Application of Weather Criterion to a Damaged Passenger Ship-A Proposal of Guidance to the Master to Safe Return to Port

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ABSTRACT

At the International Maritime Organization (IMO), guidelines for reference by masters in assessing operational damage stability for safe return to port by own power or tow is to be developed. To contribute to the works at the IMO, a method to assess the capability for safe voyage to port is proposed on the basis of the weather criterion which is used to guarantee the safety of a dead ship in intact condition in beam wind and waves. To apply the criterion to a damaged ship, a simple prediction method for the roll damping created by internal water is deduced on the basis of experimental data. Using the predicted roll damping, a wind speed limitation for safe return to port of a damaged passenger ships can be calculated by the weather criterion. The results demonstrate that threshold in term of wind speed depends on ship size and water depth on flooded deck as well as damage length.

KEYWORDS

Safe Return to Port, Weather Criterion, Damage Stability, Roll Damping, Flooded Ship

INTRODUCTION

In recent years, a lot of large passenger ship that can carry several thousand passengers and crew and is also 300m near length is in service in the world. The examination started as movement to review safety to an emergency of such large passenger ship in the 72th Marine Safety Council in 1999. After that, in IMO strengthening the safety of passenger ship is aimed at, and the development of stability requirements for a safe returning to port is one of them.

This is the one based on the idea that returning to port by a passenger ship itself even if she is damaged might be safer than making a lot of passengers and crew escape with lifeboats and life-saving-raft. In next SLF51 meeting of IMO, "Design requirement for the stability for a safe returning to port by own power or tow" and "Guideline on the service of returning to the captain" have been enumerated as an examination item. The item that the captain should judge after the damage will be enumerated in a latter guideline idea, and especially it is thought that the guidance about how to judge whether she can safely return to a port is needed.

In this study, it is tried to apply the Weather Criterion for intact condition to a damaged and flooded ship as a proposal of guidance to the master for safe returning to a port of the ship, and to calculate the limit velocity of wind to return safely to a port. The basic idea of this concept is that master can select the return to a port with passengers and crews if the maximum wind speed by the forecast until returning to the port is smaller than the calculated limitation of wind speed, and must select the evacuation from his ship if it is opposite. The information of the criteria of wind speed can be useful for the masters when he should judge after damage of the ship.

OVERVIEW IN THIS STUDY

The outline of Weather Criterion in IS-code is shown in Fig.1. This criterion guarantees that the ship in dead ship condition doesn't sink and capsize in severe sea condition. The criterion requires that area "*b*" is equal to or greater than area "*a*" on GZ curve as shown in Fig.1. Each symbol in Fig.1 is defined as follows.

l_{w1}: a steady wind heeling lever

l_{w2}: a gust wind heeling lever ($l_{w1}\times 1.5$)

φ_s: angle of heel under action of steady wind

φ_1: angle of roll to windward due to wave action

φ_2: angle of down flooding or 50º whichever is less

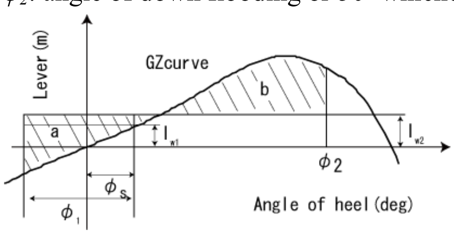

Fig. 1: Concept of Weather Criterion in IS-code.

The heeling lever l_{w1} and resonance roll angle φ_1 in Fig.1 are calculated by the following Eqs.1 and 2.

$$l_{w1} = \frac{504AZ}{1000g\Delta} \tag{1}$$

where A, Z, g and Δ denote projected lateral area of the portion of the ship above water, vertical distance from the centre of A to the centre of the underwater lateral area, gravitational acceleration and displacement (ton), respectively.

$$\phi_1 = 109kX_1X_2\sqrt{rs} \tag{2}$$

where k is a coefficient depending on relative area of bilge keels, X_1 depends on the beam to draught ratio, X_2 is the function of the block coefficient C_B, r is the effective wave slope coefficient, s is wave steepness, respectively. In Weather Criterion, it is assumed that wave steepness varies by the resonance roll period, and the table of natural roll period and wave steepness is given as shown in Appendix.

