MAIN LONGITUDINAL STRESSES IN SHIPS.

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In this paper it is intended to survey briefly the development of the classical method of comparing the longitudinal strength of ships, and to suggest a simplification.

Historical.

The study of investigations into the longitudinal strength of ships has now a history extending over quite a respectable period, for as early as 1746 Bouguer, in his « Traité du Navire » calculated the bending moments on floating geometrical solids approximating in form to ships. Thereafter. the matter received further attention. but the first systematic consideration of the bending moments imposed in a ship in service is found in « Shipbuilding, Theoretical and Practical ». by W. J. Macquorn Rankine. published in 1866. In this remarkable work. the following rule is given — « In ships of similar figures with weights similarly distributed. the greatest bending moments are proportional to the products of the displacements and lengths », and for ships of various geometric forms. having the weight of hull and cargo distributed over the length in an arbitrary manner. Rankine gives the bendeng moments in the still water. hogging and sagging conditions in terms of the product of the displacement. the length and a factor. The question of relating these bending moments to specific ships, however, was left to W. J. John. who in his classic paper « On the Strength of Iron Ships » (Ref. 1) considered the case of a ship 104 m. (300 ft.) in length balanced on a wave the length of the ship and 3,65 m. (12,0 ft.) in height. In this paper the well known expression Maximum Hogging Moment = Displacement × Length/35 appears; a formula for Bending Moment which has had a wide currency ever since. It is of interest to note that John made his calculations for a ship in the end of voyage condition for which he estimated the constant to be 38. and concluded that, making allowance for higher waves and a less favourable distribution of cargo. the constant would reach the figure 35.

In this study, which has influenced greatly subsequent ideas on the matter. the affect of the still water bending menment was neglected, but twenty years later, in an important paper by Vivet (Ref. 2), the fundamental ideas enunciated by Rankine were again emphasised. Vivet remarked that the Bending Moment depends on two terms « one is none other than the moment in still water; the second depends entirely on the movement of the centre of buoyancy under the influence of the wave». In this paper the still water and wave components of the bending moments of several ships are investigated, and a formula is introduced to give the total bending moment. This formula can be expressed in a form in which the bending moment in still water and the bending moment due to the wave appear separately. In spite of the work of Vivet, which was followed by others, notably Alexander (Ref. 3) and Suyehiro (Ref. 4) the bending moment on a ship in a seaway was generally considered as a whole, until recently. The late Dr. J. Foster King, however, in two papers (Ref. 5 and 6), exerted his strong influence to direct the study of the subject back to fundamentals, and now there is again a disposition to examine the bending moment in its two components, that due to the still water bending, and that due to the wave. The author strongly supports this technique, and in a paper (Ref. 7) suggested a method of calculation by which this could be done quickly. The usual method, of blalancing the ships on a wave, and integrating the resultant load curve is tedious, and, sometimes does not lead to particularly accurate results. As an alternative it is sufficient to compute the bending moment in still water by means of the following formula :

Let Mf = Moment of weight forward amidships;

M_1f = » buoyancy » »

Ma = » weight abaft »

M_1a = » buoyancy » »

Then $Mf - M_1f = Ma - M_1a = B.M.$

An aproximation to the moment of buoyancy may be made by using the formula Mean Bending Moment = Half Displacement × mean L.C.B. of fore and aft bodies.

$= D/2 \times (0.165\ Cb + 0.074)L$ where Cb = Block Coefficient.

The Wave Bending Moment may be computed from the formula w.b.m. = bL^3B where L is the length, B the beam and b is a coefficient depending on Cb. Values for b are given in the appendix. It should be noted that these constants apply to the load draft of about 0,06L; wide experience with these formulae shows that for ordinary forms they are remarkably accurate. Designers can, of course, use constants derived from their own experience.

Stresses in Still Water.

