Strength of Ships.

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Introduction.

Having been attached for 30 years in the Glasgow School of Naval Architecture in the University and having been for many years a Honorary Member of your Society, it has been my desire to contribute something of interest on your Twenty-fifth Anniversary. My many friends in Japan will I hope understand why I ventured to hope that I might be able to give something of interest and value to their transactions. The decision to offer a paper was made under repeated representations from the Council of the London Institution of Naval Architects that a paper should be given to the Japanese Institution. Pressure of work and uncertainty of time of completing it prevented me making the attempt to meet the wishes of the London Institution, but with a view to the possibility of being able to give a paper I instructed Dr. Robb, formerly Assistant to me in Glasgow University, and now a member of my Firm's staff, to prepare some notes on the subject of The Development of the Strength of Ships During the Last Thirty Years, especially covering the subjects of study in the University of Glasgow which bear on the strength of ships. This subject has been made one of special interest and we are not without reasons to believe that the Glasgow School is not behind any other school in its knowledge of this branch of Naval Architecture. Dr. Robb has done much more than collect notes for my treatment of the subject but has written an illuminating contribution, which though primarily intended for my assistance in preparing the paper appears to me to give so much more than I could give in the time that I cannot improve upon it. I, therefore, submit for your consideration that this paper be taken as it stands as a contribution from the Glasgow University School, up to the time that I left it; to the Japanese Institution of Naval Architects, for their favourable consideration.

J. H. Biles.

Historical and General.

Development in the application of theories of structures to the problem of the strength of ships may not unreasonably be likened to the survey and opening-up of new territory. But the survey and opening-up has not been a continuous process in which every advance has been made with a full knowledge of previous surveys; it has rather been a spasmodic process, with long intervals of time between successive new ventures, intervals of time during which the results of previous surveys have been lost or forgotten, so that paths "into the jungle" have become completely overgrown and have been opened up afresh in ignorance of previous surveys and of whether the paths so reopened seem likely to lead to the summit of knowledge or merely deeper into the jungle. The purpose of this paper is to make a record of the explorations that have been made, to link up, as far as possible, their results, and then endeavour to indicate the directions and character of further efforts.

So far back as the middle of the 18th Century attempts were made to determine the character of the forces tending to change the shape of ships and Bouguer's work offers the first indication of the graphical illustration of the variation of weight and buoyancy throughout the length; no attempt was made to plot accurate curves of weight and buoyancy, but the idea that forces were set up by local inequalities of weight and buoyancy seems undoubtedly to have been present in Bouguer's mind. Following on Bouguer's work Euler developed the consideration of the bending moment at a section, the bending moment being the difference between the moments, about the section under consideration, of the upward force of buoyancy and the downward force of weight. In passing, it is worth noting that Euler includes in the bending moment a component moment arising from the horizontal pressure of the water on the portion of the ship on one side of the section at which the bending moment is taken; it was evidently thought that such a moment was involved in the consideration since the ship does not break asunder under the moments due to the vertical forces mentioned. And so it would seem that Euler confused the moment of the external forces at a section with the moment of the internal forces set up in resistance to the external moment. Although Euler subse-

quently left out of account the moment due to the horizontal component of water pressure it reappears for a time about a century after his investigations and is discussed in some of the early considerations of the strength of iron ships. Then in the early days of the 19th Century Dr. Young presented before the Royal Society of Great Britain the result of an investigation into the effects of unequal distribution of weight and buoyancy throughout the length of a ship. In this work there is found the first indication of a curve of "loads." Dr. Young's curve of loads was not obtained graphically from the curves of weight and buoyancy but was obtained by taking the difference between weight and buoyancy for a number of section of finite length along the ship; hence the curve does not show so many irregularities as a modern curve of loads.

The problem of the strength of ships does not again become prominent until about the middle of the 19th Century. By that time iron ships were being built whose lengths were up to, and even beyond, the limit of length which had been reached for wood ships; and concurrently with the development in material of construction there had been a development in form, the bluff bows of the wood sailing ship having given way to the very fine bows deemed advantageous for mechanical propulsion. But these developments had not been accompanied by a general understanding either of the forces acting on the structure or of the means of resisting the disruptive effects of the forces; and so there were many instances of defective construction.

The following quotations throw light on an interesting stage in the development of the consideration of the external forces acting on the structures of ships.—

"We look, then, for examples to see where iron ships have most frequently shown weakness. My own observation leads me to the conclusion that at the gunwale and sides, amidships and at the hollow ends below the water-line, these indications are most generally to be observed: the former is indicated by open seams, broken rivets, and fractured stringer plates; the latter by a continual compression and expansion of the side plates as the pressure varies, when the ship plunges into or emerges from the sea in bad weather."*

"....it is important that the strength of a ship should be distributed with equality

* Grantham. On the Strength of Iron Ships. Trans. I.N.A., 1860.

throughout; it will also be evident that the weight of the ship as well as of the cargo should be distributed with reference to the form of the hull, and the consequent buoyancy which has to sustain each portion of it. Nothing can be more injudicious than the plans which are often to be seen in regard to this subject, and may be observed very strikingly in some of our long fine ships, where the weight of forecastle, bowsprit, anchors, chains, etc., is placed without reference to the amount of buoyancy under them. The immense leverage thus occasioned acts immediately on the midship body of the ship, and is no doubt the origin of derangements frequently ascribed to other causes. I mention this here as being especially applicable to iron ships, in which fulness of form has been carried to a much greater extent than in wooden ships.”*

“If we take a vessel . . . we shall approximate nearly to the facts by treating it as a simple beam; actually a vessel is placed in this position, either when supported at each end of the waves or when rising on the crest of another wave, supported at the centre, with the stem and stern partially suspended. Now in these positions the ship undergoes alternately a strain of compression and a strain of tension along the whole section of the deck, corresponding with equal strains of tension and compression along the whole section of the keel, the strains being reversed according as the vessel is supported at the ends or the centre. These are, in fact, the alternate strains to which every long vessel is exposed, particularly in seas where the distances between the crests of the waves does not exceed the length of the ship.”†

Thus it is evident that, so far as external forces are concerned, there was not any considerable development in the Century that had elapsed after the date of Bouguer's investigation. There was still the same uncertain groping after a quantitative expression of the effects of inequalities of weight and buoyancy; and Dr. Young's work seemed almost to have passed into oblivion, although a passing reference was made to it in 1866 in a discussion on “Safety of Life at Sea” at a meeting of the Institution of Naval Architects.

* Grantham. On the Strength of Iron Ships. Trans. I.N.A., 1860.

† Fairbairn. On the Strength of Iron Ships. Trans. I.N.A., 1860.

