Evaluation Method of Absorbed Energy in Collision of Ships with Anti-Collision Structure

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ABSTRACT

To verify the effectiveness of Minorsky's formula that is used in the current regulation of ships with collision resistant structure, a simplified analysis method based on rigid-plastic analysis is developed. The collision of the test ship with a T2 tanker and a Suezmax class tanker is analyzed, and it was shown that Minorsky's formula, which assumes the same collapse length for the striking and the struck ship, gives an incorrect estimation of the energy balance when the strength of the ship bow and side have a big difference. Also, the results are compared with those by dynamic FEM analysis, and good agreement is observed. It was shown that the simplified analysis method is an effective tool in the early design stage, and in developing regulations.

1. INTRODUCTION

In the design of ships, it is common to design the structure so as to stand against the wave load, and no accidental load is considered. However, in the design of ship that carries hazardous material, or design of tanker whose accident may cause environmental pollution, the consideration of the crashworthiness in design is necessary.

For the evaluation of absorbed energy in ship collision, there are several possible method including detail FEM simulation, experiment, and simplified analysis method. Experiment need large-scale models to avoid scale effect, which will cost a lot of money and time, and quite limited use of it is possible. Recent progress of computer hardware and finite element simulation code which employed explicit time integration method enabled large scale finite element simulation of collision behavior, and that is used extensively in the research work done by ASIS[1]. However, it also turned out that the finite element simulation requires quite a lot of know-how, such as treatment of weld line or rupture criteria, and requires a lot of computer resource and computational time. In that sense, those methods are not suitable to be used in the design stage, or in the regulation. For these reason, the simplified analysis method needs to be developed.

There are a couple of simplified analysis methods to evaluate the energy that structures absorb in ship collision. Minorsky’s formula [2] is one of the oldest and most widely used, including the KAISA No. 520 by Ministry of Transportation of Japan. KAISA No. 520 regulate the irradiated nuclear fuel carrier ship to have certain crashworthiness against collision. Minorsky derived an empirical formula based on the volume of damaged steel. He followed a semi-analytical approach based on the cases of actual collision. However, this formula does not include the structural style of striking ship bow and struck ship side as parameters, but only damaged volume of steel is considered. The absorbed energy of the side shell is not included explicitly, either.

Woisin, G. modified the second term in the Minorsky's formula referring to the investigation of some experimental results [3]. The definition of the resistance factor is also changed to consider the strength ratio of the stem of the striking ship and the side structure of the struck ship. However, the basis of Woisin's modification stands on the experiments in which the models were of resistance type with anti-collision barriers of nuclear powered ships, whose structures are considerably different from commercial ships. Therefore, the applicability and the accuracy of this method may be limited in the case of conventional ships.

In this paper, a simplified analysis method based on the rigid-plastic deformation is applied to the collision of the ship with anti-collision barriers, and compared with the Minorsky’s formula. For the striking ships, T-2 tanker, which is used in the current regulation of the Ministry of Transportation as a striking ship, and Suezmax tanker, which is more realistic candidate, is considered. The collapse mode and resistance force, energy absorption of each structural member is considered, and the relation between collapse length and force, and an equilibrium of force is considered to decide the collapse length of both striking and struck ship.

2. ANALYSIS METHOD

Analysis Condition and Type of Ships

For the struck ship, a nuclear fuel carrier ship of displacement 7,000 ton with section shown in Fig. 1 is employed. The side structure of this ship has anti-collision decks with thickness about 30 mm high tensile steel. For striking ship, a T-2 tanker (displacement 23,400 ton) and a Suezmax tanker (displacement 172, 000 ton) are considered. T-2 tankers are old ships that do not exist any more. However, in KAISA No. 520 it is required that the bow should not reach the transverse bulkhead of struck ship when T-2 tanker struck the nuclear fuel carrier ship with speed of 15 knot. To compare the method with the same collision condition, T-2 tanker is employed as a candidate of striking ship. The relative position of T-2 tanker and struck ship is shown in Fig. 1.

For more realistic striking ship, a Suezmax tanker （150,000 DWT）is employed. When the Suezmax tanker is in fully loaded condition, struck ship will be hold between bulbous bow and stem as shown in Fig 2 right, and ship’s movement including roll and heave cannot be neglected. Therefore, in this analysis, only the tanker in ballast condition is considered, whose relative position is shown in Fig. 2 left. In this situation, the bulbous bow of tanker collides directly to the side of the struck ship, and movement of the ship except sway can be neglected.

