NUMERICAL ANALYSIS ON SHIP-SHIP COLLISION RESISTANCE IN DESIGN OF "KAIEI-MARU" CLASSIFIED AS INF 3 SHIP

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ABSTRACT

It is well known that ship structural design for collision resistance is very important to assure security of packages, which contains spent nuclear fuels. As for the regulation of safe carriage of the spent nuclear fuel, the International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships (INF code) is commonly referred, which covers specifications of damage satiability, structural consideration and so on. However, nothing is mentioned about collision resistance of hull girder in this code. On the other hand, the official notice "Kaisa No.520" issued by the Japan Ministry of Transport includes the statement about collision resistance of hull girder.

In "Kaisa No.520", the analysis based on the Minorsky's method is applied for ship design of collision resistance structures. In the construction of the past ships, that was applied for the structural design of the hull girders. This simplified method is effective for the structural design in the initial stage because of comparatively light computational works. However, in the Minorsky's method T-2 tanker is adopted as the striking ship and the outer shell is not taken into account as the structural member of the collision resistance. To achieve more detailed evaluation of collision resistance of hull girder, a numerical procedure introducing the nonlinear finite element analysis of ship-ship collision was proposed by the regulation research panel of the Shipbuilding Research Association of Japan. In the procedure, VLCC (Very Large Crude Oil Carrier) is adopted as the striking ship. By using the procedure, some numerical analysis results were already published.

Mitsui Engineering & Shipbuilding Co., LTD. (MES) has accumulated experience to analyze and evaluate collision resistance of ships. Based on these experiences, the numerical analysis was applied for the first time to actual design of the exclusive ships which transports spent nuclear fuels. This paper describes the numerical computation conducted in the design of Kaiei-Maru, which was constructed by MES in 2006. The procedure using the finite element analysis and the method to evaluate the collision resistance of the hull girder are presented as the first practical example, which has not been adopted before in the design of this kind of ships.

INTRODUCTION

It is very important to assure security of packages in the construction of ships to transport spent nuclear fuels in the viewpoint of environmental safety. There are some regulations to be satisfied and design of such ships is carried out based on the international and/or the domestic regulations. Especially, assurance of the security when ship-ship collision occurs is very important element on the design of the ship transporting the spent nuclear fuels.

As for estimation methods of the collision resistance strength of the hull girder, the method proposed by Minorsky [1] is often used, however, there are some conservative assumptions about the given striking ship and the structural members of the struck ship. Because of those, some studies are reported as the complement of the method [2]. In Japan, the survey organized by Shipbuilding Research Association of Japan was carried out in 1996 and the method to estimate the collision resistance of hull girder quantitatively was studied. As the result of the survey, the guideline was proposed to evaluate collision resistance of the hull girder by using the nonlinear finite element method [3]. Despite such effort, the actual applications have not been seen that the nonlinear finite element method is applied to initial design of hull girder to confirm the collision resistance.

MES was received order of the ship to transport spent nuclear fuels from Nuclear Fuel Transport Co., LTD. She was constructed in 2006 and named "Kaiei-Maru". In the design stage of the ship, the effort to achieve the collision resistance of the hull girder was made by using some estimation methods, which were not only the Minorsky's method but also the nonlinear finite element method. In this paper, the process of the design and the evaluation is presented as the design procedure of such ships, which was carried out by using the nonlinear finite element method.

OUTLINE OF KAIEI-MARU

Firstly, the outline of Kaiei-Maru is described in this section. More detailed information about her should be referred to Ref. 4. She was constructed at Tamano Works of MES to transport spent nuclear fuels and replaced Hinoura-Maru, which was constructed about 30 years ago. Principal dimensions of Kaiei-Maru are shown in Tab. 1. In the INF code, ships are classified into 3 classes dependent on the amount of the package and Kaiei-Maru is classified as INF Class 3 ship, which can transport the irradiated nuclear fuels. The exterior view of Kaiei-Maru is shown in Fig. 1. This ship has four cargos inside double hull structures and four decks between the double hulls. The schematic of the mid-ship section is shown in Fig. 2.

