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THE RESEARCH ON THE EFFECT OF THE SUPERSTRUCTURE ON THE STRENGTH OF THE SHIP

CONTENTS

Chapter 1 Introduction

Recently, by the development of electric resistance strain gages, results of strain measurements came to be recorded with confidence. Encouraged by this, strain measurements in actual ships were often executed at several places, and many facts which had been veiled in the fog were uncovered. For example, regarding the effects of the deck house on the longitudinal strength, it was found that measured strains at deck houses were far below compared with the strains which are predicted by the elementary beam theory on the assumption that main hulls and deck houses behave corporately together as a single beam. The fundamental research which has been attacked by several investigators seems to explain these facts only qualitatively, and it is not sufficient to be applied to the design of the structure.

As an attempt to shorten this gap, this committee intended the following experiments.

(1) Actual ship experiments.

(2) Steel box-typed model experiments.

(3) Photo-elastic experiments and calluloid model experiments. Among them, (1) and (3) are finished, while (2) is to be continued on the models of various types and scantlings. But the theoretical explanation about the results of the experiments is not finished and a general conclusion can not be given now. In this report, only the results of the experiments are described mainly.

Chapter 2 Actual ship experiments

To examine the behaviour of the superstructures and deck houses for the longitudinal bending, strain distribution of "Brazil Maru", an emigrant vessel ($L \times B \times D = 145^m \times 19.6^m \times 11.9^m$) which had a long bridge, was measured on the occasion of launching at Kobe shipyard (the Shin Mitsubishi Heavy Industry Co.) on 6th April 1954.

The positions of the strain measurements were located mainly near the midship section as shown in Fig. 1. Number of measuring positions were 22 points at Fr. No. $92\frac{1}{2}$ and 7 points at Fr. No. $80\frac{1}{2}$ and $103\frac{1}{2}$, respectively. The gages were set at the both surfaces of plates and

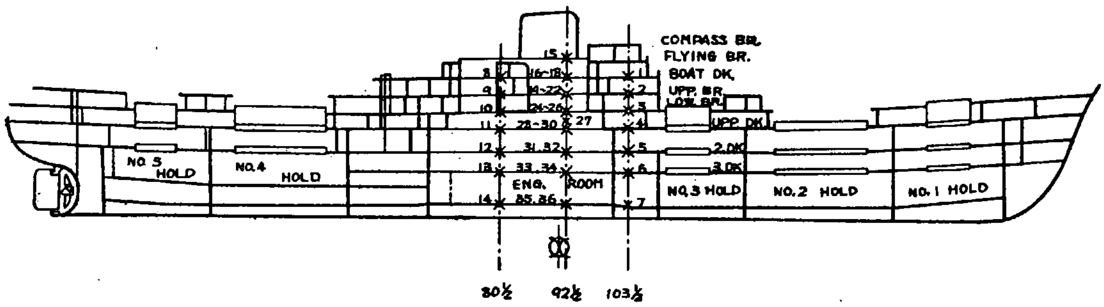

Fig. 1 Locations of Strain Gages (BURAZIL MARU)

mean values of them were read at each position. But, as one of 3 sets of meters was damaged during the measurement, values read at the positions from No. 1 to No. 12 cannot be relied.

Fig. 2. Shows longitudinal strain distribution. The value plotted are the difference between the values at the "lift by stern" and at the "afloat" condition. Fig. 2 (a), in which the values at the sides of the decks are plotted, shows that the strains vary linearly in accordance with the elementary beam theory up to the lower bridge deck level. From here upward the strains, instead of following the straight line proportionally, diminish in intensity linearly up to the boat deck. And the stress at the flying deck increases abruptly again, but this irregular tendency is doubtful and the re-examination will be necessary for the reason described below. The violent vibration at these parts, during the launching, was recorded, since at that time the construction process from the boat deck upward had not yet been finished and many connections were only bolted and in addition the vessel was launched by means of the "ball bearing system". Because of the long lower bridge deck (the bridge length is about 2/3 of the ship length), the lower bridge