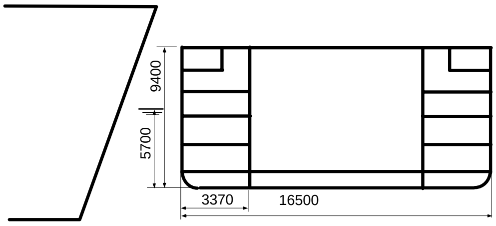
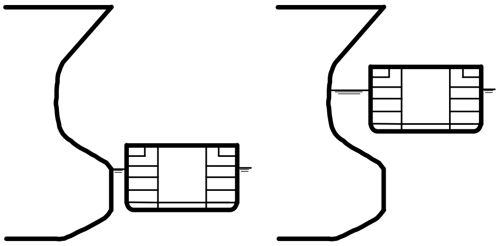


Fig. 1 Collision of T-2 tanker



Ballast Condition Fully Loaded Condition

Fig. 2 Collision of Suezmax tanker

2.2 Energy Absorbed by the Structure

The behavior of collision can be divided into the behavior of striking ship and struck ship. Also for the evaluation of energy, the ship movement in the water should be considered. Considering the equilibrium of momentum, the energy that should be absorbed by structure becomes as follows.

$$E = \frac{\Delta_B}{2+1.43\frac{\Delta_B}{\Delta_A}} * V_B^2 \qquad (1)$$

where Δ_A, Δ_B are the displacement of the struck and striking ship respectively, and V_B is the velocity of the striking ship.

2.3 Crushing Mechanics of Ship Bow Structure

The crushing behavior of a ship bow in head-on collision can be idealized as the collision of a ship towards rigid plane. In the early stage of response during deformations, buckling of plate components is prime failure mode. After buckling occurs in the plating, axial shortening of the structures is mainly caused by plastic deformations.

Wierzbicki [4] have done some fundamental researches on the crushing behavior of plate intersections. Yang and Caldwell [5] extended this theory to bow structure of ships, assuming that a section between two frames crushes frame by frame from the front to end of the bow. Wang et. al. [6] proposed a simple one-term formula for predicting the crushing strength of a bow structure, introducing two factors that represent energy absorption ability of structures and energy absorption reduction effect caused by inclination of plates with respect to collision load, as follows. This was verified using experimental data and finite element simulation.

$$P_m = \sum_i \alpha_{Ii} \alpha_{Ei} \sigma_0 A_i \qquad (2)$$

where

α_{Ii} : Inclination effect factor

α_{Ei} : Energy absorption factor

σ_0 : Flow stress (average of yield and fracture stress)

A_i : Sectional area

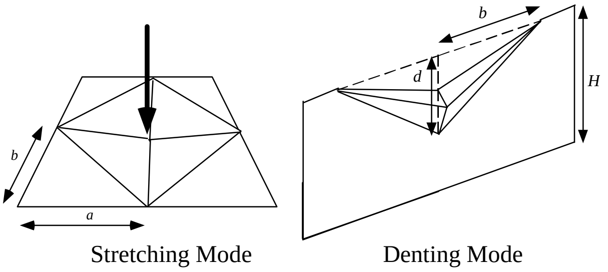
2.4 Crushing Mechanics of Ship Side Structure

Damage of the side structure in collision is progressive process. As indentation increases further, the more structures become involved. It has been confirmed that the elastic energy involved in local elastic deformations and in overall elastic vibratory response to the collision is negligible compared with the plastic energy. Here, it is assumed that the striking object is rigid and only the struck side absorbs the plastic energy. Ito et. al.[7] proposed the method to divide the ship structure in several elements, and employed the technique similar to finite element method. However, it is not simple enough to be used with hand calculation. Ohtsubo et.al. [8] proposed the simplified method based on the rigid-plastic analysis that assumes stretching mode (Fig. 3 left) for outer shell, and denting mode (Fig. 3 right) for webs. This showed good agreement with experiments and FEM analysis. In this paper, same approach is employed.