Novelties in the design process are the shielding analysis using MCNP and the collision resistance evaluation using the nonlinear finite element method. Details about MCNP analysis are referred to Ref. 4. In this paper, mainly the latter analysis is described.

Table 1. Principle dimensions of Kaiei-Maru

Loa（m）	B（m）	D（m）
100	16.5	9.4

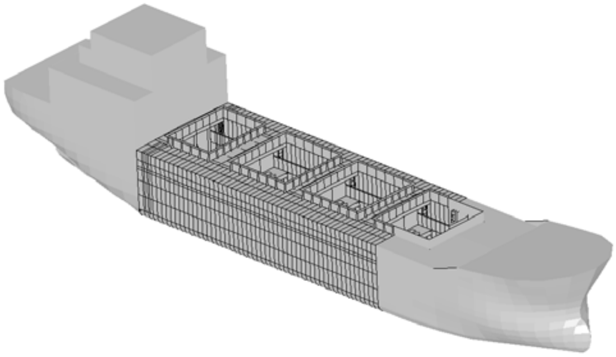


Figure 1. Overview of Kaiei-Maru

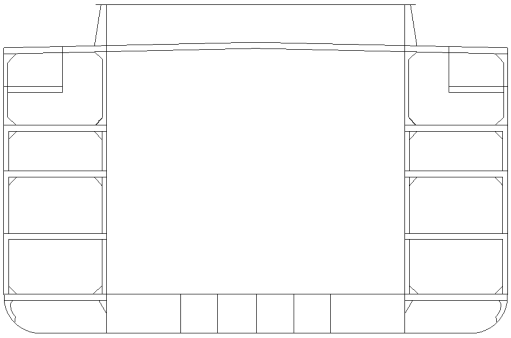


Figure 2. Typical mid-Ship section

REGULATIONS AND STRUCTURAL DESIGN

As for the international regulations, design of ship is generally carried out based on SOLAS, MARPOL and so on. However, explicit notations are not found about collision resistance of hull girder. On the other hand, "Kaisa No.520", the official notice in Japan, requires the structural design using the method based on the Minorsky to achieve collision resistance and the stem of the striking ship should not reach the depth given in the rule. It seems that this method is suitable for the initial design of the ship since the results are obtained by simple calculations. On the other hand, it seems that the method has some conservative assumptions. In this method, the striking ship is defined as T-2 tanker and the outer shell of the struck ship is not taken into account as the structural member of the collision resistance.

Considering this background, Shipbuilding Research Association of Japan established the regulation research panel No.46 (RR46) and the finite element analysis was performed to obtain knowledge in depth [3]. In the RR46, the numerical procedure using detailed numerical model was proposed to evaluate the collision resistance of the hull girder. Structural failure and ship motions during the collision phenomena were taken into account in the numerical analysis. In this method, VLCC was adopted as the striking ship.

However, the example using the proposed numerical procedure has not been seen in actual designs. The design of Kaiei-Maru was the first design using the nonlinear finite element method proposed in the RR46.

DESIGN PROCESS

In the design of Kaiei-Maru, the collision resistance of the hull girder was estimated by two methods. The one is the method based on the Minorsky and the other is the nonlinear finite element analysis proposed by the RR46. As for the regulation, the design was carried out based on the rule of NK (Nippon Kaiji Kyokai), JG (Japanese Government) that covers SOLAS, MARPOL and so on, and “Kaisa No.520”. The estimation based on the Minorsky’s method is required by “Kaisa No.520”. The estimation by using the finite element method was not required by the regulation but was suggested by the domestic committee. In the actual design, the former method was used in the first stage to evaluate the collision resistance of the hull girder.

