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UNITED STATES EXPERIMENTAL MODEL BASIN

NAVY YARD, WASHINGTON, D.C.

SERVICE STRAIN TESTS OF HULL STRUCTURES

BY LT. COMDR. W. P. ROOP, (CC), U.S.N.

EXPERIMENTAL MODEL BASIN
ERECTED 1898
BUREAU OF
CONSTRUCTION AND REPAIR
NAVY DEPARTMENT

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JANUARY 1940

REPORT NO. 467

SERVICE STRAIN TESTS OF HULL STRUCTURES

A Review of Work of the
Experimental Model Basin
to and including the year 1939

by

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U.S. Experimental Model Basin
Navy Yard, Washington, D.C.

January 1940 Report No. 467

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SERVICE STRAIN TESTS OF HULL STRUCTURES

SUMMARY

Service strain tests have now gone through a development at the U.S. Experimental Model Basin extending over about ten years. In that time the objectives have been defined, and the practical means of attaining them have been improved; a clearer understanding of the circumstances attending such work is now possible. In this report successive attempts to measure service stresses * are described, with reference to reports submitted, and the necessary conditions for successful work of this nature are discussed.

INTRODUCTION

Herewith is offered a review of the work of the U. S. Experimental Model Basin in strain measurements on surface ships under service load; its purpose is to define the problem as it exists at the present time, to permit an estimate of the situation with respect to continuation and extension of such testing, and to outline plans for obtaining, in a reasonable time, not an ultimate solution, but the completion of a definite part of the existing program.

The broader undertaking of summarizing published information on this subject from other sources, as well as all considerations of laboratory strength tests of ship-members and full-scale tests under controlled load, as well as work on submarines, will be taken up separately.

DEFINITION OF THE PROBLEM

1. Preliminary Statement

The general purpose of full-scale strain tests is to collect data as to the behavior of the actual ship under service load, which will serve to give an indication of the ability of the ship successfully to resist those loads. It is clear that until much more extensive data become available, an element of extrapolation is necessary. Strain gage data tell only what a ship has done; the real question is: What can it do?

The main source of information on this subject hitherto has been the study of casualties - cases in which structures proved inadequate to service requirements. The object of service strain tests is to make it unnecessary to await casualties in order to discover how to prevent them.

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* In this report stress is considered equal to strain multiplied by Young's Modulus. With this understanding, the two words are frequently used interchangeably.

2. Indirect Procedure Needed

When direct measurement shows values of actual stress reasonably comparable with maximum predicted values, some reassurance as to the validity of the nominal design calculations is afforded. This is not often the case, however. The observed values are usually not very high and they cannot be directly identified with the design values. It has hitherto been thought necessary, therefore, in addition to observing actual stresses under actual loads, to proceed further indirectly as follows:

(A) Load Ratio: To find the ratio between load as calculated in design procedure and the load actually occurring.

(B) Load Extrapolation: To estimate the margin by which loads due to the action of the sea may exceed that causing observed stress. This involves statistical[+] procedure.

(C) Stress Distribution: To evaluate the following ratios, all referred to the calculated or design stress, at the location of its maximum value in the ship:

(a) The calculated stresses at the observing stations under nominal * load

(b) The actual stresses at the observing stations under nominal load

(c) The predicted stresses at the observing stations under a load value adopted as maximum in the light of statistical data on actual loads.

3. Restatement of Objectives

The ultimate objective, specifically, is to apply the results of direct observation to the correction of design procedure, so that calculated values of working stress may be found which are directly comparable with the physical properties of the material. The practical details of modifications of design procedure which may in future be proposed need not be discussed here. The immediate objectives are:

First, measurement of actual stress under service loads;

+ "Statistical" in current technical usage, and in the present report, means "subject to chance" or "valid only in connection with large numbers of instances." The action of the waves of the sea in producing loads on the structure of a ship can not be completely described in terms of any one wave, but calls for consideration of the great variety of waves which occur. "Statistical" refers to an average, and also to the deviations from the average, of very numerous cases.

