（昭和 31 年 11 月造船協会秋季講演会に於て講演）

Investigation on the Influence of Ship Forms upon the Strength of Ships Going in Waves

By Kazuo Ochi, *Kogakushi*, *Member**

Abstract

The purpose of this paper is to consider the influence of ship forms upon the slamming and strength of ships going in waves. The self propulsion tests were performed in the experimental tank on two model ships, the U and V-form ship. Ship motions, acceleration, pressures, and stresses were measured on various wave lengths and heights. The comparative merits on the effect of ship forms are discussed from the experimental results.

[I] Introduction

The object of the present paper is to describe the influence of ship forms upon the slamming and strength of ships going in waves. For these purposes, the experiments were made in the Mejiro Experimental Tank on the two different form model ships, the U-form and theV-form ship, each has the same principal dimensions.

[II] Expression of Ship Forms

There are many expression methods about the form of the forepart of ships such as Dr. King's[1], Mr. Lehmann's[2], and the Japanese Committee's[3], but it is difficult to determine whose method is the best one. The author adopts a method of taking the ratio of the sectional area of body plan to the typical box form area at 1/2 LWL, at L/10 station from F.P. This coefficient is named as "k coefficient" as is shown in Fig. 1.

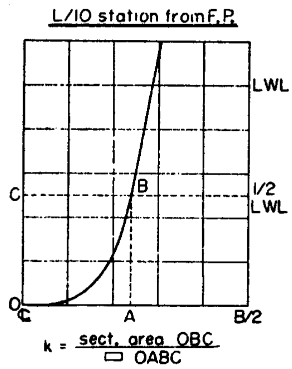


Fig. 1 Ship form coefficient K

[III] Outline of Experiments

(1) Model Ships

The two types of model ship, made of brass, were used in the experiments, namely the forms of the forepart of them were the typical U-form and V-form ship, though they had the same principal dimensions. The principal dimensions and other important characteristics of the model ships are shown in Table 1 and their body plans are shown in Fig. 2.

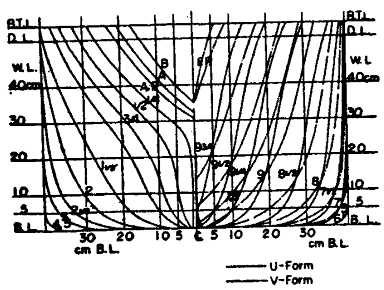


Fig. 2 Body plans of model ships

原稿受付．昭和 31 年7月 11 日

* Transportation Technical Research Institute, Ship Structure Division.

1) King, J. F.: Heavy Weather Damage. Trans. NECI of Eng. & Ship. (1934-35) p.151

2) Lehmann, G. : Bodenschäden ins Vorschiff und die neuen Vorschriften der Klassificationsgesellschaften. Schiffbau (1936) S. 129

3) Report of the Investigation Committee on the Damages of Diesel Ships. Soc. of Nav. Arch. of Japan. (1936) (in Japanese)

Table 1 Model Ship Characteristics

Type	U-form ship	V-form ship
Length L_{pp}	600.0cm	600.0
Breadth B_m	82.6cm	82.6
Depth D_m	53.0cm	53.0
Draft d_{max}	35.5cm	35.5
Displacement ∇_{max}	1,334kg	1,334
Block coeff. C_b	0.741	0.741
Prismatic coeff. C_p	0.751	0.751
Midship area coeff. $C_{⊠}$	0.986	0.986
Water plane coeff. C_W	0.829	0.836
Ship form coeff. k	0.812	0.656
C. B. from ⊠	2.7cm fore	2.7
C. B. above B. L.	18.5cm	18.5
Radius of gyration in air	——	0.298L
Natural pitching period, afloat (d=20cm)	1.30sec.	1.20
Natural heaving period, afloat (d=20cm)	1.37sec	1.25
Hull weight	262.8kg	258.0
I/y at ⊠ to deck	352cm³	352
I/y at ⊠ to bottom	459cm³	459

(2) **Method of Experiments**

The experiments were performed among the waves in the 200 metre tank of the Mejiro Model Basin. All runs were made in head seas under the self propulsion method. Therefore, the model ship was allowed to pitch, heave and surge freely among the waves. The type of experiments is divided in two parts as shown in Table 2.

