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PROGRESSIVE COLLAPSE TEST OF SHIP STRUCTURES IN WAVES

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ABSTRACT

The external loads and structural ultimate strength are two important aspects for the safety of ship hull girder. It may collapse in case the structural capacity is less than the external forces in extreme seas. In the present research, progressive collapse test is performed to investigate the collapse mechanism of ship structure in waves. External load with time history and corresponding structural collapse behavior are measured and discussed to demonstrate the interaction of fluid and structures.

Keywords: Ship hull girder, Progressive collapse behavior, Ultimate strength, External force, Collapse test

INTRODUCTION

Based on a study, with the development of society and the progress of economy, the international trade supported by shipping becomes more and more common. According to the statistical document, there are more than 1200 ship accidents all over the world from 2005 to 2014 [1], which caused not only loss of lives and properties but also seriously environmental problem such as pollution due to spilled oil. The main reason of these accidents is the ship structural ultimate strength is insufficient to resist the external loads acting on the ship hull in extreme seas. Ship wrecks and rules of related ship organizations make it necessary to study the progressive collapse behavior of ship structures in waves.

In traditional, ship structural ultimate strength is evaluated considering the structure itself. One frame space model or hold model is usually adopted imposing forced rotation on end cross-sections assuming that the cross-section remains plane. The bending moment is calculated by integrating the axial force multiplied by a lever in each element. The ultimate strength is defined as the maximum moment along the equilibrium path obtained by the above-mentioned static analysis. Direct calculation method, Smith method, Idealized Structural Unit Method and nonlinear finite element method can be used to carry out such analyses. However, the natural world is not controlled by pathways or curvatures, but by pressure and/or force. Bending moment-curvature relationship obtained by forced displacement method or arc length method could be far from the reality after the working bending moment has exceeded the hull girder capacity, as pointed out by Lehmann [2-6].

Considering the fluid-structure interaction and its influence on collapse behavior of ship structures, a scholar proposes a total computation system combining three-dimensional Singularity Distribution Method with Idealized Structural Unit Method [7]. The three-dimensional Singularity Distribution Method is adopted to calculate the ship motion and pressure distribution. The calculated loads including inertia forces with time history are transferred to structural model and progressive collapse behavior can be obtained. According to research, the collapse characters of a bulk carrier under alternate loading condition are demonstrated and discussed [8-9]. A scholar combined computational fluid software STAR-CCM+ and the structural analysis software ABAQUS to carry out the coupling analysis of fluid and solid of a barge, in which the hull structure is regarded as an elastic beam [10]. Other scholar calculated structural ultimate capacity of several typical ship sections considering both hydrostatic and hydrodynamic pressure to investigate the influence of lateral pressure on ultimate strength of ship hull girder [11]. To investigate the character of bending moment, a model testis carried out to describe the post-ultimate behavior of ship hull girder in waves [12]. Two rigid bodies are connected with a plastic hinge which is designed to measure the vertical bending moment caused by the fore and aft body.

In this paper, progressive collapse test in waves is carried out to investigate the collapse characteristics and ultimate capacity of ship structures. A stainless-steel test model with three holds is designed. The pressure of typical points in the bottom is measured through pressure sensor. The ship motion acceleration is recorded by acceleration sensor and inclinometer sensor. The strain distribution of three typical sections is measured by dynamic strain gauge. The weight of test model is small so that steel blocks are put in the forest and last section to form the proper still water bending moment. The wave maker produces the wave in towing tank in the condition that the wave length equals to the length of test model. With the increase of wave height, the force subjected to the test model increases so as to the structures collapse finally. The test results are discussed and compared with FEM results. The pressure, motion and stress distribution during the collapse test are demonstrated.

MODEL DESIGN

To explore the collapse mechanism of ship structures in extreme seas, the model collapse test in waves is carried out. The external forces should be larger than the structural ultimate capacity, otherwise the structural collapse cannot be happened. Due to the capacity limitation of wave maker, the wave bending moment is also limited. The test model shall be weak enough so as to be collapsed under the still water bending moment and wave bending moment [13, 14].