The constant number 504 in Eq.1 is the wind pressure under the steady wind with 26m/sec of wind speed. Therefore, Eq.1 can be changed to Eq.3 using a wind speed, U_w.

$$l_{w1} = \frac{504\left(U_W/26\right)^2 \cdot AZ}{1000g\Delta} \tag{3}$$

Using Eq.3, the limiting wind speed at a=b can be obtained.

Due to flooding water in damaged compartments, some variables in the weather criterion are changed from intact condition, for example, the displacement, the center of gravity, the values of the static *GZ*, roll natural period, the roll damping and wave steepness. Taking these changes into account, each coefficient in Eqs.2 and 3 is decided. To take the change of the roll damping due to internal water into account, a following correction factor k_w is introduced.

$$\phi_1 = 109k_wkX_1X_2\sqrt{rs} \tag{4}$$

where k_w denotes the ratio of the roll damping coefficient before and after flooding as shown in Eq.5.

$$k_w = B_{44}/B_{44}' \tag{5}$$

EXPERIMENT OF TWO DIMENSIONAL TANK

To create a simple predicted formula of the roll damping due to inside water, forced oscillation tests of a two-dimensional tank is conducted to measure the roll damping. Since damage compartments near mid-ship section may be most dangerous, a rectangular compartment is selected.

Experimental Procedure

Schematic view of the forced oscillation tests is shown in Fig.2. The aquril tank with internal water is fixed on the forced oscillation mechanism. Forced roll moment and roll angle are measured by using strain gauges and a potentiometer, respectively. *OG* in Fig.2 is the distance from the rotation center to the bottom of the tank (+ if the rotation center is below the tank bottom).

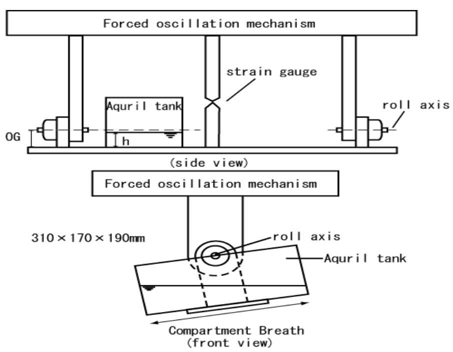

Fig. 2: Schematic view of forced oscillation test

In the experiment, water depth h, roll amplitude φ_0, OG and circular frequency ω are systematically changed. The effect of inertia force is subtracted by using experimental data for the case of no inside water.

In the analysis of the measured data, a motion equation of single-degree-of-freedom can be used as Eq.6.

$$I_{44}\ddot{\phi} + B_{44}\dot{\phi} = M_{\phi e} \tag{6}$$

where I_{44}, B_{44} and $M_{\varphi e}$ denote the roll inertia moment coefficient, the roll damping coefficient and the forced roll moment, respectively. The tank is forced to roll sinusoidally around the rotation center as $\varphi=\varphi_0\sin\omega t$, and the measured forced roll moment $M_{\varphi e}$ can be expressed as Eq.7.

$$M_{\phi e} = L_A \sin(\omega t + \varepsilon) \tag{7}$$

where L_A and ε denote roll moment amplitude and phase difference between roll motion and force. These values are obtained by expanding the measured data to a Fourier Series. Then, the roll damping coefficient B_{44} can be expressed as Eq.8.

$$B_{44} = \frac{L_A \sin\varepsilon}{\omega\phi_0} \tag{8}$$

The roll damping coefficient B_{44} and circular frequency of roll motion ω are non-dimensionalized as Eqs.9 and 10, respectively.

$$\hat{B}_{44} = \frac{B_{44}}{\rho \cdot B_{comp}{}^5}\sqrt{\frac{B_{comp}}{2g}} \tag{9}$$

$$\hat{\omega} = \omega / \omega_0 \tag{10}$$

where B_{comp} denotes the breadth of the tank, the circular frequency ω_0 is the frequency when the height of hydraulic jump is highest as pointed out by Dillingham[1)] as expressed by Eq.11.

$$\omega_0 = \frac{\pi}{B}\sqrt{gh} \tag{11}$$

This frequency ω_0 is a function of water depth in the tank, and increases with inside-water depth.