Table 2 Experimental Condition

Item	Wave length L_W	Wave height H_W	Draft d	Trim by stern
Influence of wave length	450cm 600 700 800	20cm	20cm	+8cm
Influence of wave height	600cm	8cm 12 16 20 21.5(V) 23 (V)	20cm	+8cm

In all experiments, the pitching, heaving, surging motion, bow acceleration, bottom and side pressures, deck and bottom stresses were measured. The location of measuring apparatus in the case of the U-form ship is shown in Fig. 3.

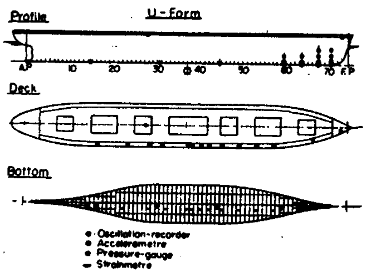


Fig. 3 Arrangement of measuring apparatus of the U-form ship

[IV] Results of Experiments and Conclusions

(1) **Ship Motion and Slamming**

(i) The relation between period of encounter and ship slamming

The encounter period of ship and wave T_e, the natural pitching and heaving period T_p, T_h are shown in Fig. 4. The natural pitching and heaving period obtained in the hove-to condition in still water are T_{po}, T_{ho}, the pitching period obtained in the advancing condition in still water is T_p. The value of T_p on the box-form model ship in the previous experiments[4) 5) 6)] is also written in this figure for reference.

Although the severest slamming occurd just at the ship speed at which the encounter period coincided with the natural pitching, heaving period of ships in the case of the box-form ship, but in the case of the general merchant ship forms, the severest slamming occurs always at somewhat higher speed than the pitching synchronized speed notwithstanding of any wave lengths. ....(Conclusion 1)

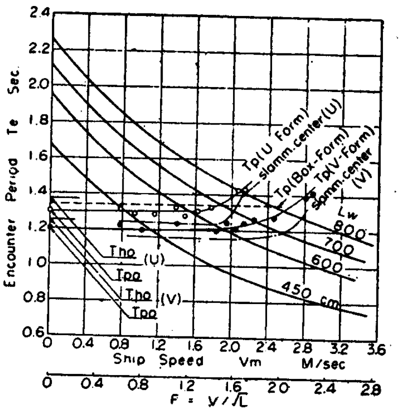


Fig. 4 Encounter period of various wave lengths

The reason of this fact is that the phase lag between wave and pitch, which is the very important factor for the slamming, takes the worst value at higher speed than the synchronized speed as recognized in Fig. 9, while it takes the worst value just at the synchronized speed in the box-form ship.

(ii) Pitching, heaving amplitudes and slamming

Fig. 5 shows the relation between the ratio of pitching angle to the maximum wave slope $\phi_T/2\phi_W$ and the tuning factor T_{po}/T_e. The value of $\phi_T/2\phi_W$ indicates the maximum value at about T_{po}/T_e is 0.9~1.0, therefore it is recognized that the pitching motion of ships nearly synchronizes with the wave. ....(2)

The finer the ship form, the larger the pitching angle becomes at the light draft. ....(3)

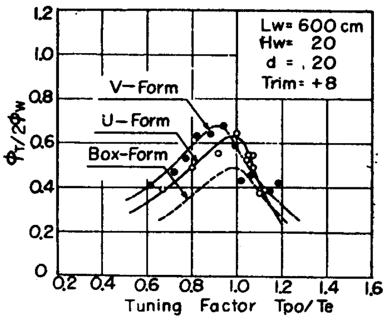


Fig. 5 Pitch angle ratio $\phi_T/2\phi_W$ versus tuning factor T_{po}/T_e

The reason is that the finer the ship form, the less the resistance of the fore part of ships when it strikes against the water surface due to pitching, accordingly the motion of ships will be more freely permitted.