The reaction force of each mode can be written as follows, while *a*, *b* and *d* is the shape of failure area shown in Fig. 3, and δ is the indentation length.

$$F_p = 2\sigma_0 t \frac{a^2+b^2}{ab}\delta \qquad \text{(Stretching)} \qquad (3)$$

$$F_m = 2.32\sigma_0 \left(2b\right)^{0.33} t^{1.67} \qquad \text{(Denting)} \qquad (4)$$



Stretching Mode Denting Mode

Fig. 3 Failure Mode of Ship Side

The overall reaction force is sum of them, and energy absorption can be calculated as integration of the force against failure length. Also, when the strain of the outer plate exceeds the failure strain, the rupture of outer plate is assumed to occur, and the reaction force of outer plate is assumed to become zero. The average strain of stretching mode can be calculated as follows.

$$\varepsilon = \frac{1}{2}\left(\frac{\delta}{a}\right)^2 \qquad (5)$$

In this analysis, the rupture strain is taken to be 0.2.

The progressive damage model when a T-2 tanker strikes is shown in Figure 4. When the bow of T-2 tanker touches upper deck, denting occurs on the upper deck and stretching occurs on the outer plate. When the bow of striking ship touches another deck, the denting of another deck occurs and stretching area increases. By this progressive analysis, the relation of failure length and reaction force can be derived.

Based on these relations of failure length and reaction force of bow and that of side structure, which is derived with the assumption that the other structure is rigid, the failure length of each structure is determined based on the equilibrium of the reaction force. On the other hand, Minorsky's formula assumes same failure length for both striking and struck ship, and does not consider relative strength of bow and side.

3. ANALYSIS RESULTS

3.1 Collision with T-2 Tanker

As described before, the analysis of the collision when T-2 tanker (23,400 ton) strikes the nuclear fuel transport ship is carried out. From equation (1), the energy that should be absorbed by structural failure is 206 MJ.

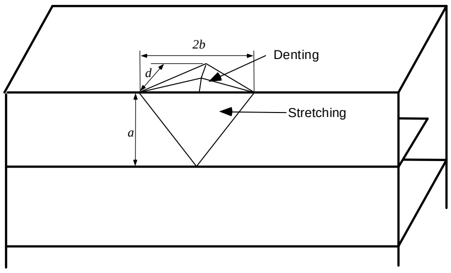
The progressive failure mode is shown in Fig. 4. 1st stage is from the point bow touches upper deck to the point when the bow touches 1st deck. (δ =0～223 mm, Fig. 4 top) Denting occurs on upper deck and stretching occurs between upper and 1st deck. After the bow touches 1st deck until the bow touches 2nd deck (stage 2. δ =223～446 mm, Fig, 4 middle), denting occurs on the upper and 1st deck and stretching occurs between upper and 2nd deck. This progressive analysis is carried out until stage 6 (Fig.4 bottom), from the bow touches transverse bulkhead (stage 6) until the bow reaches transverse bulkhead.

The parameter *a* is determined geometrically (the length between decks) and the parameter *b* is determined to minimize the overall reaction force. The failure length vs. reaction force of side is shown in Fig. 5. In this case, the damage area becomes wide and the strain of outer plate in equation (5) does not exceed the rupture strain 0.2 and no rupture of outer plate occurs.

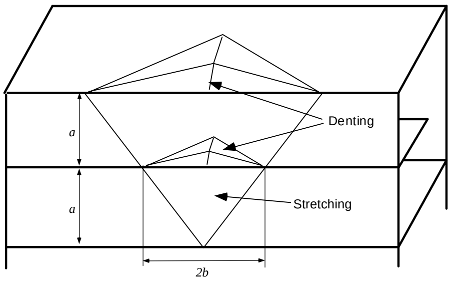
Also, the failure length vs. reaction force of the bow of T-2 tanker based on equation (2) is shown in Fig. 6.

Using these 2 relations, the failure length of bow and side can be determined as shown in Fig. 7. Each graph is placed side by side, and for certain force, the failure length of each structure can be determined. The energy absorption is the area below the line. The force is increased until energy becomes the energy to be absorbed by structure. When the reaction force reaches 35 MN, the failure length of bow becomes 7,500 mm, while the failure length of side becomes 900 mm. The energy absorption becomes 206 MJ. (Hatched area)

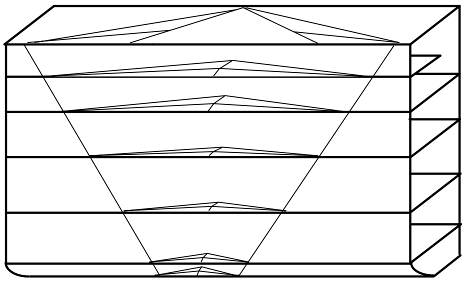
In this case, since the side structure of struck ship is much stronger than the bow of striking ship, failure of bow is much larger and most of the energy is absorbed by the bow of striking ship. The struck ship used in this analysis was designed to have almost critical strength when evaluated with Minorsky's formula. However, current analysis result shows that this ship has much more safety margin. The energy absorption for