In the method of the first stage, the minimum energy, E_1, that was necessary for two ships to become same speed after the collision was derived from the kinetic energy and the conservation of momentum. In addition, the energy, E_2, absorbed by the structure of the two ships in collision is derived from the empirical formula with calculation of resistance factor. The resistance factor is dependent on the volume of the structure in which the overlapped region between the striking ship and the struck ship. The penetration depth to be estimated was given by the rule. In the design, two energy, E_1 and E_2, were compared and it was required that the energy E_2 should be larger than the energy E_1. The criterion is that the stem of the striking ship should not reach the depth determined in the rule. After this calculation in the actual design, the security in the viewpoint of the collision resistance structure was confirmed and the scantlings of the structure were determined.

Next, the method proposed by the RR46 is explained as the second design stage. As the condition of the collision, it is recommended that the striking ship collides into the mid-cargo of the struck ship in service with an angle 90 degree. Figure 3 shows the schematic of the top view before the collision occurs. The loading condition of the struck ship is assumed to be full load condition. On the other hand, the loading conditions of the striking ship are assumed to be ballast condition and full load one. The loading conditions of two cases are summarized in Tab. 2. The striking ship is assumed to be VLCC. Principal dimensions of VLCC are shown in Tab. 3. Figure 4 shows the side view of each case before the collision. The speed of the struck ship is 80% MCR and that of the striking ship is 15kts.

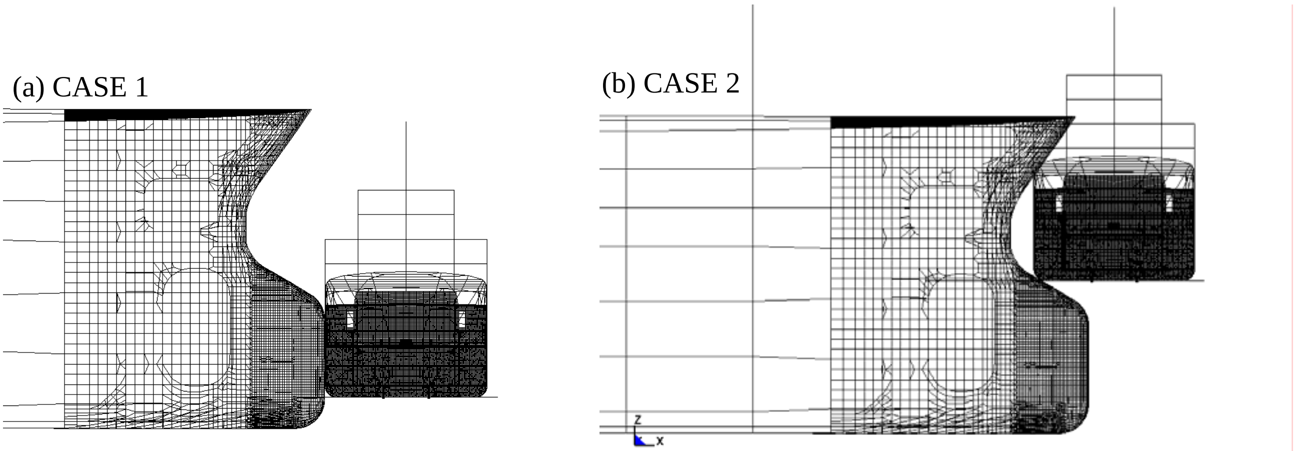
Figure 3. Top view of collision

Table 2. Conditions of calculations

	Struck Ship		Striking Ship	
	Condition	Speed	Condition	Speed
CASE 1	Full Load	80% MCR	Ballast	15kts
CASE 2	Full Load	80% MCR	Full Load	15kts

Table 3. Principle dimensions of striking ship

Lpp（m）	B（m）	D（m）
320.0	58.0	31.0



(a) CASE 1

(b) CASE 2

Figure 4. Side view of each case

In this guideline, the following items are necessary to be considered when the finite element analysis is performed.