But while endeavouring to give quantitative expression to the external forces acting on the structures of ships consideration was given also to the internal forces. Fairbairn in 1860 investigated the sufficiency of the structure of an iron ship by means of the "beam" formula

$$W = \frac{a.d.c.*}{1}$$

where a=area of material in deck and for six feet down the sides.

d=effective depth of girder; this is really the "lever arm" of the internal couple, the distance between the centre of "pull" force in the deck and the centre of "push" force in the bottom.

c=a constant, taken to be 60 on account of the joints being only double riveted.

l=length of ship.

W=permissible load.

Fairbairn's application of the expression is open to question, but the expression itself is not incorrect; it may be written

$$\frac{W.l}{c'} = p \times a.d,$$

if c is replaced by ($c' \times p$).

$\frac{W.l}{c'}$ represents the bending moment, or external moment; and ($p \times a.d$) represents the moment of the stress, or internal moment, if p represents the unit stress.

But even if Fairbairn's application of the expression above is open to question his deduction was sound. At the date of his investigation there was a decided tendency to keep down the amount of iron in the upper part of ship structures on account of stability considerations, so that the structures were totally unfitted to resist "hogging" moments. It was to this defect that Fairbairn directed attention and his views are summed up in the following sentence:

"Hitherto I have contended for equal sections at the top and bottom; but cases may arise where stronger bottoms are necessary, as in screw steamers which take the ground, but in other cases, the nearer the deck and bottom approach each

* Fairbairn. On the Strength of Iron Ships. Trans. I.N.A., 1860.

other in sectional area the better.”*

The first indication curves of weight and buoyancy for iron ships is found in the Transaction of the Institution of Naval Architects for 1869†; and by the early 'seventies the graphical representation of the variation of weight and buoyancy had developed into the graphical determination of curves of shearing force and bending moment. The erroneous addition of a bending moment due to the horizontal component of water pressure was revived in some of the early strength calculations. Further, the weight curves were not plotted in detail as is now the case; there were only two items considered—"hull" and "equipment"—the weight of each item being calculated for a series of definite fractions of the length of the ship, so that the curves were much more regular than present-day curves. In general, apart from the two matters mentioned, the method of calculation was the same as it is today.

The determination of curves of shearing force and bending moment was soon followed by an attempt to evaluate the effects of the bending moment on the structure and in the Transactions of the Institution of Naval Architects for 1872 there are complete calculations for the "modulus of section", or $\frac{I}{y}$, with deductions for rivet holes and with the wood deck considered in terms of its equivalent area of iron‡; indeed the calculations are carried out exactly as in present day practice.

The increasing considerations given to curves of shearing force and bending moment and the desire to compare ship with ship led in time to the adoption of "standard" conditions for the calculation so that all comparisons should have a common basis. But it took about ten years from the introduction of curves of shearing force and bending moment until the need for a "standard" ratio of wave-height to wave-length was fully realized§; and it took a further ten years before the desirability of investigating the worst possible conditions of loading was brought into prominence.||

Soon after the introduction of strength calculations as they are now made the desir-

* Fairbairn. On the Strength of Iron Ships. Trans. I.N.A., 1860.

† Reed. On Long and Short Iron-Clads. Trans. I.N.A., 1869.

‡ Scott. On a New System of Longitudinal Shipbuilding. Trans. I.N.A., 1872.

§ Rundell. Freeboard and Displacement in Relation to Strains in Ships among Waves. Trans. I.N.A., 1881.

|| Denny. Some Notes on the Strength of Steamers. Trans. I.N.A., 1892.

ability of investigating the stresses in the inclined condition was raised *; but twenty years elapsed before the work was undertaken. And the results were such as to indicate that there is no need to consider this state of affairs; while the fact that the ship is inclined increases the stress for a given bending moment the inclination itself can only as a general rule arise from the course of the ship being inclined to the waves instead of normal to them, so that the bending moment must be reduced.

The effects of the ship actually being in motion amongst the waves, and not poised on the crests, was also raised as a subject for consideration in the early days of strength calculations, and the effect of heaving was fully treated at a fairly early stage in the development of the consideration of the strength of ships. But here again the results of investigation show that the calculation is not one that need ever be made again, for the character of the effect in any particular case is not such as to vary the character of the statical results; the effect of heaving certainly does affect the statical results quantitatively but not to such an extent as to bridge the wide gap between present day calculated stress figures and the actual breaking stress of the material of construction.

The effects of pitching have not been treated so fully as the effects of heaving and it is not at present possible to state that this effect also may be rejected from consideration. Certainly such results as have been published indicate that the effect of pitching is shown more by an increase in *local* loading than by any change of shearing force or bending moment.

Finally there is the consideration of the structure of the wave known as the "Smith" correction.† Here again is a case in which quantitative effects can not be determined, but only qualitative effects; and the effects are such as to reduce the shearing forces and bending moments obtained on the assumption that the ships are momentarily at rest on waves in which the variation of pressure is hydrostatic.

Reverting now to the consideration of the effects in the girder of forces applied on the girder it is patent that there has been no change in the method of determining the internal "moment of resistance" to bending; the calculation of this quantity is

* John. On the Strength of Iron Ships. Discussed by Wm. Froude. Trans. I.N.A., 1874.

† Smith. Hogging and Sagging Strains in a Seaway as Influenced by Wave Structure. Trans. I.N.A., 1883.

carried out today on the same lines as the calculation made in 1872 and referred to above. But the stresses associated with bending moments do not *comprise* all the effects of the forces arising from local inequalities of weight and buoyancy. The stresses associated with shearing forces must also be brought under consideration. There are indications that this was done in the last days of wood shipbuilding in an endeavour to account for the "spewing" of oakum from the seams in the region of the bilges and the "rolling" of the copper sheathing in the same region. But no results of the investigation were published and the consideration of "shearing stresses" was not brought into prominence until 1890 when Prof. Jenkins discussed the subject before the Institution of Naval Architects.* Since that date the consideration of shearing stress on a ship structure has been developed only by Dr. Suyehiro before your Society.

It has been pointed out that so far back as 1860 Fairbairn indicated the desirability of placing material at the top of the ship girder; and the necessity for doing so was emphasized in 1872 in these words:—

"It also holds . . . that the level of the topmost deck is the right position for placing the stringers which are used to give longitudinal strength."†

Practice, however, lagged behind these principles, and at the time when Prof. Jenkins read his paper on shearing stress it was common to find the heavy material disposed at the second deck instead of at the first deck, and Prof. Jenkins' results were invoked in support of the custom. Actually, however, there was a serious error in these results in regard to the shearing stress at a deck. The general character of the shearing stress at a deck is shown in Fig. 2 of Dr. Suyehiro's contribution to Vol. XXIX of your Journal; and it is shown that the presence of a deck increases the shearing stress on the shell plating at the deck. Prof. Jenkins, however, considered that the presence of a deck reduced the shearing stress very considerably, his argument being that b in the expression $q = \frac{F.A.\bar{y}}{b.I}$ was the breadth of the ship at the deck. In the discussion on Prof. Jenkins' paper this incorrect interpretation was questioned, although the incorrectness was

* Jenkins. On the Strength of Ships with Special Reference to the Distribution of Shearing Stress over a Transverse Section. Trans. I.N.A., 1890.