It is now proposed to examine the stresses on ships in some detail, in order to assess the importance of the two components, and to see whether the usual assumption that the most suitable criterion of the strength of a ship is the stress induced when the ship is balanced on a wave of its own length, can be justified. Since such a calculation, it must be emphasised, is only intended to give comparative results between ship and ship, the precise height of the wave used is not of fundamental importance, but obviously, the closer the assumed conditions are to actual conditions, the better. By custom, however, the height of the wave is taken as 1/20 of its length, as this is thought to lead to results reasonably in accordance with service results. As a matter of interest it may be noted that Vivet in his calculations, to which reference has already been made, did not use a standard wave having a constant relation between height and length. He based his calculations on observations made by Lt. Paris, and adopted a height which varied from 1/20 of the length to 1/30 as the length was increased from 30 m. (100 ft.) to 185 m. (600 ft.). Here it should be emphasised that, whatever the stresses sustained through the influence of waves may be, there is no doubt that the stresses obtained from the still water calculation approximate very closely to those sustained by the ships in that condition. The main result of the Newcombia and Neverita experiments (Ref. 8 and 9) is that a ship behaves for all intents and purposes as a girder, and that the Euler-Bernouilli formula for calculating the stresses gives acceptable results. There are, of course, certain refinements which may be adopted, and which will help to reconcile theoretical and observed results, but it is not intended to consider them here.

For the purposes of this paper, it is intended to consider one family of ships – single screw diesel engined cargo ship of the shelter deck type having the lengths of 91,5 m., 122 m. and 137 m. The dimensions and particulars are given in Tables IV-VII.

The bending moments in still water have been computed on the assumption that one half of the fuel has been burned out, a condition which it has been found is reasonably in accordance with average loading in a ship. The calculations have been made on the assumption that the holds are loaded with a homogeneous cargo. From the results (Table VII) two main conclusions may be drawn.

1) The ships are subjected to a hogging moment.

2) The bending moment is not greatly affected by altering the Block Coefficient from 0,75 to 0,70. The reduction in displacement is counterbalanced by the increase in distance between the centres of effort of the weight and buoyancy in the fore and after bodies. As may be seen from the calculation, this increase follows from the longer machinery space in the finer ship, so that the cargo is moved away from midships, and the movement of the centre of effort of the buoyancy towards midships with reduction of Block Coefficient.

Next, the stress due to the hogging bending moment has been calculated and here only the tensile stress at the deck is considered; the compressive stress on the bottom may result in some ships in deformation of the bottom plating, but it is not intended to consider that phenomenon here. The sectional modulus used is that derived from the Load Line formula $I/y = fB.D.$ where B = Beam, d = Draught, and f is a factor. The stresses are therefore :

L m.	91,5		122		137	
ft.	300		400		450	
Section modulus						
cm^2	12400		30400		44500	
m^2 ft.	6,300		15,450		22,600	
Block Coefft.	0,70	0,75	0,70	0,75	0,70	0,75
Stiil Water B. M. (Hogging) tonnes						
m.	5550	5250	14400	14400	19500	20500
tons ft.	18000	17000	46500	46500	63000	66500
Corresponding						
Stress kg./cm^2	445	425	475	475	440	460
tons/in^2	2,8	2,7	3,0	3,0	2,8	2,9

It is therefore apparent that for this family of ships the stress in still water, calculated on the above assumptions, which, it may be repeated give a reasonable average of service results, does not vary greatly..

Stresses due to Waves.

Having obtained the stress in still water, the stress due to the passage of the wave must be considered. First of all, the stresses were calculated on the assumption that the ships are placed on a standard wave having a length equal to the length of the ship, and having a height equal to 1/20 of the length. For this purpose the wave bending moments have been calculated from the formula.

W.B.M. = b $L^3B \times 10^{-5}$ where b = 82,5 when Cb = 0,75
(Hogging) 77,0 when Cb = 0,70

This gives the following bending moments and stresses.

L (m) . . .	91,5		122		137	
ft . . .	300		400		450	
Block coefft. .	0,70	0,75	0,70	0,75	0,70	0,75
Wave B.M. (Hogging) tonnes						
m. . . .	8100	8700	23600	25200	36200	39000
tons ft. . .	26000	28000	75000	82000	116000	126000
Corresponding						
Stress kg./cm^2 .	650	700	775	825	815	870
tons/in^2 . .	4,10	4,45	4,90	5,25	5,15	5,5

In this calculation, the hogging moment alone was considered, since when taken with the still water moment in the loaded condition, with modern ships, it is the more important. It can also be established that the assumtion that a wave the length of the ship represents the most severe conditions and this is shown in the appendix to the paper. For example, it may be argued that if a ship 122 m. (400 ft.) in length meets waves 122 m. (400 ft.) long and 6,1 m. (20 ft.) high, the same wave will be met by the ship 91,5 m. (300 ft.) long and calculations should be made accordingly. As is shown in the appendix, the effect on the 91,5 m. (300 ft.) ship of a wave 122 m. × 6,1 m. (400 ft. × 20 ft.) is the same as that of one 91,5 m. × 4,6 m. (300 ft. × 15 ft.).