(1) Large deformation of stiffened panel with elasto-plastic behavior
(2) Ductile material failure of steel plate and stiffener
(3) Work-hardening behavior in terms of material strength
(4) Global rigid motion and inertial effect of ship body
(5) Contact behavior between finite elements

In addition, the following four items are recommended to be taken it into account.

(6) Friction energy
(7) Restoring force and hydrodynamic force
(8) Strain rate effect of material strength
(9) Failure of fillet welding

In the design process, (1), (2) and (3) were taken into account by using LS-DYNA [5], which was the commercial software based on the nonlinear finite element method. As for (2), the material failure was judged from maximum plastic strain, which depended on element size. The material behavior in (3) was given as elastic perfectly plastic material. Mild steel and two types of high tensile steel were applied to the construction of Kaiei-Maru and the material constant used in the numerical model was derived from the inspection certificates. The global motion of ships described in (4) was modeled by giving the characteristics to the rigid body, which was equivalent to the mass and inertia including added mass effects. The contact force in (5) was taken into account by using the function of LS-DYNA.

The friction behavior in (6) was modeled by giving the friction coefficient as 0.3. The restoring force in (7) was modeled as discrete spring elements in such a way that natural periods of the rolling, pitching and heaving motion were the same as those of the actual ship. The added mass effects were modeled by increasing the mass of the rigid body part. Since the main motion of the struck ship after collision was swaying one, the added mass to the direction of the swaying motion was taken into account. On the other hand, for VLCC, the added mass to the direction of surging motion is modeled. The strain rate effects of material in (8) were modeled by using the Cowper-Symonds relation. As for (9), not only the tearing of the steel plate but also the failure of welded joints was important to estimate the collision behavior and was taken into account in this analysis.

Numerical model used in this design is shown in Fig. 5. In this model, the hold part of the struck ship and the stem part of the striking ship was modeled as elasto-plastic element. The other parts of both ships were modeled as rigid body element and inertia of mass and moment were given. Number of elements of the struck ship was 493,204 elements and that of the striking ship was 43,235 elements. These models consisted of shell elements and beam elements. In the modeling of side longitudinal stiffeners, the webs and the faceplates were modeled by using shell elements and beam elements, respectively. Typical size of mesh near the collision part was 150mm. The packages and the mount structure between the packages and the decks were not modeled in this analysis.

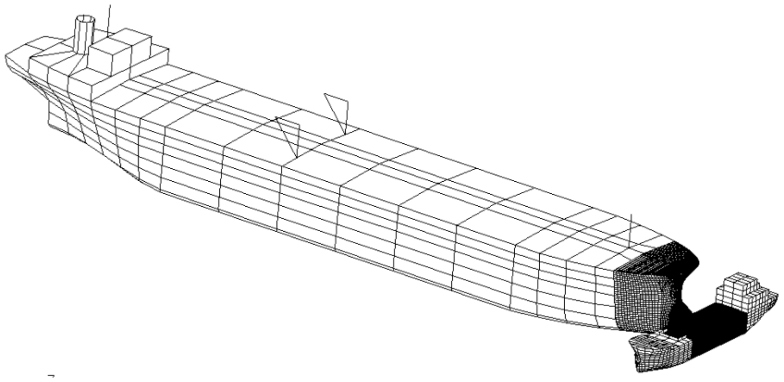


Figure 5. Finite element model

RESULTS AND EVALUATION

Figure 6 shows the time history of energy. Kinetic energy, strain energy and friction energy are shown in this figure. The initial value of the total kinetic energy equals the summation of the initial kinetic energy of both ships. The kinetic energy of the striking ship is very large compared to that of the struck ship. As also shown in this figure, the initial kinetic energy was dissipated into the strain energy and the friction energy during the collision phenomena. Total energy through the calculation was well conserved.