Experimental Result

In Figs.3 and 4, measured roll damping coefficients for φ_0=3° and φ_0=15° are shown, respectively.

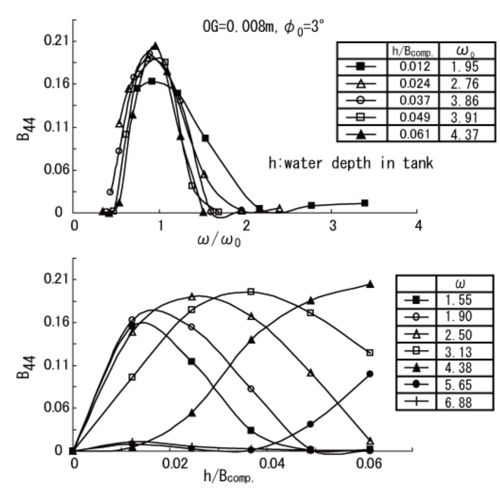

Fig. 3: Effect of inside water on roll damping coefficient

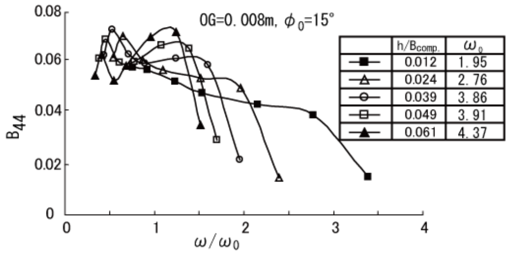

Fig. 4: Effect of inside water on roll damping coefficient

As shown in the upper figure in Fig.3, the roll damping has a peak when ω/ω_0=1. When roll angle is relatively big, however, no obvious peak appears as shown in Fig.4, and the roll damping is considerably small. This may be because that inside water does not move with constant phase difference, but violently moves. The lower figure in Fig.3 shows that the roll damping in each frequency has a peak in certain water depth.

On the basis of these experimental results, a prediction formula for the roll damping coefficient created by flooded water is deduced as Eq.12 by using an exponential function as a function of circular frequency, water depth, roll angle and center of gravity. It should be noted that the prediction formula is valid only in smaller roll angle.

$$\widehat{B}_{44} = A(x_2, x_3, x_4)\cdot C(x_1, x_2)^{B(x_2,x_3)}\cdot \exp\left[-C(x_1,x_2)^{B(x_2,x_3)}\right]\times\frac{l_{comp}}{B_{comp}}$$

$$\begin{cases} A(x_2,x_3,x_4) = \dfrac{1.8x_2 - 0.0347x_3 + 0.429}{1.2x_4 + 1} \\ B(x_2,x_3) \quad = 40.842x_2 - 0.1833x_3 + 2.1 \\ C(x_1,x_2) \quad = \dfrac{1}{\pi}\sqrt{\dfrac{B}{g}}\cdot\left(\dfrac{x_1}{\sqrt{x_2}}\right) = \dfrac{\omega}{\omega_0} \end{cases} \tag{12}$$

where x_1 denotes ω, x_2 $h/B_{comp.}$, x_3 φ_0 (deg), x_4 OG/B, l_{comp} and B_{comp} are the length and breadth of flooding compartment, respectively.

Fig.5 demonstrates the dependency of the roll damping on circular frequency and water depth. In the upper figure, the roll damping has a peak when ω/ω_0 is nearly unity, and in the lower figure, the roll damping in each frequency has a peak in certain water depth.