† Scott. On a New System of Longitudinal Shipbuilding. Trans. I.N.A., 1872.

not actually demonstrated until a much later date ; but the fact that Prof. Jenkins' results were not quite correct was not generally realized, and the reduction of stress at the deck shown by him was thought to justify the rejection of the principles of distribution of material shown by consideration of the expression for "moment of resistance."

In passing, it may be worth emphasizing that shearing force and bending moment are not separate and distinct causes, nor are shearing stress and bending stress separate and distinct effects of the respective causes. The custom of considering these causes and effects as if they were independent seems to be a legacy from the early days of strength calculations ; and it is to some extent justified by the fact that the visible signs of shear stress do not seem to be so numerous as the visible signs of bending stress. The truth is, however, that shearing force and bending moment are merely components of the resultant action which is termed "flexure," the investigation of the component actions being the only way in which the combined action may be treated. Likewise shearing stress and bending stress are only component effects, the investigation of the components being the only one so far found possible and of practical value.

Turning now to the consideration of transverse strength it would seem that this branch of the general subject of strength of ships was, in the early days of iron ships, rather neglected ; an explanation of the neglect is contained in the following quotation from a paper read before the Institution of Naval Architects in 1862 :—

"It might . . . be supposed that a ship was weakest across, and that the strains tending to break a ship crossways, or athwartships, were manifold greater than those tending to break her through the middle by forces acting at her ends and straining her lengthways. But it is notorious, on the contrary, that iron ships of this (transverse) construction have often broken across the centre and that the ends have parted from the middle, shewing weakness lengthways ; whereas, rarely, if ever, has the starboard side of a ship parted from the larboard, or the topsides from the bottom, showing transverse weakness."*

The rather restricted field of vision indicated in these words was not favourable to a

* Scott Russel. On the Longitudinal System in the Structure of Iron Ships. Trans. I.N.A., 1862.

consideration of the problem of strength of ships as a whole; but increasing experience of iron ships, and increasing consideration given to their structural arrangements, brought about, not a widening of the field of vision, but at least a change in the direction of vision. So in due course the following opinion was expressed:—

“In most of the scientific investigations that have been published in recent years as to the strength of iron ships, and the strains to which they are subject, attention has been directed almost entirely to the features of the ship when viewed as a girder. I am not sure that in pursuing the question of longitudinal strains so exclusively as has been done, there is not a tendency to magnify the importance of the girder theory and I am sure I speak in accordance with the experience of those who have had the best opportunities of forming a judgment on the subject when I say that straining at sea is oftener due to transverse or local weakness than to deficiency of longitudinal strength.” *

Attention was thus directed to the desirability of investigating the transverse strength of ships; and in 1882 the first quantitative treatment of the subject was contributed to the Transactions of the Institution of Naval Architects by Messrs. Read and Jenkins.† Their method of attacking the very complicated problem presented by the action of the forces on, and in, the transverse framing of a ship is exceedingly interesting as an illustration of the determination of the moment and force acting at a point from the condition that their effect at the point must be of a certain character, the magnitude of the effect being quite unknown.

Taking the case of a ship in dry-dock supported on a line of keel blocks, and considering a “frame-ring” remote from bulkheads Read and Jenkins started with the condition that a point on the bilge there must be in operation a moment and a force, the moment exerted by the floor on the frame being equal and opposite to that exerted by the frame on the floor, the vertical and horizontal components of the force being in the same way equal and opposite, and the effect of the moment and component forces on the frame being such that only the *slope* at the point is changed, the presence of the

* John. On Transverse and other Strains of Ships. Trans. I.N.A., 1877.

† Read and Jenkins. On the Transverse Strains of Iron Merchant Vessels. Trans. I.N.A., 1882.

floor preventing horizontal motion of the lower end of the frame. The limitation that the deflection of the frame is zero made it possible to determine the horizontal component force for any chosen values of the vertical component force and the moment.

Actually Read and Jenkins chose two values of the vertical component force, and for each of these values a series of values of the moment; from the limitation as regards deflection they calculated the values of the horizontal component force corresponding to the assumed values of the vertical component and the associated values of the moment. For each set of three associated values they calculated the slope of the frame at the bilge, and then plotted two curves of change of slope, relatively to the vertical, on a base of moment, one curve for each assumed value of the vertical component force.

Turning to the consideration of the floor, Read and Jenkins plotted, on the same base line as for the slopes of the frame, two curves of slope relatively to the horizontal for the two values of the vertical component force assumed for the frame, using throughout the relations between vertical and horizontal component forces and the associated moment found from the consideration that the deflection of the frame should be zero. A further condition then became of importance, namely, that the change of slope of the frame at the point on the bilge under consideration must be the same as the change of slope of the floor; and so two sets of values of the moment and component forces were determined from the intersections of the two sets of plotted curves of change of slope.

It remained, then, to determine the actual moment. The first step was the determination of the deflections of the floor for the two sets of values of moment, vertical component force, and horizontal component force, these values of the deflection were plotted on the same base line as the curves of slope. There was then the consideration that the vertical force on the floor at the keel blocks must be twice the vertical component force plus the weight of the floor; the vertical force on the floor is the whole weight of the "frame-ring," or the whole thrust of the keel blocks, for part of the thrust of the keel block, is transmitted by way of the pillars to the deck beams and is borne by them. So that there were two values of the deflection associated with two values of the upward thrust on the floor; and the values of the upward thrust were plotted on a base of deflection. For each tier of deck beams the

upward thrust necessary to produce the two deflections of the floor were calculated, and the various thrusts superposed on the curve of thrust on the floor. Thus the topmost curve became a curve of total upward thrust of keel blocks, or weight of the "frame-ring," on a base of deflection of floor; and since the actual weight of the "frame-ring" could be calculated the position of the ordinate of the curve corresponding to this actual weight gave the actual value of the deflection of the floor.

But for this actual deflection of the floor the corresponding upward thrust *borne by the floor alone* was determinable from the first plotted curve of upward thrust; and so the actual vertical component force acting on the floor at the bilge was determined. Then, turning to the curves of deflection of the floor on the base of moment, the value of the moment at the bilge corresponding to the actual deflection was determined. Finally from the relation connecting the horizontal component force with the other two associated quantities the horizontal component force was determined.

