorable combination of the compounding effects can be attained when the stress direction at the free end of a longitudinal is as nearly parallel to the hull or bulkhead plating as possible, in conjunction with a decrease in the magnitude of this stress. The direction may be controlled by smooth contour endings and the stress magnitude reduced by a reduction in end cross-sectional area. It has been found that the most favorable combination results when the end contour of a longitudinal is cut to a radius.

(3) Transition temperature was the most important characteristic in comparing the results of variable end geometry of the Type L specimens. Load and energy absorption

were less critically affected by changes in type of endings.

(4) The study reported herein does not lend itself to a critical separation of geometrical and welding notch effects. It is essential to keep in mind that the most favorable geometric condition would be nullified by a weld containing flaws.

PART 3

THE EFFECTS OF FASTENING METHODS ON CLEAVAGE FRACTURE

INTRODUCTION

Fabrication of the components of steel structure involves methods of connecting the components to form the integrated structure. Excluding welding, such means include bolting, riveting, manually welded studs, automatically welded studs, and explosively driven studs. Each of these means involves operations on the base material which can be expected to have some effect on that material's structural ability. The items included in this study are: drilled holes, punched holes, reamed punched holes, rivets in punched holes, Nelson studs, manually welded studs, and Ramset studs. The evaluation of the fastening methods has depended upon tensile tests at 0°F.

The specific types of specimens selected for investigation are classified as follows:

Specimen Type	Description
FD	1-in. diameter drilled hole
FP	1-in. diameter punched hole
FPR	1-in. diameter punched hole, reamed to 1/32 in. dia.
FR	Hot rivet in 1 in. diameter punched hole
FSW	1/2-in. diameter manually welded stud
FSN	1/2-in. diameter Nelson stud
FSR	1/4-in. diameter Ramset stud

Specimen Fabrication and Materials. The basic specimen selected for this investigation was the 3-in. by 3/4-in. by 40-in. specimen used in the Edge Effects Program for room temperature tests and similar to that illustrated in Fig. 3-1. At the mid length of the specimens the appropriate detail was introduced as shown in Fig. 3-1.

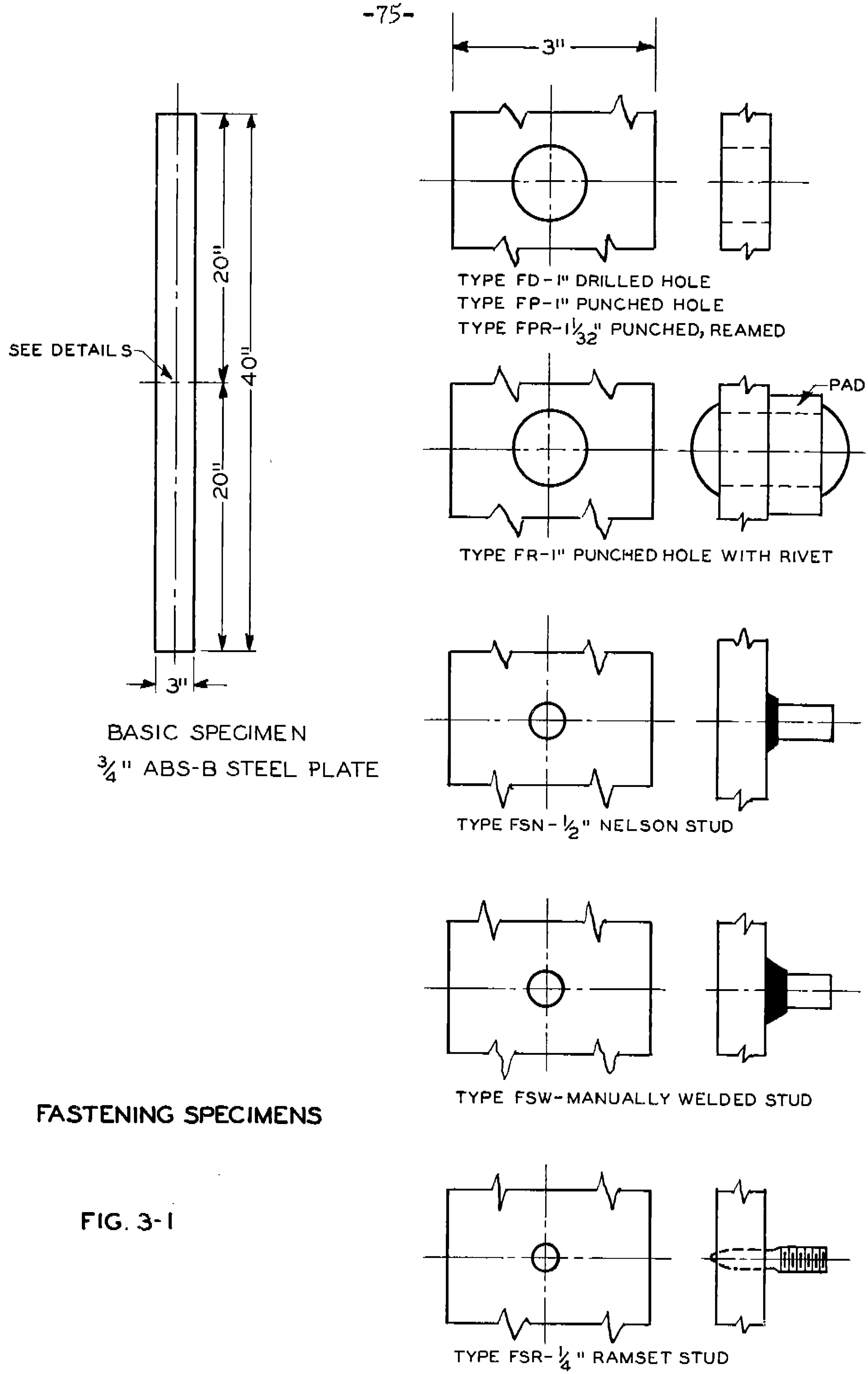
The specimens were flame cut from a 3/4-in. thick plate, and all fastenings except the Ramset stud were prepared by personnel of the Sun Shipbuilding and Dry Dock Company in Chester, Pennsylvania. A technician from the Ramset Company installed the Ramset fasteners.