* Note on Nominal Calculations
"Nominal" means "existing in name only, not real or actual".
Procedure in strength design has been very explicitly standarized, both with respect to load and to section modulus; the values of bending load in foot-tons and of maximum stress in tons per square inch, resulting from these calculations, are herein referred to as nominal load and stress. Ultimately it may become feasible to revise this procedure so as to obtain design values agreeing more nearly than at present with those actually occurring in service.

Second, estimate of margin by which observed values of stress may be exceeded due to occurrence of greater loads or other circumstance.

TESTS: DESCRIPTION AND DISCUSSION

1. U.S.S. CUYAMA

The first project of the U. S. Experimental Model Basin in this field was carried out on the U.S.S. CUYAMA. It was reported in 1930 in Experimental Model Basin Report 260 and in 1931 in Experimental Model Basin Report 297. Emphasis in these tests was placed in the following points:

(A) Continuous autographic record at sea of tensile deformation of three principal strength members in the main deck;

(B) Static calibration of the ship in still water, by records of tensile deformation as in (A), under known load changes due to shift of cargo and ballast;

(C) Conversion, by use of the calibration factor, of tensile deformation data to terms of load, and from these values of load, combined with observations on wind, sea, fetch, and duration of storm conditions, an estimate of the maximum load values to be expected;

(D) Measurement of the effective * rigidity of the assembled structure and its correlation with the ship's fundamental frequency of vibration in a vertical plane, with nodes near the quarter points.

The original purpose of data on rigidity and natural frequency was to afford an experimental value for the product EI; the combination of stress and load values yields an experimental value of section modulus, I/y. When the position of the neutral axis is known, y is determined, and both E and I may then be found separately. For the CUYAMA no data on height of neutral axis were taken, and it was assumed to be in its calculated position.

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* Note on "Effective Values" of elastic quantities

Strict and explicit conventions exist for calculation of moment of inertia of a ship section, leading to precisely defined values of stress per unit bending load at all points of the section. Even in conventional procedure, however, it is recognized that actions may differ as between hogging and sagging loads. A number of other circumstances not contemplated by the usual calculations arise, and these are left to be covered by the margins of strength provided by safety factors. Typical examples are given by local concentrations of stress and by plating partially buckled. The only completely sound way of allowing for such circumstances is by a thorough analysis of their consequences and by introduction of corrections in appropriate form into the calculations.

As an approximation, however, the concept of "effective value" has partial validity, and it is widely used for its practical convenience. An effective value of an elastic quantity (moment of inertia, section modulus) is the reduced or modified value which, when introduced in place of the value obtained by conventional calculations, and combined with known load values, will give observed stress values.

Comment on the CUYAMA tests is offered as follows:

(1) The maximum load which can occur in service, estimated by extrapolation from observed values, was in rough agreement with nominal loads on this ship.

(2) The scheme for load extrapolation, while of limited accuracy in practice, is better than anything else hitherto proposed. As more extensive records are taken, and as more ships are fitted with recording gear, extrapolation will become less necessary and more accurate.

(3) Data on stress distribution were quite inadequate, and consisted only of a few rather qualitative indications around the hatches on the main deck.

(4) Natural frequency is an insensitive indicator of the rigidity, since only the square root of the rigidity is involved.

(5) No consideration was given to the endurance of the ship. Its strength was considered sufficient because its effective values of section modulus and rigidity were within fair agreement with calculated values.

2. U.S.S. HAMILTON

Following the CUYAMA tests, laboratory work was taken up on the project of measuring rigidity and natural frequency on both model and full scale, and in U.S.Experimental Model Basin Report 372 the application of this procedure to the U.S.S. HAMILTON (DD 141) is described. Due to large corrections for incidental actions, especially for effect of water set in motion by the ship's vibration, results obtained were not very certain or precise, and no estimate of effective rigidity made upon the results of these tests was considered justified.

3. U.S.S. DEWEY

The next case was that of the U.S.S. DEWEY (DD 349) on which, in March 1935, an effort was made to obtain comparative distribution of stress due to sea action at two sections of the ship, Frame 69 and Frame 92; bending deflections of the ship as a whole were also observed by photographing a row of lights seen end on, extending from Frame 49 to Frame 152. Stress values were taken at about 50 different stations by scratch gages of latch-key type, and at about 18 stations by Huggenberger gages, which require visual observation.