In this way the system of moment and forces acting at the bilge was determined and hence the moment acting at every point between the lowest beam knee and the centre-keelson.

The investigation made by Read and Jenkins is limited in scope; it is restricted to the case of a ship in dry-dock, although the ship may be "light" or loaded; it gives results only for the portion of the structure below the lowest beam knee; and it does not seem to be applicable in cases where there are "wing" pillars. But the investigation brought to light the very important fact that it is possible to strengthen a floor by stiffening the frame connected to it; in effect, the stiffening of the frame causes it to accept an increased burden and correspondingly reduces the burden on the floors. This principle underlies the fitting of web frames in machinery spaces.

The subject of transverse strength was not investigated again for nearly 20 years, Bruhn's earliest work on transverse strength having been published in 1901.*

Bruhn's investigations were carried out by the application of The Principle of Least Work, an elegant method permitting of the consideration of every conceivable variation of

* Bruhn. The Transverse Strength of Ships. Trans. I.N.A., 1901, also Some Points in Connection with the Transverse Strength of Ships. Trans. I.N.A., 1904.

loading and structural arrangement but a method whose description would be out of place here, even if it were necessary.

Bruhn's investigations cover a wide range of variations in loading and in structural arrangement, and from the results it is possible to deduce some general principles. For example, the addition of a tier of beams to a single-deck ship not only tends to a reduction in the bending moment on the frames but tends also to a reduction in the bending moment on the upper deck beams. That this should be so is obvious when it is considered that the bending moment on the upper deck beams is in part due to the bending moment on the frame being transmitted round the gunwale by the beam knee; the addition of a tier of beams reduces the bending moment on the frame and so affects the upper beam. This is actually borne out in practice, as is shown by Registration Society regulations.

As regards the effect of position of hold pillars it is shown, as might be expected, that the bending moment acting on the floors at the centre-line is greater when there are two rows of pillars than when there is only a centre-line row. The difference is not great in the cases treated, namely, the cases of closely spaced pillars. But the small difference actually traced indicates the probability of a considerable difference between the bending moment on the floor of a ship with widely-spaced columns and the bending moment on the floor of a similar ship with a centre line row of closely-spaced pillars. In practice no discrimination is made between such cases, the scantlings of floors being determined without regard to pillaring arrangements; but the desirability of discrimination may well be borne in mind.

Bruhn's results confirm the truth of the principle established by Read and Jenkins, namely, that it is possible to strengthen a floor by stiffening the associated frame. And both sets of investigators agree in placing no structural value on side stringers. Practice has now come into line with theoretical investigation in the matter of side stringers, albeit only recently; but even the most recent theoretical considerations have lost sight of the inter-relation of frame and floor stiffness.

The Application of Existing Knowledge.

Quantitative application of existing knowledge is confined in practice to the calculation of the bending, or, more properly the longitudinal, stress from the expression $p = \frac{M \cdot y}{I}$. The quantity M , the bending moment, is determined for the ship poised momentarily on the crest, or across the trough, of a wave whose length is the same as the length of the ship and whose height is one-twentieth of the length; the pressure in the wave is assumed to be hydrostatic; and the ship is assumed to be loaded with cargo but having all coal, fresh water, and stores, carried amidships for the "hogging" condition and all fresh water, stores, etc., carried in the ends consumed for the "sagging" condition. So that the bending moments are calculated for the worst conditions of loading, subject to the reservation that these conditions are actually possible. These conditions of loading and the associated position of the ship on the wave are taken as "standards"; and the stress p is determined for the "standard" condition.

There is not, and should not be, however, a standard value of the longitudinal stress. Thicknesses of plating adopted in practice always embody a margin against the possibility of reduction as the result of corrosion; and this margin is constant in amount for all scantlings. Hence in large ships the margin forms an appreciably smaller proportion of the thickness than it does in small ships; and on this account the stress figure p is greater for large ships than for small ships. Further, the larger the ship the less frequently does she encounter waves of her own length; and so the fewer are the alternation of maximum stress. Hence on this account also is it reasonable to adopt higher stress figures for large ships than for small ones. Finally, observation of waves shows that the heights of waves commonly encountered are not strictly proportional to their lengths, the ratio of height to length being less for long waves than for short waves. Since the "standard" bending moment calculations are based on a constant height-length ratio for the waves they give bending moments which are, for long ships, excessive, and compensation for excess of bending moment is obtained by working to an increased stress figure.

It is, therefore, obvious that there should be a relation connecting the length of ship and the permissible stress figure. Such a relation can be derived from the investigations.

of the British Load Line Committee.* In order to arrive at a standard of longitudinal strength the Committee prepared midship sections for a large series of ships of varying dimensions, the scantlings being taken from the rules of the principal Registration Societies. For each midship section the quantity $\frac{I}{y}$ was calculated, and the values so obtained were plotted on suitable bases and cross-faired. From the various curves it was possible to arrive at a standard of longitudinal strength, as expressed by $\frac{I}{y}$, for ships of any size within the limits of the investigations. This standard is given by $\frac{I}{y} = f.B.d.$ where B is the breadth of ship, d is the draught, and f is a factor varying with length.

Now for similar ships differing in dimensions

$$M \propto L^2.B.d.$$

$$\text{and } \frac{p}{y} = \frac{M}{I}, \text{ or } \frac{M}{p} = \frac{I}{y};$$

$$\text{whence } \frac{I}{y} \propto \frac{L^2.B.d}{p}.$$

Comparing this expression with that adopted by the Load Line Committee it is seen

$$\text{that } f \propto \frac{L^2}{p} \text{ or } p \propto \frac{L^2}{f}$$

In the table below, the length of ship is given in Cols. 1, the corresponding value of f, as given by the Load Line Committee, in Cols. 2, and the value of $\frac{L^2}{f}$ (actually $\frac{L^2}{10,000 f}$) in Cols. 3. The quantity $= \frac{L^2}{10,000 f}$ may be termed the "Stress Factor."

1. Length of Ship. Ft.	2. f.	3. Stress Factor	1. Length.	2. f.	3. Stress Factor.	1. Length.	2. f.	3. Stress Factor.
100	2.00	.50	280	6.90	1.14	460	15.70	1.35
120	2.25	.64	300	7.70	1.17	480	16.80	1.37
140	2.60	.75	320	8.60	1.19	500	18.00	1.39
160	3.00	.85	340	9.50	1.22	520	19.20	1.41
180	3.50	.93	360	10.50	1.23	540	20.40	1.43
200	4.00	1.00	380	11.50	1.26	560	21.70	1.45
220	4.60	1.05	400	12.50	1.28	580	23.10	1.46
240	5.30	1.09	420	13.50	1.31	600	24.60	1.47
260	6.10	1.11	440	14.60	1.33			

* Abell. Some Questions in Connection with the Work of the Load Line Committee. Trans. I.N.A., 1916.