Nonlinear finite element method is used to estimate the ultimate capacity of preliminary designed test model. Double-span section model is adopted and forced rotation angle is added in the end section. As the increase of rotation angle, the relationship between vertical bending moment and rotation angle can be achieved. The maximum bending moment represents the structural ultimate strength. The ultimate strength of test model is designed a little smaller than external loads including still water bending moment and wave bending moment. The procedure of model design is summarized in Fig. 1.

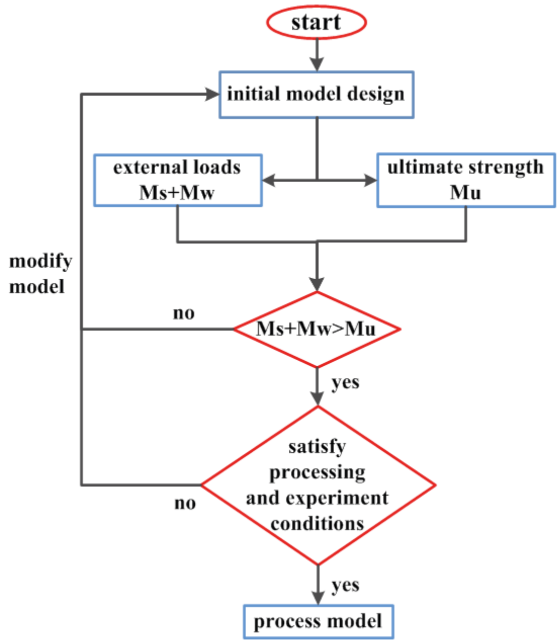


Fig. 1. Model design procedure

There are three holds for the test model. The fore and aft hold can be considered as loading part and the middle hold is the test one. There is deck opening at the end of loading hold in order to put mass block to enlarge the still water bending moment. The length of each hold is 2.25m so the length of test model is 6.75m. The width and depth are 1.25m and 0.3m, respectively. The space of bottom longitudinal is 0.25mand that of side longitudinal is 0.15m. The plate thickness of loading holds is 3mm and the stiffener size is -20x3mm. The plate thickness of the middle hold, namely test part, is 0.5mmand the stiffener size is -20x0.5mm. The dimensions of test model are shown in Fig. 2 [15].

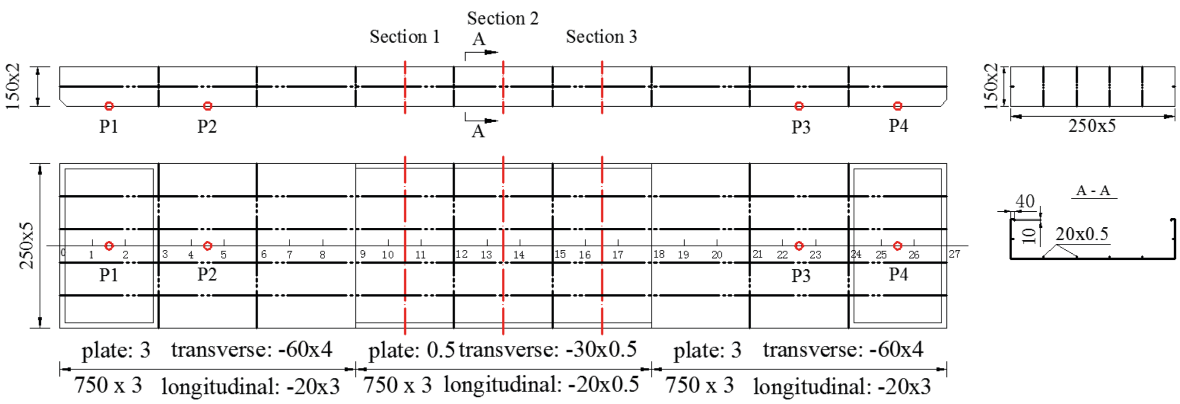


Fig. 2. Model dimensions and Measurement point of lateral pressure

MODEL TEST

Not only the external forces subjected to the test model but also the structural progressive collapse procedures are included in the test. The pressure distribution, the ship motion and the strain distribution in the still water and in the wave are recorded.