The immediate aim in these tests was a comparison of strength conditions at two different sections of the ship, and this question was approached by measurement of stress at a number of stations in each section, and by autographic record of the bending of the whole ship. The bending curves showed a slight but significant shift of the point of maximum curvature forward from amidships. If this curve can be accepted as accurate to this degree of detail, this would indicate that the maximum ratio of bending moment to sectional moment of inertia lies forward of amidships, perhaps in the vicinity of the break of the forecastle.

The stress data appeared at first analysis to be so scattered and inconsistent as not to lend themselves to any sort of analysis at all, and in case of the scratch-gage data, this is confirmed by further study.

From the Huggenberger data, however, it is possible to extract more information than was at first supposed. Since the question of how to handle apparently discordant data is sure to recur, it has been given extended study, and is discussed in the appendix to this report.

The Huggenberger gages were read visually in observation cycles which were of length equal to about one or two pitching cycles. Signals of "Read" and "Cease reading" were made simultaneously for all gage stations, and the maximum and minimum readings during the interval were recorded by hand. No attention was given to phase differences between stations, except that readings in the lower part of the ship are assumed to be opposite in phase to those in the upper part. No separation of hog from sag was attempted, and only range of stress was considered. No separate measure of load was taken, but an indication of relative variation of load range from cycle to cycle is afforded by the stress data themselves. By dividing out the load values, a series of values of stress per unit load was obtained for each station, and since these are nominally equal, their actual disparities afford a measure of dispersion and hence of precision of the observations.

The best series of observations indicated load ranges of from 10 to 23 thousand foot-tons with a mean error of about 25 per cent. There is rather definite evidence that the neutral axis lies above its calculated position by a foot or more.

4. U.S.S. MAHAN and U.S.S. FLUSSER

Scratch gages were improved with respect to time record and recording points and the new gages were given a trial on the U.S.S. MAHAN (DD 364) in October 1936. The time scale was subjected to central electrical control in order to obtain simultaneous observations. An approach to the separate recording of load was provided by an autographic accelerometer. Special attention was given to locating a null line on the record to permit separation of hogging from sagging stresses.

Only preliminary work was possible on the MAHAN, but similar work was carried out later on a vessel of the same class, the U.S.S. FLUSSER (DD 368).

In arrangement of gage stations, emphasis was placed on two separate aspects of stress measurement; in addition to the longitudinal tensile-compressive-stress components, the matter of shear was also taken up, in view of indications that wrinkling under shear action in the side plating might be significant. Rosettes for observation of shear consisted of 4 gages, one pair at 45 degrees and one pair at 135 degrees with the neutral axis. One such rosette was made up of scratch gages, and one of Whittemore gages, photographically read.

With improved time control, it was intended to obtain maximum tensile and compressive values from all gages in each load cycle. In actually reducing the data, however, it was found not feasible to do more than to follow the range of variation without reference to the null value. The best comparisons possible from different stations are made in terms of values of range obtained in an observation cycle which may include several loading cycles.

By photographic observation the problem of time control is partly solved, but at rather large expense in cost of equipment and effort in using it and in reducing data.

A brief account of these tests is given in a memorandum entitled "Structural Strength Investigation of U.S.S. FLUSSER at Sea," DD364-379/S1-2(2), 29 March 1937, filed at the U.S. Experimental Model Basin.

5. Static Tests on U.S.S. FLUSSER and U.S.S. TUCKER

Measurements of stress and bending deflection under static load were also made on both the U.S.S. FLUSSER (DD 368) and U.S.S. TUCKER (DD 374). Although the loads obtainable were small, because of the smallness of shiftable weights, it is believed that the data might repay further analysis. In particular, as noted in a Memorandum of 17 March 1937, no comparison of strains with bending moments was made. However, such a review of the data would fall within the scope of the present purpose only if it permitted obtaining a conversion factor for reducing strain data taken at sea to terms of load. Since the strain data taken at sea in this case are not very extensive, this procedure is considered to be not justified.