The relation between the ratio of the heaving amplitude to the wave height Z_T/H_W and the tuning factor T_{ho}/T_e is shown in Fig. 6. The value of Z_T/H_W indicates the maximum value at T_{ho}/T_e is 1.05~1.15. This means that the heaving synchronized speed is somewhat higher than the pitching synchronized speed, just as similarly recognized in the experiments on the box-form ship. ....(4)

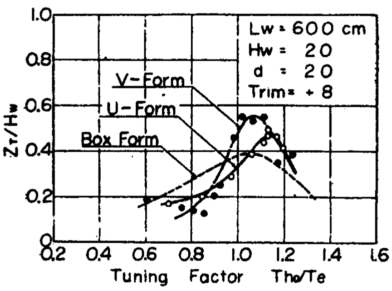


Fig. 6 Heave amplitude ratio Z/H_W versus tuning factor T_{ho}/T_e

This conclusion is quite agree with the experimental results of Dr. Lewis[7)] and Professor Korvin-Kroukovsky[8)].

There are many investigations and discussions on the problem whether the slamming occurs due

4) Akita, Y. & Ochi, K.; Investigations on the Strength of Ships Going in Waves by Model Experiments. (1st. Report, The Influence of Ship Speed and wave Height) Trans. Soc. Nav. Arch. of Japan. (1954). (in Japanese)
5) Ditto. (2nd. Report, The Influence of wave Length). (1954).
6) Ditto. (3rd. Report, The Influence of Ship Draft and Trim). (1955).
7) Lewis, E. V.: Ship Speeds in Irregular Seas. Trans. SNAME (1955)
8) Korvin-Krokovsky, B. V. : Investigation of Ship Motions in RegularWaves. Trans. SNAME (1955)

to pitching or heaving[9)10)11)12)13)14)15)]. But it is a matter of consideration that the slamming phenomenon has a close relation with bow emergence. Therefore, the slamming depends no doubt both on pitching and heaving, but it may safely be said that the pitching is pre-eminent between these two factors, taking consideration of the above mentioned facts. ....(5)

(iii) Bow acceleration and slamming

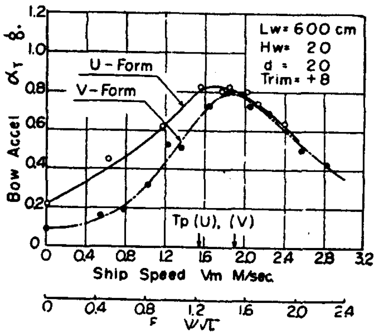


Fig. 7 Bow acceleration amplitude α_T

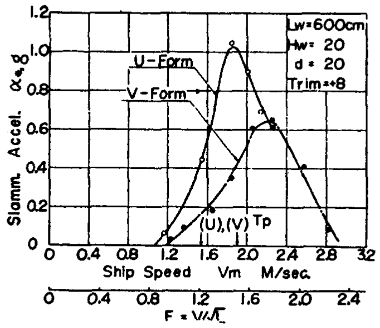


Fig. 8 Slamming acceleration α_*

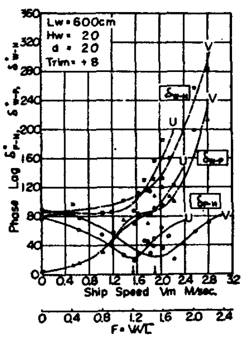


Fig. 9 Phase lag between pitch, heave and wave against ship speed

The vertical acceleration of ship bow is divided in two parts; the one is the acceleration due to waves, the other is the sudden acceleration due to slamming. Dr. Szebehely[16)] named this latter one as the sudden deceleration. Fig. 7 shows the total amplitude of wave acceleration versus ship speed. This amplitude is the resultant accelerations of pitching and heaving, but it is a matter of course the pitching component takes the greater part of it.

It is clear in this figure, the amplitude of wave acceleration indicates the maximum value nearly at the pitching synchronized speed. ....(6)

Whereas, the slamming acceleration indicates the maximum value at tolerably higher speed than the synchronized speed as shown in Fig. 8. Moreover, this speed coincides with the ship speed at which the slamming stress of ship deck indicates the maximum value, as stated later. ....(7)

The magnitude of the slamming acceleration varies considerably according to ship forms; the slamming acceleration of the U-form ship is much greater than that of the V-form ship. ....(8)

Inasmuch as the slamming acceleration is seriously influenced by the bottom flatness, it may be conceivable that the U-form ship indicates the larger value than the V-form ship.

