JJ46/III

FLAT PLATES

PROGRESS REPORT

on

CAUSES OF CLEAVAGE FRACTURE IN SHIP PLATE: FLAT PLATE TESTS

by

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Under Navy Contract NObs-31222

COMMITTEE ON SHIP CONSTRUCTION
DIVISION OF ENGINEERING & INDUSTRIAL RESEARCH
NATIONAL RESEARCH COUNCIL

Advisory to

BUREAU OF SHIPS, NAVY DEPARTMENT
Under Contract NObs-34231

Serial No. SSC-2

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August 23, 1946

August 23, 1946

Chief, Bureau of Ships
Navy Department
Washington 25, D. C.

Dear Sir:

Attached is Report Serial No. SSC-2, entitled "Causes of Cleavage Fracture in Ship Plate: Flat Plate Tests". This report has been submitted by the contractor as a progress report on the work done on Research Project SR-92 under Contract NObs-31222 between the Bureau of Ships, Navy Department and the University of California.

The report has been reviewed and acceptance recommended by representatives of the Committee on Ship Construction, Division of Engineering and Industrial Research, NRC, in accordance with the terms of the contract between the Bureau of Ships, Navy Department and the National Academy of Sciences.

Very truly yours,

Frederick M. Feiker
Chairman, Division of Engineering
and Industrial Research

Enclosure

PREFACE

The Navy Department through the Bureau of Ships is distributing this report to those agencies and individuals that were actively associated with this research program. This report represents a part of the research work contracted for under the section of the Navy's directive "to investigate the design and construction of welded steel merchant vessels".

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Technical Report

Navy BuShips Contract NObs 31222

Project NRC-92/

CAUSES OF CLEAVAGE FRACTURE IN SHIP PLATE

FLAT PLATE TESTS

April 1946

From: University of California, Berkeley, California
M. P. O'Brien, Technical Representative

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CONTENTS

Abstract

This report summarizes the principal results of the tests on wide flat plates completed up to April 15, 1946, under the U.S. Navy Bureau of Ships contract NObs-31222. The program of investigation was begun under OSRD contract OEMsr 1418 and was originally designated as Project NRC 92. The work of this and related investigations has been coordinated with the advice of the War Metallurgy Committee.

The investigational work which is the subject of the report is concerned with the "Causes of Brittle (Cleavage) Fracture in Ship Plate," and specifically pertains to that part of the investigation which has to do with the failure of wide, flat plates at various temperatures.

The principal materials used in the tests were three lots of semi-killed, hull quality steels. Two of these steels were of medium carbon and manganese content, tested in "as-rolled" condition, while the third was of somewhat lower carbon and higher manganese content and was tested in the "as-rolled" condition and also after having received a normalizing treatment.

There were later included in the program of tests one lot of nickel-alloy steel with a nickel content of 3.34 percent, tested in the "as-rolled" condition, one lot of fully killed steel with a 0.16 percent carbon and 0.85 percent manganese content, also tested in "as-rolled" condition, and one lot of fully killed 0.21 percent carbon, 1.05 percent manganese steel that was tested after it had been quenched and drawn. The steels were furnished by the manufacturers in the form of 3/4 in. by 6 ft. by 10 ft. plates.

The specimens in the principal program of tests were tested in tension in widths of 72, 48, 24, and 12 in. The specimens all contained a narrow, central, transverse slot having a length of one-fourth of the plate width. Tests were made at each of a number of temperatures in order to determine the range of temperature within which the mode of failure changed from a ductile, shear type to a brittle, cleavage type.

In these tests, observations were made to determine the maximum load, failure load, strain distribution across the faces of the plates over several gage lengths, energy absorbed to maximum load, the mode of fracture, and the reduction of thickness near the break. Whenever observations could be made, the load at the development of cracks was also recorded.

The tension tests of the severely-notched flat plates indicated that the transition temperatures for the semi-killed steels may vary considerably, although they lay within the range of normal atmospheric temperature. Under the given conditions of test, for one lot of the medium carbon steels the transition range was found to be in the region of freezing temperature while for the other lot, which was almost identical in chemical composition, the transition range was above room temperature. The transition temperature of the low carbon semi-killed steels, both in the normalized and as-rolled conditions, was found to be in the region of freezing temperature. The tests of 12-in. wide plates of fully-killed, quenched and drawn steel indicated that the transition range of this steel also lies in the region of freezing temperature. The transition range for the nickel alloy steel was found to be in the sub-zero region.