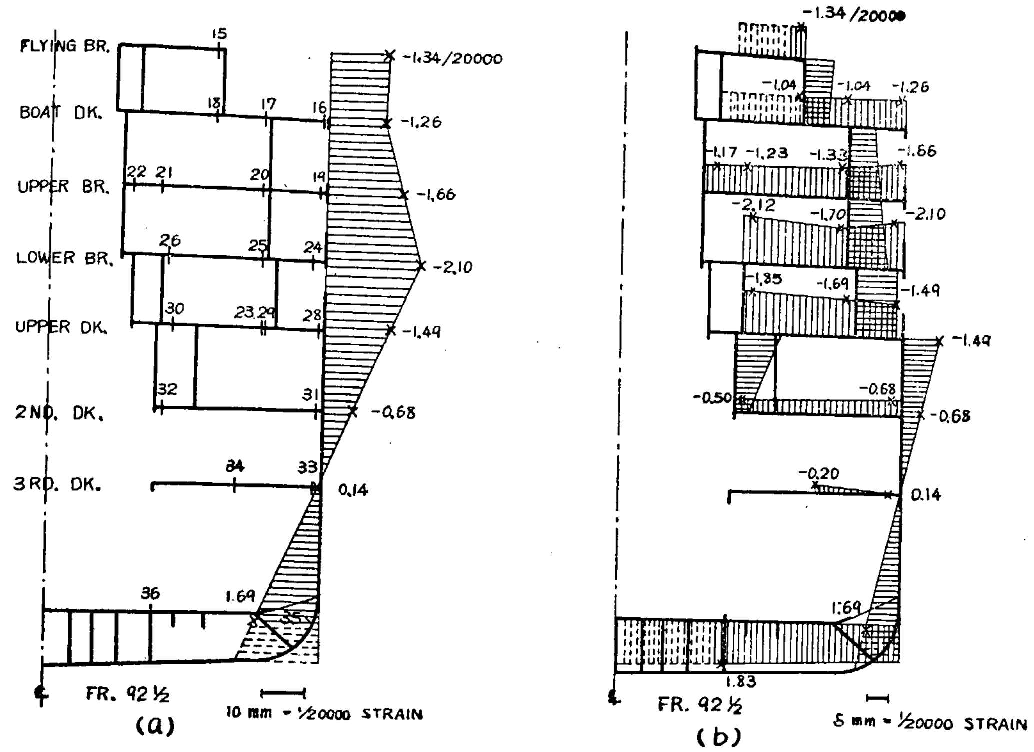

Fig. 2 Longitudinal Strain Distributions at Fr 92 1/2

behaved together with the main hull according to the elementary beam theory, though the authorized strength deck is the upper deck. The remaining part, besides the irregularity at the flying deck, distorts also according to the elementary beam theory, but reverse in curvature; the main part was bent in the sagging condition and the remaining part in

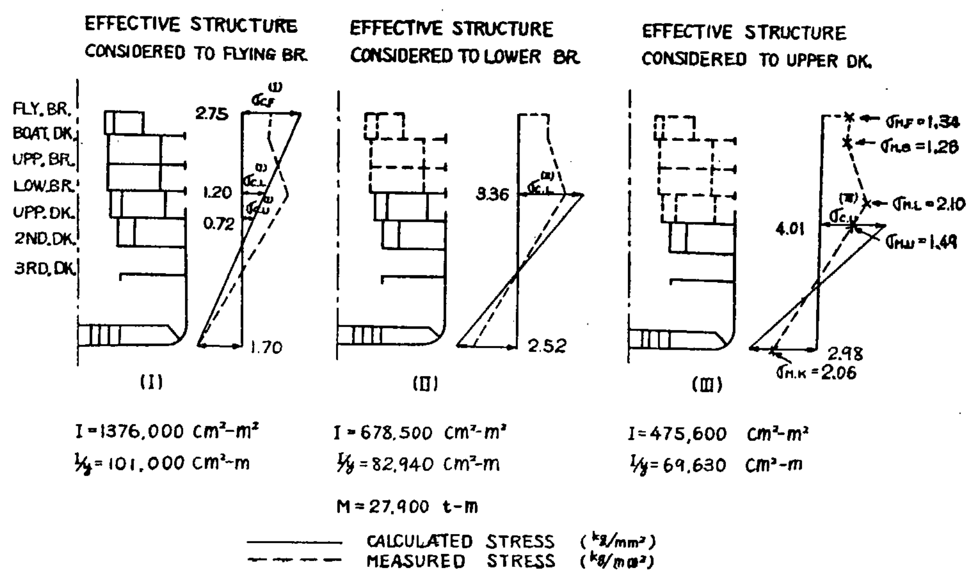

Fig. 3 Longitudinal Stresses as affected by Hull Girder Stiffness

the hogging. Fig. 2 (b), shows the stress distribution across the deck. The general rule on the stress distribution cannot be obtained, because the stress intensity decreases from the deck edge inboard at some deck, and increases at the other.

To measure the transverse strain, the No. 23 gage was set near the No. 29 gage at the edge of the upper deck. From the reading of the No. 23 gage, we find that the constraint in the transverse direction is very slight and then the longitudinal stress may be obtained simply by the longitudinal strain times Young's modulus. The longitudinal stress calculated as above results in being underestimated by only one per cent for this case.

To examine the effect of the deck house on the longitudinal strength, that is, to examine the reduction of stresses at the main hull by attaching the deck house to the main hull, the stress distribution of the hull is computed by the elementary beam theory for the following 3 cases. In the case I, it is assumed that the vessel behaves as if a single beam, with all longitudinal material up to the flying deck fully effective. In the case III, the deck house structure above the upper deck is neglected. The case II is the intermediate condition. Computed stress distribution for each case is shown together with the measured stresses in Fig. 3.

Table 1 summerizes the calculated values of the stress reduction at each deck, together with the values at "President Wilson"[1] for the

Table 1 Stress Reductions

	Top Deck Factor	Stress Reduction at Low. BR. (Prom. DK)			Stress Reduction at Upper DK		
		Theoretical	Measured	Sup. Struct. Eff.	Theoretical	Measured	Sup. Struct. Eff.
	%	η_T (%)	η_M (%)	η_S (%)	η_T (%)	η_M (%)	η_S (%)
	$\frac{\sigma_{M.F}}{\sigma_{C.F}^{(I)}}$	$\frac{\sigma_{C.L}^{(II)}-\sigma_{C.L}^{(I)}}{\sigma_{C.L}^{(II)}}$	$\frac{\sigma_{C.L}^{(II)}-\sigma_{M.L}}{\sigma_{C.L}^{(II)}}$	$\frac{\eta_M}{\eta_T}$	$\frac{\sigma_{C.U}^{(III)}-\sigma_{C.U}^{(I)}}{\sigma_{C.U}^{(III)}}$	$\frac{\sigma_{C.U}^{(III)}-\sigma_{M.U}}{\sigma_{C.U}^{(III)}}$	$\frac{\eta_M}{\eta_T}$
Burazil Maru	48.7	64.3	37.5	58.3	82.0	62.8	76.6
President Wilson	26.0	39.6	23.8	60.1	—	—	—

convenience of comparison. The "top deck factor" in this table is defined as a ratio of the measured stress at the uppermost deck (σ_{MF}) and the relevant stress ($\sigma_{CF}^{(I)}$) for the case I above mentioned. This value is 48.7% at "Brazil Maru" and 26% at "P. Wilson"; the value in the former is unreliable by the reason mentioned already. The "stress