Stage 1 (T2)



Stage 2 (T2)



Stage 6 (T2)

Fig. 4 Progressive Failure when Struck by T-2 Tanker

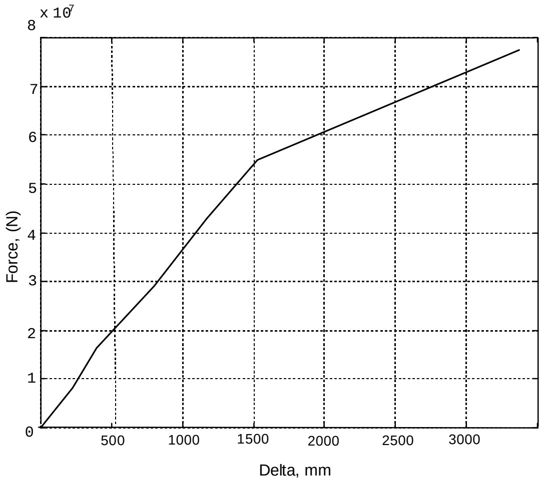


Fig. 5 Failure length vs. reaction force of side

both bow and side is compared for Minorsky's formula and current analysis in Table 1. In Minorsky's formula struck ship absorbs more energy than striking ship, since the failure length is assumed to be same for bow and side. However, since the strength of each structure is different, the failure length should be different and present analysis is more appropriate. In the present analysis striking ship absorbs most energy.

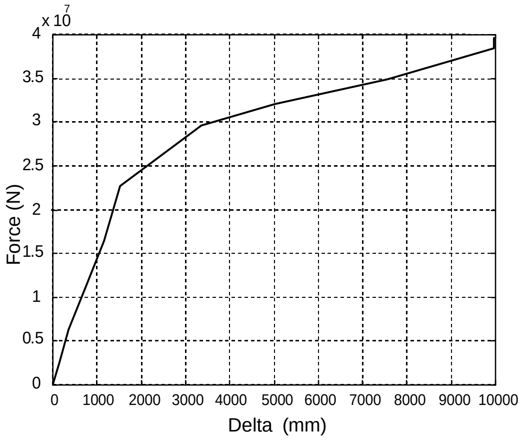


Fig. 6 Failure length vs. reaction force of bow

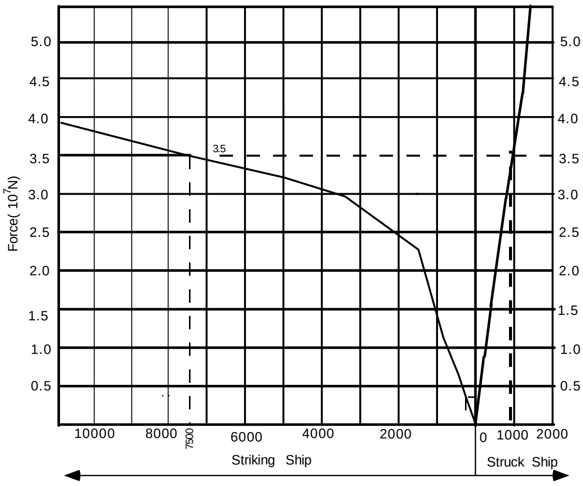


Fig. 7 Collapse analysis considering bow and side (T2)

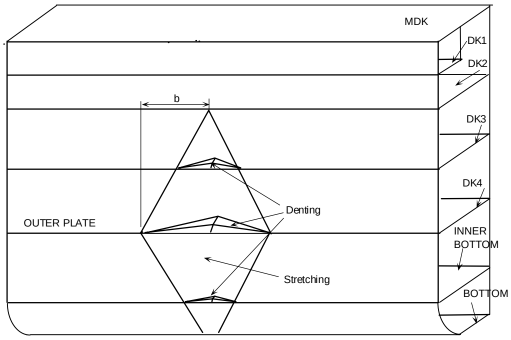
Table 1 Comparison of Minorsky's and present analysis

	Struck ship (MJ)	Striking ship (MJ)	Total (MJ)
Minorsky	160.7	57.3	218
Present analysis	15.5	197.5	213