It was found that, regardless of the mode of fracture, the nominal strength (average stress on net section of plate at maximum load) of the plate decreased as the width of the plate increased.

For the semi-killed steels the reduction in thickness at the root of the notch for plates that failed either by shear or cleavage was of the same order of magnitude. The reduction in thickness at the edges of the plate, however, differed markedly for the two modes of failure; for specimens failing by shear, the reduction increased to about four times the reduction at the notch while for the plates with cleavage failures the reduction in thickness decreased considerably toward the edges of the plate.

A number of supplemental studies were made to provide additional information on certain questions raised by the principal tests; of these, two are reported herein. One study was concerned with the maximum strains within the plate near the zone of fracture; a microhardness survey on samples sectioned from selected fractured plates was used as the basis for determining the strains. The second study was made by the use of 3-in. wide, edge-notched tensile bars, in order to develop a simple and rapid means for investigating the notch sensitivity of plate steel over a wide range of conditions.

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

Fig.
No.

LIST OF FIGURES (continued)

Technical Report

Navy BuShips Contract NObs 31222

Project NRC 92

CLEAVAGE FRACTURE OF SHIP PLATE AS INFLUENCED BY DESIGN AND METALLURGICAL FACTORS

Flat Plate Tests

April 1946

From: University of California, Berkeley, California
M.P. O'Brien, Technical Representative

Report Prepared by:
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Introduction

The work covered by this report is part of the research program to determine the factors which are responsible for the brittle type failure of ship plate, a program started by the Office of Scientific Research and Development, and now being continued under the auspices of the United States Navy and coordinated with advice of the War Metallurgy Committee. The work undertaken by the University of California is divided into two parts as follows:

Part A: Tests conducted principally on flat plates of different types of steel and of various sizes, containing notches.

Part B: Tests conducted on built up sections, simulating a hatch corner structure.

This report covers the experimental work performed under Part A--the tests conducted on notched flat plates.

The work on this project was started at the University of California in November 1944 upon authorization from the Office of Scientific Research and Development and the general features of the program of investigation have been developed as a result of conferences between the representatives of the War Metallurgy Committee and representatives of the University. At a meeting of the Advisory Committee, held in October 1944, it was pointed out that residual welding stresses in ship steel structures do not appear to be as important a factor in causing the failure of welded ships as had been originally suspected. Consequently it was felt that an investigation of the notch sensitivity of ship steels in the form of large plates offered a promising approach to the ship fracture problem. The investigation proposed was to determine the temperatures at which there occurs the transition from ductile, shear-type failures to brittle, cleavage-type failures, for various steels and for various sizes of steel plates. The investigation was to be confined primarily to 3/4-in. thick plate which would be tested in 72, 48, 24, and 12-in. widths. These specimens were to contain transverse notches at the mid-sections. The steels to be investigated were as follows: a rimmed steel, two semi-killed steels, and a fully-killed steel. The two semi-killed steels were to be of such composition and microstructure as to exhibit different transition temperatures. Subsequently a nickel alloy steel, a quenched and drawn fully-killed steel, and a fully-killed steel of special composition were included in the test program.

The Advisory Committee recommended that the part of the investigation concerned with flat plates be divided into two parts - one to be conducted at the University of California (Project NRC-92), and the other to be conducted at the University of Illinois (Project NRC-93). The University of California was to test the semi-killed steels, and the University of Illinois was to test the rimmed and the fully-killed steels.

To determine the effect of notch geometry, a series of tests were conducted at the David Taylor Model Basin. These tests served as a guide for the design of the large specimens. On the basis of these tests and also a series of preliminary tests at the University of Illinois, the shape of notch and the ratio of notch width to plate width was chosen for the principal tests on the large flat plates.

A previous report (Cleavage Fracture of Ship Plate as Influenced by Design and Metallurgical Factors NS-336, Part II -- Flat Plate Tests: OSRD No. 6452, Serial No. M-608, January 194) covered the progress of the work on the semi-killed steels up to August 31, 1945, under the OSRD contract OEM sr-1418. The results of the continuation of this work to date of April 1946, under United States Navy Contract NObs 31222, are described in this report.

Experimental Work

Test Program

Scope. -- The principal phase of the work on this project involved tension tests on notched flat plates of the several steels, in various widths, each at a number of temperatures, in order to determine the transition temperature ranges at which the mode of failure changed from the ductile shear type to the brittle cleavage type. In these tests the following was determined: the maximum load, load at failure, the mode of fracture, the amount of energy absorbed up to the maximum load, and the reduction of thickness near the break. For a number of the plate specimens the strain distribution across the faces of the plates over each of the several of the gage lengths was determined, and whenever possible the load at development of cracks was recorded.