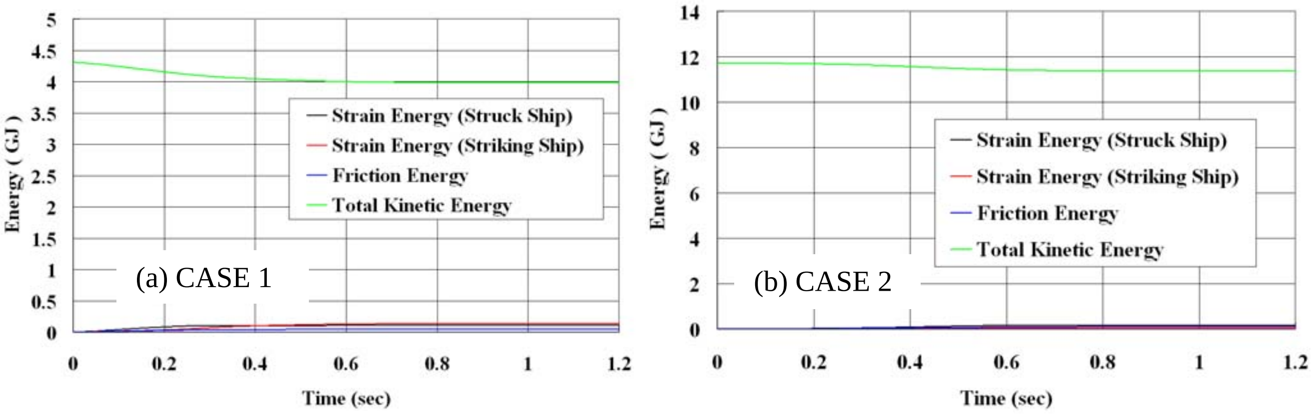


Figure 6. Time histories of energy

The time histories of ship velocity and contact force are shown in Fig. 7 and Fig. 8, respectively. Figure 7 shows the velocity of the swaying direction for the struck ship and that of the surging deirection for the striking ship as the main direction of the motion during the collision. The direction of the force shown in Fig. 8 is that of the movement of VLCC. Since total mass of the struck ship is very small compared to that of the striking ship, after the collision occurs, the struck ship is pushed out in the direction of the movement of the striking ship. Therefore at the final stage of the collision, the velocity of the swaying motion of the struck ship becomes almost same as that of the surging motion of the striking ship. As found from Fig. 8 (a), the contact force in CASE 1 reaches the peak value at the time 0.2sec. and decreased gradually until about 1.2 sec. On the other hand, in CASE 2 the peak force is found at the time 0.5sec. The reason for this is because the geometrical difference of the vow structure of the striking ship at the point of collision.