TEST CONTENT

The encountered wave length equals to the length of test model. The position of the crest is different with the movement of waves. So, the lateral pressure value of typical position in the bottom can represent the wave situation which can be used to calculate the wave bending moment.

The ship motion includes three translational motions and three rotational motions. The acceleration sensors are used to measure the translational motions such as surge, sway and heave and inclinometer sensors are adopted to test the rotational motions such as roll, pitch and yaw. The inertia forces are obtained by multiplying the mass by the corresponding acceleration [16].

The structural stress distribution during the collapse is the important affairs. In order to get the bending moment, the strain test points shall be distributed in the typical section of test part. There are test points in the stiffener position and the panel center of the middle section where the bending moment shall be the largest. The test points in neighbor section are also distributed to validate and/or eliminate incorrect data.

TEST POINTS

The pressure test points shall be able to represent the wave situation. The wave length is basically equal to the model length. There are totally four test points locating at the bottom center of two end sections in the loading hold, as shown in Fig. 2.

The elastoplastic deformation is comparatively smaller than the movement of rigid body. Two acceleration sensors are enough to describe the translational motion situation. They are arranged in the deck at the center of each loading hold [17]. The rotational motion of test part is interesting and worth measuring. Two inclinometer sensors are placed at fore and aft end of test part to record the rotational situation during the collapse test. The arrangement of sensors is shown in Fig. 3.

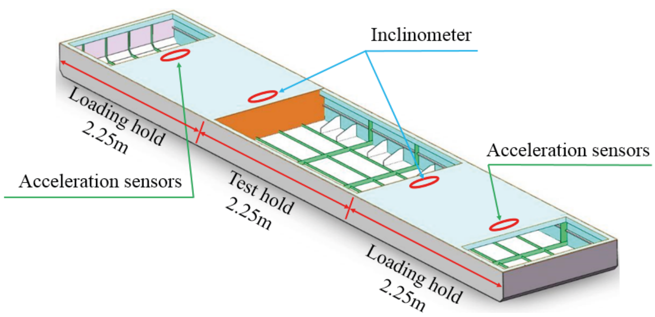


Fig. 3. Measurement point of ship motion

In order to realize the structural response during the collapse test in waves, the strain test points are distributed in the typical section of test part. The midst section will suffer the largest vertical bending moment so that all the positions of stiffener and center of panel are considered as stress test point. To describe the strain distribution in depth direction, seven test points are arranged in the same distance in the side shell from bottom to the upper deck. In the fore or aft section of the midst section, there are strain test points at the position of stiffener and the joints between side shell and bottom and deck. The position of sections for strain test points is schemed in Fig. 2 and the distribution of strain test points is shown in Fig. 4.

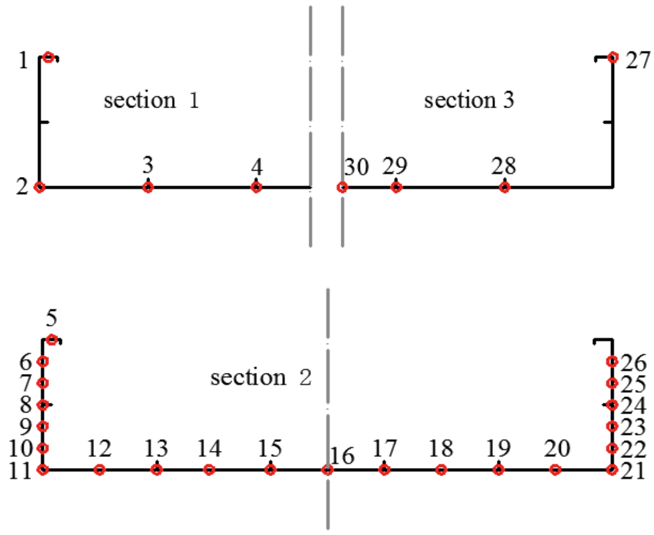


Fig. 4. Strain test points distribution

TEST PROCEDURE

To verify the character of test model, the test under hydrostatic condition is performed firstly. The mass block is put to the end section and thus the still water bending moment is produced. The stress distribution is measured with different weight of mass block to check the fundamental character of test model such as neutral axis, stress distribution and deformation distribution.