In conjunction with the principal series of tests, various standard identification tests of the steels were performed, and also to provide a basis for the interpretation and amplification of the data a number of supplementary studies were made which included the microhardness survey of some of the fractured plates, microscopic examination of the metal for several of the specimens, and a complete series of tests on three-inch wide bars which were made from plates of various thicknesses, having edges finished in three various ways: plain flame cut edges, notched flame cut edges, and sheared edges.

Materials. -- Three lots of semi-killed steel, one lot of nickel alloy, one lot of fully killed, and one lot of quenched and drawn steel were used in the principal series of plate tests. These were designated as steels A, B, C, N, H, and Q in the order named. Description of the steels and the general program of tests are given in Table 1.

All plates from each of the six lots of steel obtained for this investigation were made from the same heat. The general nature of the steels as indicated by the abstracts of the mill reports is given in Table 2.

These steels were furnished to the laboratory by the manufacturers in the form of 3/4 in. by 6 ft. by 10 ft. plates; the 10-ft. dimension was in the direction of rolling.

Flat Plate Specimens. -- Plate specimens were tested in widths of 72 in., 48 in., 24 in., and 12 in. All specimens were full thickness as rolled, i.e. 3/4 in.

The plates were notched at the mid-section with a slot having a length equal to one-quarter of the plate width. The form of this notch is shown in Fig. 1. The wider part of the notch was made by flame cutting between two 1/2-in. drilled holes. By use of an ordinary hack saw straight cuts were made outward from the edges of the drilled holes, toward the edges of the plate, for a distance of 1 in. at each side. Each hacksaw cut was then extended for an additional 1/8 in. by means of a jeweler's saw having a blade 0.010 in. thick. For the 72-in. plates the overall length of slot thus made was 18 in.

Identification Tests. -- To accompany the principal tests a program of "identification" tests was undertaken with the following objectives:

1. To obtain a representative description of the materials used, in terms of "standard" tests, all made on comparable basis.

2. To insure that an adequate indication of properties would be provided, so that test results from special experiments might be tied back to accepted indicator tests.

3. To provide a means for detecting variation in the material supplied in any one lot.

The results of the chemical analysis and the standard tension and hardness tests are given in Tables 3 and 4. The results of the Charpy Impact tests are given in Figures 6 to 11.

Methods of Testing.

Loading. -- The flat plate specimens were loaded in a three-million-lb. Baldwin-Southwark testing machine. A typical arrangement for testing is shown in Figure 3. The load increments during the test were usually small so that at least 10 complete sets of strain readings were taken during the loading period. This procedure coupled with the use of six continuous-recording SR-4 strain recorders yielded sufficient data to allow the plotting of a load-elongation curve, shown in Figure 2. By the use of this curve, the energy absorbed by the specimen up to the maximum load (or in some cases to failure) could be calculated.

Gaging Methods, 72-in. Wide Plates. -- Both elastic and plastic strains were measured so as to obtain a load-strain history of the specimens. A strain-gage layout typical of that used for most of the plates tested is shown in Fig. 4. SR-4 electric strain gages were used and readings were taken at a number of loads within the elastic range of the material of the test specimen so that the elastic strain distribution could be calculated. Since the results of many of the earlier tests showed similar stress distributions for the plates of the various steels, in order to conserve time, the SR-4 gages were omitted from several of the plates tested during the latter part of the program.

Plastic strains were measured over 2-in. gage lengths by means of the clip gages developed on Project NRC-75. These strain measurements, however, were omitted for those plates on which no SR-4 gages were used. Plastic strains were also measured over 24-in. and 54-in. gage lengths by means of resistance-wire extensometers. These gages consisted of 0.008-in. diameter manganin wire stretched between insulated terminals located at the ends of the gage lengths. As the specimen stretched, the wires elongated and decreased in diameter, thus causing a change in resistance, which was registered on SR-4 strain indicators. Calibrations were made on a special jig so that the indicator reading could be directly converted to strain.

On one face of each specimen was punched a 1-in. grid in the path of the fracture, as shown in Fig. 5. A similar grid with 5-in. spacing between points was placed on the specimen and extended to the limits of the 54-in. gage length. Measurements with a special mechanical gage were made on the grid before the test and after fracture so that residual strain measurements could be obtained. Readings were reproducible to within ±0.002 in. The results of these grid measurements for the various plates tested are presented in Appendix A.