(iv) Phase lag and slamming

The phases lag between pitching and heaving $\delta_{P\text{-}H}$, between wave and pitching $\delta_{W\text{-}P}$, between wave and heaving $\delta_{W\text{-}H}$, are shown in Fig. 9. The varying states of these phase lags measured on the U and V-form ships are very close agreement with the results of the box-form ship. (Ref. 15. Fig. 4). The particularly important factor for the occurrence of slamming may be the phase lag $\delta_{W\text{-}P}$. This factor shows the worst value at the speed of slamming centre, both on the U and V-form ships. Therefore, the phase lag $\delta_{W\text{-}P}$ has the close relation with the slamming phenomenon. ....(9)

9) Lehmann, G.: (cf.) Ref. (2)
10) Kempf, G.: Resonanzschwingungen von Schiffen im Seegang. WRH (1926)
11) Kent, J. L.: The Cause and Prevention of Slamming on Ships in A Seaway. Trans. NECI (1948-49) p. 451
12) Watanabe, Y.: On the Slamming of A Ship. Trans. Soc. Nav. Arch. of Japan. (1953) p. 65 (in Japanese)
13) Lewis, E. V.: (cf.) Ref. (7)
14) Szebehely, V.G. & Lum, S. Y. M.: Model Experiments on Slamming of A Liberty Ship in Head Seas. TMB Report 914
15) Akita, Y. & Ochi, K.: Model Experiment on the Strength of Ships Moving in Waves. Trans. SNAME (1955)
16) Szebehely, V. G.: On Slamming. 7th Inter. Conference on Ship Hydro. (1954)

(v) Bow emergence

It is a well known fact that the slamming will never occur without ship bow emerges out of wave surface. For slamming, the length of flat bottom which emerges out of wave surface is a very important factor. This fact is ascertained from the consideration of Fig. 10. This figure shows the emergence of the forefoot of the flat bottom out of wave surface.

As previously stated, the pitching, heaving amplitudes of the V-form ship are larger than those of the U-form ship. Then, it may be suggested the flat bottom of the V-form ship is easier to emerge out of wave surface than the U-form ship. But, actually, contrary to this expectation, the forefoot of the U-form is susceptible to emerge out of wave surface following to the ship motion, for the reason of its position is near the F.P.; whereas the forefoot of the V-form is at some distant from F. P.; therefore it is not easy to emerge.

In short, from this point of view, the V-form ship has advantage over the U-form ship. ....(10)

Fig. 11 shows the ship behaviors among waves at the hove-to condition, the slamming speed and at high speed.

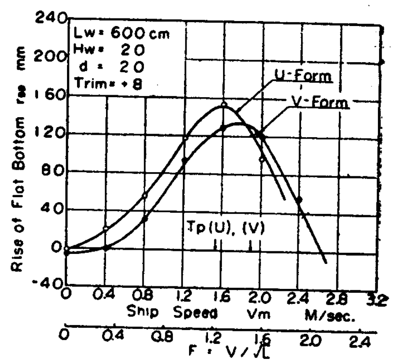


Fig. 10 Rise of flat bottom out of wave surface

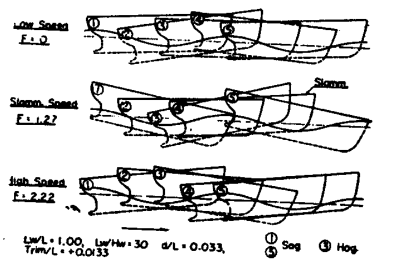


Fig. 11 Ship behavior in waves

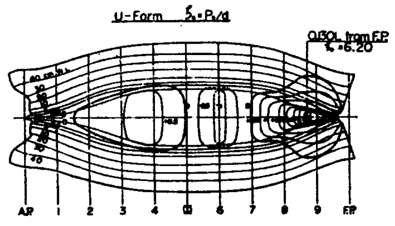
(2) Bottom Pressure

The water pressure which is delivered to ship bottom among the waves is divided in two parts. The one is the water pressure due to the wave and ship motion, the other is the impact water pressure which is recognized only at the instant of ship slamming. The latter is named as the slamming pressure. The slamming pressure is particularly important to the strength of ships, therefore the present paper will describe on the intensity and distribution of the slamming pressure.

