Experimental investigation on one damaged passenger ship in regular and irregular beam waves

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ABSTRACT

The motion and the internal water height of one passenger ship in intact and damaged state are investigated experimentally. The experimental methodology is introduced in detail. The effect of the damaged opening's size and the quality of the simulated wave are examined carefully before the formal case study. The time history of the intact and damaged ship motion in regular and irregular beam waves are presented and compared to the numerical predictions. Results indicate that the roll amplitude of the damaged ship is smaller than that of the intact one under the testing damaged conditions, but it doesn't mean a safer circumstance for the damaged ship due to the existence of the constant heeling angle. The numerical prediction of the ship motion in regular and irregular waves match the experimental results with certain accuracy, calling for further modifications to the flooding model.

Keywords: *Damage stability; Experimental approach; Water height; Roll motion*

1. INTRODUCTION

Recently, damage stability has drawn a great deal of attention in the field of ship hydrodynamics, due to its great theoretic value and practical significance. The flow through the damaged opening shows prominent nonlinear characteristics and the water sloshing inside the damaged cabin has a profound influence on the damaged ship's motion, which changes the ship attitude directly and leads the ship to capsize in some extreme environment. Among researches on the damage stability, model test is a most effective approach to obtain the characteristics of the damaged ship's motion and corresponding influence factors.

The first systematic experiment on the damage stability can date back to 1961. A specialist group was set up by the predecessor of International Maritime Organization, IMCO, to review the existing damage stability standards in the view of safety and practicability. Bird & Browne (1974) carried a series of model tests, laying the groundwork for later experiments. In their experiments, the motion of one damaged RoRo ship, i.e. heave, pitch and yaw, in beam waves was investigated in detail, of which power was lost due to the severe damage. The ship consisted of the hull, vehicle deck, watertight bulkheads, superstructure, propeller and rudder. The vertical position of the center-of-gravity and the remaining freeboard were adjusted by the weights on the driving screw and the volume of displacement, respectively. The damaged opening located at the bow or midship on the windward side or the lee side. The internal configuration of the damaged cabin was ignored and permeability for all cabins was assumed 100%. The Darbyshire wave spectrum was adopted, compared to the JONSWAP spectrum commonly used nowadays and the capsizal direction was recorded during the test. The research work of Riola *et al.* (1997) was also representative with a typical ferry. It was assumed that the adjacent two cabins below the vehicle deck on the starboard side of the amidships were flooded. The damaged opening was rectangular and the length was in accordance with the regulation of SLOAS, and the JONSWAP spectrum in beam wave was taken. Three different significance wave heights were selected, and residual freeboard and metacentric height were combined into nine load conditions for the test. The model drifts freely, allowing six degrees-of-freedom. The roll motion, water height at 18 distribution points on the vehicle deck and waver rise at the damaged opening were measured. A waterproof camera was installed in the damaged compartment to record the flooding process.

Vassalos *et al.* (1997) studied the influence of the shape of damaged opening on the inflow through model tests. In particular, they pointed out the trapezoidal opening was not conductive to the discharge of water, so the rectangular opening specified in SOLAS regulation can bear higher significant wave height than trapezoidal opening. Ikeda (2000) studied the large amplitude roll motion in the middle stage of water inflow after sudden damage of one passenger ship through experimental tests. They simplified the design of different cabin arrangement and studied their effects on roll motion. The test results showed that the roll motion in the middle inflow stage was very sensitive to the arrangement in the cabin and the area of the damaged opening. Gao (2000) conducted a series of damaged stability tests on a containership in regular and irregular waves. The model was in a free floating state, and the damaged opening was in a trapezoidal shape, which was located at the midship and starboard of the ship. They have analyzed the roll response of the ship after damage, the water surface rise and wave surface rise in the cabin under different states, and given a general conclusion between the GM value and the roll response after damage, which provided a useful reference for the model test of damaged cabin stability in waves.

ITTC also conducted many bechmark tests for damaged ship stability, including free roll decay curve, motion responses in regular and irregular waves, and the transient flooding process (Papanikolaou & Spanos, 2004). Later van Walree and Papanikolaou (2007) introduced flooding process in ITTC benchchmark study.