The material used for all specimens was an American Bureau of Shipping Grade B steel as described in Part 3 of this report. The chemical composition and physical properties of the steel are given in the Appendix.

Specimen Instrumentation and Testing. Specimen instrumentation and testing procedures employed for these tests are similar to those described in Part 1.

Two specimens of each type were tested at 0°F. The specimens were loaded slowly, and simultaneous readings of load, elongation, and temperature were made. Energies to maximum load and fracture load were computed from the load vs. elongation curves. The test data are tabulated in Table 3-I.

Fracture Origins. Fastening methods deserve critical study if they prove to be the causes of cleavage fracture.



FASTENING SPECIMENS

FIG. 3-1

TABLE 3-I

SUMMARY OF TEST DATA FOR FASTENING SPECIMENS

Specimen Size: 3/4 in. by 3 in. by 40 in.
All Edges Machine Guided Flame Cut

Specimen	Description	°F	% Shear	Max. Load Kips	Energy to Max. Load In.-Kips	Elong. to Max. Load Inches	Fracture Load Kips	Energy to Fract. Load In.-Kips	Elong. to Fracture Load Inches	% Reduct. of Thickness at Fracture	Ultimate Tensile Stress KSI
EG-FD-N13	(1" Drilled	0	0	108	74.8	0.875	50	80.5	1.01	8.74	72
EG-FD-N12	(Hole	0	0	109	85.5	0.885	109	85.5	0.885	17.7	76
EG-FP-N14	(1" Punched	0	0	99	35	0.425	99	35	0.425	1.148	68.8
EG-FP-N15	(Hole	0	0	98	37	0.455	98	37	0.455	2.40	70
EG-FPR-N17	(1" Punched &	0	0	104	44	0.550	104	44	0.550	4.94	72.2
EG-FPR-N16	(Reamed Hole	0	10	103	45	0.500	92	52	0.550	6.03	71.3
EG-FR-N19	(1" Punched	0	0	99	37.5	0.450	90	45	0.525	0.939	66.0
EG-FR-N18	(Hole with (Rivet	0	0	101	43.5	0.550	98	51.5	0.590	1.139	67.3
EG-FSW-N8	(3/4"Manually	0	70	152	538	4.00	125	551.2	4.90	28.	67.5
EG-FSW-N10	(Welded stud	0	75	153	425	3.25	125	639	4.65	28.55	68.0
EG-FSN-N7	(1/2" Nelson	0	0	148	541	4.1				7.8	65.8
EG-FSN-N9	(Stud	0	5	152	494	3.50	128	653	4.625	26.35	67.5
EG-FSR-N11	(1/4" Ramset	0	0	141	208	1.75	141	218	1.775	4.46	68.5
EG-FSR-N6	(Stud	0	100	140	220	1.875	50	248	2.125	11.18	68.0

The fracture surfaces of each of the specimens tested in this program were examined in an effort to determine the location of the fracture origin.