(i) Distribution of slamming pressure

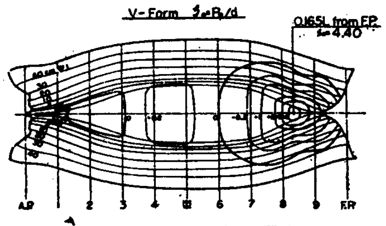
The distribution of the slamming pressures which are delivered to the ships bottom and side is shown in Fig. 12 and Fig. 13 in the value of P_*/d. Ship speed in these figures are the slamming speeds respectively.

The maximum value of the slamming pressure P_*/d is 6.20 on the U-form, 4.40 on the V-form ship. Therefore, it seems permissible that the value of the maximum P_*/d decreases as the ship form becomes fine.....(11)



Lw/L	Lw/Hw	d/L	Trim/L	F = V/√L
1.00	30.00	0.033	+0.0133	1.38

Fig. 12 Slamming pressure distribution of the U-form ship



Lw/L	Lw/Hw	d/L	Trim/L	F = V/√L
1.00	30.00	0.033	+0.0133	1.54

Fig. 13 Slamming pressure distribution of the V-form ship

The pressure range of the V-form ship is fairly larger than the U-form ship owing to the severe ship motion. ....(12)

Even though the pressure range is large in the V-form ship, the absolute value of the slamming pressure is not so large as it causes the heavy damage to the ship bottom.

There are some opinions on the problem whether the maximum slamming pressure is recognized at the location near the keel or near the bilge of ship bottom. Dr. Szebehely[17] said it was near

17) Szebehely, V. G.: (cf.) Ref. (16)

the bilge from his theoretical consideration, while Dr. Jasper, Birmingham[18] and Dr. Greenspon[19] said the largest pressure occured at the keel line in the experiments of USCGC UNIMAK. The author has examined the pressure distribution around the ship girth in detail, and ascertained the maximum pressure was recognized along the keel line. ....(13)

(ii) Ship form and slamming pressure

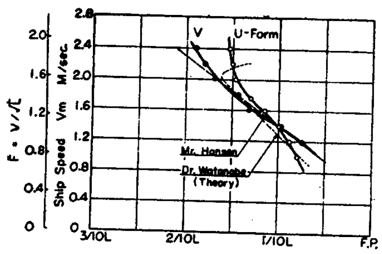


Fig. 14 Position of the max. slamming pressure at various ship speeds

The relation between the ship speed and the position of the maximum slamming pressure is shown in Fig. 14. The figure suggests the very interesting relation between ship speed and the position of the damaged part. The theoretical value given by the theory of Dr. Watanabe[20], the values given by Mr. Hansen[21] are also shown in this figure. All these curves suggest that the position is close to F. P. at low ship speed, and distant from F.P. at high speed. The results of the model ship experiments are in very close agreement with the curves given by them. From the consideration of this figure, it is quite possible to determine the damaged part of the merchant ship due to the slamming. The range of it is about 0.08L～0.20L form F. P. ....(14)

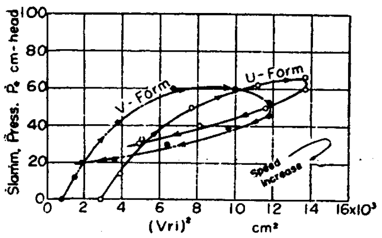


Fig. 15 Slamming pressure versus relative velocity

(iii) Relative velocity and slamming pressure

Fig. 15 shows the relation between the relative velocity at the instant of slamming and the slamming pressure. It is easy to suppose that the slamming pressure would be proportional to the square of the relative velocity. Several papers have described on this problem[22)23)].