Gaging Methods, 48 In., 24 In., and 12 In. Wide Plates. -- For the 48, 24 and 12 in. wide plates, strains were measured during the loading by means of resistance wire extensometers having a gage length equal to three-fourths of the plate widths. A few of the plates were equipped with SR-4 gages, laid in a pattern similar to that of the 72 in. plates, in order to check the stress distribution in the elastic range.

Residual strains were determined from a grid system similar to that used on the 72-in. wide plates.

Temperature Control. -- Except for tests made at room temperature, the specimens were enclosed during test in a chamber made of plywood, which extended over the full length of the test plate. The temperature of the air within this chamber was adjusted by circulating through it air which was heated or cooled in a heat exchanger set up near the specimen. Dry ice was used for cooling. A view of a test set-up in which a temperature-control chamber was employed is shown in Fig. 3.

The temperature distribution in a specimen was measured by means of several thermocouples soldered to the surface of the plate. The temperature was regulated manually through operation of a blower in the duct connecting the heat-exchanger with the temperature-control chamber. A typical thermocouple installation for a 72-in. wide specimen is indicated in Fig. 4.

Test Results

General Remarks

Pursuant to the primary purpose of the project, namely, to study the causes of brittle failure of ship-plate, all the steels selected for investigation were tested in tension in the form of notched plates over ranges of temperature so as to define within reasonable limits the transition from the shear to the cleavage mode of fracture. The severity of notch employed in the test plates was such as to cause the transition to occur within the normal range of atmospheric temperatures for the semi-killed steels of normal composition - - the steels that were the principal materials of this phase of the investigation. The subsequent inclusion of additional special steels in the program of tests yielded data the general pattern of which differed somewhat from that obtained from the semi-killed steels.

In the semi-killed class the steels A and C were essentially identical chemically, containing about 0.25 percent carbon and 0.47 percent manganese. The difference in these two heats of steel lies primarily in the metallurgical structure. Steel C had a slightly coarser grain structure than steel A, indicating that steel C had a higher finishing temperature. Steel C was harder, stronger, and less ductile than its chemically similar counterpart, steel A. Since steels A and C were made in different plants, different rolling practices were probably used, contributing to differences in the metallurgical structures of the two steels. It is perhaps fortunate that these differences did exist because it emphasizes the importance of metallurgical structure and minor variations in chemical composition in determining the properties of the steel. Steels A and C were tested only in the as-rolled condition.

Some of the plates of steel B were purposely heat-treated to give two conditions of metallurgical structure for comparison; part of the heat was furnished as-rolled and the other part was normalized. The normalizing treatment resulted in different microstructure. The grain size of the normalized steel was slightly larger than that of the as-rolled steel, but there was otherwise little difference in the microstructure. The properties determined by flat plate tests of the as-rolled and normalized steel B did not differ as much as did those of steels A and C. The normalized steel was slightly lower in strength than the as-rolled steel. Normalizing may sometimes benefit a coarse-grained as-rolled steel by refining the grain structure. If, however, the as-rolled steel has a fine grain size, the normalizing treatment may cause an increase in grain size and thus may be detrimental. In the case of the steel B the as-rolled structure was very fine and was apparently slightly more suitable than the structure obtained by normalizing. Steel A probably would not be improved by normalizing and might even be made slightly worse, whereas the steel C probably would be improved by such a treatment.

One of the secondary purposes of the plate tests was to determine the effect of plate width on relative load-carrying capacity and on notch sensitivity. It should be noted, however, that the test specimens in the various widths do not form a true "size-effect" series because all the plates were of the same thickness and were therefore not geometrically similar.

Another factor which should be considered in the examination of the results is that cracks usually formed at the root of the notch before the maximum load was reached. When the plates failed by shear, the cracks propagated for some distance before the maximum load was reached; in the case of the 72-in. wide plates, the maximum load was reached when the cracks had progressed about 2 to 4 inches from the ends of the notch.

The notch geometry changed when the first crack formed at the base of the saw cut and changed continually as the fracture progressed. In some cases the change in the notch geometry was sufficient to cause the type of fracture to change from shear to cleavage during the progress of the failure. It is also to be noted that not only the notch geometry but the average stress, the local stress and in some cases the temperature at the apex of the crack were continually changing during the test causing changes in the type of fracture.