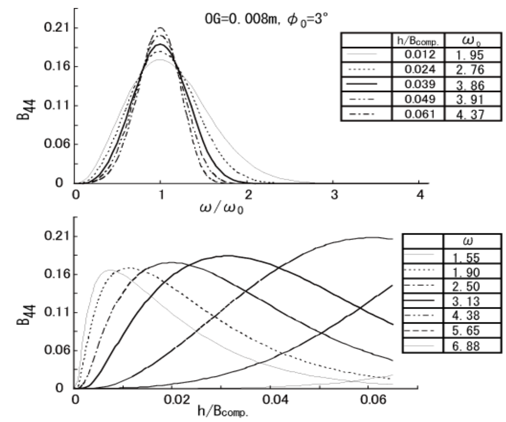

Fig. 5: Calculated roll dampings by the proposed prediction method

EXPERIMENTS OF 3D SHIP MODEL

Outline of Model Experiment

To confirm accuracy of the deduced prediction formula, free roll decay tests are carried out by using a model ship with flooded compartments.

The ship used in the experiments is a 1/125 scale model of the 110,000GT passenger ship designed by Fincanticri for an international cooperated research on damage stability of large passenger ships in IMO. The body plan and the principal particulars are shown in Fig.6 and Table 1, respectively.

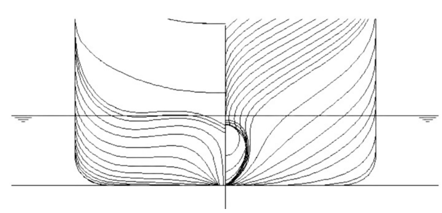

Fig. 6: Body plan of ship

As a damaged and flooded compartment, a compartment near the mid-ship is selected. The breadth and length of it are 287mm and 120mm, respectively. Since the effect of the roll damping on damaged openings is small, as pointed out by Hamano et al 1997[2)], the compartment has no damaged openings in this experiment.

Table 1: Principal particulars of ship

	Type A	Type B	Model
Scale	1/1	62/100	1/125
L_{OA}	290 m	180 m	2.200 m
L_{PP}	242.24 m	150.19 m	1.933 m
Breadth	36 m	22.32 m	0.287 m
Draft	8.4 m	5.208 m	0.067 m
Displacement	53,010 ton	12,623 ton	26.98 kg
GM	1.579 m	4.48 m	0.0126 m
KG	17.9 m	7.6 m	0.143 m
T_{roll}	21.05 sec	8.59 sec	1.88 sec
C coefficient	1.48		
Bilge keel width	1.1 m	0.682 m	----------
Bilge keel location	s.s.3.0-5.0 , s.s.5.25-6.0		----------

Result of Model Experiment

Fig.7 shows the change of roll natural period obtained by the free roll decay tests, and Fig.8 shows the comparison of the measured roll damping and the prediction formula.

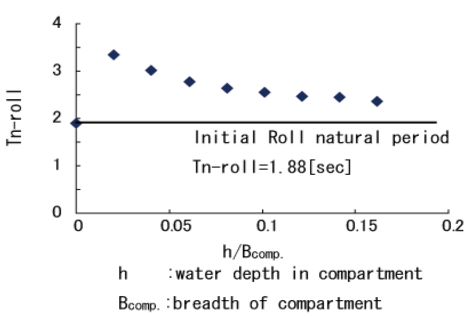

Fig. 7: Change of natural roll period due to increasing flooded water

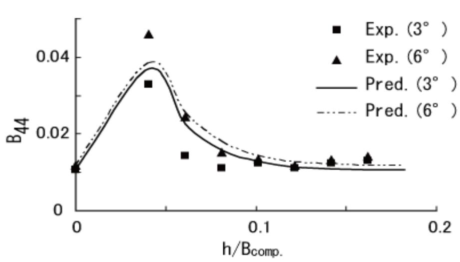

Fig. 8: Comparison of experimental and predicted results of roll damping of the flooded ship