(1) See reference (1)

reduction" means the contribution of the deck house. The stress at the specified deck ($\sigma_{CL}^{(II)}$, or $\sigma_{CL}^{(III)}$), which are predicted by assuming that all sectional area below the deck concerned are fully effective and the remaining part neglected (case II or III), may be considered to be reduced by the existence of the remaining part. Thus the "stress reduction" is defined as follows.

theoretical reduction $\eta_T = \dfrac{\sigma_{CL}^{(II)\ or\ (III)} - \sigma_{CL}^{(I)}}{\sigma_{CL}^{(II)\ or\ (III)}}$

measured reduction $\eta_M = \dfrac{\sigma_{CL}^{(II)\ or\ (III)} - \sigma_{ML}}{\sigma_{CL}^{(II)\ or\ (III)}}$

The "theoretical reduction" is the maximum value of stress reduction from the theoretical point of view. The relevant stress at the deck concerned (say $\sigma_{CL}^{(I)}$) is calculated on the assumption that all the section of the hull were fully effective (case I). The "measured stress reduction" is the actual value of that. In this case measured stress (σ_{ML}) is to be adopted instead of the stress $\sigma_{CL}^{(I)}$. The "superstructure efficiency" η in Table 1 is defined by the ratio of η_M and η_T. This means the efficiency of the deck house regarding the "stress reduction". The value of η_M of "Brazil Maru" is larger than that of "P. Wilson", but this trend is reverse as for η, since η_T is too large at the former. This means that from the theoretical possibility, at "Brazil Maru" the efficiency of the deck house as to the "stress reduction" is lower than that of "P. Wilson", though absolute value of the actual stress reduction of the former is larger.

Now, we compare the measured stresses with the stresses computed by the "H. H. Bleich's theory".[2] "Bleich's theory" is following; the main hull structure and the deck house structure are distorted according to the elementary beam theory, respectively. And in this theory, it is assumed that these two beams are connected each other in the vertical direction with the deck regarded as an elastic spring, the stiffness factor of which is κ, and are connected so tightly in the longitudinal direction as the longitudinal strains along the connective line is the same each other. At "Brazil Maru", we regard the structure below the lower bridge deck level as a main hull. Then the stiffness factor κ of the lower bridge deck is given by

$$\kappa = 2(P_1 + P_2)$$

where P_1, P_2 are the loads, which act at the positions of the side wall of the deck house at the midship section of unit length, and yield unit

(2) See reference (2)

deflection at that points at the same time, as shown in Fig. 4. For the convenience of the calculation, it is assumed that the sectional area and the moment of inertia of these two beams are invariable along the length, respectively. The adopted values are the mean values of these at Fr. No. 80, 90 and 103. The calculated stress distribution according to the "Bleich's theory" is shown in Fig. 5 and by chance this accords fairly well with the measured stress distribution. But this calculation according to the "Bleich's theory" neglects the variation of the stiff-

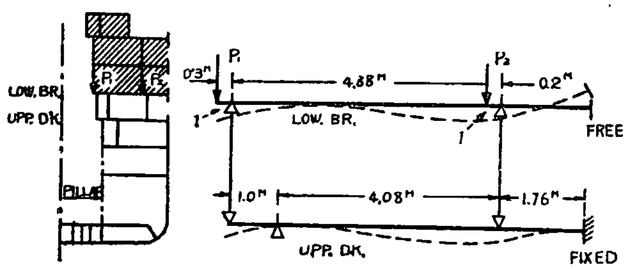

Fig. 4

ness factor κ along the length depending mainly on bulkheads, and also neglects at the same time the variation of the sectional area and moment of inertia of the structure along the length. In addition, "equally distributed load", Bleigh so calls, is adopted as the load curve, though the discrepancy according to this seems to be not so great. Then the accuracy of the results of this calculation may not be so highly appreciated.

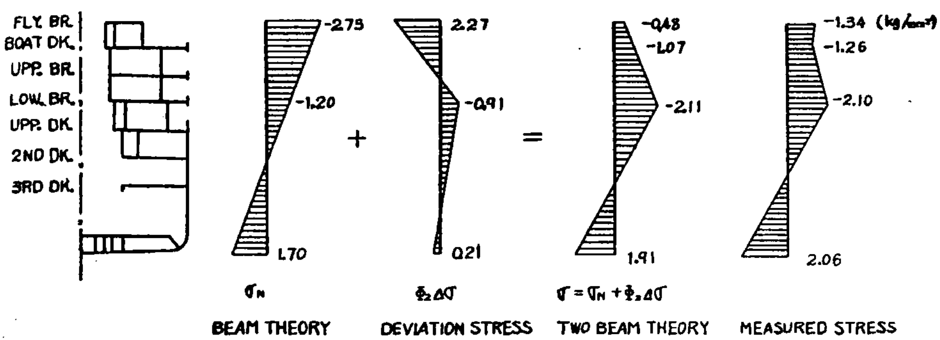

Fig. 5 Comparison of Theoretical and Measured Stresses

Generally speaking, in actual vessels, the section changes complicatedly along the length and the stiffness factor of the deck changes irregularly, and this method of computation require the re-examination. Further, for the case that the length of the deck house is too short to be regarded as a beam, this method is ineffective and the more adequate method of the computation which we are now researching, is to be established.

