NIPPON STEEL & SUMITOMO METAL TECHNICAL REPORT No. 110 SEPTEMBER 2015

Technical Report

UDC 669 . 14 . 018 . 293 : 539 . 55

Development and Adoption of Steel Plate (NSafe™-Hull) for Shipbuilding with Improved Collision Safety

Teppei OKAWA*
Kazuhisa YANAGITA
Akinori INAMI
Yasuhira YAMADA
Kazutoshi ICHIKAWA
Hiroyuki SHIRAHATA
Kohji ISHIDA
Tomoaki INAI

Abstract

Ship collision and grounding and subsequent damages and foundering are serious maritime accidents which may cause losses in valuable human lives and resources and environmental damages. Newly developed NSafe™-Hull has excellent ductility (elongation), which enables to prevent fatal damages for ship structures even if ship collision or grounding occurs. Technical concepts and material properties of NSafe-Hull are described in the present paper. The world-first adoption of NSafe-Hull for the ship structure is reviewed and its effects are demonstrated through the collision simulation by nonlinear finite element method.

1. Introduction

In recent years, marine accidents involving ships have been decreasing in number. However, serious maritime disasters do occur from time to time. Of them, the collision and grounding of ships are the most frequent.[1)] They can cause great property damage and loss of life. Besides, if crude oil spills out of a tanker, there is a fear of it polluting the ocean environment extensively. It is, therefore, important not only to provide measures against the collision and grounding of vessels but also to discuss ways of minimizing the damage caused by a sea disaster if it should occur.

Improving the safety of ships in a maritime accident has been attracting much more attention than ever on a global basis. In fact, various methods of improving the crashworthiness of ships have been proposed. They include, for example, the use of a sandwich steel plate system with a layer of elastomer (“core”);[2)] the filling of the side structure of vessels with multicellular glass hollow spheres to increase reaction force on collision and thereby improve the collision resistance;[3)] and the installation of a sandwich panel of longitudinal strips of steel plate on each side of an LPG vessel to have a very good crashworthy property.[4)]

Aside from the introduction of a heterogeneous material to the vessel or the modification of the vessel structure mentioned above, if there is an approach to reducing the damage to a ship caused by a collision or grounding by improving the properties of the steel materials used in the ship without increasing neither the ship weight nor the burden of ship construction and inspection, it is considered a realistic method for improving the safety of ships from the standpoint of economic rationality too. For example, it might be possible to enhance the collision resistance of a ship by applying a highly ductile steel plate to the right parts of the vessel body and letting the steel plate absorb the energy of collision. Namely, by employing highly ductile steel plate for the sides, bottom, fuel tank, etc. of the ship, it is considered possible to prevent the occurrence of fractures in the ship, the entry of seawater into the cargo holds, and the spillage of oil even in the case of a collision or grounding.

Based on the above concept, Nippon Steel & Sumitomo Metal Corporation has come up with NSafe™-Hull—a high-strength steel plate having excellent ductility. In a joint project with Imabari Shipbuilding Co., Ltd. and the National Maritime Research Institute, the company discussed the applicability of NSafe-Hull to actual vessels and verified its effectiveness by collision simulations. This study describes the concept of development and the properties of NSafe-Hull and outlines the collision simulations carried out.

2. Target of Development

For a steel plate to be able to absorb the energy of collision effectively, it is necessary that it be good in both strength and ductility. Therefore, the target of development of NSafe-Hull was to secure much higher ductility (elongation) than conventional steel KD36 for shipbuilding (Nippon Kaiji Kyokai (Class NK) rules & inspection

* Researcher, Dr.Eng., Oita R&D Lab.
1 Oaza-Nishinosu, Oita City, Oita Pref. 870-0992

procedure) without impairing the strength, toughness, and weldability of KD36. In addition, since NSafe-Hull was assumed to be used for the outer panels, inner hull, sections, etc. of a vessel, it was decided that the maximum plate thickness be 40 mm and that the plate have adequate HAZ (heat affected zone) toughness capable of adapting one-side-one-pass welding (heat input: 20 kJ/mm).