6. U.S.S. BAGLEY

Loads of significant value were finally obtained in the U.S.S. BAGLEY (DD 386), in January 1938. Gages used were of scratch type only, incorporating further improvements in time record, and with lengthened base. The number of gages was reduced and the operation of the gages was almost completely automatic. Load data consisted only of the log entries on wind and sea. The statistical nature of the data was definitely recognized, but interpretation in terms of static load seemed possible. A report with detailed data and discussion was prepared in August 1939.

Visual observations with hand strain gages on the U.S.S. SOMERS (DD 381) at about the same time were unsuccessful.

7. U.S.S. PHOENIX

On the U.S.S. PHOENIX (CL 46) in March 1939, in addition to scratch gages, two new instruments were given a trial. The first was a recording gage with base long enough to give a record on paper as in a tape chronograph. This is a very complete record and it shows tensile deformation as a function of time in full detail. The second new instrument is a stress counter, in which, for the first time, a direct record of the frequency of large stresses is obtained. Its purpose is to keep a running cumulative count of the number of cycles in which stress exceeding a certain value occurs. When applied to a series of graduated stress values, this type of instrument gives directly the data needed for constructing a distribution curve giving the probability of occurrence of stresses of different intensity. A fuller account of stress counters and the records obtained from them will be given separately.

8. U.S.S. ST. LOUIS

An attempt to obtain complete independence of supervision except that available from the ship's force was made on the U.S.S. ST. LOUIS (CL 49). Gages are similar to those used in the test of the PHOENIX.

CONCLUSIONS

1. Types of Tests

Service strain tests made by the Experimental Model Basin have been of three types, differing in purpose and technique:

(A) By multiple scratch gages simultaneous values of range of stress are obtained at a large number of stations, extending over limited times;

(B) Chronographic or photographic records give full details of variation with time within the load cycle at a limited number of stations;

(C) Counters take a cumulative record of numbers of cycles in which range exceeds given limits.

2. Data Obtainable

The information obtainable from measurements of the three types above is as follows:

(A) Multiple scratch gages give mainly relative values of stress ranges at different stations; simultaneous readings give stresses all due to the same load, although its value is unknown. Such values serve to supplement data on distribution of stress over the ship as obtained from calculation and from laboratory tests. They permit comparisons between actual stresses at different stations but afford no clue to the correctness of the assumptions used in process of design for strength beyond those referring to stress distribution, unless accompanied by separate estimate of load values.

(B) Detailed time records of stress serve chiefly to indicate the nature of load variation. If accompanied by some sort of indication of loads causing the observed stresses, they may furnish the data essential for extrapolation and estimate of stresses which actually occur under extreme load conditions. If synchronized time records are taken at different stations, they may afford data as to variation in phase of load action as affected by such complications as rolling of the ship.

(C) The purpose of counters is to give the basic data for construction of a curve of probability of stress ranges exceeding various limits. The counter differs from all other devices for service strain measurement in that it eliminates the time variable. Instead of focusing attention on instantaneous values of stress, and so requiring also knowledge of the simultaneous load, the counter, if its record is sufficiently extended, indicates probability of occurrence of a given value of stress without reference to the load.

3. Future Tests

No single one of the three types of service strain tests can give all the necessary information. But by a combination of the three, there is a possibility of replacing the logical plan followed on the CUYAMA by another in which the static calibration might become unnecessary. If data from counters could be extended to all possible conditions of service, the use of load values as a means of extrapolation would no longer be necessary.

Until such counter data become available, however, evaluation of load remains almost indispensible; without it, results obtainable from strain gages are strictly limited in significance.

RECOMMENDATION

The U. S. Experimental Model Basin is proceeding to increase its instrumental equipment with the benefit of the experience and in the light of the ideas thus outlined. At a convenient opportunity it is proposed to apply these instruments to a major project of stress measurement at sea with the expectation of obtaining more complete and significant data than any now available. Definite proposals of this nature will be made separately.