In the case of specimens containing holes, the majority of the fractures originated as small tears at the sides of the holes after elongation by the tensile load. The tears apparently served as notches favoring cleavage fracture. Fig. 3-2 is a photograph of a Type FPR, punched and reamed hole specimen, which is typical of these fractures. All specimens appeared to fracture in a similar manner except those specimens with welded studs, such as Type FSW, with manually welded studs, and Type FSN, with automatically welded Nelson studs. These latter two types fractured several inches above or below the stud. The two tests, using Ramset studs, had fractures initiating at the studs.

DISCUSSION OF TEST RESULTS

Two types of welded studs, Type FSW, having a manually welded stud, and Type FSN, with Nelson studs, did not produce conditions to initiate fractures at the stud. This discussion, therefore, will be confined to the remaining types wherein fracture initiation occurred at the fastening for test temperatures of 0°F.

Of the specimens which fractured through the fastenings, Type FD with the drilled hole was generally better than other types into which a hole was introduced. The punched hole of

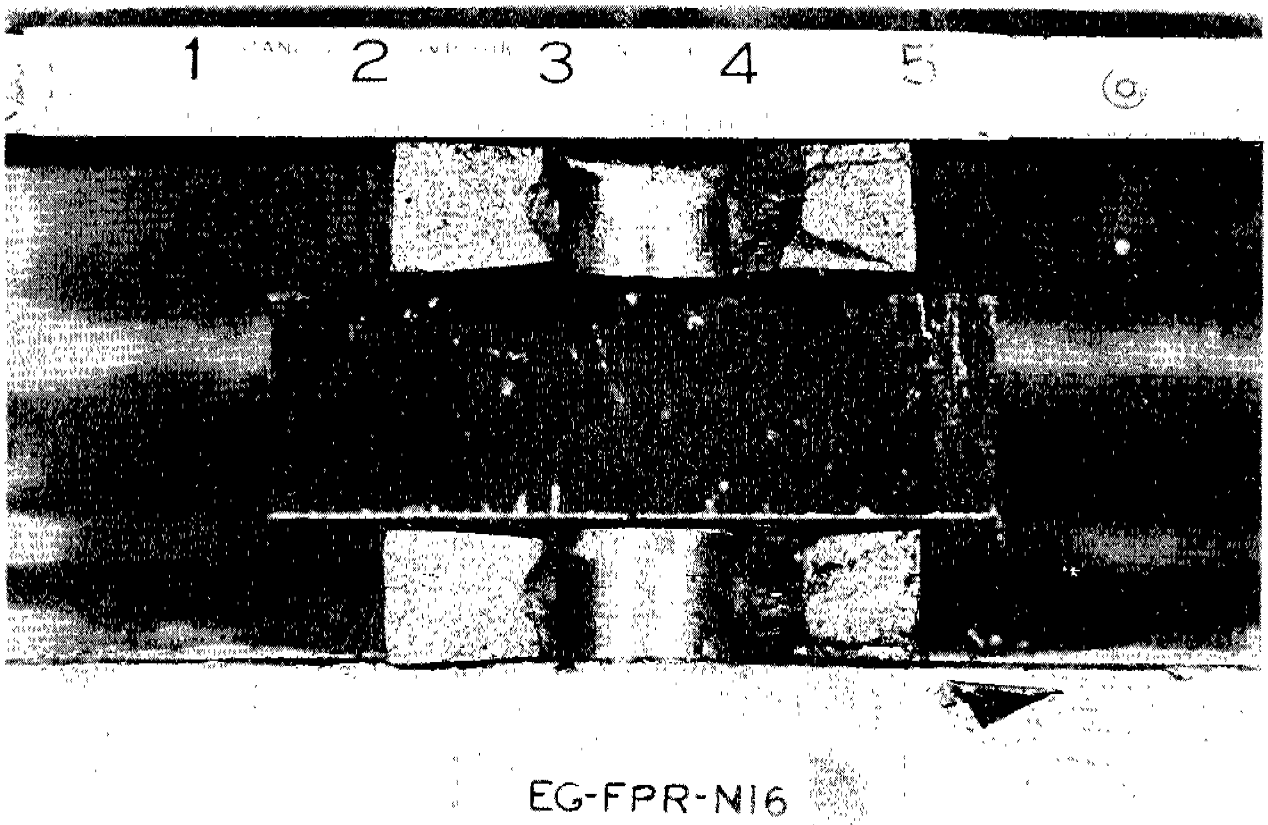


Fig. 3-2. Photograph of Fracture Surfaces of a Punched and Reamed Specimen.