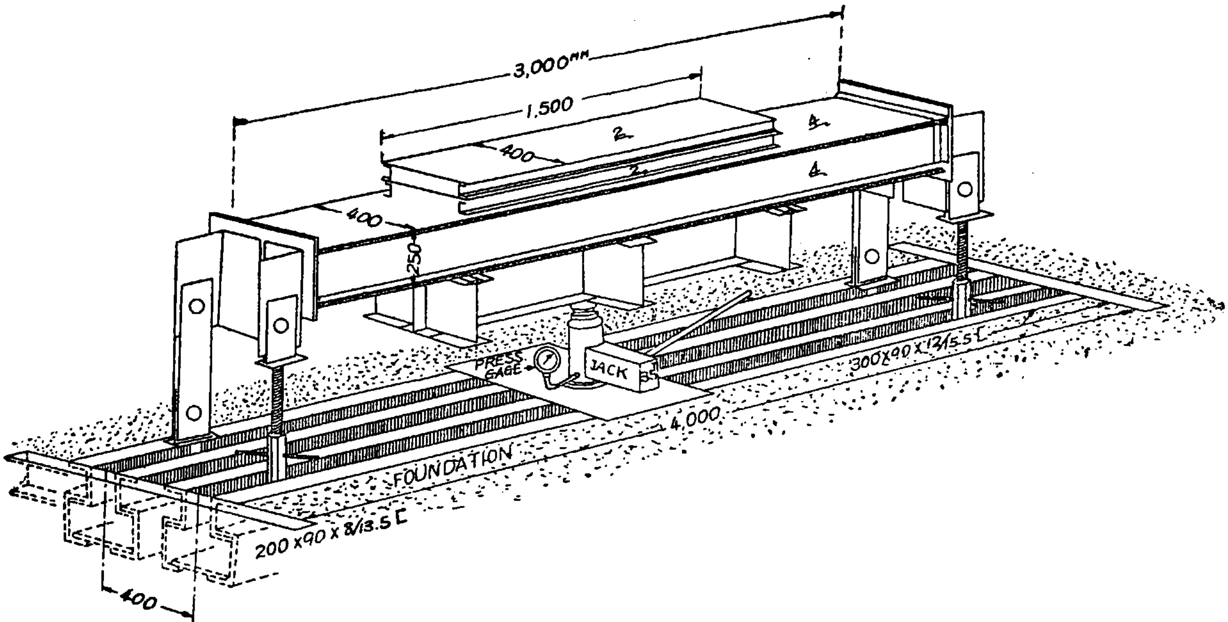

Fig. 6 Ship Model and Loading Apparatus

Chapter 3 Steel box-typed model experiments

As a basic research for the effectiveness of the superstructures or the deck houses, bending experiments were excuted on box-typed models which might be regarded as simplified ship structures. The sketch of the loading apparatus and the test models is shown in Fig. 6. The apparatus is set on the foundation which consists of eight pieces of channel bar, and load is applied by the oil jack, the capacity of which is 35 tons, and models are able to be loaded by uniform bending or by bending by the concentrated load at the middle optionally. The screws which are seen in the figure is set for the purpose to adjust the model to be subject to a symmetrical loading across the section. The box girder ($L \times B \times D = 3000^{mm} \times 400^{mm} \times 250^{mm}$), which is composed of plates (thickness$=4^{mm}$) and angles, represents the main hull structure and the box girder (thickness$=2^{mm}$), which is set on the main hull, represents the superstructure or the deck house. And angles and plates are bolted in order to be resolved optionally.

The sorts of the models are following.

Case A–0 : the main hull, only,
Case A–1 : the main hull and one layer of the deck house,
Case A–2 : the main hull and two layers of the deck houses, and
Case B–1, B–2 : the bulkheads are attached at the positions of the deck house ends for case A–1, and case A–2, respectively.

Further, the experiments are being still now excuted, for example, for the cases described below ;

Case : number of bulkheads are altered,
Case : positions of bulkheads are altered,
Case : length of the deck house is altered,
Case : stiffness of the upper deck is altered,
Case : transverse span of the house walls of the uppermost deck is shortened, and
Case : entrance holes in the house walls are opened.

In this experiments, models were bent by the concentrated load at the middle. And strains were measured by "SR–4" strain gage at the midsection (section A) and at the section near the house end (section C) and at the intermediate section (section B). The gages are attached to the both surfaces of the plate at the same positions, and at the side wall of the main hull and deck house wall the mean values on the both surfaces were read and at the deck the values on the both surfaces were measured separately to examine the effect by the deflection of the plate. Further, at the deck the transverse strains were measured, and at the lower part of the house wall rosette gages were used to get the shearing stresses. Dial gages were used to measure the deflection. The deflection of the side shell was measured at the upper deck regarding the unstrained upper deck line as a base line, and the deflection of the deck house was measured at the position of the wall side.

At first, on the joints of the main hull and deck house, the slip was observed, but by increasing the diameter of the bolts and using the binding agent "araldite cold setting adhesive type 101", this slip vanish completely. This binding agent was used successfully in the experiments after that.

The summary of the results of the experiments which have been excuted up to now is following.

Case A–0 (main hull only). In this case the measured longitudinal strains at the side plate vary linearly, and they accord fairly well with the strains calculated by the elementary beam theory. At the deck, strains were measured in two directions, but strains in the transverse direction were small, and the state of stress is able to be regarded as "uni-axial" condition. The effective breadth of the deck is naturally about 100 per cent of the actual breadth.