These values of Stress Factor express the results of Registration Society experience as far as variation of permissible stress with length is concerned; but they do not make any allowance for variation in type. Suppose, however, it is necessary to determine the scantlings of a ship 400 feet long, and that for an earlier ship of the same type, say 350 feet long, a strength calculation gives a stress figure of 7 tons per sq. inch. The value of the Stress Factor is 1.28 for 400 feet length and 1.23 for 350 feet length. The stress which may be worked to in the design of the 400 feet ship is then, $7 \times \frac{1.28}{1.23} = 7.3$ tons per sq. inch. The Stress Factors may be used in this way for all types of ships; but the strength calculation for a new design must always be made on exactly the same lines as the earlier calculation used as a basis, and it is permissible only to compare similar types of ship for similar service. In brief, all results are only comparative, not absolute; therefore the basis of comparison must be the same.

The Stress Factors may be applied also to the consideration of the variation of scantlings with dimensions initiated by Wm. Froude.* The three principal cases are:—

- (1) Length altered, other dimensions unchanged.
- (2) Breadth ,, ,, ,, ,,
- (3) Depth ,, ,, ,, ,, but draught varying as depth.

These three cases may be treated separately: but their results can be combined in any desired manner.

(1) *Length altered.* The lengths L_1 and L_2 correspond to Stress Factors F_1 and F_2 and to stresses p_1 and p_2 .

$$M \propto L^2, \text{ whence } \frac{M_1}{M_2} = \frac{L_1^2}{L_2^2}$$

$I = A.k^2$, A being the sectional area of the longitudinal material and k its radius of gyration about the neutral axis. Alteration in length does not affect the value of k nor the value of y .

$$p = \frac{M.y}{I} = \frac{M.y}{A.k^2}.$$

* Froude. On Useful Displacement as Limited by Weight of Structure and of Propulsive Power. Trans. I.N.A., 1874.

Since the Stress Factor F varies with p , and y and k are constant,

$$F \propto \frac{M}{A}, \text{ whence } A \propto \frac{M}{F}.$$

Since breadth and depth are unchanged, variation in the sectional area of the longitudinal material can be obtained only by varying the thickness, and $A \propto t$.

$$\text{Hence } \frac{A_1}{A_2} \propto \frac{t_1}{t_2} \propto \frac{M_1}{M_2} \times \frac{F_2}{F_1},$$

$$\text{whence } t_1 = t_2 \times \frac{I_1^2}{I_2^2} \times \frac{F_2}{F_1}.$$

(2) *Breadth altered.* In this case there is alteration neither in stress factor nor in stress.

$$M \propto B, \text{ whence } \frac{M_1}{M_2} = \frac{B_1}{B_2}.$$

Due to the alteration in breadth the sectional area of the horizontal plating, and therefore its moment of inertia, varies as B without any alteration being made to the thickness. The quantities k and y are unaltered.

Consider the horizontal plating. $p = \frac{M \cdot y}{A \cdot k^2}$. Since y and k are constant, and p is constant since length is constant, A must vary as M . But M varies as B and A varies as B ; whence A varies as M and, therefore, an alteration in breadth alone does not call for any alteration in the thickness of horizontal plating.

Consider the vertical plating. In order that A may vary as M the thickness of the vertical plating must vary as B . Therefore

$$\sqrt{t_1} = \sqrt{t_2} \times \frac{B_1}{B_2}.$$

(3) *Depth altered and draught varying as depth.* In this case again there is alteration neither in stress factor nor in stress.

$$M \propto d \propto D, \text{ whence } \frac{M_1}{M_2} = \frac{D_1}{D_2}.$$

k and y vary as D .

Consider the horizontal plating. In order that p may be unchanged

$$\frac{M_1 y_1}{A_1 k_1^2} = \frac{M_2 y_2}{A_2 k_2^2},$$

$$\text{or} \quad \frac{A_1}{A_2} = \frac{M_1}{M_2} \cdot \frac{y_1}{y_2} \cdot \frac{k_2^2}{k_1^2} = \frac{D_1}{D_2} \cdot \frac{D_1}{D_2} \cdot \frac{D_2^2}{D_1^2} = 1.$$

Consequently A_1 must equal A_2 and, since breadths are the same, thicknesses, must be the same.

Consider the vertical plating. As found above $A_1 = A_2$. In order that this may hold good the thickness must vary as $\frac{1}{D}$.*

Any desired variations in dimensions can be treated by combinations of these three cases. But while this method of determining the variation of scantlings is suitable for preliminary purposes it is only approximate since it is based on the assumption that the vertical spacing of decks, and the height of the double bottom, vary directly as the depth of the ship.

More important even than the quantitative application of existing knowledge is the use of that knowledge as a guiding light in the search for general principles of construction. A very early statement of the general problem presented by a ship structure is contained in these words:—

“An iron ship may be said to consist of two main parts of construction—the *skin* of the ship, comprehending all the iron plates which form the exterior in contact with the sea, and the *internal strengthening* which is given to this skin by means of plates and angle iron bars connected with the skin, but lying wholly within the ship.”†

This statement may usefully be supplemented by an even earlier statement:—

“...I may observe that the whole question rests on a few simple considerations. 1st. The enormous strain which a flat plate of iron can sustain when exerted in the direction of the plane of its surface; and that plates of iron, unlike the planks of a ship, may be so united as to form one centre shell, and to be nearly as strong as if it had no seams. 2nd. The necessity of preserving the form thus given to the shell; and that this is done by applying other plates or bars at right angles to it. For convenience of securing these to the shell, bars of an angular

* See paper “On Large Cargo Steamers” by Prof. J. H. Biles. Trans. I.N.A., 1900.

† Scott Russell. On the Longitudinal System in the Structure of Iron Ships. Trans. I.N.A., 1862.

form have been made, called angle-iron,—the form best adapted for attaching them to the plates they are intended to stiffen, that the projecting portion having the principal office to perform, the other should be as small as possible, so as not to add unnecessary weight. 3rd. The importance of bearing in mind that the chief strain which the ship, when built, has to sustain is similar to that which is required in an ordinary girder, and that any serious departure from this principle will lead to errors of construction.” *

The problem having been stated, it remains to see whether the general principles of the solution can be determined from consideration of the investigations that have so far been made.

It is obvious that, considering the ship purely as a girder, subject to a bending moment only in the plane of symmetry of the cross-section, the most economical distribution of the material is that in which the major portion is arranged at the top and bottom of the girder, in the so-called “flanges,” and an amount is arranged in the so called “web” of the girder sufficient only to withstand the shearing forces. The “strength deck” and the bottom correspond to the flanges, and the shell plating corresponds to the web. Hence on this restricted consideration of the problem the most economical arrangement of the material would be one in which there is a heavy “strength deck” and a heavy outer bottom, and relatively thin side plating whose maximum thickness would be found at the “quarter-lengths” about mid-depth.