Katayama & Ikeda (2005) verified the exchange coefficient was related to the geometry of damaged opening and vent condition in cabins. Lee *et al.* (2012) conducted free roll decay and motion responses tests in calm water, and the effects of the flooding water on the roll decay motion of a ship were investigated. Begovic *et al.* (2013) conducted mode tests in intact and damaged state on DTMB 5415, studied the influence of scale ratio, and second order drift forces of damaged ship through the comparison of captive and free running model tests. Manderbacka *et al.* (2014) investigated the coupling effect between internal sloshing and liquid flow inside the cabin through model tests. Domeh *et al.* (2015) studied the effects of compartment permeability, internal compartment layout and opening size on the motion response of damaged ships in waves with and without speed. The result showed that the permeability of the cabin has little effect on the heave and pitch responses at zero speed. When the ship is sailing, the permeability of the cabin and the size of the breach have a great influence on the heave and pitch response, while the layout of the internal cabin has little influence on the heave and pitch response.

Model test is obviously an effective method to study the dynamic behavior of damaged ship. It can provide reference and support for ship design to ensure or improve the survivability of damaged ship. The focus of this paper is to experimentally study the flooding process and motion of one damaged passenger ship in calm water and beam waves. In Section 2, the experimental setups are described in detail. Results of roll motion and internal water height in different wave conditions are presented in Section 3.

2. EXPERIMENTAL SETUPS

2.1 Ship model

In this experiment, Froude number and Strouhal number are proposed as the principle to design the ship model and set the experimental parameters, which are defined in Equation 1.

$$Fr = \frac{V}{\sqrt{gL}}\ ,\ Str = \frac{VT}{L} \tag{1}$$

Note that the gravitational acceleration is same for the full-scale ship and the ship model. According to Equation 1, one can easily obtain that the scale ratio for the velocity is the square root of that of the length and so is the time. However, since another important dimensionless number, Reynolds number, cannot be kept unchanged while keep the same Froude number, a small scale ratio usually results in an obvious error between simulation results and the real physics. Besides, enough internal space for the measure apparatus is also needed. For the ship model used in this experiment, a scale ratio of 1:49.5 for the length is adopted and other scale ratios can be defined accordingly.

Flooding water has a great impact on ships with no-bulkhead cabins, such as Ro-Ro passenger ships, which are usually used in damage stability researches. As presented in Figure 1, a damaged passenger ship model with two propellers and two rudders is investigated experimentally. To ensure the structure strength and the water tightness, the ship is manufactured by integral moulding of glass fiber reinforced plastic material and a rib-frame structure is adopted. Inside the cabins, floors are covered by wooden plates for installing the measuring apparatus. Water repellent treatments are applied in cabins apart from the damaged one. The deck is also sealed by a plexiglass plate fixed by sealing rings and detachable screws. Principle parameters of the ship model are listed in Table 2. The position of the center-of-gravity and the longitudinal moment of inertia are adjusted by a dedicated cradle. The transverse moment of inertia and metacentric height are checked by the free roll experiment and inclination experiment, respectively.

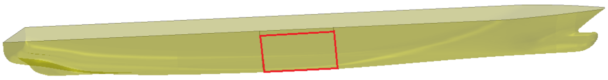

Figure 1: The geometry of the damaged hull (the position of the damaged cabin is marked in red)

Table 1: Principal parameters for the ship

Items	Dimension	Full-scale ship
L_{pp}	m	247.7
B	m	35.5
d	m	8.3
V	m^3	52218.7
L_{cg}	m	-6.5
KG	m	16.4
KB	m	4.5
GM	m	2.2
T_φ	s	17.48

2.2 Damaged cabin

Two interconnected compartments made of 10 mm thick plexiglass plates are investigated in the experiment, as illustrated in Figure 2. This kind of damaged form is referenced to Lee et al (2012).

Two compartments are connected through a 60mm*160mm rectangular hole with a 243 mm offset from the port and 138 mm offset from the bottom side. The cabin locates at the starboard of the ship near the longitudinal position of the center-of-gravity. More information of the cabin's position and size is presented in Table 2. Note that all values are measured inside the compartment.