It is now useful to consider to what extent the waves of the sea during a storm conform with the theoretical trochoidal wave, and what is more important, whether there is any co-relation between the stresses calculated on the usual assumption, and those actually experienced in service.

Perhaps the principal characteristic of the ocean storm wave is its irregular form. Nevertheless, to study the motion of a ship in a seaway, it has been necessary to assume an idealised concept of a wave, and the use of the sinusoidal wave, or the trochoidal wave form, has made it possible to arrive at certain theoretical conclusions on the behaviour of ships. In some respects too, these assumed wave surfaces correspond to a reasonable extent with the actual conditions. For instance, observations made on the pressure effects of ocean storm waves seem to demonstrate that the wave does in effect act in accordance with the trochoidal theory. So far, the most extensive observations reported on the configuration of ocean waves are those made during the experimental voyages of the « San Francisco » (Ref. 10) and the stereoscopic records taken on that occasion show clearly the confusion and lack of symmetry of storm waves. The records of the experimental voyages of the « Ocean Vulcan » are at the time of writing not available, but the wave profiles given in the preliminary report on these experiments (Ref. 11) seem to confirm the previous findings. Not only is the wave profile on the ship irregular, but it differs on the two sides of the ship. M. A. Pommellet (Ref. 12) contends that the ocean swell is formed of groups of waves along the direction of propagation. A heavy sea subjected to wind force is comprised of groups of waves, with a lateral length small in relation to the distance from trough to trough. The surface of the sea, in his opinion, can be considered to be constituted at any given moment of a series of waves of slightly variable direction, speed and length, the two last mentioned characteristics being related. Photographs of storm waves in M. Pommellet's and Dr. Schnadel's papers, confirm the absence of any specific regularity in ocean waves. Dr. Schnadel remarked that in general the largest waves mainly rolled up in groups of two, three or four, while smaller waves intervened. The appearance of such groups of larger waves was generally connected with a violent squall. Nevertheless, from time to time, there is interaction between groups of waves, so that, as is well known, the sea lessens or increases without alteration of the wind force. Occasionally therefore, single waves of regular form are encountered. Dr. Schnadel instances a wave of 186 m. long and 16,5 m. high having been encountered in the North Atlantic during a storm.

Enough has been said to indicate that waves are generally irregular, and here it may be mentioned that M. Pommellet is of the opinion that, contrary to the general belief, the irregularity persists in large oceans even when the conditions which produce swell have disappeared; superficial agitation due mostly to the local effect of the wind disappears, but the general configuration of the sea, seen on a large scale, does not seem to alter.

It is held, however, that the theoretical wave profile is a safe one to adopt, for strength and other calculations, since it leads to severe conditions, and for this reason, it is useful to consider what characteristics such a wave should possess. So far as strength calculations are concerned, the relation between the height and the length is the important factor. Many observations have been made of waves at sea, and the following table from Cornish's work (Ref. 13) may be quoted:

Table I.

Wind speed mètres/sec.	Wave speed mètres/sec.	Wave Period	Wave Length	Height	Length / Height
14	11	7	66 m. (215 ft)	6,6 m. (21,5 ft)	10
22	18	11,4	204 m. (670 ft)	10,7 m. (35,0 ft)	19
30,4	34,3	15,5	376 m. (1230 ft)	14,5 m. (47,5 ft)	2,5

A recent paper by Weinblum and Saint-Denis « On the Motion of Ships at Sea » (Ref. 14) includes several diagrams. from which it is apparent that a young wave, i.e. one which has a speed of about 1/4 of the wind velocity may have a ratio of height to length 1/10; but in general this only applies to short waves, i.e. those under 140 m. long. A curve prepared from observations made by the Scripps Institute of Oceanography in the North Pacific Ocean gives the certain values for most extreme conditions over a long period of time for that ocean which are shown in Table II; it is emphasised that the figures do not represent limiting heights of long waves, for instance those in the North Atlantic :

Table II.