Case A–1, A–2 (main hull and deck house of one or two layers). In both these cases, since the trend of the stress distribution is similar, the following description will be made mainly for the case A–2. Fig. 7

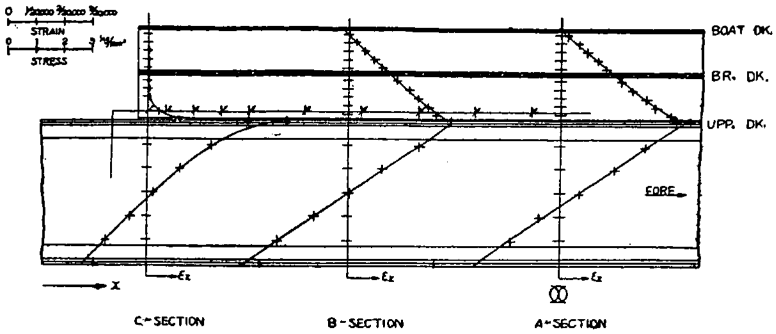

Fig. 7 Longitudinal Strain Distribution (Case A–2)

shows the longitudinal strain distribution at the side shell and deck house wall, and the shearing stress distribution at the lower part of the house wall. At the section A and B the longitudinal strains at the side shell follow the straight line closely, but at the section C the stress concentration occurs near the upper deck. Though the strain of the bottom at the section A is far remote from the strain predicted by following the straight line, it seems to result from the local distortion

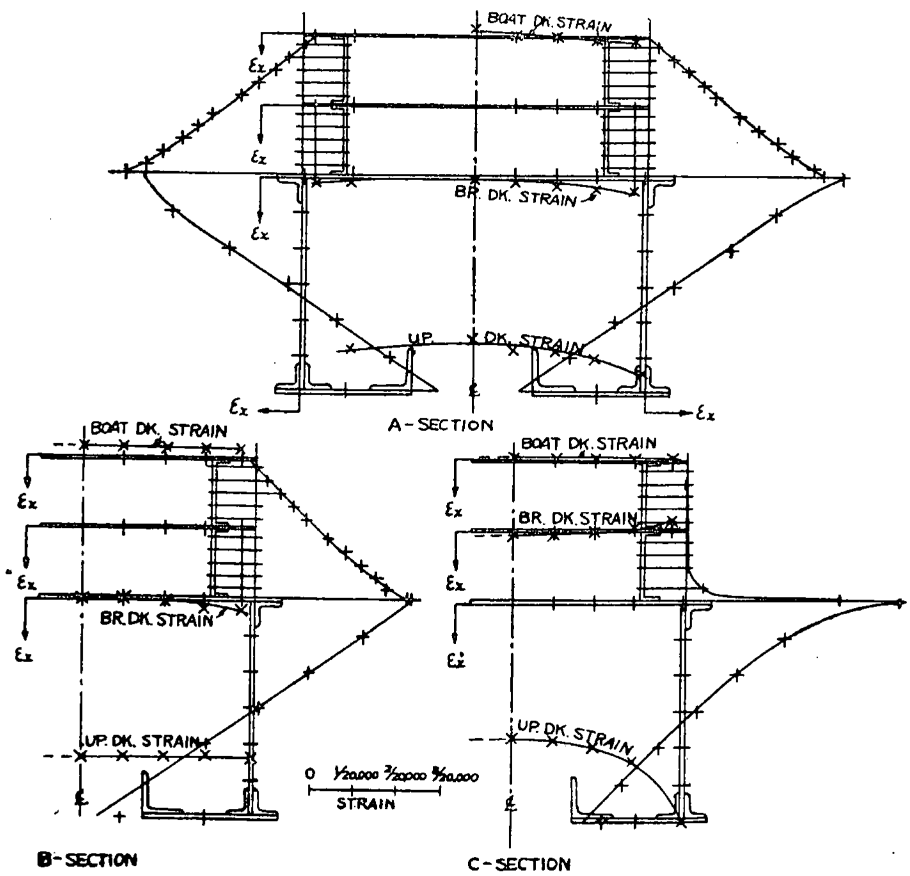

Fig. 8 Longitudinal Strain Distribution (Case A–2)

by the head of the jack and is of no significance. The chain line in the figure is the one for the case A-0. (At every test the model was loaded until the reading of the gage fitted at the uppermost of the side shell indicated the condition that the longitudinal strain was 3/20,000 at both surfaces). The longitudinal strains at the house wall follow the straight line nearly, showing the effect of the shear-lag slightly. In the case A, because the rigidity of the deck is small for lack of beams and bulkheads, the effectiveness of the house is small and the shearing stress at the lower edge of the house wall (τ_x) is small in spite of the house length reaching the half length of the ship. Fig. 8 shows the longitudinal strains at the section A, B and C. Fig. 9 shows the stresses and strains

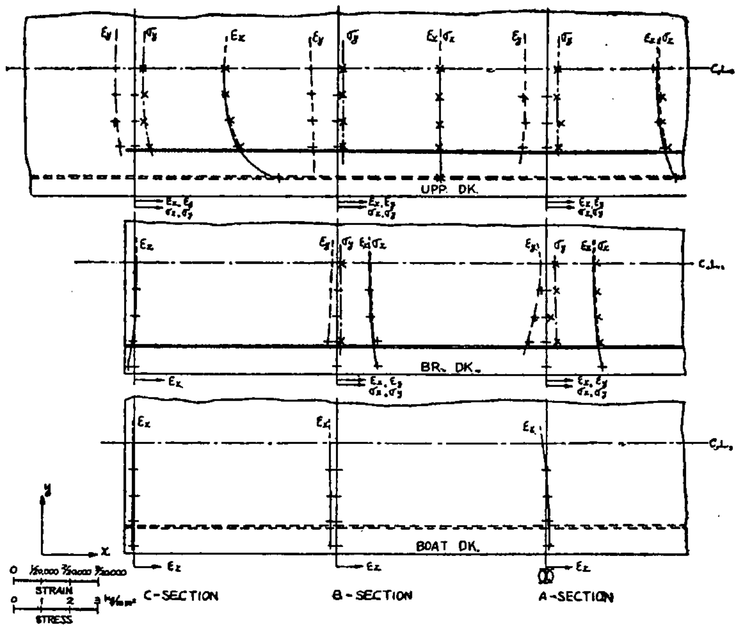

Fig. 9 Stress and Strain Distribution
σx, εx : Longitudinal Stress and Strain.
σy, εy : Transverse Stress and Strain.

at each deck. The values in this figure are the mean of the values at both surfaces of the plate. The difference of the measured strains at both surfaces of the deck is large both in longitudinal and transverse directions, especially on the upper deck, showing that the effects due to the deflection normal to plane of the plate are large.