APPENDIX – REDUCTION OF DATA

With Special Reference to Tests on U.S.S. DEWEY.

Service strains are caused by dynamic loads, and the interpretation of measurements of service strains involves more intricate considerations than in case of static loads. In general the variation with time complicates things in three different ways:

First, at a given point in the structure, the effects of inertia are added to the effects of external forces (weight, buoyancy, elastic action) in determining load.

Second, in comparing values of load or stress at different points, the possibility of phase differences, or lack of synchronization at the two points, must not be ignored.

Third, since the ship is in motion (for example, rolling) variations of load occur, not only in magnitude and distribution, but also in orientation.

Two almost opposite methods of analysis may be applied. In the first, momentary and simultaneous values of the pertinent quantities may be combined for a given instant so as to reduce the problem to equivalent static terms. In the other the phenomena may be defined in terms of continuing variation, as maximum range of variation in a given interval, or, in case of periodic motion, of amplitude. The complete solution, by which loads and stresses might be measured in full detail as continuing functions of time, is not at present within the bounds of feasibility.

These two methods of analysis will be referred to in what follows as (1) the static method and (2) the statistical method.

The static method of analysis has the merit of dealing in familiar terms. It is a matter of opinion whether this offsets its emphasis on what happens at a particular instant to the neglect of other instants, possibly more significant. In addition the instrumental difficulties of accurate synchronization are so great that it has not actually been accomplished at the Experimental Model Basin to more than a very limited degree. The problem of synchronization is simplified if the ship can be subjected to periodic loading by a vibration generator. This, however, is an artificial method of loading. Though superior to static loading it still leaves the whole task of evaluating actual loads to be accomplished separately.

The statistical method of analysis involves novel and difficult ideas, the consideration of which, however, can not be avoided. Even if full synchronization of stress data from different stations and separate evaluation of load were possible, and a series of static conditions could each be given complete analysis, the step from what has occurred to what might occur would still remain.

Objectives and methods of statistical analysis of data on strength of ships cannot be fully defined until more experimental data have been accumulated. Expectation of future experience becomes more certain only as the data become more copious;

for the present, the main object is to assure that the data obtained will be suitable for the purpose as their volume increases. The best way to do this is to try to analyze data known in advance to be insufficient for final conclusions. A good group of such data is available from the tests on the U.S.S. DEWEY.

For a beginning, we thus have a series of stress ranges at different stations on the ship, each of which gives the spread between the highest and the lowest values obtained in a given observation cycle. Similar data are available for a series of observation cycles.

No direct data on load were taken. Nevertheless it is possible to obtain some information about loads with the help of some fairly plausible assumptions, as follows:

> Assumption 1. The ratio of observed range of stress at a given station to the (unknown) maximum range of bending load on the ship during the same cycle approaches an average value with increasing numbers of cycles. This value depends mainly on the location of the station.
>
> In case of stations in the extreme elements of the midship section, this ratio (or rather its reciprocal) will be called the service section modulus of the ship.
>
> Assumption 2. There exists a statistical neutral axis such that the product of the distance of a station in the midship section from this axis by the dynamic section modulus gives the ratio of stress to load for that station.
>
> Assumption 3. The range of bending load at sections other than the midship section diminishes to zero at the ends of the ship. Purely for convenience, it is assumed that for that part of the mid-length in which measurements of stress are made, the load range is proportional to the section modulus; under this condition, the ratio of stress at any station to bending load amidships will not depend on the longitudinal position of the station.

The task as it now presents itself is that of obtaining valid relations between the service section modulus as thus defined and the static section modulus as calculated by standard procedure. If load range values were available, the service section modulus would be obtained by dividing them into corresponding stress range values. But that easy way out is not available, and it becomes necessary to ask what conclusions may be derived from stress data alone, combined with the idea that there is a service section modulus which is characteristic of the ship, and does not depend on the magnitude of the load.