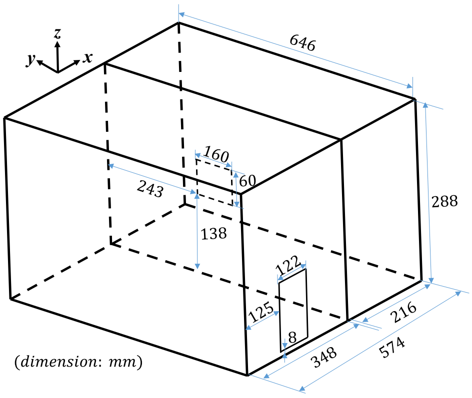

Figure 2: The sketch of the damaged cabin (model scale)

Table 2: Principal parameters for the damaged cabin (dimension: mm, model scale)

Item	Cabin 1 with a damaged opening	Cabin 2
x-direction length	348	216
y-direction length	646	646
z-direction length	288	288

To examine the influence of the damaged opening's size, two rectangular openings are investigated in the experiment, which are formed instantaneously by a self-designed windlass-rope-plate mechanism, as showed in Figure 3. The damaged opening locates at the position with 125 mm offset from the port and 8 mm offset from the bottom side. Two openings differ only in the height, i.e. 143 mm for O1 and 70 mm for O2, which stands for cross-waterline damage and under-waterline damage, respectively.

Figure 3: Self-designed electrically operated valve for controlling the opening's size.

2.3 Measurements

The interested physical quantities in the experiment are the incoming wave height, internal water height and ship's kinematic parameters. A servo-type wave height gauge is set 2 m away from the hull upstream to measure the incoming wave height without evident disturbance to the incoming flow of the hull. A capacitive wave height gauge array is utilized to measure the instantaneous water height at several typical position, as illustrated in Figure 4. The time history of the ship's attitude, such as roll, pitch and heave, are recorded by a gyroscope and the acceleration is obtained by sensors installed on interested positions. Signals from the above apparatus are processed by an amplifier and then stored on the hard disk for further analysis.

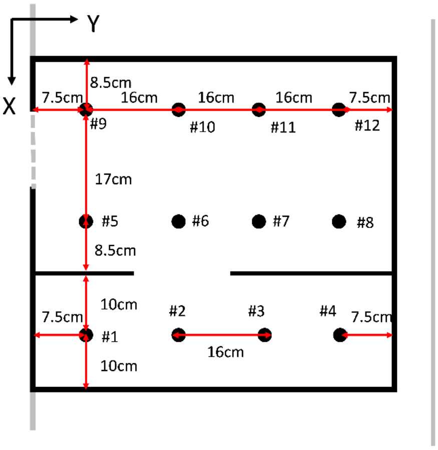

Figure 4: Arrangement of the capacitive wave height gauge array inside the cabin.

2.4 Wave conditions

The experiments are carried out in the seakeeping basin of China Ship Scientific Research Center (CSSRC). Several elastic strings tied the ship model to the towing carriage to constrain ship's drifting, as presented in Figure 5. The existence of the springs should not alter the first resonance frequency of the system, which means the natural period of the spring should be more than 10 times of that of the ship model.

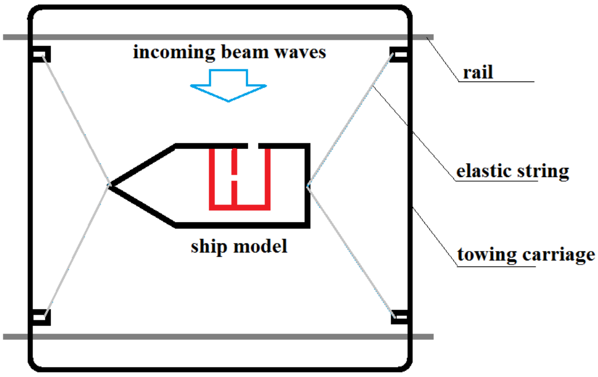

Figure 5: The sketch of the experimental arrangement (the damaged cabin is marked in red)