The first qualifying consideration is, then, the fact that the bending moment is not necessarily confined to the plane of symmetry of the cross-section; and so the strength deck and outer bottom may not always be the top and bottom members of the girder. On the other hand it is hardly reasonable to consider the ship inclined to 90 degrees so that the side plating forms the flanges of the girder. But a condition lying somewhere between the two extremes is one that must be considered, and in such a condition the top and bottom members of the girder are respectively the sheerstrake together with the strength deck stringer plate and the bilge plating. In this condition, however, the bending moment is not likely to be a maximum and so for the purpose of determining the

* Grantham. On the Strength of Iron Ships. Trans. I.N.A., 1860.

stress on the material it need hardly be considered; but the fact that the condition is possible shows the desirability of carrying some of the material from the top and bottom of the girder respectively down and up the sides, so thickening the upper and lower portions of the web beyond the amount required from consideration of the shearing force acting on the upright girder. This consideration provides a justification for the presence of a heavy "sheer" strake. Further it seems to indicate that an economical arrangement of material is attained by "massing" it at the corners of the girder; but, in general, the presence of a double bottom rather weakens the argument against massing material at the bilge.

There follows the consideration that the loads borne by the girder and actually transmitted to it by way of the shell of the girder; so that at least part of the shell has a double duty to perform—to transmit loads, actually the water support, to the girder, and then to resist the disruptive effect of the loads so transmitted. This consideration demands, in the first place, a thickness of side shell, or web, greater than is required, for mere resistance to shearing force; and it leads up to the more important consideration relating to the manner in which the shell should be stiffened in order that it may perform its function of transmitting loads to the girder.

The problem of the stiffening of the shell of the "box" girder that a ship is may not unreasonably be termed the secondary problem of the strength of ships, the primary problem being the consideration of the strength of the girder as a whole. And the solution of the secondary problem is conditioned by the arrangements within the ships, or "box" girder, for the carriage of passengers and/or cargo.

The arrangements for the carriage of passengers and/or cargo may involve the provision of relatively spaced closely bulkheads, or they may involve the provision of relatively closely spaced decks; more generally the arrangements involve a combination of these two features. The presence of bulkheads provides a certain amount of initial stiffening to the whole shell of the girder; the presence of decks provides a certain amount of initial stiffening to the vertical shell. Hence the secondary problem may be restated as that of stiffening the shell while taking advantage of the presence of the structure necessarily provided within the girder; in effect the problem is that of stiffening a number of

rectangular "panels" of plating.

The most efficient arrangement of stiffeners on any "panel" is, obviously, that in which they are arranged in the direction of the shorter dimension. Such being the case it is evident that the direction of the shell stiffening will depend on the relation between the distances apart of the decks, and the distances apart of the bulkheads. In the ordinary merchant steamer the decks are much nearer each other than are the bulkheads. Hence in this case the shell stiffeners should be arranged from deck to deck; in effect, transverse framing is most economical. On the other hand, in oil tankers there is not such a wide difference between the spacing of the decks and the spacing of the bulkheads as to permit of a definite statement as to the most economical disposition of the framing.

This general argument was summed up so long ago as 1880 in these words:—

".....it is easier to impart to the sides by spanning the short distance between the rigid iron decks and rigid bottom than by spanning longitudinally the whole length of a ship's hold."*

The foregoing consideration applies directly to the stiffening of the side shell. But as a general rule it applies also to the stiffening of the bottom shell, although not with such great force. It does not, however, take into account the argument that longitudinal framing provides material also for resistance to bending; nor should it be necessary to take account of this argument if the general principle relating to the strength of the ship girder as a whole is sound, namely, that material required to resist bending should be disposed in the shell of the girder. In effect, framing should not be called upon to do double duty, to stiffen the shell and also to act with the shell in resistance to bending moments on the girder as a whole; if the framing is stronger than it need be for the performance of the first function the excess material or rather, part of it, should be removed to the shell where it will be more efficient in performing the second function.

The Inadequacy of Existing Knowledge.

This last consideration brings up into prominence the fact that the solutions of the

* John. On Cellular Construction of Merchant Ships. Trans. I.N.A., 1880.

problems of strength so far discussed are really only approximate solutions. They are, in fact, based on the assumption that it is possible to separate the functions of the various elements of the ship structure and provide the material adequate to these functions so separated. In practice, however, almost every element of the structure performs multiple functions; and this fact must be borne in mind as qualifying all the approximate solutions. For example, it has been virtually assumed that the shell of the girder is independent of the members supplied for the stiffening of the shell; whereas, in fact, the shell not only acts as the main member of the girder in resistance to bending moments but acts also along with the members fitted to give transverse strength to the girder.

In their investigations of transverse strength Read and Jenkins, likewise Bruhn, assumed that a width of shell plating equal to a frame space acted with the frame. Such an assumption is not perfectly justifiable. For example, taking an extreme case, it is hardly conceivable that with a very wide frame-spacing, say two or three times present day practice, the whole width of the strip of plating would act efficiently with the actual frame; the deflection of the plating between the frames would probably seriously modify the action of the plating as regards co-operation with the frame. So far it has not been found possible to assign to each and every frame section the appropriate width of plating which should be taken into account. A series of experiments on girders composed of sectional material and strips of plating to represent frame girders was carried out by Bruhn and the breaking stresses calculated on the bases of the moments of inertia of the complete girders were found to be reasonable. On these results it has been suggested that in association with a frame there should be included a strip of plating of width equal to 30 times the thickness of the plating. But in these experiments the loads were not applied to the girders by way of the strips of plating, as is actually the case in ship frames; consequently the strips were not subject to deflections independent of the deflections of the girders. So that to assign a width of plating on the basis of these experiments does not seem altogether sound. Attempts have been made to obtain information on this matter by consideration of the deflections of bulkheads in the experiments of the British Bulkhead Committee, but without giving any result of practical value. Hence this

important consideration in the strength of ships remains to be explored.

Superposed on its function as the shell of the box girder and its function as an element of the frame girder the shell plating is called on to resist water pressure. The combination of the stress due to the bending moment on the structure as a whole and those due to water pressure is, in general, comparatively simple since the stresses are in the same direction and process is simple addition. But the further addition of stresses as right angles introduces a complication. It is known that a material which may fail by compression shows a higher ultimate stress when subjected to compression in two directions at right angles than when subject to compression in one direction only. It would be interesting to know if a similar proposition holds good for material subject to tension in two directions at right angles, and whether the combined effect of tension and compression in two directions at right angles to each other is a reduction in ultimate strength.