Considering the capacity of wave maker, the structural response of the hull structures under different loading conditions in wave is analyzed to determine the weight of mass block and the test wave parameters. In the test, a total of five cases are conducted, as shown in Table 1. The pressure with time history is measured for each pressure test point. The translational acceleration and rotational acceleration with time history and the strain distribution are measured under every loading condition and wave condition.

TEST RESULT

HYDROSTATIC TEST

In order to verify the fundamental character of test model, the test on hydrostatic pressure is performed firstly. The different weight of mass block is acted in the model to produce the different vertical bending moment. The structural response shall be in elastic range so that the weight of mass block is limited to less than 200kg. The relationship between draught and mass block weight is summarized in Table 2. The longitudinal stress distribution of test points in side shell is plotted in Fig. 5. The depth of zero longitudinal stress distribution represents the position of neutral axis. So, the neutral axis of test model locates at the position of depth 100mm. The tangential stiffness of above and below the neutral axis is different because the structures below the neutral axis are subjected to not only the longitudinal bending moment but also the lateral pressure [18]. The lateral pressure causes the bending of plating which leads to the bending stress components. The stress of structures below the still water surface includes the bending stress components caused by lateral pressure and in-plane stress components caused by the longitudinal bending moment. So, the tangential stiffness of lower structures becomes weak.

Tab. 1. Test cases

Case No.	Mass block (kg)	Wave height (mm)	Wave frequency (rad/s)	Wave length (mm)	period (s)
D1-1	200	50	2.92	7225	2.151
D1-2	200	100	2.92	7225	2.151
D2-1	600	40	2.98	6937	2.107
D2-2	600	80	2.98	6937	2.107
D2-3	600	120	2.98	6937	2.107

Tab. 2. Draught with different weight of mass block

Case No.	Mass block (kg)	Draught (mm)
H1	0	72.79
H2	50	78.82
H3	100	84.85
H4	150	90.89
H5	200	96.92

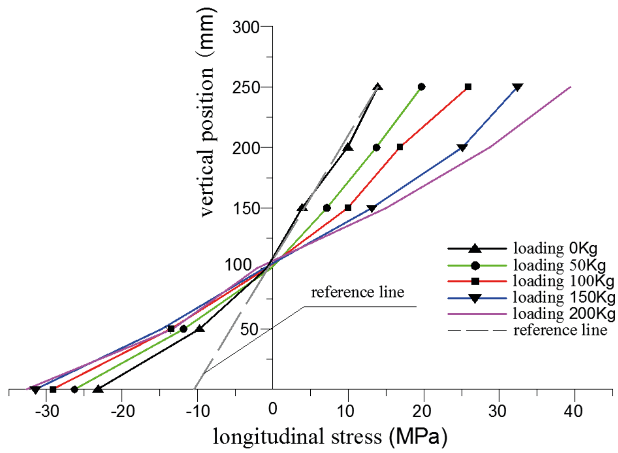


Fig. 5. Longitudinal stress with different weight of mass block

COLLAPSE TEST

According to the preliminary numerical analysis, the ship structures will be collapsed when the weight of mass block is 600kg and the wave height is 120mm. In order to demonstrate the structural response characteristics in waves, the pre-test is carried out for the weight of mass block 200kg and wave height of 50 mm and 100 mm respectively. Then, the collapse test is conducted under the conditions of weight of mass block 600kg and wave height 40 mm, 80 mm and 120 mm respectively. The pressure distribution with time history, ship motion characteristics and the corresponding structural condition are measured.