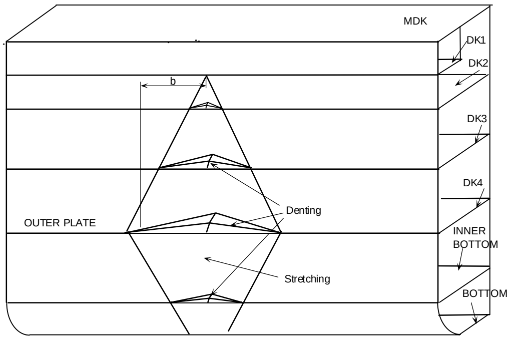
3.2 Collision with Suezmax Tanker

Next, the collision with a Suezmax tanker in ballast condition (displacement 65,000 ton) is analyzed. This is more reasonable choice for striking ship. The relative vertical position will become as Fig. 2 left. The detail FEM analysis is carried out in RR46 (regulation research panel No. 46) of JSRA (the Shipbuilding Research Association of Japan), and compared with present analysis. The energy that should be absorbed by structure is 232 MJ from equation (1).

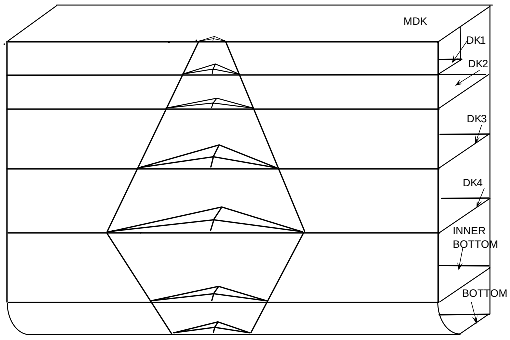
The analysis of ship side is carried out progressively as shown in Fig. 8. As before, the failure mode of deck is assumed to be denting, while the failure mode of outer shell is assumed to be stretching. In the first stage (δ = 0~1000 mm) denting occurs 3rd, 4th and inner bottom. Stretching occurs on outer shell between 2nd deck and bottom. After bow touches 2nd deck, denting also occurs on 2nd deck and stretching area becomes between 1st deck and bottom. (stage 2, δ = 1000~2700 mm) This progressive analysis is continued until stage 4, which is after denting occurs on upper deck. After taking summation of reaction forces of outer shell and decks, the relation of failure length and reaction force can be derives as shown in Fig. 9. Again, since the damage area becomes wide and the strain of outer plate in equation (5) does not exceed the failure strain and no rupture of outer plate occurs, and reaction force increases monotonically.



Stage 1



Stage 2



Stage 4 (Suezmax)

Fig. 8 Progressive Failure when Struck by Suezmax Tanker

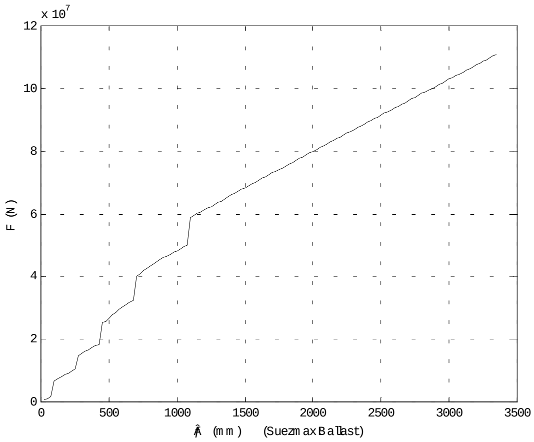


Fig. 9 Failure Length vs. Reaction Force of Side Structure (Suezmax)

Next, the collapse analysis of ship bow is carried out using equation (2). The inner structure of bulbous bow of Suezmax tanker (FEM model) is shown in Fig. 10. The relation of failure length and reaction force is shown in Fig.11.

Using these two relations, the failure length of bow and side structure can be determined as shown in Fig. 12. Considering the force balance, at the reaction force 66 MN the failure length of bow and ship side can be determined as shown in Fig. 12 with sign S1, and at the reaction force 77 MN, the failure length is shown as sign S2. The energy absorption at each stage is shown in Table 2. The sum of energy of bow and side structure becomes as

Until S1: 178 MJ+66 MJ = 244 MJ

Until S2: 410 MJ+94 MJ = 504 MJ

Since the energy that should be absorbed by structural failure when the Suezmax tanker strikes the carrier ship in 15 knot is 232 MJ, the failure come to end before it reaches S1. At this stage, the indentation to the side structure of carrier ship is less than 2,000 mm and still there are more than 1,000 mm margin until the bow reaches transverse bulkhead.