The combined effect of the three explicit assumptions listed is to make the ratio of stress range to midship load range, when divided by distance from neutral axis, nominally equal at all stations. This equality is only nominal, and actually is affected, from cycle to cycle, by such actions as the rolling of the ship. These actions average out, however, and the results of one series of observations, if sufficiently extended, should approach those of another long series.. The assumptions permit combining results from all the stations and so broadening the base of the averaging operation. Each station yields a version * of the service section modulus, and by accumulating a sufficient number of such versions a consensus+ is obtained which may be accepted as a sufficient approximation to the truth.

The assumptions permit combination of stress data from various stations, but the variation from cycle to cycle persists, as it is caused by the variation in magnitude of load. However, since the load value in each cycle is for all stations the same, namely the range of bending load amidships, the combination of cycles is equivalent to combining increments of load in a static test, in which an average ratio is obtained by dividing by the combined corresponding increments of stress.

In carrying out the scheme thus suggested, two major difficulties occur: the first is in locating a service neutral axis, the second in evaluating a constant of proportionality, to apply to the ratio of stress range to load range.

If static conditions existed, the neutral axis would be easy to locate by simple linear interpolation between stresses at two stations. However, the variability of conditions results in a wandering of the neutral axis so that the result of interpolation between values of stress range at two stations is only to obtain the position of an axis whose property is defined in terms of averages.

With respect to the second difficulty, matters are worse. In fact by the measure of stress alone it is not possible to separate the two quantities, load and rigidity. Stress over load equals distance from neutral axis over moment of inertia, and the evaluation of the ratio involves evaluation of both factors.

By way of example, a sample set of observations from the tests on the DEWEY are shown. These data are of a rather low degree of precision, because of the small loads encountered by the ship; nevertheless, the procedure in reducing them serves to illustrate how some results may be gleaned from a source which at first sight seems rather unpromising. A similar procedure is also applicable to data of greater consistency if, as is hoped, these are found to be obtainable. If a considerably higher precision is attained, other methods also are available.

The observed stresses from the DEWEY are given in Table 1 in pounds per square inch range during each of a series of 19 observation cycles, at each of 10 stations.

The calculated values of I/y are known for each station, and since this gives a local value for ratio of load to stress, division gives for each station a

*"Version" is used to mean "an account from a particular point of view as contrasted with another account".

+"Consensus" is used to mean "unified or convergent trend".

TABLE 1 – OBSERVED STRESSES

Station * / Cycle	69SP	69GP	69CL	69GS	69LP	69LS	92GP	92GS	92LP	92LS	Units
Height above base	20.1	19.5	20.3	19.5	2.1	2.1	19.5	19.5	2.1	2.1	feet
1	2.8	4.4	4.8	7.6	4.2	–	1.2	3.6	5.9	6.2	kip/in.^{2}
2	3.4	5.1	4.2	5.5	4.2	–	2.5	2.4	5.3	6.2	"
3	3.4	6.4	3.0	5.0	3.4	5.3	3.7	3.6	4.1	8.7	"
4	3.4	5.1	4.2	5.5	2.5	8.8	3.1	3.6	5.9	6.9	"
5	3.4	5.7	4.2	5.2	4.2	4.4	3.7	3.0	6.5	5.0	"
6	3.9	6.4	5.4	7.4	5.1	10.5	4.9	4.2	6.5	2.5	"
7	3.9	6.4	6.6	5.7	4.2	9.6	6.2	3.6	7.1	8.1	"
8	2.8	3.8	2.4	4.4	3.4	7.0	3.7	2.4	4.7	4.4	"
9	5.1	7.6	6.6	9.5	8.5	15.8	6.2	5.4	9.4	12.5	"
10	3.4	4.4	4.8	6.8	4.2	7.0	3.7	3.6	5.9	6.2	"
11	3.9	5.7	6.6	7.8	–	9.6	1.2	4.2	6.5	8.7	"
12	3.4	5.1	4.2	4.2	4.2	7.9	2.5	2.4	6.5	6.2	"
13	4.5	7.0	6.6	10.1	5.9	12.3	7.4	4.8	7.7	10.0	"
14	3.4	5.1	6.0	6.1	3.4	8.8	3.7	3.6	5.3	6.2	"
15	3.9	6.4	7.8	9.8	9.3	8.8	4.9	4.2	7.1	10.0	"
16	2.8	4.4	4.2	7.4	4.2	8.8	3.7	3.0	4.7	3.7	"
17	6.7	8.7	9.6	11.9	22.9	17.5	6.2	6.0	12.4	12.5	"
18	3.4	–	2.4	5.4	–	6.1	2.5	1.8	4.7	6.9	"
19	1.1	2.5	1.8	5.0	4.2	–	2.5	1.2	3.5	3.1	"
Average	3.61	5.57	5.02	6.80	–5.76	–9.26	3.87	3.50	–5.77	–7.05	"
$\frac{y}{I}$ = (σ/M)	.554	.521	.566	.521	–.454	–.454	.521	.521	–.454	–.454	kip/in.^{2} per** 1000 lb/in.^{2}
M	6.52	10.70	8.87	13.05	12.69	20.40	7.43	6.72	12.70	15.53	1000 ft–tons
Height of Neutral Axis	14.5	10.7	12.5	8.9	11.1	16.5	13.5	14.1	11.1	13.1	feet