As shown in Fig.7, the roll natural period gradually approaches a certain value with increasing water depth in the compartment after having a peak. This peak seems to correspond to the peak of roll damping as described later, and it is caused that the roll damping induced by inside water increases dramatically. It should be noted that the roll natural period approaches to a slightly longer period than that in intact condition with increasing water depth. This is because of that an increase of inertia moment and the free water effect due to inside water. As shown in Fig.8, the measured roll dampings are in fairly good agreement with predicted ones, and has a large peak at $h/B_{comp.}$=0.05, then gradually decreases with increase of $h/B_{comp.}$, finally settled at the value for intact condition. It can be safely said that the proposed prediction formula has enough accuracy.

APPLICATION OF WEATHER CRITERION TO A FLOODED SHIP

In this section, Weather Criterion is applied to a damaged and flooded ship to calculate the limiting wind speed for her safe voyage. The ship is the 110,000GT passenger ship used in the model experiment. The bilge keels designed for the ship are divided into two parts, a short forward and a long aft ones. The numbers of flooded compartments are assumed to be one, two and four. In the compartments, four layers of inside decks are arranged as shown in Fig.9. The application is done for final stages of flooding, that means that inside and outside water levels are the same. In the intact condition, the wind speed limitation is calculated to be 28.08m/sec by Weather Criterion which is larger than 26m/sec settled in the criterion. Therefore, this ship satisfies this requirement in intact condition.

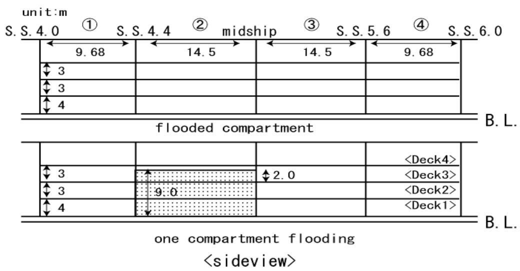

Fig. 9: Deck arrangement in flooded compartment

The change of *GZ* curves due to flooding is shown in Fig.10. The *GZ* decreases with increasing numbers of flooded compartments. For examples, in four-compartment-flooding the *GZ* decreases by about 50% from intact condition.

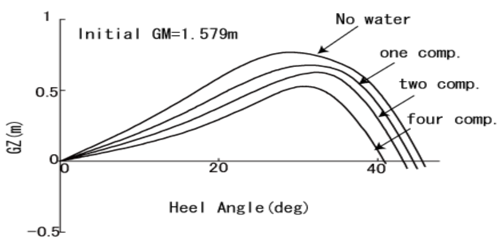

Fig. 10: GZ-curves for various flooded condition

In the prediction of the roll damping after flooding, the internal water depth *h* is determined as the depth on the uppermost deck under the inside-water surface. Giving an example of one-compartment-flooding, the water depth is 9.0m from the lowest deck or the double bottom deck, but due to having decks of two layers under the water surface, the water depth used in the calculation should be 2.0m at distance from Deck 3 to the surface of inside water. Fig.11 shows an example of the calculated resulting *GZ* curve for a one compartment flooding case

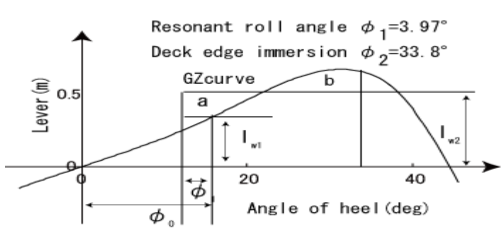

Fig. 11: Application of Weather Criterion to damaged ships in one-compartment flooding case

As shown in Table 2, it can be seen that the limiting wind speed in all flooded conditions was greater than that in intact condition. This is caused that the resonance roll angle φ_1 becomes smaller than those in intact condition due to increase of the roll damping by flooding.