Different cases are investigated experimentally at zero speed, namely the damaged ship in calm water, the intact and damaged ship in regular waves with steepness 0.01, 0.02, 0.03, and the intact and damaged ship in irregular waves with different random seeds. Here we take calm water, wave steepness 0.03, and one randoom seed as examples. The case conditions are listed in Table 3 and 4, respectively. The regular waves are simulated by a cosine function while the ITTC dual-parameter spectrum model is utilized to model the irregular waves. According to the relevant ITTC procedure for seakeeping model test in irregular waves, the model should undergo more than 200 non-repetitive waves. The least duration for single case is 8.5 min, which equivalent to 1 hour at full scale.

$$S_{\zeta} = \frac{173 H_{1/3}^2}{\omega^5 T_{01}^4} \exp\left(-\frac{691}{\omega^4 T_{01}^4}\right) \tag{2}$$

where $H_{1/3}$ is the significant wave height and T_{01} is the wave period, which can be related to the spectrum peak period by Equation 3.

$$T_{01} = T_P / 1.2958 \tag{3}$$

Table 3: Wave parameters in calm and regular waves.

No.	Period/s	Wave slope	Damaged Types
S1	calm water		O1
S2	calm water		O2
R1	17.48	0.03	/
R2	17.48	0.03	O1
R3	19.35	0.03	/
R4	19.35	0.03	O1

Table 4: Wave parameters in irregular waves.

No.	Significant wave height/m	Peak period/s	Damaged Types	Random seed
I1	6.0	12.4	/	1
I2	6.0	12.4	O1	1

3. RESULTS AND DISCUSSION

3.1 Effects of the damaged opening's size

For case S1 and S2 in calm water, special attentions are paid to the internal water height at several position and the results are presented in Figures 6-7. The water height grows rapidly to a certain value after the damage happens and begins to oscillate about it. The developing time for the flow at the large opening is shorter than that of the small one, but in the mean time it takes a much longer time for the flow to settle down at large opening, reflecting notable unsteady characteristics. Besides, the ultimate water level in S1 is higher than that in S2 at the corresponding position which is consistent with the intuition. However, the differences in the water height has limited influence on ship's roll expect for the initial state, as showed in Figure 8. Therefore, in the following case study, only the large damaged opening is applied.

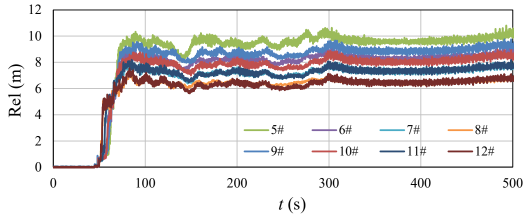

Figure 6: Internal water height measured by the wave height gauge array in calm water for S1 type.

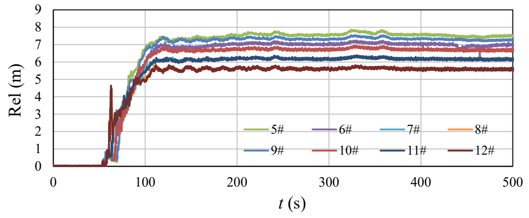

Figure 7: Internal water height measured by the wave height gauge array in calm water for S2 type.

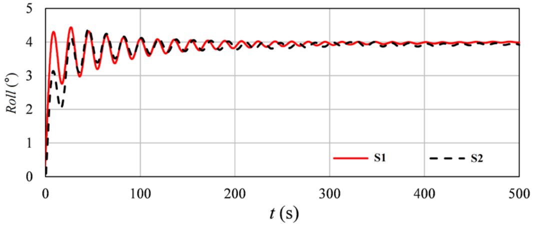

Figure 8: Time history of roll motion in calm water.