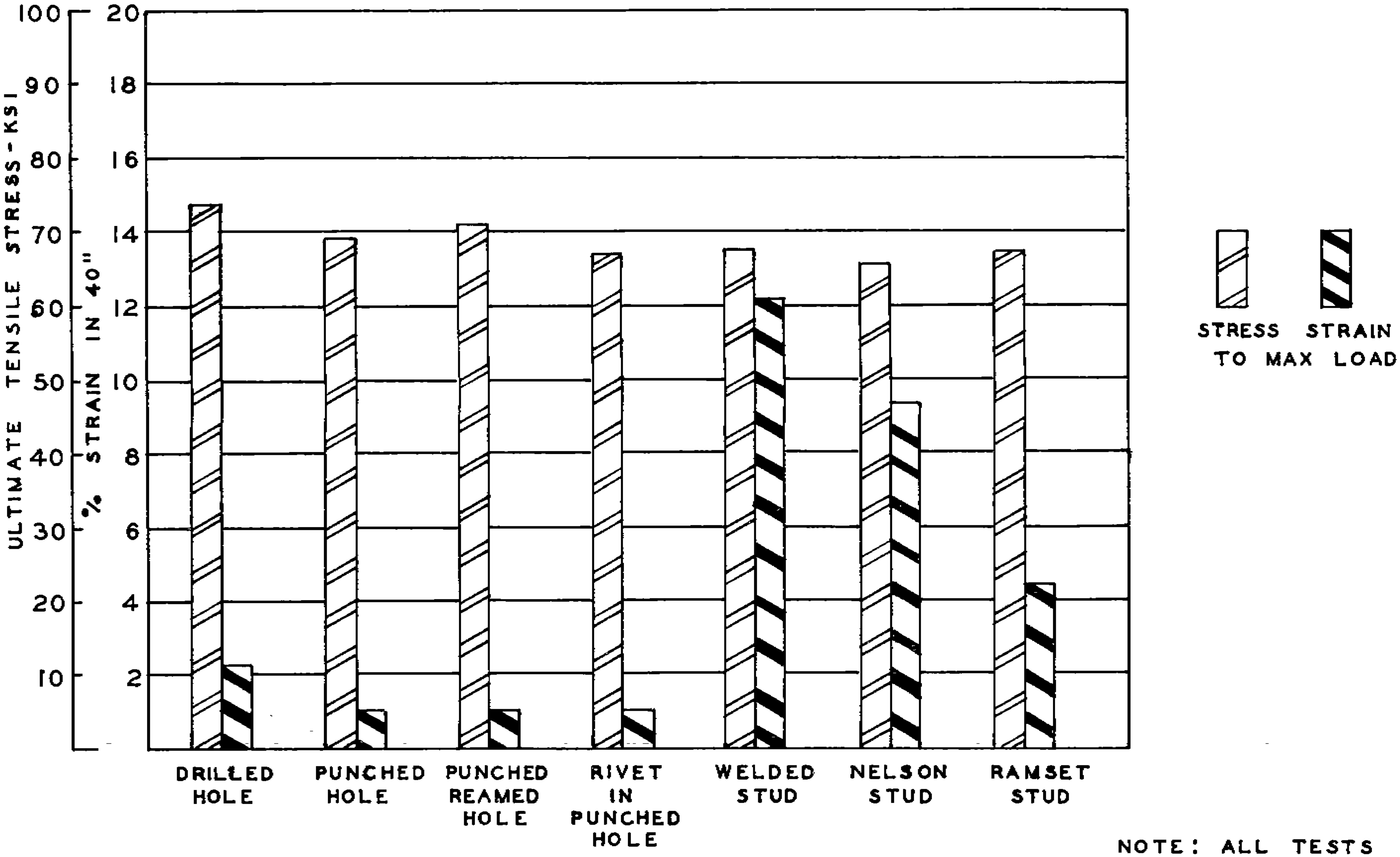
the same diameter as the drilled hole reached approximately the same level of ultimate tensile stress as the drilled hole specimen, but the elongation was only one-half as great, as illustrated in Fig. 3-3. It appears that the punching process effectively cold worked the zone around the hole, so that the localized area suffered loss of ductility without appreciable loss of tensile strength. (This is analogous to the relative behavior of the sheared edge specimens vs. the machined edge specimens as reported in Part 1.) Introducing a rivet (driven hot) into a punched hole did not change the level of stress and strain at which the specimen fractured.

The reamed punched hole, Type FPR, exhibited approximately the same stress and strain levels as the unreamed punched hole. It appears that mild reaming cannot remove all of the cold worked material adjacent to the hole, although the microscopic cracks might have been removed.

In the case of the Ramset stud, fractures which initiated at the stud were accompanied by energy absorption which, while materially better than for the various other hole type specimens, was materially less than for the manually and automatically welded studs.