* Station Designations: Number gives frame; SP, stringer; GP and GS, deck girder, p and s; CL, center line (deck); LP and LS, longitudinal, p and s.

** Negative sign denotes reversed phase, or compression when stress elsewhere is tensile.

version of the value for average load range for all cycles, given in the line next to the last of Table 1.

The actual bending moment at any given time on any given section can have only a unique value. On the assumption that this applies also in the dynamic terms in which these data are being handled, and that the discrepancies are errors of observation, it is inferred that the load range on Frame 69 as indicated by these data is the average for the first six stations, or 12.04 foot-tons, and at Frame 92, 10.60 foot-tons. Since

TABLE 2 – OBSERVED VALUES OF RATIO OF STRESS RANGE TO DISTANCE FROM NEUTRAL AXIS. EQUAL TO RATIO OF LOAD RANGE IN FOOT-KIPS TO MOMENT OF INERTIA. UNITS OF 1000 IN.^{2} FT.^{2}

Station / Cycle	69SP	69GP	69CL	69GS	69LP	69LS	92GP	92GS	92LP	92LS	Average	Mean Error ±
1	0.37	.64	.62	1.10	.40	—	.17	.52	.56	.59	.55	.17
2	.45	.74	.55	.80	.40	—	.36	.35	.51	.59	.52	.13
3	.45	.93	.39	.73	.32	.51	.54	.52	.39	.83	.56	.16
4	.45	.74	.55	.80	.24	.84	.45	.52	.56	.66	.58	.14
5	.45	.83	.55	.75	.40	.42	.54	.44	.62	.48	.59	.13
6	.52	.93	.70	1.07	.49	1.00	.71	.61	.62	.24	.69	.19
7	.52	.93	.86	.83	.40	.92	.90	.52	.68	.77	.73	.16
8	.37	.55	.31	.64	.32	.67	.54	.35	.45	.42	.46	.12
9	.68	1.10	.86	1.38	.81	1.50	.90	.78	.90	1.19	1.01	.23
10	.45	.64	.62	.99	.40	.67	.54	.52	.56	.59	.60	.11
11	.52	.83	.86	1.13	—	.92	.17	.61	.62	.83	.65	.20
12	.45	.74	.55	.61	.40	.75	.36	.35	.62	.59	.54	.12
13	.60	1.01	.86	1.46	.56	1.17	1.07	.70	.73	.95	.91	.22
14	.45	.74	.78	.88	.32	.84	.54	.52	.51	.59	.62	.16
15	.52	.93	1.01	1.42	.89	.84	.71	.61	.68	.95	.86	.18
16	.37	.64	.55	1.07	.40	.84	.54	.43	.45	.35	.56	.17
17	.89	1.26	1.25	1.73	2.18	1.67	.90	.87	1.18	1.19	1.31	.33
18	.45	—	.31	.78	—	.58	.36	.26	.45	.66	.48	.14
19	.15	.36	.23	.73	.40	—	.36	.17	.33	.30	.34	.11

the actual moment at Frame 69 can hardly be greater than at Frame 92, the difference is again attributed to experimental error and the grand average, 11.46 foot-tons, is accepted as the best approximation to the actual average load range at either section.