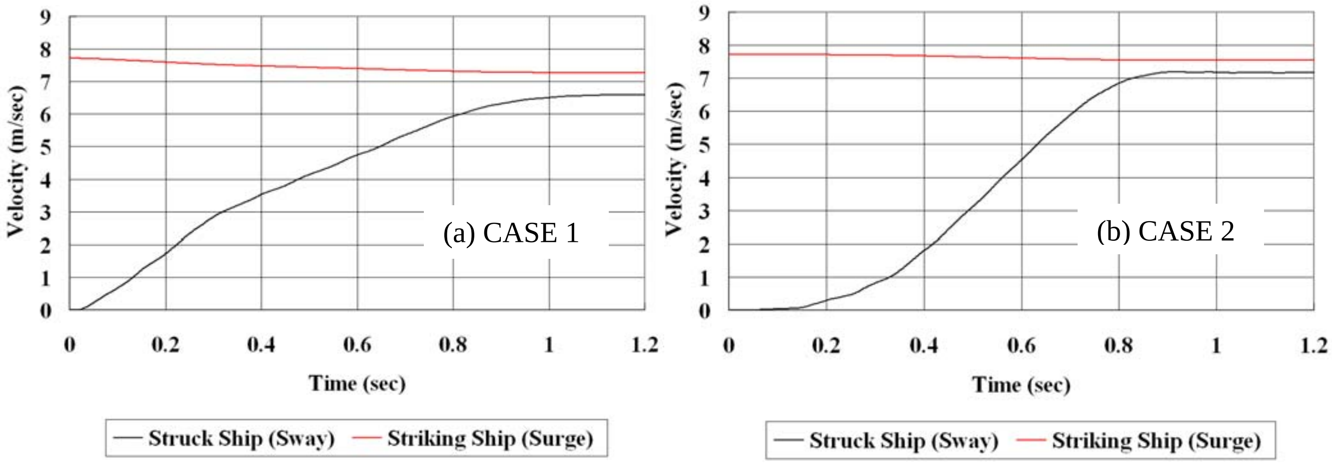


Figure 7. Time histories of velocities

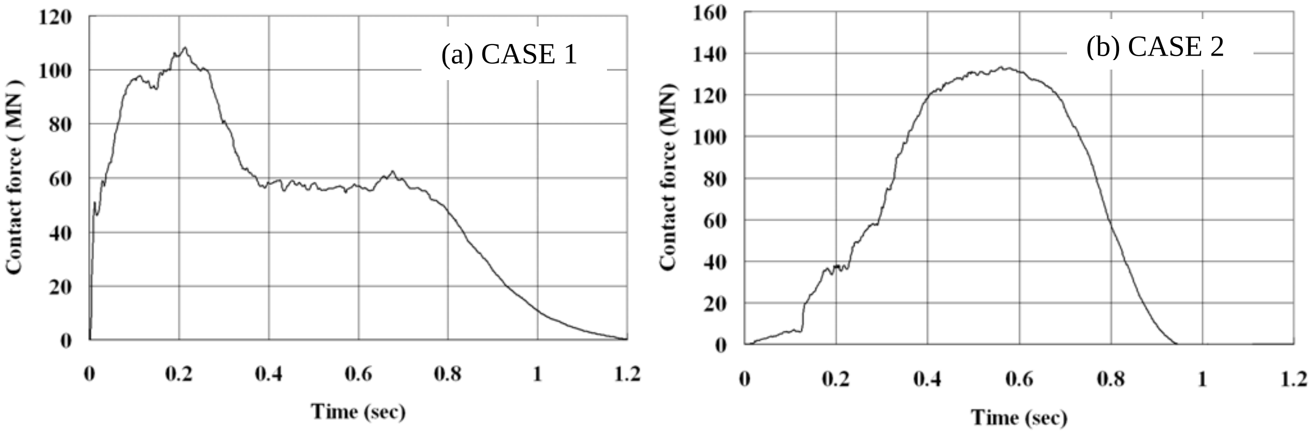


Figure 8. Time histories of contact forces

Next, the result and the evaluation are shown about the deformation of the longitudinal bulkhead, which is the main purpose of this numerical analysis. In the guideline, it is recommended that the safety of the package should be judged whether the deformed longitudinal bulkhead contacts with the package or not. The maximum deformation was obtained from the reduced distance between two longitudinal bulkheads. It should be noticed that the deformation of the side structure opposite to the collision side was not found in this analysis. Figure 9 shows the transverse section of the struck ship at the final stage of the collision. Table 4 shows the maximum deformation of the longitudinal bulkhead. In Tab. 4, the initial distance between the longitudinal bulkhead and the package is shown when the possible largest package is supposed to be loaded. As shown in the table, the maximum deformation is lesser than the initial distance and it is confirmed that the longitudinal bulkhead does not collide against the package. This was judged that the package would be safe even if the ship-ship collision occurs against Kaiei-Maru.

In the construction of Kaiei-Maru, these calculations and the evaluation were carried out in the initial stage of the design and the collision resistance of the hull girder was adequately confirmed.