Case B (bulkheads are fitted at the end of the deck house). In this experiment, the main hull is loaded upward at the middle, and the main hull tends to be bent in the hogging condition and the deck house structure in the sagging condition, if the rigidity of the deck is small. Bulkheads work to prevent the house from bending in the sagging condition by compelling the house the same deflection with the main hull. The deck house, pulled downward at both ends by the bulkheads, tends to act together with the main hull according to the intensity of the constraint. In the case B, the deck house is effective compared with the case A where the 'strains at the boat deck are nearly negligible. In the case B the strains at the boat deck are respectable, but still it bends in the sagging condition, showing that two bulkheads are not sufficient.

To compare the measured stresses with the stresses calculated in accordance with the "Bleich's theory", they are piotted in Fig. 10 for the case A-1 and A-2. The magnitude of the concentrated load, in applying the "Bleich's theory", was infered from the bending moment which was calculated from the measured strains at the section, and the stiffness factor was calculated on the assumption that the deck plate of

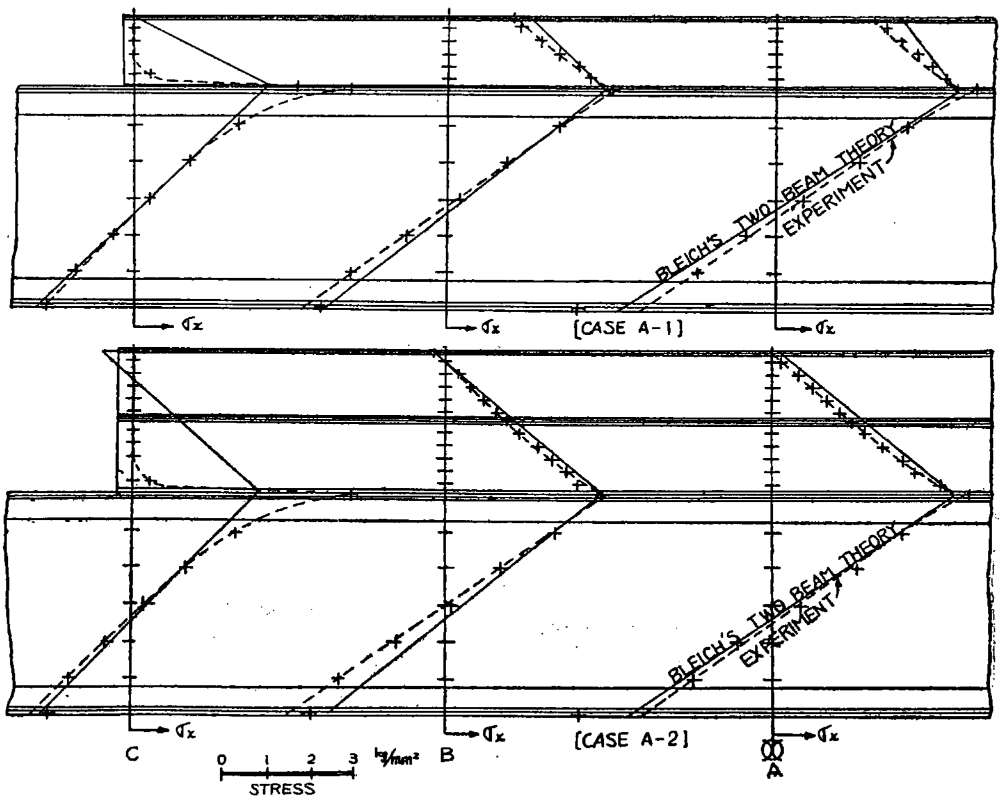

Fig. 10 Comparison of Theoretical and Experimental Stresses

unit length was considered as a beam fixed at both ends. At the section A and B, the measured stresses and calculated stresses agree fairly well with each other for the case A-2. The agreement is not so well for the case A-1. At the section C, the calculated stresses do not accord with the measured stresses naturally, because in the elementary beam theory the effect of the shear lag is not considered. The "Bleich's theory" is adequate besides the house end, when as in this case the deck house is long and the stiffness of the deck is uniform along the length.

As for the stress reduction defined in the chapter 2, $\eta_T=45.8\%$, $\eta_M=26.4\%$ and $\eta=57.6\%$ for the case A-1, $\eta_T=73.4\%$, $\eta_M=29.8\%$ and $\eta=40.6\%$ for the case A-2. In the case A-2, the "measured reduction" at the upper deck is large but the "superstructure efficiency" is small compared with the case A-1.

Chapter 4 Photo-elastic experiments and celluloid model experiments

Description stated above is mainly about the effectivity of the deck house. In this chapter, description is about the superstructure which is distinguished from the deck house by the definition that the side wall of the superstructure is in the plane of the side plate of the main hull, while the side wall of the deck house is not so. To research the effect of the superstructure on the longitudinal strength and the stress concentration at the discontinuous part of the structure, following experiments were excuted for the plate models.

a) Photo-elastic experiments

The loading apparatus and an example of the models are shown in Fig. 11. The type of the loading is uniform bending. The dimension

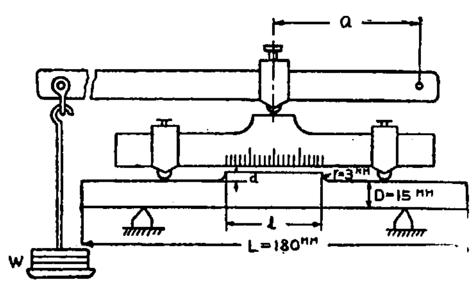

Fig. 11 Specimen and Loading Apparatus

of the models are following; length of the main hull $L=180^{mm}$, depth of the main hull $D=15^{mm}$, radius at the end of the superstructure $r=3^{mm}$ and length and height of the superstructure (l, h, respectively) are tabulated in Table 2 for each model.