Table 2: Results of wind criteria of a ship for safe return to port

	Numbers of flooded compartments			
	no	one	two	four
$h/B_{comp.}$	0	0.056	0.074	0.02
φ_1(deg)	16.61	3.97	5.19	0.25
φ_2(deg)	35.6	33.8	32.2	28.4
ω/ω_0	1	0.69	0.53	0.94
k_w	1	0.27	0.41	0.021
U_w(m/sec)	28.08	34.36	32.03	33.48

However, it should be noted that the limiting wind speed varies with scale of flooding conditions. The cause of the variation can be understood as follows. Resonance roll angle greatly depends on the change of the roll damping due to inside water. Also, the frequency ω_0 when the roll damping has a peak depends on inside-water depth. Therefore, it is considered that limiting wind speed is changed by relative levels between inside-water surface and the deck just bellow the surface.

To investigate the effect of inside-water depth, *h*, on limiting wind speed for safe return to port, the deck height is changed in case of one and four compartment flooding. The limiting wind speeds are calculated when the roll damping becomes the maximum, ω/ω_0=1 and the minimum or the same as that in intact condition, k_w=1. The limiting wind speed can be expected to be maximum in the former case, and to be minimum in the latter case. The calculated limiting wind speed, U_w, for each cases in one and four damaged compartments is shown in Table 3.

Table 3: Results of wind criteria of a ship for safe return to port

	one comp. flooding		four comp. flooding	
	B_{44}-min	B_{44}-max	B_{44}-min	B_{44}-max
$h/B_{comp.}$	0.19	0.026	0.19	0.018
φ_1(deg)	13.2	1.1	12.1	0.25
φ_2(deg)	33.7	33.7	28.4	28.4
ω/ω_0	0.37	1.0	0.29	1.02
k_w	1	0.039	1	0.022
U_w(m/sec)	28.66	36.02	24.68	33.48

The results shown in Table 3 demonstrate that the limiting wind speed, U_w, varies with deck arrangement. In one-compartment-flooding it varies from 28.66 to 36.02 m/sec, and in four-compartment-flooding it varies from 24.68 to 33.48m/sec. Since the limiting wind speed of the ship in intact condition is 28.08m/sec as mentioned before, in one-compartment-flooding it is found that the limiting wind speeds in any deck arrangements are larger than those in intact condition. This means that the damaged ship can sail safely in severe sea conditions than the intact ship. On the other hand, the limiting wind speed in four-compartment-flooding becomes smaller than that in intact condition. As shown in Fig.10, GZ-curve in four-compartment-flooding is smaller than that in two-compartment-flooding. Therefore, it is considered that the limiting wind speed depends on the value of *GZ* after flooding as well as relative levels between inside-water surface and the deck just bellow the surface.

EFFECT OF SHIP SIZE ON LIMITING WIND SPEED

Generally speaking, a smaller ship can be influenced more than a larger ship by sea conditions. Therefore, the effect of ship size on the limiting wind speed is investigated. The large passenger ship used above is scaled down to a smaller ship with 180m length as shown in Table 1. The larger ship is called Type A and the smaller one Type B, respectively. The *GM* values of the ships are determined as *C* coefficients (=Area *a*/Area *b*: see Fig.1) are 1.05 and 1.48, respectively. The changes of *GM* in each flooded condition are shown in Fig.12. It can be seen that the change of *GM* for the bigger one Type A due to flooding is greater, and in the case of *C*=1.05, *GM* decreases up to 70 percent. On the other hand, for the smaller one Type B, 25 percent in the case of *C*=1.05.

The flooded compartment is assumed to be symmetrical about the mid-ship section, and the length is changed from 5% to 30% of L_{pp}. The roll damping, which significantly depends on water depth on the most upper flooded deck, is assumed to be minimum, because it causes the most severe solusion of the limiting wind speed.