Most extreme conditions over a long period of Time for the North Pacific Ocean.

Wave Length mètres	feet	Height métres	feet	Length / Height
60	(200)	5,4	(18,0)	11,0
100	(330)	9,0	(29,5)	11,0
140	(460)	12,0	(39,0)	11,7
180	(590)	13,0	(43,0)	14,0
220	(720)	11,2	(37,0)	19,7

Finally, some results taken from Schnadel's paper may be cited :

Table III.

Wind speed metres per sec.	Height Metres	feet	Length Metres	feet	Length / Height
8	70	(230)	7,5	(24,5)	9,3
30	180	(590)	13,5	(44,0)	13,3
12	200	(660)	18,5	(61,0)	10,8
	130	(425)	9,1	(30,0)	14,3
	186	(610)	16,8	(55,0)	11,1

These results show that the ratio of length of wave to height is not constant, but tends to increase with length of wave.

Stresses experienced in Service.

We may conclude, therefore, that while the sea is generally confused during a storm on occasion a regular wave may be encountered, and that, as Vivet assumed, the height does nor bear a constant relation to the length of the wave. It is now necessary to consider what stresses are imposed on a ship at sea by the the action of the waves, and whether they can be related to the theoretical stresses calculated on the usual assumptions. It was mainly to answer this question that the experimental voyages of the « San Francisco » and the « Ocean Vulcan » were undertaken, and it is unfortunate for the purposes of this paper that so far, only a preliminary report of the later one, which was carried out with all the resources of modern science at its disposal, has been published. It is therefore necessary to rely almost completely on the « San Francisco » results, a note on which has already been given before this Congress (Ref. 15). During the voyage storms were encountered in which the wind force reached 12 on the Beaufort scale and the vessel was forced to lie to. In this period, the most useful stress reading were recorded, and these were converted to bending moments, by multiplying them by the section modulus. Incidentally, no allowance was made for rivet holes, a pratice which has been amply justified by the results in the still water bending moment experiments on the « Neverita » and « Newcombia ». In presenting his information, Dr. Schnadel employed the artifice of deriving the « effective wave » from the Bending Moment. The « effective wave » is a trochoidal wave of the length of the ship having such a height that it will induce a bending moment equal to that induced by the actual confused storm waves. The essential result obtained is that the greatest effective wave height for the ship on the wave crest is L/23,5 and when in the hollow L/18. The extreme value found for the ship in the sagging condition was due to an impact, which increased the moment. In general, Schnadel concluded that :

a) The greatest stresses are sustained when the ship is in the trough of the wave. Here the stresses are accentuated by impacts, which always result in an increased compression of the deck, and tension of the bottom.

b) The greatest « effective wave » height derived for a ship on the crest of a wave was L/23,5, and for a ship in the trough L/18.

c) The maximum hogging moment was not found with the longest wave, but with waves the height of which is greatest within the ship's length.

d) The effective wave height is less than would result from the application of the Smith correction to the actual wave.

e) Hogging stresses may be increased when steaming against wind and waves.

f) Dynamic stresses are not great, but such stresses are a function of the speed of the ship in relation to that of the waves.

Putting the matter in another way, the results show that the maximum tensile stress on the upper deck of the « San Francisco » in the storm was 550 kg/cm² (3,5 tons/in²) and the maximum compressive stress 850 kg/cm² (5,4 tons per in²). These stresses were superimposed on the still water stress of 550 kg/cm² (3,5 tons in²) tensile. For the « Ocean Vulcan » the preliminary report notes that during one voyage when the ship was hove to in a gale of Force 8 with waves 165 m. (550 ft.) long by 9 m. (30 ft.) to 10,5 m. (35 ft.) high the stress due to the wave at times exceeded ± 625 kg/cm² (4 tons/in²); the still water stress on that occasion which appears to have been a ballast voyage in the North Atlantic in winter, is not given. It should be remarked that these two ships were of the same type; the dimensions and characteristics are as follows :

« San Francisco »

Dimensions : 131,0 m. (430 ft.) × 18,0 m. (57. ft.) × 11,5 m./9,06 m. (37,7 ft./29,7 ft.)