3.2 Results in regular beam waves

The time history of roll motion is presented in Figure 9 . For the intact ship, the equilibrium attitude is the upright state and the roll amplitude 26.3° is bigger than that of a damaged ship, 12.69° when the wave period is equal to natural roll period 17.48s. Due to the asymmetry by the damaged cabin and the flooding water, there is an obvious heeling angle, i.e. 6.59°, for the damaged ship and the ultimate roll motion of the damaged ship is a steady oscillation about the heeling angle with a relative small amplitude. It seems safer for the damaged ship under the testing sea condition. However, it cannot be applied to all conditions, especially for the extreme sea conditions in which the heeling angle for the damaged ship is big enough and the maximum heeling angle may exceed the permitted value even with small roll amplitude. The same conclusion can be also inferred from Figure 10 when the wave period is equal to natual roll period 19.35s for damaged state.

For comparison, the numerical prediction based on potential flow method and a flooding model derived from the modified Bernoulli's equation are also presented, as showed in Figures 11-12. Details of the methodology can be found in Bu et al (2018, 2020).

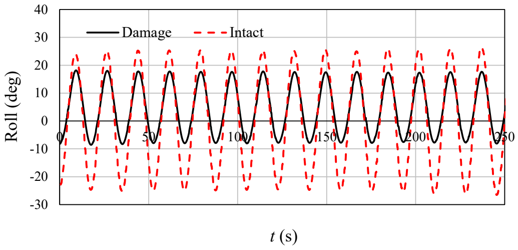

Figure 9: Roll motion in intact and damaged state for R1 and R2

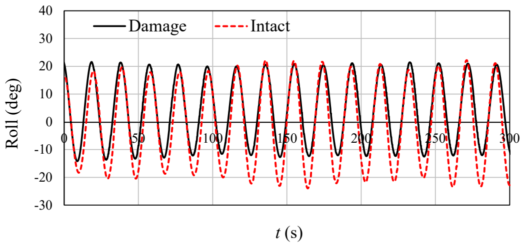

Figure 10: Roll motion in intact and damaged state for R3 and R4

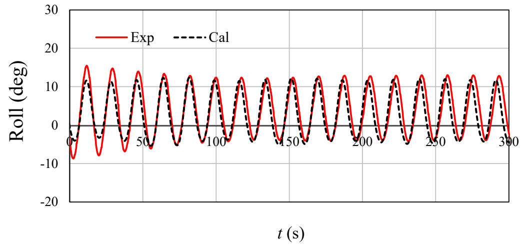

Figure 11: Comparison of roll motion between model test and numerical simulation for R2

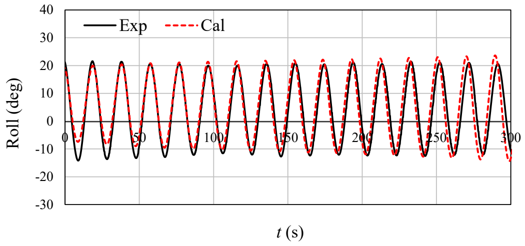

Figure 12: Comparison of roll motion between model test and numerical simulation for R4

3.3 Internal water height in regular beam waves

High-speed camera is used to capture the instantaneous free surface of the internal flooding water and photos of the internal free surface at different moments are presented in Figures 13-15. When the damaged opening comes into being, water rushes into the cabin due to the pressure difference, resulting in nonlinear water surface's curling and breakup. However, when the flooding water reaches a stable state, the free surface can be approximate as a plane to some extent.

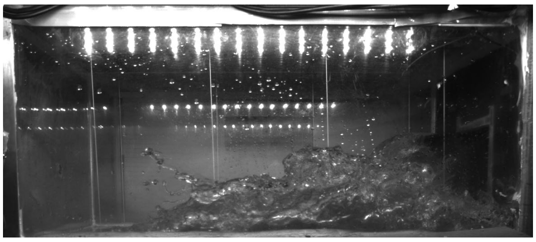

Figure 13: Photos of the internal free surface at different moments (T=17.48s, H/λ=0.03)

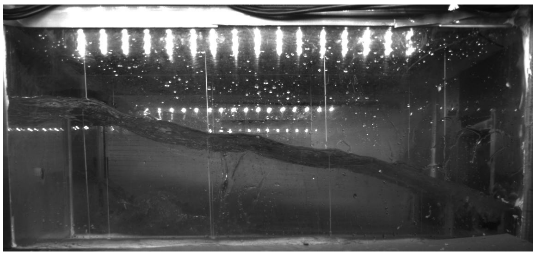

Figure 14: Photos of the internal free surface at different moments (T=17.48s, H/λ=0.03)