When the weight of mass block is 200kg and wave height is 50mm and 100mm, the ship structures are in the elastic situation. The test results demonstrate that the test system works well, and the response of test model satisfies the requirement. In case the weight of mass blockis600kg, the loads acting on the ship structures will increase with the increase of the wave height. When the wave height reaches to 120mm, the collapse of ship structures will be taken place. Due to page limitation, the results in elastic stage are not described and only those of structural collapse are shown in the paper. In fact, the results in elastic stage can be considered as the primary stage of collapse behavior.

The schematic diagram of the position of the model and the wave under the conditions of collapse test is shown in Fig. 6. The wave crest locates at the middle of test model so that the ship hull is in hogging condition. With the movement of the wave crest, the loads acting on the ship structures are also different and so as the ship motion and structural response. A wave-height gauge is placed in front of the test model and the sampling frequency is set to 50Hz. The measured wave height distribution with time history is shown in Fig. 7. To facilitate the analysis of various test results, the sampling frequencies of other instruments such as pressure sensor, acceleration sensor, inclinometers sensor and dynamic strain gauges are also set to 50Hz. The variation of the lateral pressure with time history at the pressure test points in the bottom can represent the relative position of the wave and the test model. The lateral pressure distribution of the typical measuring point (No. 4 test point locating at the fore hold) is shown in Fig. 8. The average vertical acceleration of the fore and aft acceleration test points is expressed in Fig. 9. The relative rotation angle measured by the inclinometers is demonstrated in Fig. 10. All measured results are sinusoidal distribution with time history and the period is 2.107s which is consistent with the characters of wave.