The foregoing considerations are all based on the assumption that the ship is a simple box girder; but this primary assumption required consideration. There must be large openings in the top "flange" for access to the interior of the girder; and there must be superstructures on the girder so that it may be suited for its function as a ship. These two qualifying considerations are closely related, involving as they do an investigation of the effects of "discontinuities" in the structure. But for convenience they may be treated separately.

The fact that discontinuities may offer opportunities for the development of fractures is not at all a modern idea. So far back as 1866, in some ships of extreme proportions of length to breadth and width:—

"There are, however, to be found instances of great caution used in long vessels. In those above alluded to the decks are entirely of iron; the hatches are carefully constructed with rounded corners, so as to avoid angular points where fractures may commence." *

But it was not until more than 30 years had elapsed that any attempt was made actually to investigate the effects of discontinuities.

* Grantham. Length of Iron Ships, in reference to recent Losses at Sea. Trans. I.N.A., 1866.

The effect of a hole in a piece of material subject to tension, for example, a hatch in the deck of a ship, is most clearly illustrated by a consideration of the lines of principal stress in the material adjacent to the hole. Such illustrations have frequently been given in recent years*; and they show that the lines of principal stress bend round the hole, the changes in direction of the lines relatively to the centre-line of the material being due to the superposition of a shear stress on the longitudinal stress. Investigations shew that there is practically no stress in two approximately triangular regions of material whose bases are the ends of the holes; and they indicate that the stress is not uniformly distributed across the section of the material in the region of the hole and for a distance on either side of it whose boundaries are given by the intersections with the sides of the material of lines at 45 degrees extending from the corners of the opening and across the centre-line of the material.

These facts have a direct bearing on the question of the arrangement of material in the "strength" deck. It is evident that the deck plating in the triangular regions at the ends of hatches is of no use for purposes of longitudinal strength and can be of use only for "platform" purposes. Further, as a general rule the hatches and machinery openings are so close together that between them there is no position where the stress is uniformly distributed across the deck; in other words the openings are so close together that there is no position between them where the stress lines are parallel to the centre line and uniformly spaced. So it is clear that material within the line of hatches and machinery openings is not fully effective in resistance to bending moments; and this consideration explains the modern, but not yet universal, custom of making such material thinner than that between the line of hatches and the side of the ship.

There is also the consideration that the shear is maximum at the corners of the opening and it is in these places that fractures have actually occurred and doublings have been fitted in order to obviate the occurrence of fractures. The investigations that have been made on the effect of discontinuities have dealt only with specimens of uniform

* Bruhn: The Stresses at the Discontinuities in a Ship's Structure. Trans. I.N.A., 1899.

Coker: The Determination, by Photo-elastic Methods, of the Distribution of Stress in Plates of Variable Cross Section, with some Applications to Ships' Plating. Trans. I.N.A., 1911.

thickness throughout. If, however, the material within the line of the openings is reduced in thickness as compared with the material abreast the openings the shear at the corners of the openings is also reduced. Hence the arrangement of the effective material of the "strength" deck abreast the line of the openings, and not trespassing within that line is not only the most suitable arrangement on the general consideration but carries with it a reduction in liability to fracture at the corners of the openings.

The consideration of discontinuities brings up a minor matter in connection with the ordinary method of applying strength calculations. It is almost universal practice to include in the calculation of the "moment of resistance" of the cross section the whole width of deck plating from side to side. Obviously this practice is wrong. And it cannot fairly be justified on the ground that strength calculations are comparative and that similarity of method is more important than accuracy of method, for it may lead to the comparison of ships having relatively wide openings with ships having relatively narrow openings, and of ships in which the correct principle of disposition of deck material is applied with ships in which the principle is not applied. Thus the incorrect method of calculation may result in the determination of figures which are appreciably non-comparable.

It has been pointed out that investigations on the effects of discontinuities do not properly reproduce the actual present-day facts in that they were made on specimens of uniform thickness. They differ from the actual facts also in that they were made on specimens in which the lines of principal stress are axial in the regions remote from the openings. The lines of principal stress in the deck of a ship are not parallel with the centre-line, even in the ideal case in which there are no openings in the deck: the distribution of shear stress across the deck in the manner indicated by Dr. Suyehiro involves curvature of the lines of principal stress. And this fact may slightly modify the general conclusions stated above although the concentration of the effective "strength" deck plating in the region abreast the hatches must tend to reduce the curvature of the stress lines.

The effect of the discontinuity at the end of a "closed bridge" is similar in general character to that of a discontinuity in a deck: but the exaggeration of stress at the

corner is more pronounced, in part due to the fact that the direct stresses are not uniform in magnitude across the material below the discontinuity but increase with distance from the neutral axis towards the corner of discontinuity, and in part due to the fact that, in general, the ends of such "closed bridges" are near the regions of maximum shear. Hence the need for large doublings and increased edge riveting at the ends of such erections.

Closely allied to the consideration of the effects of discontinuities and allied also to the consideration of the most effective distribution of the material in a girder is the consideration of the construction of long deckhouses. It is common practice to carry the "strength" deck over the top of any closed erection which covers more than 30 per cent. of the length amidships. And on top of such erections are commonly superposed further "open" erections; the stiffening and strengthening of these "open" erections presents a formidable problem.

An early investigation which has a bearing on the question of the construction of long deckhouses dealt with the effect of *adding* material above the top member of a girder, and it was shewn that such an action does not necessarily strengthen the girder but may actually render the added material liable to stresses considerably greater than the stresses in the original girder.* The superposition of a deckhouse above the strength deck of a ship is such an addition as was treated in this investigation, and it follows that the stress in the material of the deckhouse may be considerably greater than the stress in the strength deck. A method of construction which has been adopted for the purpose of preventing the stress in the deckhouse exceeding the stress at the strength deck is the arranging of the deckhouse in two or three separate lengths separated by "expansion" joints running from the top of the superstructure down to the strength deck; the idea underlying this action is that the superstructure is thereby rendered so flexible that it accommodates itself to the curvature of the strength deck without being called upon to resist the forces operating on the strength deck. But the degree of flexibility involved in the idea of a perfectly flexible superstructure is much greater than can be achieved in

* Purvis. On the Effect of Depth upon the Strength of a Girder to resist Bending Strains; also discussion by W. John. Trans. I.N.A., 1878.

practice; the fulfilment of the idea would require the arranging of expansion joints every 20 or 30 feet. Hence it is not possible to construct long deckhouses so that they shall not be stressed by taking part in the functioning of the girder; and, in fact, as is indicated by observed fractures, the arranging of expansion joints is merely the provision of additional discontinuities.