But, actually, the ship motion and the phase lag between ship and wave vary in obedience to ship speeds, consequently the slamming pressure would not be exactly proportional to the square of the relative velocity. The experimental curves describe the loops with increase of ship speeds, but it may be permissible to conclude that the slamming pressure nearly proportional to the square of the relative velocity. ....(15)

(3) Hull Strength

The hull strength of ships going in waves is divided in two parts. The one is the hogging and sagging stress due to the waves, the other is the slamming stress produced by the heavy blows at the instant of ship slamming. The wave stress is comparatively small as is generally supposed, while the slamming stress is fairly large, then the latter should be noted particularly on the problem of the hull strength of ships.

(i) Wave stress

The hogging and sagging stresses measured on ship deck at midship $\left(\text{at Fr. No. } 37\frac{1}{2}\right)$ are

18) Jasper, N.H. & Birmingham, J. T.: Sea Tests of the USCGC UNIMAK. Part 1, General Outline of Tests and Test Results. TMB Report 976

19) Greenspon, J. E.: Ditto. Part 3, Pressures, Strains and Deflections of the Bottom Plating Incident to Slamming. TMB Report 978

20) Watanabe, Y.: (cf.) Ref. (12)

21) Hansen, K. E.: Pounding of Ships and Strengthening of Bottoms Forwards. Shipbuild. & Ship. Record. (1935) p. 656

22) Yoshiki, M. Yamamoto, Y. and Fujita, Y.: On the Slamming Tests of A Wooden Model Ship. Trans. Soc. Nav. Arch. of Japan (1954) (in Japanese)

23) Szebehely, V. G. & Todd, M. A.: Ship Slamming in Head Seas. TMB Report 913

shown in Fig. 16. The value of the conventional calculated stress, and the calculated stress modified by the Smith' effect are also contained in this figure.

The striking feature is that both the hogging and sagging stress increases at high speeds in any wave lengths. ....(16)

The reason of this phenomenon is that the ship is heave-in condition at high speeds at the hogging instant, while the ship is heave-out condition at the sagging instant. Therefore the bending moment will be increased at high speeds. This property of increasing trend of hull stress at high speed was also recognized in the experiments of Dr. Lewis[24] on the T2-SE-A1 tanker.

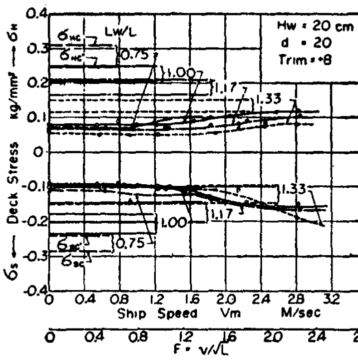


Fig. 16 Hogging, sagging deck stress of the V-form Ship

Another interesting feature is the effect of wave length. The calculated stresses σ_{HO}, σ_{SO}, σ_{HO}', σ_{SO}', (with Smith' effect) take the maximum values in the wave whose length is 450cm, because the value of L_W/H_W is large. Whereas, the measured stresses show the maximum values in the wave whose length is equal to the ship length ($L_W/H_W=30.0$), even at the hove-to condition. This result may be taken to indicate that the important effects of ship motion upon the strength of ships, though they are not usually considered in the conventional calculation method.

Comparing the measured stresses with the calculated ones, the effective wave height ratios are obtained by the same method in the previous paper[25]. The values of the effective wave height ratio η are fairly small both on the U and V-form ship, comparing with that of the box-form ship. These values are $\eta_H=0.25$ (U), 0.24 (V), and $\eta_S=0.28$ (U), 0.31 (V) in the wave whicn has a length equal to that of the ship. ....(17)

With Smith' effect, the values increase to $\eta_H'=0.30$ (U), 0.34 (V), and $\eta_S'=0.34$ (U), 0.39 (V). ....(18)

(ii) Slamming stress

The relation between the slamming stress and ship speed is shown in Fig. 17. The ship speed where the slamming stress shows the maximum value is in very close agreement with the ship speed of the maximum slamming acceleration and pressure. The maximum values of the slamming stresses on the U and V-form ship are exceedingly small than the value which was previously obtained in the experiments on the box-form ship. The maximum value of the slamming stress against wave length is shown in Fig. 18. From this figure, the minimum and the maximum wave lengths L_{WS}, L_{WL} which cause the slamming at light draft are obtained. The value of L_{WS}/L is 0.74 both for the U and V-form ships, and the value of L_{WL}/L is 1.36 for the U-form, 1.39 for the V-form ship. ....(19)