SUMMARY STATEMENTS

The investigation into the effects of fastenings on cleavage fracture was extremely limited in scope and tests were conducted at a single testing temperature, 0°F. It would



SUMMARY: AVERAGE TENSILE STRESS AND PERCENT STRAIN FOR SPECIMENS WITH VARIOUS FASTENINGS

FIG. 3-3

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be impossible to make broad conclusions on the basis of the limited data available; however, certain observations of a general nature can be summarized:

(1) The cold working of localized areas caused by punching holes results in a measurable loss in ductility and energy absorbing capacity.

(2) Welded studs, either manually welded or automatically welded, did not provide conditions to initiate cleavage fracture at 0°F.

(3) Studs driven by one explosive process did provide conditions to initiate cleavage fracture at 0°F, primarily due to the localized cold working.

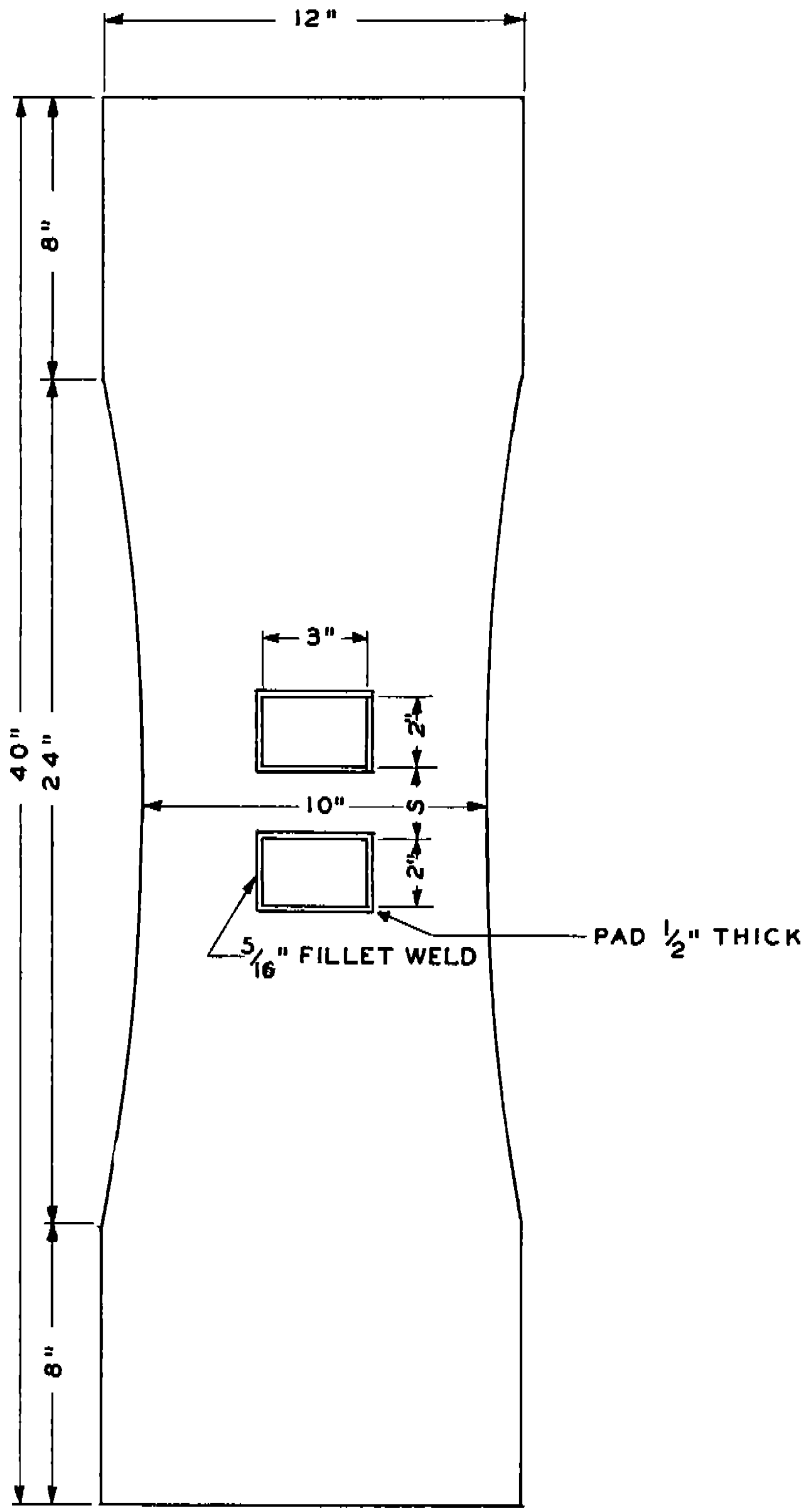
PART 4

EFFECT OF WELDED PADS ON TENSION MEMBERS

INTRODUCTION

Welded pads on a ship deck or hull plate have provided conditions to establish either a crack or a complete cleavage fracture of the steel plate to which the pad is welded. The effects of the welded pad are of two types, one type being the lateral restraint inhibiting transverse deformations. This is easily noted in a tensile test by the fact that the pad may often cause sufficient lateral restraint to produce a necking down in width in the main tension plate above or below the pad. The second effect is the part which the welding around the pad plays in establishing conditions for crack initiation. It was expected at the start of these investigations that the second effect, that of welding, would be susceptible to the distance between pads or the distance between the toes of the adjacent fillet welds. As will be explained later, this separation of the pads and the overlapping of the heat-affected zones due to welding did not produce a noticeable effect on strength.

The tensile specimens used for these tests were made of the same ABS-B grade steel that was used in other parts of this report, with all welding done with the E6010 electrode. All fillet welds were 5/16 in. minimal size. The specimen details are shown in Fig. 4-1. Seven specimens in all were



NOTE: "S" DIMENSION VARIABLE.

FIG. 4-1

WELD PROXIMITY SPECIMEN

tested, with complete data taken on all but one of the specimens. These data are shown in Table 4-I. This table indicates testing temperature, character of the fracture in terms of per cent shear fracture, maximum loads, elongation to maximum load measured over a 40-in. gage length, and the energies to maximum load. The table also presents the information obtained relating to the fracture load. The notation of the test specimens is indicated in the table but requires explanation. For example, WP 5/8 in. - N3 signifies a welded proximity test with two fillet welded pads 5/8 in. apart. The N3 notation is a shop notation.