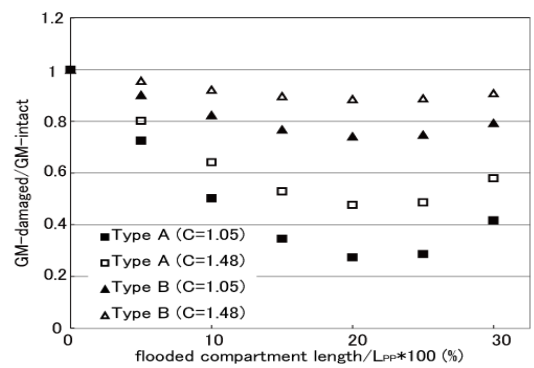

Fig. 12: Reduction of *GM* of different size ships for various flooded conditions

Table 4: Results of wind speed limits of different size ships for safe return to port

U_w	flooded compartment length/Lpp×100 (%)						
(m/sec)	0	5	10	15	20	25	30
Type A (C=1.05)	26.24	26.46	25.45	22.94	21.71	20.22	19.44
Type B (C=1.05)	26.43	27.93	28.56	27.29	25.67	24.28	20.56
Type A (C=1.48)	29.36	29.88	29.74	28.33	27.42	26.03	24.54
Type B (C=1.48)	36.34	37.84	38.22	36.58	32.77	28.7	19.71

The results of the limiting wind speed are shown in Table 4 and Fig. 13. The limiting wind speeds of the smaller ship, Type B, are greater than those of the larger one, Type A when the length of flooded compartment is small. This may be caused by difference of the initial *GM* values of the ships. On the contrary, as the length of flooded compartment increases, the limiting wind speeds of the smaller ship, Type B, become smaller than those of the larger one, Type A.

Using the results of the limiting wind speed obtained by applying Weather Criterion to a damaged ship, the master can understand the safety level during the voyage to the port.

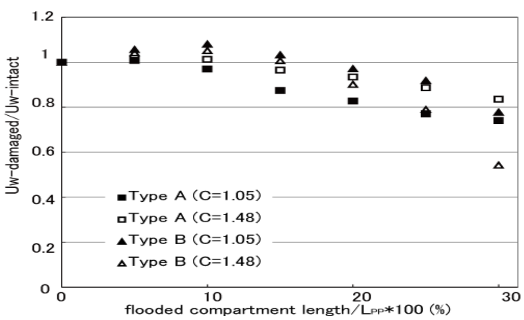

Fig. 13: Comparison of wind speed limits of different size ships for safe to return to port in various flooded conditions

CONCLUSION

Following conclusions are obtained by this study.

1) The authors proposed a simple prediction formula of the roll damping induced by inside water due to flooding, and confirmed that the accuracy of the prediction through experiments of a model ship.

2) To establish a guideline to Master for safe return to port with passengers, Weather Criterion for an intact ship is applied to a damaged and flooded ship, and the limiting wind speed for safety voyage is obtained.

3) Depending on water depth on the most upper flooded deck in a compartment, the limiting wind speeds sometimes become larger than those in its intact condition.

4) The results of the limiting wind speed can support the decision making of the master of a damaged ship for return to port with passengers or not.

ACKNOWLEDMENTS

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APPENDIX

Correlation table of natural roll period T and wave steepness *s* proposed in SLF47.

Table A－1: Values of factor *s*

T	*s*
≤6	0.100
7	0.098
8	0.093
12	0.065
14	0.053
16	0.044
18	0.038
20	0.032
22	0.028
24	0.025
26	0.023
28	0.021
≥30	0.020

(Intermediate values in these tables should be obtained by linear interpolation)

Rolling period T:

$$T = \frac{2CB}{\sqrt{GM}} \text{ (sec)}$$

where: C=0.373+0.023(B/d)－0.043(L/100)

The symbols in the above tables and formula for the rolling period are defined as follows:

L = length of the ship at waterline

B = moulded breadth of the ship

d = mean moulded draught of the ship

GM = metacentric height corrected for free surface effect