Displacement :	13070 tonnes (12900 tons)	When stresses were recorded
Draught :	7,25 m. (28,8 ft.)	
Block coefficient :	0,744	

« Ocean Vulcan »

Dimensions : 127 m. (416 ft.) × 17,3 m. (56,8 ft.) × 11,35 m./8,72 m. (37,3 ft./28,6 ft.)

Displacement :	13950 tonnes (13750 tons)	load
Draught :	8,18 (26,8 ft.)	
Block coefficient :	0,763	

From this information we can say, therefore, that for ships about 130 m. (420 ft.) long of block coefficients of about. 0,76, stress due to the waves reach a magnitude of about 700 kg/cm^2 (5 tons/in^2). It is also apparent that the Smith correction does not account for the whole difference between the effects of the actual and the theoretical wave, and that the expedient adopted by Schnadel — that of deriving the « effective wave » from the bending moment — demonstrates the uncertainty of the matter. In his work, Schnadel emphasises very properly that the influence of the size and speed of the ship on the « effective wave » can only be learned by further measurements on ships of a different type. The larger and faster cargo or passenger ships may experience very different effects.

It is open to doubt, furthermore, that small variations in the form of the ships, which may affect the calculed wave bending moment, will greatly influence the actual stresses experienced. The block coefficient, for instance, has an important effect in the theoretical calculation and, as has already been indicated, when the block coefficient is reduced the wave bending moment and hence the stresses are reduced also. But the lower block coefficient is associated with the higher speed, and it is difficult to think that the dynamic effects are not increased thereby. It seems probable, therefore that these factors cancel out. If this is so, the stress resulting from the passage of the wave will not differ greatly between the full and the fine ship. The most that can be said about these wave stresses, is that they may bear some relationship to the stresses calculated by assuming that the ship is poised on a static wave. From a large number of calculations of static wave, it seems reasonable to think that the stresses due to the wave vary with length of ship in the following way:

Length :	(m.)	91,5	122,0	137,0
	(ft.)	(300 ft.)	(400 ft.)	(450 ft.)
Stress :	(kg./cm^2.)	550	650	700
	(tons/in^2.)	(3,5)	(4,1)	(4,5)

These wave stresses, it may be emphasised, are additions to the still water stresses, which are determined to a great extent by the disposition of the cargo in the ships, and it is certain that the still water stresses may vary considerably. For example, in a normal condition of loading, the stress in the upper deck of a 122 m. (400 ft.) ship among waves may be 1100 kg/cm^2 (7 tons/in^2) which may be split up into a still water stress of 450 kg/cm^2 (2,9 tons/in^2) assuming the cargo is homogeneously loaded, and a wave stress of 650 kg/cm^2 (4,1 tons/in^2). If the cargo is not loaded in a homogeneous manner, the still water stress may well rise to 650 kg/cm^2 (4,1 tons/in^2) or over, giving a total stress of 1300 kg/cm^2 (8,2 tons/in^2) or more.

For the same external conditions of heavy weather the stress due to the wave will be constant and hence the total stress will be governed by the still water stress. It is therefore suggested that the relative strength of a ship may best be judged from the stresses induced in still water and not from the total stress. The still water component of the stress can be calculated and used as a basis of comparison; the wave component is to a much greater extent an uncertain quantity.

Conclusion.

We are, therefore, drawn to the conclusion that in the present state of knowledge the only precise standards of stress are those sustained by the ship in still water. These are due to the form and characteristics of the ship and to the loading. It has already been emphasised that in the modern dry cargo ship the still water bending moment is almost invariably a hogging one, and here it may be observed that such was the case in the« San Francisco » on the occasions to which reference has been made.

It has been shown also that the still water stress for the family of ships considered does not vary greatly, and is of the order of 475 kg/cm^2 (3,0 tons/in^2) tensile on the upper deck when the ship is homogeneously loaded, and the bunkers are half consumed. Departures from this ideal condition will affect these stresses to a greater or lesser extent, and experience has shown that with injudicious loading they may be greatly exceeded. The author is therefore of the opinion that the most reasonable and most direct method of comparing, in similar ships, stresses induced in service is to consider the stresses calculated in the still water condition and not those derived from the conventional assumption that the ship is poised on a wave.