The detail FEM analysis carried out in RR46 also showed almost same failure length, and while energy absorption ratio of ship bow and ship side in simplified analysis was 73 % and 27 %, the FEM analysis showed 71 % and 29 %.

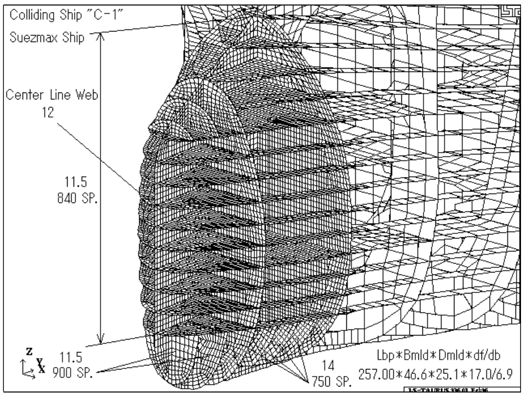


Fig. 10 Model of Bow (Suezmax)

Also, when the failure reaches S2, which absorbs more than 2 times of the energy that should be absorbed, the failure length of struck ship side is still 2,300 mm and still enough margin until bow reaches transverse bulkhead.

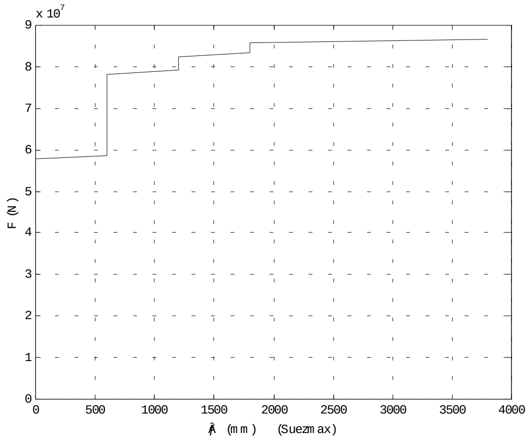


Fig. 11 Failure Length vs. Reaction Force of Bow Structure (Suezmax)

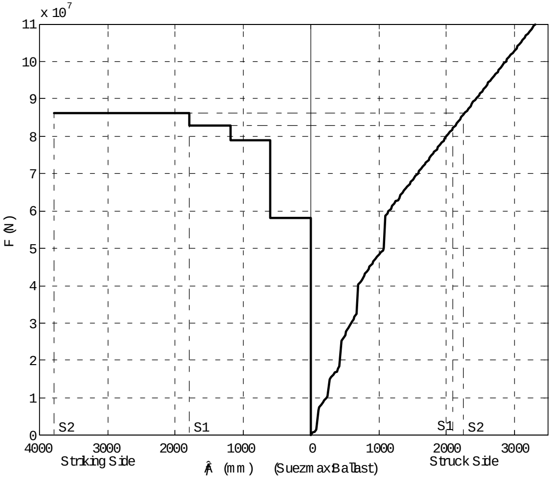


Fig. 12 Failure Analysis Considering Bow and Side Structure (Suezmax)

Table 2 Energy Absorption of Struck and Striking Ship

	Ship	Failure (mm)	Energy (MJ)
Until S_1	Striking	2,700	178
	Struck	1,950	66
Until S_2	Striking	5,700	410
	Struck	2,300	94

4. CONCLUDING REMARK

For the evaluation of the absorbed energy in ship collision, a simplified analysis method is developed that is based on rigid-plastic deformation analysis. Comparison is made with the Minorsky's formula, which is used in the current regulation of nuclear fuel transport ship. For striking ship, T-2 tanker and Suezmax tanker is employed. From the analysis with T-2 tanker, it turned out that using Minorsky's formula may not be appropriate, especially when one of the structures is much stronger than the other one. Also, by comparing the simplified method and FEM simulation for the case of collision with Suezmax tanker, it was shown that the simplified analysis method gives reasonable results with much less time and without a lot of know-how that is required in FEM simulation.

However, it is not yet true to say that the simplified analysis method can be applied to any collision behavior. For example, the collision conditions shown in Fig. 2 left cannot be analyzed with current quasi-static analysis, since the ship motion and failure mode interact each other as ship motion and frictions, and dynamic analysis is necessary. The authors are extending the simplified analysis method to this case.

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