The wave length which is severest for the slamming is also obtained from this figure. The severest wave length is 615cm ($L_W/L=1.03$) for the U-form and 660cm ($L_W/L=1.10$) for the V-form ship. ....(20)

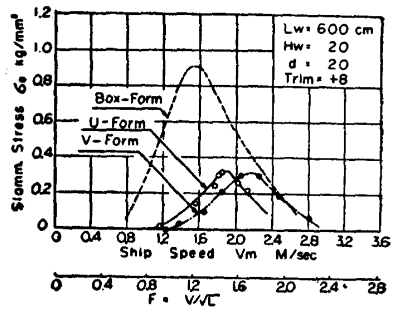


Fig. 17 Slamming stress against ship speed

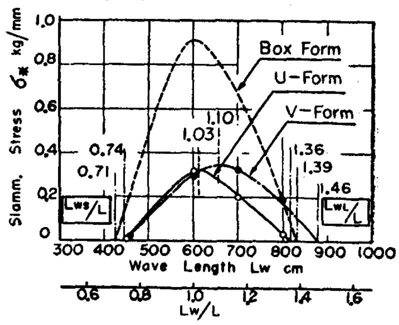


Fig. 18 Slamming stress against wave length

24) Lewis, E. V.: Ship Model Tests to Determine Bending Moments in Waves. Trans. SNAME (1954)

25) Akita, Y. & Ochi, K.: (cf.) Ref. (4)

It is a very interesting and important matter to consider the relation between the wave length and ship length for the slamming. From several investigations, it seems perfectly permissible to believe that the wave whose length is somewhat longer than ship length is severe for the slamming. Dr. Lewis[26] said in his paper that the wave length which had significant effect on the motions of ordinary ship ranged from about 1 to 2.5 L, and the Investigation Committee of Japan[27] described in its report that it was from 1.0 to 1.2 L on the basis of the materials of the damaged ships in the North Pacific Ocean. Including the effect of ship forms on this problem, the severest wave length for the slamming is plotted against the ship form coefficient k as shown in Fig. 19. From this figure, it is conceivable that the finer the ship form, the long wave is more severe for the slamming. As the value of k in general cargo ship ranges about 0.60～0.83, therefore the wave whose length is about 1.03～1.14 L is severe for the slamming. ....(21)

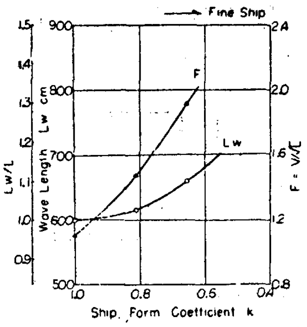


Fig. 19 Severest wave length and ship speed versus ship coefficient k

Also, it may be concluded the finer the ship form, the high speed is more severe. ....(22)

(iii) Slamming zone

From the value of the slamming stress on various ship speeds and wave lengths, the slamming zone is obtained as shown in Fig. 20. It seems that the range of the slamming zone is somewhat larger in the V-form ship than in the U-form ship, and also it is likely that the V-form is better in comparatively low speed ($F<1.3$), and the U-form ship is better in comparatively high speed ($F>2.0$). ....(23)

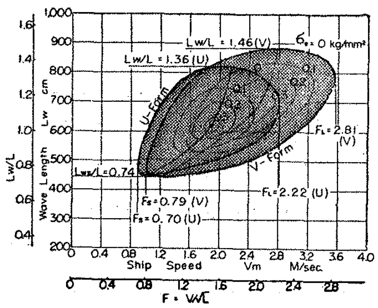


Fig. 20 Slamming Zone

As to the minimum ship speed F_S at which the slamming occurs, F_S is 0.70 for the U-form ship and 0.79 for the V-form ship. ....(24)

(iv) Wave height effect

The effect of wave height concerning the slamming stress is shown in Fig. 21. The experiments were made at the slamming speeds. The minimum wave height which occurs the slamming H_{WS} is 11.2 cm ($L_W/H_W=53.5$), and this value is the same as that of obtained on the slamming pressure. ....(25)