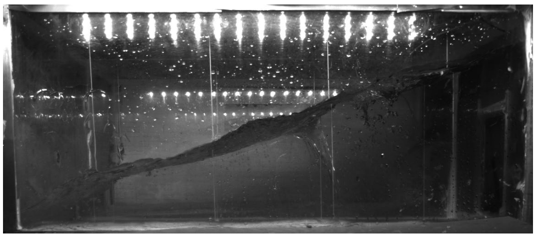

Figure 15: Photos of the internal free surface at different moments (T=17.48, H/λ=0.03)

3.4 Results in the irregular beam waves

The time history of the roll motions in I1 and I2 are plotted in Figures 16-19, respectively. It's evident that the roll amplitude of the damaged ship is smaller than that of the intact one, similar to the result in regular wave. However, the maximum heeling angle, i.e. the heeling angle plus the maximum roll amplitude, of the damaged ship exceeds the intact ship's, which verifies the statement in Section 3.2. The numerical predictions match the experiment results with certain accuracy, calling for further modification of the flooding model.

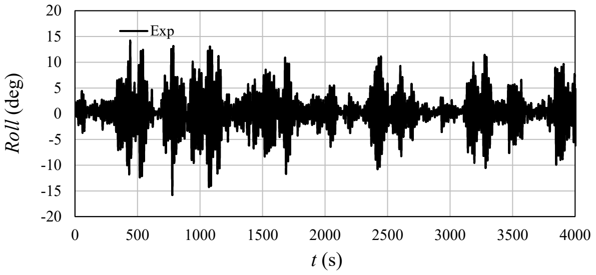

Figure 16: Time history of roll motion under intact state

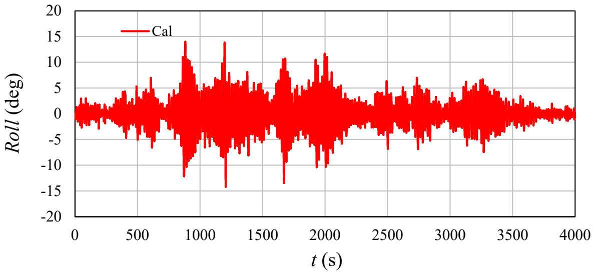

Figure 17 Time history of roll motion under intact state

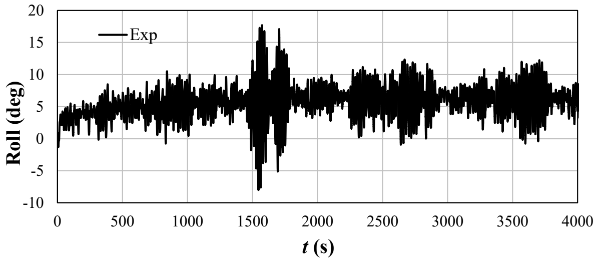

Figure 18: Time history of roll motion under damaged state

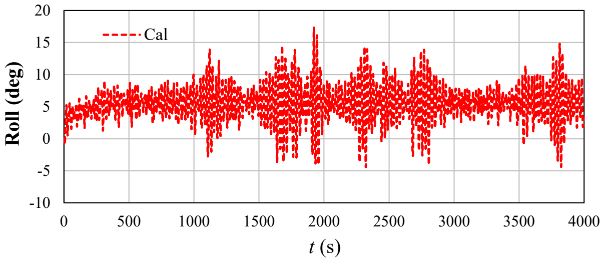

Figure 19: Time history of roll motion under damaged state

4. CONCLUSIONS

The motions of the intact ship and the damaged ship in regular and irregular beam waves are investigated experimentally. The damaged opening's size has little impact on ship's motion except for the initial development. In both regular and irregular waves, the damaged ship shows a smaller roll amplitude but an obvious constant heeling angle, making it difficult to determine whether it's safe under certain sea conditions. The numerical predictions match the experiment results with certain accuracy, calling for further modification of the flooding model.

Acknowledgments

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