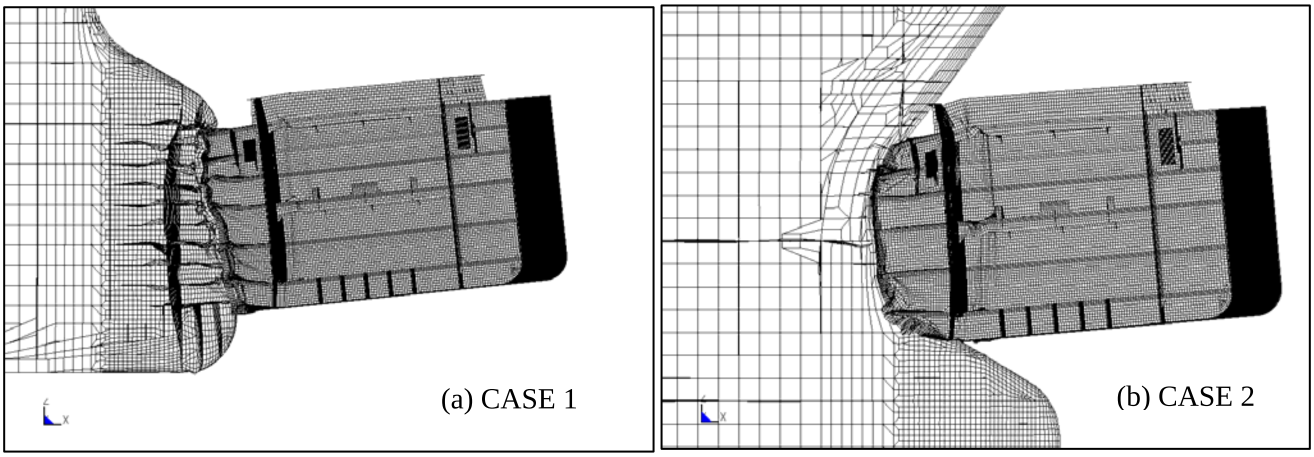


Figure 9. Transverse section of ships during collision

Table 4. Summary of deformation of inner longitudinal bulkhead

	Numerical result	Reference value
	Deformation of inner longitudinal bulkhead（mm）	Distance between package and inner longitudinal bulkhead before collision (mm)
CASE1	354	1678
CASE2	750	

CONCLUSIONS

In this paper, the procedure used in the initial design of Kaiei-Maru, classified as INF class 3 ship, was presented. That was performed to achieve the safety assurance for the package in the case of the ship-ship collision. Firstly, the evaluation was made by using the method based on the Minorsky, which used the empirical relation about energy absorption of ship collision, then the scantlings of the structure was determined. In the second stage of the design, the nonlinear finite element method proposed by the RR46 was applied to evaluate the collision resistance of the hull girder. In the analysis, the ship structures around the collision point were modeled in detail to take the large deformation and failure of the structures into account. The global motion of each ship was also taken into account.

In the design process, two cases of collision were analyzed and evaluated the minimum distance between the deformed longitudinal bulkhead and the package to judge the safety of the package. In the results of both cases, the margin was left between the longitudinal bulkhead and the package and this result was judged that the package was safe in the collision by using the method proposed by the RR46.

These design process was shown as the special consideration of the design procedure, in which the finite element analysis was applied in the initial stage of the actual design of the ship.

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REFERENCES

[1] Minorsky, V. U., An Analysis of Ship Collisions with Reference to Protection of Nuclear Power Plants, Journal of Ship Research, Vol.3, pp.1-4 (1959).

[2] Pedersen, P. and Zhang, S., Absorbed Energy in Ship Collisions and Grounding – Revising Minorsky’s method, Journal of Ship Research, Vol.44-2, June, pp.140-154 (1959).

[3] Kitamura, O. and Endo, H., Collision Simulations of an Exclusive Ship of Spent Nuclear Fuels, Proceedings of the International Workshop on Utilization of Nuclear Power in Oceans (2000).

[4] Takatsuki, H., et al., New construction of "Kaiei-Maru" for the Transport of Nuclear Fuel Materials, Proceedings of the 15th International Symposium on the Packaging and Transportation of Radioactive Materials: PATRAM 2007 (2007).

[5] LS-DYNA Theoretical Manual, Livermore Technology Information (1998).