For one example of the measurements, the stress distribution of the No. 2 model is shown in Fig. 12. The section A-A means the midship section, the section C-C is the section at the end of the superstructure

Table 2 Dimensions of Specimens

Specimen No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
d/D	0.25	〃	〃	〃	0.40	〃	〃	〃	〃	〃	0.666	0.80	0.15	0.30	0.45	0.60
l/D	2.0	3.5	5.0	6.5	1.2	1.5	2.6	4.0	5.33	2.0	〃	〃	3.6	〃	〃	〃

and the section B–B is the intermediate section. The section D–D is distant from the section C–C by the depth of the main hull D. At the section D–D of every model, the longitudinal normal stresses follow a straight line perfectly. At the section C–C, the trend of the stress concentration is seen at the upper part. The maximum stress occurs

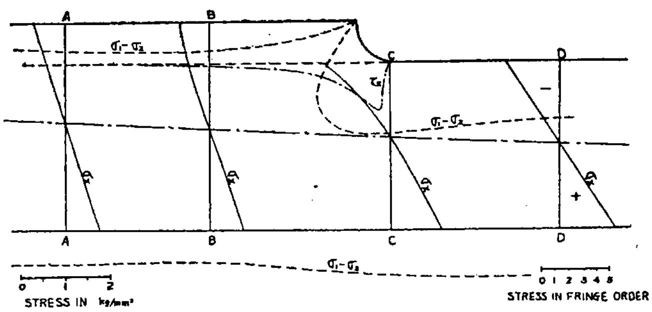

Fig. 12 Stress Distribution (No. 2 Specimen)

near the point C at the part of the arc, for every model. When the superstructure is sufficiently long the longitudinal stresses at the midship section follow a straight line, while when the length of the superstructure is not sufficient the longitudinal stresses follow such a curve as shown at the section B–B of Fig. 12 and the stress at the top does not reach the value predicted by the elementary beam theory. The shearing stresses τ_x along the connecting line between the main hull and the superstructure, are plotted by the chain line in Fig. 12. The value of τ_x

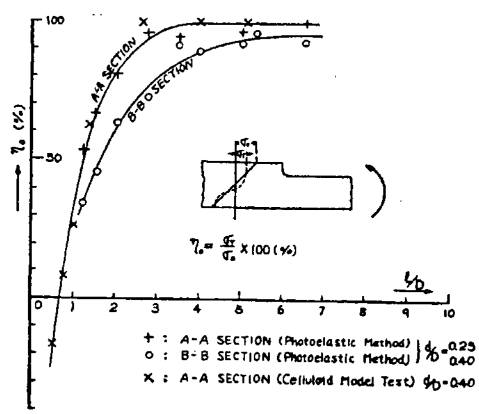

Fig. 13 Top Deck Factor

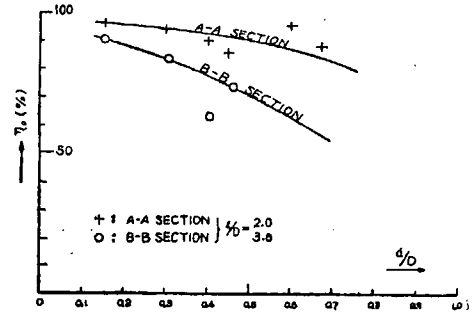

Fig. 14 Top Deck Factor

is zero at the end and increases abruptly reaching the maximum near the end, and thereafter decreases gradually to zero at the middle. The higher the superstructure is, the larger the value of τ_s is. The normal stresses σ_y in the direction of the ship depth along the connecting line which are not shown in the figure, are compressive at the ends and tensile at the middle. This means that the superstructure is prevented from distorting in the opposite curvature to the main hull. The dotted line in the figure shows the difference of the principal stresses σ_1, σ_2 at the edge.

To research the effect of the superstructure on the longitidinal strength, "top deck factor" η_0 and "stress reduction" η_M are computed. Fig. 13 shows the relation between η_0 and l/D, and Fig. 14 shows the relation between η_0 and d/D. From Fig. 13, it is pointed that the stresses at the midship are able to be predicted almost perfectly by the elementary beam theory when l/D is above 3, while the stress at the top level takes the opposite sign to the stress predicted by the elementary beam theory when l/D is under 0.7; (this discussion is for the case that

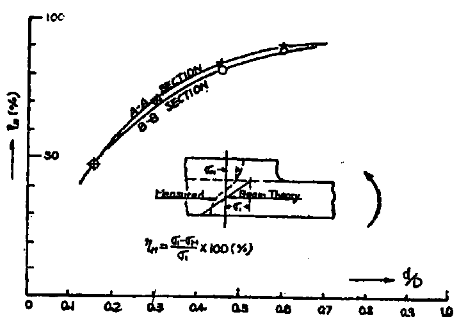

Fig. 15 Stress Reduction

$d/D=0.25\sim0.40$). Moreover, in Fig. 13 the results of the celluloid model experiments are shown at the same time. From Fig. 14, it is seen that the larger the height of the superstructure is, the lower the value of "top deck factor" is, and for $l/D=2.0\sim3.6$, the stresses of the midship section do not follow a straight line perfectly unless d/D is under 0.1. The values at the section B–B are usually under the values at the midship section as for "top deck factor." "Measured stress reduction" η_M is plotted on the base of d/D as shown in Fig. 15. In the range of the dimension of the models, η_M is independent on l/D and η_M is about 65 % at the section A–A and B–B. The stress concentration factor is about $1.2\sim1.5$ by the experiments and its relation for l or d can not be get.

b) Celluloid model experiments

The loading apparatus and the model are shown in Fig. 16. The type of loading is uniform bending. The dimension of the models are following ;

Length of the main hull L=680^{mm}, depth of the main hull D=60^{mm}, height of the superstructure d=24^{mm}, radius at the end of the superstructure r=6^{mm} and length of the superstructure l is tabulated in Table 3 for each model.