This average is simply one-tenth the total of the next-last line in Table 1. As a measure of the actual load, its standing would not be very good, since it depends on a calculated section modulus. Its present use, however, is only as a starting point for further reduction of the data, and its usefulness for this purpose lies in the fact that whatever the correct value of load may be, it is the same for all observing stations.

The average stress range varies from one station to another, but dividing by the corresponding average of load range, even though this is only approximate, gives new values of $y/I = \sigma/M$. When these are multiplied by the calculated value for I, the result is a series of values of distance from neutral axis.

If consistent, these numbers would differ from height above base only by an additive term which can be interpreted as one version for height of neutral axis above datum, shown in the last line of Table 1. Insofar as this has a single value under the circumstances, the numbers in the last line give an experimental approximation to it. The calculated value is 10.2 feet, the average observed value 12.6 feet.

In Table 2 are now presented values of the ratio of stress range to distance from neutral axis. For each observation cycle these values should be the same for all stations, as they are equal to the ratio of load range to moment of inertia. As given in the table, this ratio is in terms of foot-kips per thousand inches^2 feet^2. In Table 3 the averages for each cycle are shown, in terms of foot-tons; when multiplied by 40, the calculated value of moment of inertia in units of 1000 feet^2 inches^2, the numbers in Table 3 give load in foot-tons, as shown in the last column.

If, from any source, separately observed values of load were available, they could be used to reverse the last steps of the process, to obtain a series of observed values of section modulus, which is the real measure of the strength of the ship.

These, however, would still be statistical values, - ratios of averages. Separate evaluation of load would serve only to make it unnecessary to introduce a calculated or estimated value of moment of inertia.

The process described should serve quite successfully to average out variations in load magnitude; it would work best when applied to a ship steaming directly into a well defined series of waves in which height and length presented the principal variations to be averaged out.

On the other hand, rolling, such as would be induced by meeting regular waves obliquely, or any of various degrees of irregular motion resulting from more intricate wave action, leads to complications which may be described as variations in load pattern. Elimination of such variations would naturally require more extended series of observations.

To all this the objection may well be made that ships are not sunk by averages. This criticism is entirely just. While due consideration of fluctuations in load magnitude and load pattern gives a more complete account of loading of a ship by wave action than is possible in terms of any single wave, the solution of the problem is still incomplete until some experimental basis for an estimate of the probability of large bending loads becomes available. Only two approaches to such an estimate have been proposed. The first is based on the probability of large waves from oceanographical considerations, and correlation with load as in the CUYAMA report. The second is based on direct observation of frequency distributions of stresses by means of the counter.

TABLE 3 - U.S.S. DEWEY LOAD RANGES
DATA FROM TESTS OF 12 MARCH 1935

Observation Cycle	Ratio of Load to Rigidity foot-tons ÷ in.^{2} ft.^{2}	Load range in foot-tons (I assumed as 40 x 10^3 in.^{2} ft.^{2})
1	.24	9.6
2	.23	9.2
3	.25	10.0
4	.26	10.4
5	.26	10.4
6	.31	12.4
7	.33	13.2
8	.21	8.4
9	.45	18.0
10	.27	10.8
11	.29	11.6
12	.24	9.6
13	.41	16.4
14	.28	11.2
15	.38	15.2
16	.25	10.0
17	.58	23.2
18	.21	8.4
19	.15	6.0

SUMMARY OF APPENDIX

Where completely synchronized stress measurements are not made, and even without separate load evaluation, it may still be possible to obtain information of value from data of the sort exemplified on the U.S.S. DEWEY. However, the interpretation of such data leads into difficult and unfamiliar considerations. A first approach to such interpretation is sketched and illustrated.

REFERENCES

Since a large part of the information summarized in this report has been taken from sources available only at the Experimental Model Basin, the references in the text are intended only for convenience of future check on details, and will serve for further information of the general reader only in case of the official letters and Experimental Model Basin Reports cited.

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