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Table IV. — Particulars of ships

(English Units)

Length ft.	Beam ft.	Depth ft.	Draught ft.	Block coefft	Displa-cement tons	Speed knots	B. H. P.
300	45	27.6/	20.1	.70	5470	12.0	1,900
		20.6	20.0	.75	5800	10.5	1,400
400	55	36.33/	25.1	.70	11200	14.0	4,650
		27.83	24.9	.75	11900	12.0	3,250
450	60	41.0/	27.8	.70	15200	15.0	7,100
		32.0	27.6	.75	16100	13.0	5,000

Table V. — Hull and Machinery Weight.

(English Units)

Length ft.	Block coefft.	Machinery Weight tons	Length of Machinery Space ft.	Hull Weight tons	Light Ship tons
300	.70	400	42.0	1,480	1,880
	.75	350	40.0	1,500	1,850
400	.70	720	53.0	2,770	3,490
	.75	560	48.0	2,800	3,360
450	.70	1000	57.0	3,850	4,850
	.75	750	54.0	3,900	4,650

Table IV. — Particulars of ships.

Length 1 m.	Beam 2 m.	Depth 3 m.	Draught 4 m.	Block coefft. 5	Displa-cement 6 tonnes	Speed 7 knots	B. H. P. 8
91,5	13,7	8,7/	6,14	0,70	5560	12,0	1900
		6,3	6,10	0,75	5900	10,5	1400
122,0	16,75	11,1/	7,65	0,70	11400	14,0	4650
		8,5	7,60	0,75	12100	12,0	3250
137,0	18,3	12,5/	8,48	0,70	15450	15,0	7100
		9,75	8,42	0,75	16350	13,0	5000

NOTES - Col. 3 Depths given to shelter and 2nd Decks.
Col. 8 Trial B H.P. + 30 °/o for 0,70 Cb
Trial B.H.P. + 40 °/o for 0,75 Cb.

Table V. — Hull and Machinery Weight.

Length m.	Block coefft.	Machinery Weight tonnes	Length of Mach'y Space m.	Hull Weight tonnes	Light Ship tonnes
91,5	0,70	405	12,8	1505	1910
	0,75	355	12,2	1525	1880
122,0	0,70	730	16,2	2820	3550
	0,75	570	14,6	2850	3420
137,0	0,70	1020	17,4	3900	4920
	0,75	760	16,5	3970	4730

Table VI. — Oil Fuel Required.

(English Units)

L ft.	Range miles	Speed knots	Time hours	B.H.P.	Fuel tons	Total Fuel tons
300	6,000	12.0	500	1,900	180	200
		10.5	570	1,400	150	170
400	8,000	14.0	570	4,650	500	550
		12.0	670	3,250	400	440
450	10,000	15.0	670	7,100	890	980
		13.0	770	5,000	720	790

Table VII. — Weight of ship, cargo and fuel, and also Still Water Bending Moment.

(English Units)

Conditions with fuel half burned out.

L ft.	Block Coeff.	Light Ship tons	Fuel tons	Stores & F.W. tons	Total tons	Displacement tons	Cargo tons	Still water B. M. ft. tons
300	.70	1,880	100	50	2,030	5,320	3,290	18,000
	.75	1,850	80	50	1,980	5,670	3,690	17,000
400	.70	3,490	270	70	3,830	10,860	7,030	46,500
	.75	3,360	220	70	3,650	11,610	7,960	46,500
450	.70	4,850	490	100	5,440	14,610	9,170	63,000
	.75	4,650	390	100	5,140	15,610	10,470	66,500

Table VI. — Oil Fuel Required.

1	2	3	4	5	6	7
L	Range	Speed	Time	B.H.P.	Fuel	Total Fuel
metres	miles	knots	hrs		tonnes	tonnes
91,5	6,000	12.0	500	1,900	185	205
		10.5	570	1,400	155	170
122,0	8,000	14.0	570	4,650	510	560
		12.0	670	3,250	405	450
137,0	10,000	15.0	670	7,100	905	1000
		13.0	770	5,000	735	800

NOTES : Col. 6 Consumpt. 190 gms./b.h.p./hr for all purposes.
Col. 7 Voyage consumpt. + 10 %.