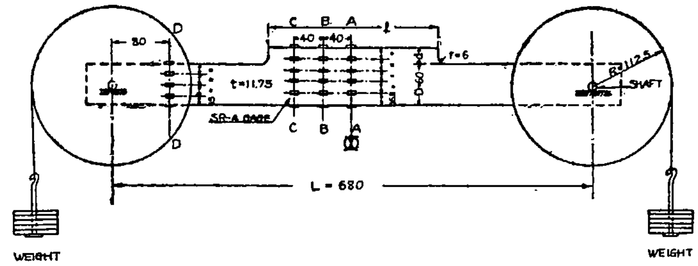

Fig. 16 Celluloid Model

Table 3 Dimensions of Specimens

Specimen No.	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
l(mm)	310	240	160	80	60	44	30
l/d	12.9	10.0	6.67	3.33	2.50	1.83	1.25
l/D	5.17	4.00	2.67	1.33	1.00	0.73	0.50

The positions of the strain measurements are shown in Fig. 16. The section A–A is the midship section, the section B–B is apart from

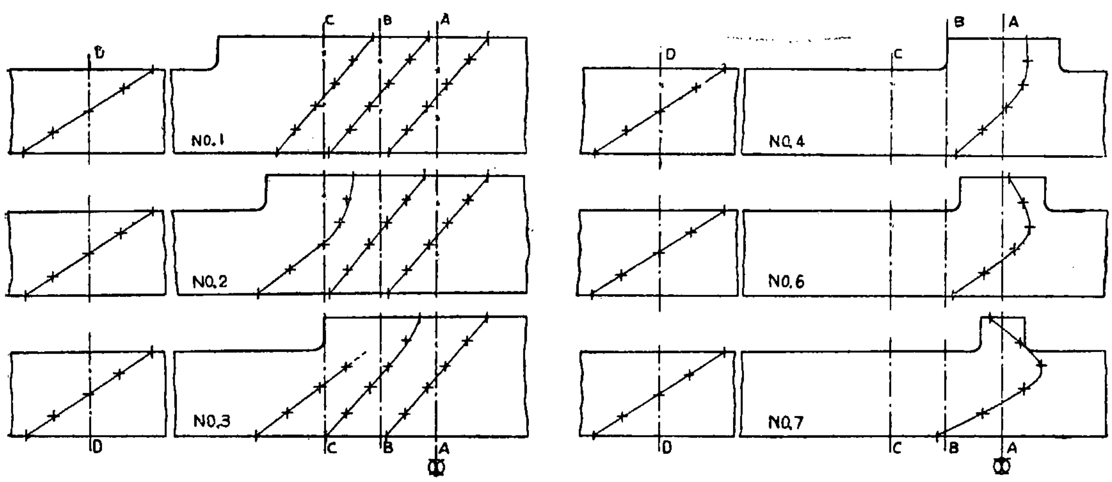

Fig. 17 Strain Distributions

the section A–A by 40^{cm}, and also the section C–C is apart from the section B–B by 40^{cm}. The section D–D is far away from the end of the superstructure. The strain gages was fitted at both surfaces of the plate. Fig. 17 shows the longitudinal strain distribution. As for the section A–A, the strains follow a straight line on No. 1, No. 2 and No. 3 models, respectively, while on No. 4 model they begin to follow a curved line and at last on No. 7 model the strain at the top edge comes to show the opposite sign. As for the section B–B the strains begin to curve on No. 3 model. As for the section C–C they begin to curve already on No. 2 model. "Top deck factor" at the section A–A coincides with the one by photo-elastic experiments as shown in Fig. 13.

Chapter 5 Summary

The results of the research by this committee were described above briefly. But experiments are now being excuted for some part of the research and the numerical analysis is also still being carried on. Therefore synthetic conclusion has not yet been obtained. The results of the individual experiments are following.

At the experiments of "Brazil Maru", "measured stress reduction" η_M is 37.5 % and "superstructure efficiency" η is 58.3 %. These figures mean that the deck house of "Brazil Maru" does not work effectively in spite of its respectable length. Moreover, since the lower bridge deck of this ship is beyond 2/3 of the ship length long, the structure under the lower bridge deck level may be considered to work together as a simple beam and this deck is to be considered as an effective strength deck. The measured stresses coincide fairly well with the stresses computed according to the "Bleich's theory", both for the actual ship and the model experiments. But the application of this theory to an actual ship still requires the re-examination. This theory seems to be adequate only when the length of the deck house is sufficient and the stiffness of the deck is invariable along the length.

The effect of the dimension of the superstructure on the "top deck factor" and "stress reduction" was researched by the photo-elastic experiments and the celluloid model experiments. According to the results of these experiments, the stresses of the midship section follow the straight line up to the top of the structure, if

$l/D > 3$ for $d/D = 0.25 \sim 0.40$ or, if

$d/D < 0.1$ for $l/D = 2.0 \sim 3.6$

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