It will be noted then, that the pads for five specimens were spaced apart in two different dimensions, 5/8-in. and 1 1/4-in. The one specimen for which no data other than visual was secured had the pads 3/16 in. apart. There is one specimen noted as WPC-N1, which had only one welded pad placed at the mid cross-section of the plate. This specimen, with one pad, was introduced into the testing program in an effort to simulate a specimen having two pads an infinite distance apart.

DISCUSSION OF TEST RESULTS

The first specimen tested, indicated as WP 13/16 in - M8 in Table 4-1 (test temperature +75°F), indicated a cleavage fracture at room temperature with the cleavage fracture triggered off by a weld defect at the toe of the fillet welds.

TABLE 4-I

TEST DATA--WELD PROXIMITIES

Specimens 40 in. long by 10 in. wide by 3/4 in. thick
Steel - ABS - Grade B

Specimen	Temp. °F	% Shear	Max. Load Kips	Energy to Max. Load In.-Kips	Elong. to Max. Load Inches 40" G.L.	Fracture Load Kips	Energy to Fracture Load In.-Kips	Elong. to Fracture Load Inches 40" G.L.	% Reduction of Thickness at Fracture
WP 5/8" - N3	85	100	476	961	2.50	80	1062	2.850	4.55
WP 1-1/4" - N 5	89	100	474	949	2.45	100	1046	2.85	9.66
WP 5/8" - N2	0	0	528	1494	3.25	528	1494	3.25	5.11
WP 1-1/4"-N4	0	0	531	1409	3.24	531	1409	3.24	7.11
WPC - N1	0	0	524	1878	4.21	524	1878	4.21	9.72
WP 1-1/4"-M10	-40	0	531	1594	3.85	531	1594	3.85	5.33
WP 13/16-M8	75	0	No data taken						

Later, however, two additional specimens as indicated in the table were tested at 85°F and 89°F, with the fracture origin being at the toe of the fillet weld of one pad with the specimens failing in 100 per cent shear. For the other tests at 0°F and -40°F, the fracture origin was at the toe of the weld, with a complete cleavage fracture resulting. This establishes the fact that conditions do prevail that are capable of allowing a cleavage fracture to be produced. It does appear, however, that proximity of the pads has little to do with the development of the cleavage fracture, as the specimens with only one pad failed in the same manner as those with two pads.

It can also be observed that the maximum load for all specimens failing by cleavage fracture are essentially the same but that they are approximately 50 kips larger than for similar specimens tested at elevated temperatures. This phenomenon of higher loads for the cleavage mode of fracture has been observed before in ordinary unnotched or mildly notched tensile specimens, and apparently, here this increase in load is a natural result of lowering the temperature. It is also interesting to note that the energy to maximum load is greater for the tests at low temperature than for the tests at elevated temperatures. This result is not completely unexpected, as in many tests performed in this laboratory this is the general rule rather than the exception, unless a specimen has been severely notched.