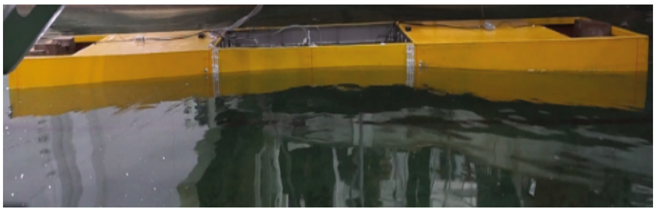


Fig. 6. Collapse test of ship hull

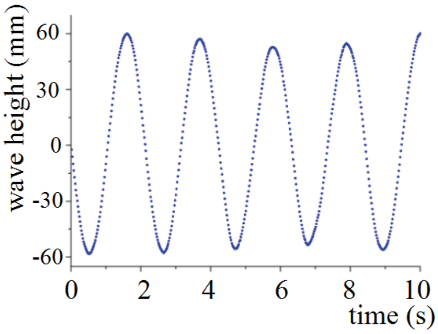


Fig. 7. Wave height

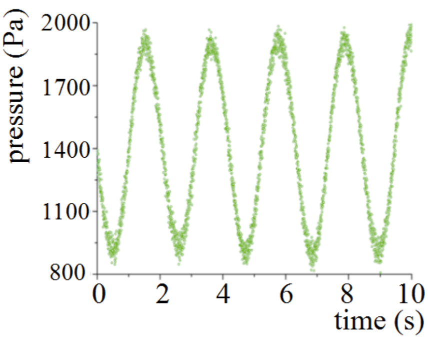


Fig. 8. Lateral pressure

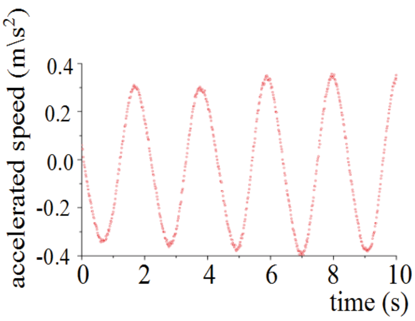


Fig. 9. Vertical acceleration

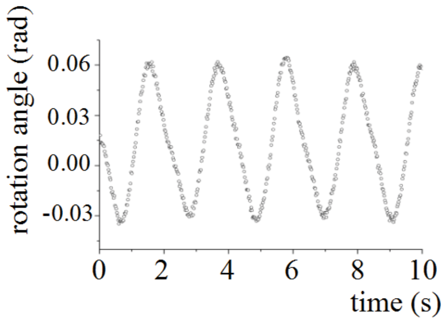
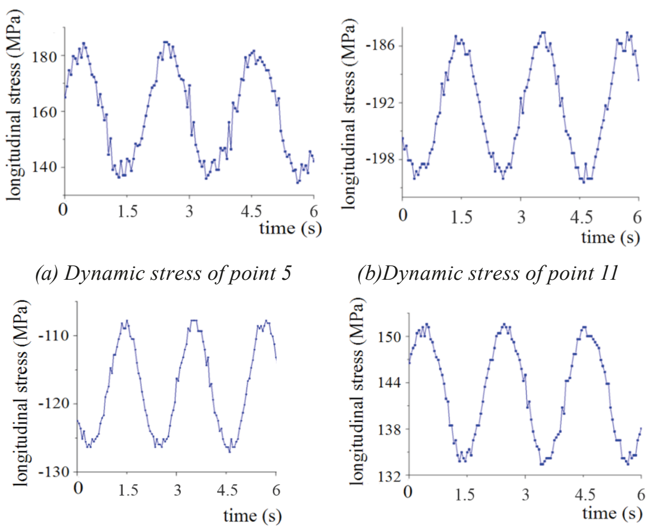


Fig. 10. Relative rotation angle

During the collapse test, the dynamic strain of test points is also measured. The dynamic stress can be calculated according to the stress-strain relationship of the specimen. The dynamic stress distribution of typical test points in the central section, such as test point 5 (locating at the deck), test point 11 (locating at the intersection between side shell and bottom), test point 19 (locating at the bottom longitudinal stiffener) and measuring point 26 (locating at the upper side of side shell) is plotted in Fig. 11. The dynamic stress of each test point demonstrates sinusoidal distribution and the period is same as wave period.



(a) Dynamic stress of point 5 *(b)Dynamic stress of point 11*

(c) Dynamic stress of point 19 *(d) Dynamic stress of point26*

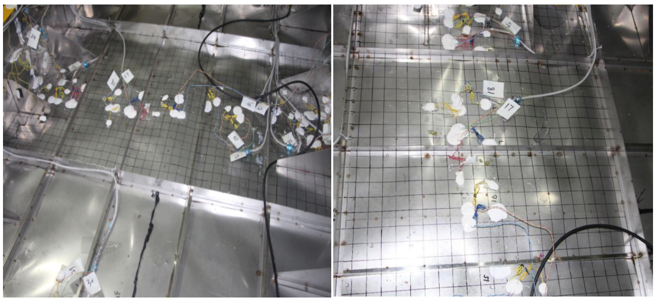
Fig. 11. Dynamic stress of typical points

RESULT ANALYSIS

COLLAPSE BEHAVIOR

The ship is a large floating structural system which is subjected to both hydrostatic load and wave load. The bottom structures of test model are subjected to lateral pressure and thus the bending stress component is generated. When the wave trough is locating in the mid length, the bottom structures are simultaneously subjected to compression caused by hogging and the bending caused by lateral pressure.

The wave load increases with the increase of wave height. When the wave crest is locating in the mid length, the buckling of bottom plating happens firstly under the compression and lateral pressure. With the movement of wave, the buckling of deck plating and the top plating of side shell are also taken place when the wave trough is locating in the mid length. Then, the load is re-distribution between the structural components. The longitudinal stiffener of bottom is buckled and yielded successively due to the compression and lateral pressure. The collapse of ship structures happens so as to loss the load-carrying capacity. The collapse mode of bottom structures is the stiffener tripping and plating buckling, as demonstrated in Fig. 12.



(a) test hold *(b) collapse part*

Fig. 12. Collapse mode of bottom structures

VERTICAL BENDING MOMENT-CURVATURE RELATIONSHIP

In the present research, the longitudinal bending moment can be obtained by performing secondary integration of the stress of each test point in the midst section. The relative rotation angle of test hold can be computed by the measured angle value at both end sections. The curvature is calculated by the relative rotation angle divided by the length of test hold. Then, the relationship of vertical bending moment and curvature can be achieved. To explore the fluid-structural interaction effect, the moment-curvature relationship obtained by structural calculation, fluid- structural interaction calculation and collapse test is compared in Fig. 13.