Table VII. — Weight of ship, cargo and fuel, and also Still Water Bending Moment.
Conditions with fuel half burned out.

1	2	3	4	5	6	7	8	9
L	Cb.	Light Ship	Fuel	Stores & F.W.	Total	Displacement	Cargo	Still water B. M.
M		tonnes	tonnes	tonnes	tonnes	tonnes	tonnes	tonnes
91,5	0,70	1910	100	50	2060	5410	3350	5550
	0,75	1880	80	50	2010	5770	3760	5250
122,0	0,70	3550	280	70	3900	11050	7150	14400
	0,75	3420	220	70	3710	11800	8090	14400
137,0	0,70	4920	500	100	5520	14850	9330	19500
	0,75	4730	400	100	5230	15850	10620	20500

NOTES : Col. 6 = Cols. 3 + 4 + 5.
Col. 7 = Load displacement — ½ (fuel, F.W., stores)
Col. 8 = Col. (7 — 6)

APPENDIX

Values of « b » at load draught.

Wave Bending Moment = $b L^3 B \times 10^{-5}$ (metric units)
$b L^3 B \times 10^{-6}$ (English units)

Block Coefft.	Hogging		Sagging	
	Metric	English units	Metric	English units
.76	84,5	23.55	95,0	26.50
.74	82,0	22.85	92,0	25.70
.72	79,0	22.10	89,5	24.90
.70	76,5	21.35	86,5	24.10
.68	74,0	20.65	83,5	23.35
.66	71,5	19.90	81,0	22.60

Variation of B.M. with length of wave.

This variation has been computed from a formula which applies to a wall sided ship, with a water line bounded by a parabola, and a wave of cosine form.

If m is index of parabola;
pL is length of wave;
h is height of wave.

Then for a ship on the crest of a wave

$$\text{Vol of wave} = \int \frac{B h}{2} \left[1 + \cos \frac{x}{p L} - \frac{x^m}{L^m} - \frac{x^m}{L^m} \cos \frac{\pi x}{p L} \right] \quad (1)$$

$$\text{Moment of wave} = \int \frac{B h}{2} \left[x + x \cos \frac{\pi x}{p L} - \frac{x^m + 1}{L^m} - \frac{x^m + 1}{L^m} \cos \frac{\pi x}{p L} \right] \quad (2)$$

Evaluating

$$\text{Vol} = \frac{BhL}{2}\Big[1 - \frac{1}{m+1} - \frac{p^2}{\pi^2}(\cos\frac{\pi}{p})\, m$$

$$+ \frac{p^3}{\pi^3}(\sin\frac{\pi}{p})\, m\,(m-1)$$

$$+ \frac{p^4}{\pi^4}(\cos\frac{\pi}{p})\, m\,(m-1)\,(m-2) - \frac{p^5}{\pi^5}\ \ldots\ \text{etc.}$$

$$\text{Moment} = \frac{BhL^2}{2}\Big[\frac{1}{2} + \frac{p^2}{\pi^2}(\cos\frac{\pi}{p}) - \frac{1}{m+2}$$

$$- \frac{p^2}{\pi^2}\cos\frac{\pi}{p}(m+1) + \frac{p^3}{\pi^3}\sin\frac{\pi}{p}(m+1)\,(m)$$

$$+ \frac{p^4}{\pi^4}\cos\frac{\pi}{p}(m+1)\,(m)\,(m-1) - \frac{p^5}{\pi^5}\ \text{etc.}\ldots$$

The C G of the original layer from which the wave is evolved is $\frac{m+1}{2\,(m+2)}$ and therefore the change in moment can be found.

For a wave having a height of 1/20 of its length, the constant « b » should be multiplied by the following factors :

Length of Wave / Length of Ship	Factor
.6	.50
.7	.73
.8	.89
1.0	1.00
1.2	1.01
1.4	.98
1.6	.88
1.8	.86
2.0	.88

These factors may be applied to ships having Block Coefficients varying from 0,70 to 0,75.

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