As has been stated, fracture origin appears to be at a single point or series of points along the toe of the fillet welds. From visual observation, the cracks began to appear at about the yield point stress of the specimen. It is believed that although these fracture origins were certainly the trigger which produced the cleavage fracture they did not produce severe notching effects; otherwise the energies and loads would have been lower for the low temperature tests.

CONCLUSIONS

Based upon certainly limited tests, it appears that only a few tentative conclusions can possibly be made. With this reservation in mind, the following tentative conclusions are stated:

1. The welding around the pads is capable of producing the trigger for the initiation of cleavage fracture at low temperature.

2. The separation or proximity of the fillet welds on separate short pads is probably unimportant, as it has been shown that one pad will suffice to set up the conditions of fracture in simple tensile specimens.

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Ewald Kasten supervised the specimen fabrication and testing programs. The welding was done by a former shipyard welder, Theodore Bartholomew. Assisting in the testing were Eugene Urban and Ewald F. Kasten. Drawings were made by John Calvin and Gordon P. Smith. Frances M. Wills has performed the stenographic duties.

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APPENDIX A

SPECIMEN TYPES

REVISED SPECIMEN DESIGNATIONS

As Reported in Progress Reports I and II of Project SR-118	As Reported in Final Report Project SR-118
I	EN1
II	EN2
III	EN3
IV	EN4
V	EN5
X-1	EN6
X-2	EN7
X-3	EN8
Y	EN9
YW-1	EF10
YW-2	EF11
YW-3	EF12
ZB	L1
ZB	L2
ZBM	L3
ZC1	L4
ZC2	L5
ZD	L6
ZE	L7
ZT	L8
XZ3	XL1
XZB	XL2
XZBM	XL3
XZC1	XL4
XZC2	XL5
XZD	XL6
XZE	XL7

APPENDIX B

MATERIALS

Insufficient steel of any given grade was available to carry out all phases of the test program. All Type EN and EF specimens were fabricated from D_N steel. The Type L specimens were first made using D_N steel, and when the supply was exhausted, steel of American Bureau of Shipping Grade B (to be designated as ABS-B) was used. All of the above steel was of nominal 3/4-in. thickness and used for main plates. For the Type L specimens the 1/2-in. thick flat bars were made of D_N and D'_N steels. The latter steel will be described subsequently. Specimens of the F and WP series used ABS-B steel. The structural tees used in the simulated bilge keel tests were of the ASTM-A7 type, while the main plates for these specimens were of ABS-B steel.

The steel designated as D'_N represents the steel obtained by normalizing a 1/2-in. thick plate of D steel. This steel was normalized by Lukens Steel at a temperature of 1650°F. Although standard normalizing procedures were used at the mill, the physical tests indicate that D'_N is different from the original D_N steel. The chemical composition of the D plate used in obtaining D'_N steel was assumed to be close to the standard of D_N steel heretofore used.

The chemical composition of the various steels used is given in tabular form:

Chemical Composition, %

Type of Steel	C	Mn	Si	Al	Ni	S
D_N and D'_N	0.19	0.54	0.19	0.019	0.15	----
ABS-B	0.16	0.67	0.02	----	0.05	0.027

The physical properties, as determined by tensile tests, are as follows:

Type of Steel	Specimen Cross-Section	Physical Properties (in rolling direction) Maximum Strength psi	Yield Strength psi	Elongation in 2", %
D_N (3/4" thick)	.505" dia.	62,600	36,300	36.5
D_N (1/2" thick)	1/2" square	59,800	37,100	42.5
D'_N (1/2" thick)	1/2" square	65,800	47,200	37.5
ABS-B (3/4" thick)	.505" dia.	60,300	34,300	40.0

All welds were made using E6010 welding electrodes. The manufacturer of this electrode indicates that the chemical analysis of the electrode is: C = 0.05 to .10%, Mn = 0.50 to 0.65%, and Si = 0.10 to 0.30%. The manufacturer also indicates that the physical properties of the weld metal should be as follows: tensile strength--65,000 to 77,000 lb. per sq. in.; yield point--54,000 to 60,000 lb. per sq. in.; elongation in 2 in.--22 to 30%.

The notch sensitive uniformity of 6-ft. by 10-ft. plates of ABS-B steel was checked by using 1-in. by 3/4-in. edge notched specimens. A series of these specimens was made from the remnants of each of the plates used in the program and tested in tension in a temperature range of -50°F to 130°F. The specimens were loaded to 15,000 lbs. in one minute, and the temperature read at that load. The reduction in specimen thickness at the notch was measured after fracture. These thickness reductions are plotted as ordinates with temperatures as abscissas and are given in Fig. B-1.