For structural calculation, double-span section model, namely longitudinal hull girder segment extending a half frame spacing in fore and aft directions from a transverse frame, is considered. A forced rotational angle is applied to both end cross-sections assuming that the cross sections remain plane. The obtained ultimate strength represents the structural itself capacity which is no relationship with the external force.

For fluid-structural interaction calculation, the wave induced load calculation is firstly performed on the test model to obtain the external loads. Then, they are converted into equivalent nodal forces and applied to the structural model. The progressive collapse analysis is performed to obtain the corresponding bending moment and curvature. The ultimate strength calculated by such method is not only related to the hull structures, but also related to the external loads.

It can be seen from Fig. 13 that the ultimate strength calculated by structural calculation is larger than that by fluid-structural interaction calculation. The structure shall deform due to the action of fluid/water pressure which lead to the bending stress component. The structural buckling occurs earlier as well as initial yielding so that the ultimate strength is reduced. The traditional structural calculation, considering the structural model itself and not considering the influence of the fluid, will cause larger ultimate capacity. The shipwreck may be happened when the actual external load is smaller than the ultimate capacity calculated by traditional structural model but larger than actual structural capacity. In addition, the test result is about 10% smaller than that of fluid-structural interaction calculation. This is because the initial deformation and welding residual stress are not considered in the fluid-structural interaction calculation. Thin plate and small stiffener are adopted in the test hold of test model so that larger initial deformation and welding residual stress are produced during the course of processing.

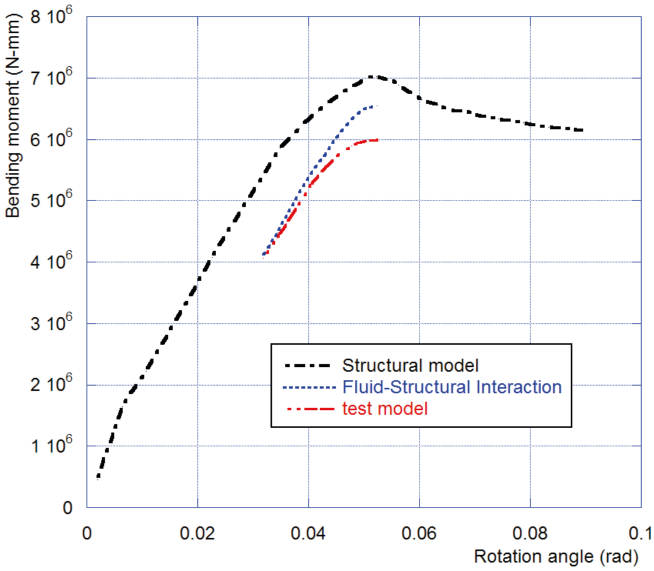


Fig. 13. Comparison on relationship of bending moment and rotation angle

CONCLUSION

In the present research, the collapse test of ship model is performed to investigate the collapse behaviour of ship structures in wave. The moment-curvature relationship obtained by collapse test is compared with that by structural calculation and fluid-structural interaction calculation. The calculation model and the influence of lateral pressure are discussed. The conclusions can be summarized as follows.

For the traditional structural calculation, the cross-section is assumed to remain plane. A forced rotational angle is applied to both end cross-sections and the maximum bending moment is defined as the structural ultimate strength. The ultimate strength obtained by such method is a little larger than actual one which may lead to dangerous situation.

The structures below the still waterline deflect under the effect of lateral pressure so as to produce the bending stress component. The structural buckling and initial yielding occur earlier and thus the ultimate strength is reduced. It is better to consider the effect of lateral pressure when structural ultimate strength is calculated.

The stiffener tripping and plating buckling of bottom structures are taken place under the longitudinal compression caused by vertical bending moment and out-of-plane bending caused by lateral pressure. With the happening of initial yielding and the spreading, the structural section losses its load-carrying capacity and reaches ultimate strength.

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