The modern method of constructing deckhouses is to bow to the necessity of incorporating them with the main girder of the ship and so arrange the scantlings that the stresses do not exceed those in the main girder.* This practice is open to the criticism that if deckhouses and promenade decks can be made strong enough to be incorporated with the main structure they ought to be made strong enough to act fully as the top member of the structure as a whole, so that by making full use of the depth of the main structure plus superstructure the required value of the "moment of resistance" could be obtained with the minimum scantlings; in other words, the modern practice is open to the criticism that it is, in effect, a revival of the obsolete practice of keeping the main structure member below the top of the girder. The adoption of the actual topmost deck as the strength deck would involve the transmission of the shear on that deck down to the main structure of the ship by way of deckhouse walls; and the construction of a deckhouse wall adequate to this function would require a knowledge of the distribution of shear stress far beyond existing knowledge.

To sum up, the state of affairs as regards knowledge of the strength of ships is that there is a good *general* theory of the action of the forces acting on and in the ship considered as a girder. This general theory has been tested approximately by the standards of experience, and closely by the experiments on H. B. M. S. "Wolf."† But the theory requires amplification in many respects. In particular, the subject of transverse strength deserves consideration; a "Standard" condition of loading is required on the lines of the standard condition that has been adopted with success in the consideration of the ship girder as a whole. The fact that cases of transverse weakness have not inspired

* King. On Large Deckhouses. Trans. I.N.A., 1913, also Montgomerie. The Scantlings of Light Superstructures. Trans. I.N.A., 1915.

† Biles. The strength of Ships, with Special Reference to Experiments and Calculations, made upon H.M.S. "Wolf." Trans. I.N.A., 1905.

and stimulated research into the question of transverse strength, as cases of longitudinal weakness reacted on the question of longitudinal strength, is not necessarily a proof that the present practice in regard to transverse strength is sound; it may just as likely be a proof that the present practice is unsound, so that research may indicate a route by which further economy in construction may be approached. Further, the general question of the distribution of stress in a complex girder deserves fuller consideration since it is likely that the real problem in the consideration of a longitudinal strength is the problem of discontinuities. A fuller knowledge of the distribution of stress throughout the structure of a ship would not only be of service for design purposes but would be of immense service in the diagnosis of observed weakness of ships; it is not unreasonable to suggest that many purely *local* weaknesses have been treated as *structural* weaknesses with the result that there has been a tendency towards *general* additions of material when mere local additions would have been sufficient.

To revert to the metaphor of the opening paragraph: the stage has now been reached at which the territory which has been partially surveyed and opened up should be the subject of a detailed survey: but the work of the detailed survey should not, of course, be imposed on those who desire to venture into new territory.

A. M. Robb.

Discussion

Prof. K. Suyehiro. :—Dr. Robb's paper is very important and instructive, and I shall be permitted to say that all of us appreciate his valuable contribution to the Society. With regard to the inadequacy of existing knowledge on the strength of ships, I agree with Dr. Robb's view. Problems of the strength of ships can neither be solved merely by pure science nor by mere experience; actual observations must be associated with them.

Even the applicability of the beam formula to a deep composite girder like a ship has much to be investigated. If the straight line distribution of the bending strain strictly occurs on a section of a ship, her bottom being subjected to an additional stress by water pressure, would in some case be stressed nearly to the point of the breakdown of material when subjected to reversal stresses.

But actual experiences have shown otherwise.

My view on this that the actual bending strain is not directly proportional to the distance from the neutral axis, but its distribution is somewhat like as shown in the

sketch. The top and bottom members of a ship, when once subjected to a severe stress above the limit of proportionality will never recover the original state, but more or less slackened, and hence the distribution of the bending strain will assume a curved form. Prof. Biles' experiment of

"Wolf" which is the only one thorough and scientific research on this branch of engineering so far we have had, seems to justify the above view. If ships are stressed in this manner, they can actually withstand a severer bending moment than that given by the beam formula.

This perhaps may partially explain the reason why ships are actually stronger than they appear. On the lack of experimental data, however, we are not in a position to say this with assuredness. Even such a simple but vital problem being still *sub judice*, we ought to make further experiments on the strength of ships for the improvement of naval architecture.

It is my present intention to study with my colleagues the stresses induced in ships navigating in the north Pacific by fitting extensometers giving a maximum reading during the voyage. Such an experiment may not be useless for the study of the longitudinal strength of ships. After all, the existing knowledge which is obtained either from mere experience or mere theory is imperfect; we have still much to learn by actual experiments having sound scientific basis.

Dr. A. M. Robb:—Prof. Suyehiro's suggestion that bending stress does not vary directly as distance from the neutral axis, but as a power of the distance, is very interesting. And while it may be a novelty to the average Naval Architect—and may on that account be rejected offhand by some—it is familiar to engineers dealing with reinforced concrete construction.

But I am afraid I cannot endorse Prof. Suyehiro's arguments in favour of his suggestion. In the first place it seems to me that the reason why ship plating does not fail

when subject to a combination of stresses arising from structural bending and from local bending due to water pressure is that the structural stresses are never so severe as are indicated by "standard" strength calculations. Further, when the "pull" stress on bottom plating is a maximum due to a sagging bending moment the local stress due to water pressure is a minimum, due to reduced immersion.

Taking now the case of the experiments on H.M.S. "Wolf", I presume that Prof. Suyehiro has in mind Figs. 269 and 270 in Sir John Biles' "Design and Construction of Ships", Vol. I. But these figures may, I think, be taken to justify the assumption of variation of stress with distance from neutral axis equally with the alternative suggested distribution; on one half of each diagram the stress lines are very nearly straight. And it is possible that an alteration should be made to Fig. 269 which might have the effect of straightening slightly the stress lines. The stresses at the centre of the deck in the severest conditions seem so high in relation to the stresses at the sides as to indicate buckling of the deck; if the deck buckled the stress in the plating would not be so great as given by the strainmeter. If the stress in the deck at the centre region is less than as shown in the diagram the deduced total force acting on the material above the neutral axis is reduced; a reduction in deduced total force acting above the neutral axis must be associated with a reduced total force acting below the neutral axis, and so with a straightening of the stress line below the neutral axis, see p. 412, Design and Construction of Ships.

While for the reasons I have endeavoured to indicate I cannot agree with Prof. Suyehiro that the stress varies as a power of the distance from the neutral axis I hope that the results of his proposed experiments will soon be available. There has been too little, and there can never be too much, experimental investigation of the problems of the strength of ships; and I am glad that Prof. Suyehiro has the opportunity of widening our knowledge.

In conclusion I desire to thank Prof. Suyehiro for his remarks on my paper and hope that it has given the Members of the Society of Naval Architects as much pleasure in the reading as I had in the writing.