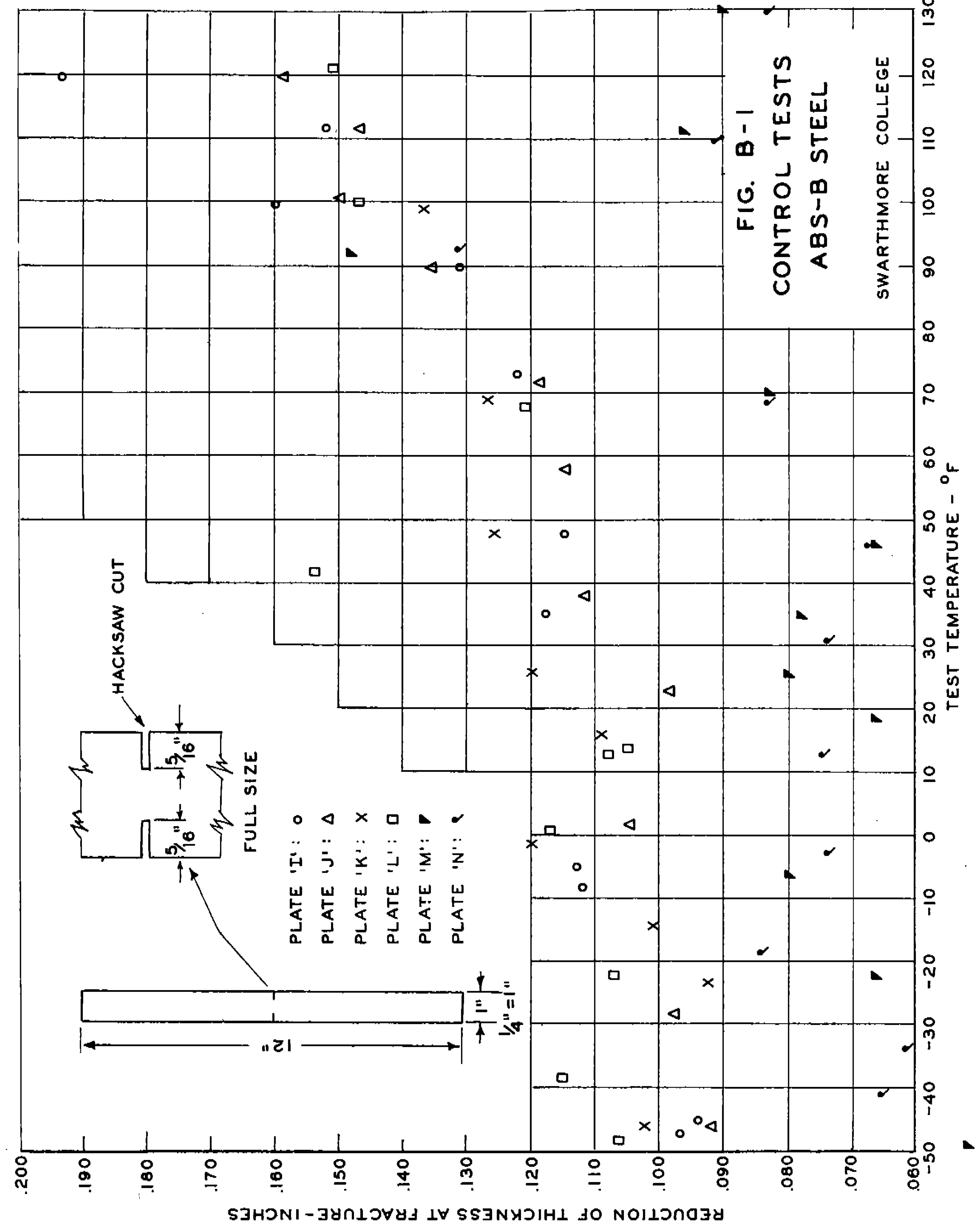
FIG. B-I
CONTROL TESTS
ABS-B STEEL
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TEST TEMPERATURE - °F
REDUCTION OF THICKNESS AT FRACTURE - INCHES
HACKSAW CUT
5/16"
5/16"
FULL SIZE
12"
1"
1/4" = 1"
PLATE 'I' : o
PLATE 'J' : Δ
PLATE 'K' : X
PLATE 'L' : □
PLATE 'M' : ◤
PLATE 'N' : ✓
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
.060
.070
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.200