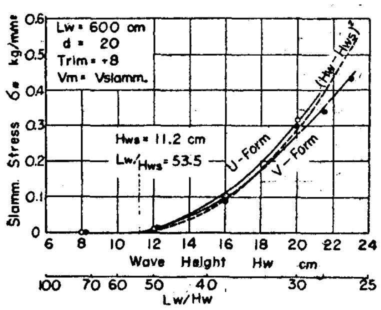


Fig. 21 Slamming stress versus wave height

The value of the slamming stress increases nearly in proportion to $(H_W-H_{WS})^2$. ....(26)

(v) Distribution of the slamming stress

Fig. 22 shows the distribution of the slamming stress measured on ship deck at the slamming speed. The striking feature in this figure is that the distribution curve indicates the maximum value not at the midship, but indicates the maximum value at somewhat forward position from midship, namely at 0.425 L from F.P. (27)

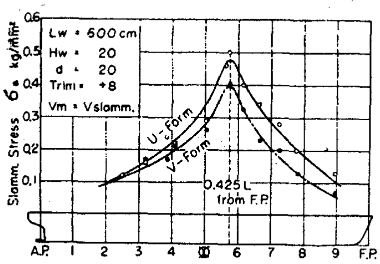


Fig. 22 Distribution of slamming stress on ship deck

This property was also obtained in the experiments on the box-form ship[28], and the positions where the maximum value is recognized are in very close agreement

26) Lewis, E. V.: (cf.) Ref. (7)

27) Investigation Committee of Japan: (cf.) Ref. (3)

28) Ochi, K.: On the Stress Distribution of Ships at the Slamming Speeds. Trans. Soc. Nav. Arch. of Japan (1955)

with each other. The reason of this phenomenon is due to the heavy blows at the ship bow by the waves. So much for the comparison between these two ships and the box-form ship, it is a very interesting that this property is not subject to the effect of ship forms. Also, this property may give some suggestions to the problem of the strengthening of ship deck.

(vi) Relation between ship form and slamming

Fig. 23 shows the relation between the ship speed and the slamming expressed in the ship form coefficients given by Dr. King, Mr. Lehmann, the Japanese Committee, and by the author. From the consideration of this figure, it is evident that both the minimum and the severest ship speeds for the slamming are high speeds in the fine form ship. ....(28)

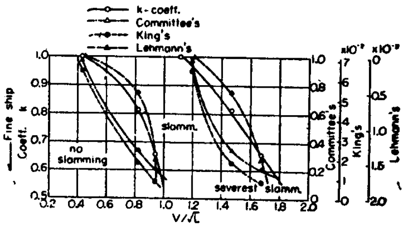


Fig. 23 Relation between the slamming and ship speed

For the purpose of diminution of the slamming pressure, it is very important to minimise the slamming acceleration as Dr. Szebehely said[29]; this is quite true. Considering the above mentioned fact, it is advisable to make the position of the forefoot distant from F. P. as far as possible in order to avoid the severe slamming. Therefore, it may be said that the Maier-form ship, the bow of which is the V-form, is eminent for the performance of ship motin and hull strength among the waves. Besides, the flare of ship bow may be effective for producing the reserve buoyancy and consequently for restraining the violent ship motion.

................(29)

By the way, it should be noted that the afore-mentioned experimental results and conclusions are in the case of comparatively light draft. Generally speaking, the slamming stress decreases remarkably in any deep drafts. The effect of ship draft will be discussed in the further studies.

Acknowledgment

The author's thanks are due to the following persons who have in many ways assisted him in the preparation of this paper : Dr. Akita for his guidance and valuable advices, Professor Terazawa, Professor Yoshiki, Professor Kihara, Professor Ohta for their much interests and encouragements to his works ; Messers. Azuma and Tani for their generous assistances to the laborious experiments and analyses. His grateful thanks are also due to Mr. Takahashi of the Kawasaki Heavy Industry Co. for the kind suggestions on the forms of the model ships.

29) Szebehely, V. G.: Progress in Theoretical & Experimental Studies of Ship Slamming. Prepared Paper for the Conference on Ships and Waves (1954)