3. Concept of Development

Generally speaking, steel strength and ductility are incompatible with each other. Ordinarily, securing the both properties simultaneously is difficult. Besides, the steel elongation measured by a tensile test can be divided into uniform elongation and local elongation, which are governed by different factors. To improve the uniform elongation, it is effective to make a complex structure consisting of “soft phase” (ferrite) and “hard phases” (second phases).[5)] By optimizing the volume fraction of each of the phases, it is possible to further improve the elongation.[6)] In addition, it has been known that refining the grains of ferrite to improve the strength of steel does not adversely influence the ductility of steel significantly.[7)] On the other hand, in order to improve the local elongation, it is effective, for example, to make the through-thickness hardness distribution uniform and refine and disperse the second phases and nonmetallic inclusions (hereinafter simply referred to as “inclusions”).[8, 9)]

For the newly developed steel (NSafe-Hull), the volume fractions of the ferrite phase and second phases were optimized through proper optimization of the chemical composition and application of the TMCP (thermomechanical control process) technology and the steel microstructure was so controlled as to refine and disperse the second phases. Consequently, both high strength and high ductility could be secured. In addition, the content of S—an impurity element—was minimized and morphology of the inclusions was controlled so as to eliminate coarse inclusions that could originate ductile fracture voids and to reduce the variation of elongation. The application of TMCP also helped reduce the carbon equivalent (*Ceq*) and weld cracking parameter of material (P_{CM}), making it possible to secure sufficient weldability and HAZ toughness.

4. Properties of NSafe-Hull

4.1 Properties of base steel

Examples of the mechanical properties of NSafe-Hull are shown in **Table 1**. For the tensile test, NK U1 test pieces were used. An example of the stress–strain curve obtained with NSafe-Hull (35 mm-thick plate) is shown in **Fig. 1**. While NSafe-Hull is comparable in strength with conventional steel (KD36), it has much higher ductility. By strictly controlling the heating, rolling, and cooling conditions in the TMCP process, it is possible to manufacture NSafe-Hull steel plate having excellent strength and ductility on a stable basis with minimum material variance.

4.2 Properties of high heat input weld

To evaluate the properties of a weld joint of NSafe-Hull with a high heat input, electrogas-arc welding was applied to the steel using the welding conditions shown in **Table 2** and the toughness of the weld joint was evaluated by Charpy impact tests. The welding material used was an NK-approved flux-cored wire (1.6 mmϕ) [0.05C-0.25Si-1.6Mn-1.4Ni-0.13Mo (mass%)]. The macrostructure of a welded joint is shown in **Photo 1**, and the Charpy impact test results are shown in **Fig. 2**. Even in the adjacent region of the fusion line (FL), the absorbed energy exceeds 150 J, indicating that the weld joint of NSafe-Hull with a high heat input have adequate HAZ toughness.

Table 1 Examples of mechanical properties of NSafe-Hull

Steel	Thickness (mm)	Tensile properties		
		Yield point (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)
A	11	410	517	30
B	18	389	508	33
C	26	384	509	32
D	35	381	505	33
NK KD36	10–40	≧355	490–620	≧16

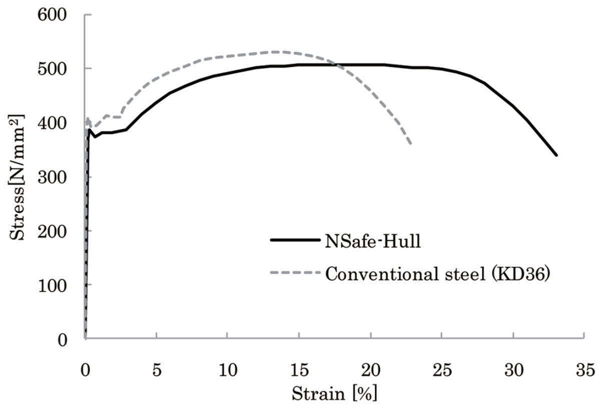


Fig. 1 Examples of stress-strain curves

Table 2 Welding conditions

Thickness (mm)	Groove angle (°)	Root gap (mm)	Welding current (A)	Voltage (V)	Welding speed (mm/min)	Heat input (kJ/mm)
35	20	9	380	39	45	20

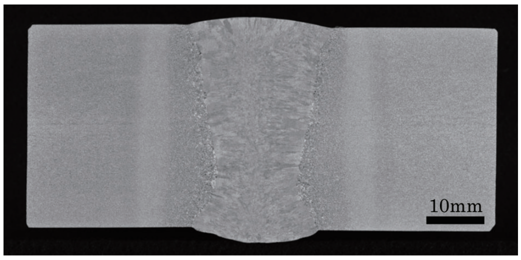


Photo 1 Macrostructure of welded joint

5. Application of NSafe-Hull to Actual Vessels and Verification of Effectiveness by Simulations

NSafe-Hull was applied for the first time to a bulk carrier constructed by Imabari Shipbuilding Co. (owner: Mitsui O.S.K. Lines, Ltd.). The bulk carrier was launched on August 2, 2014 (**Photo 2**). The principal specifications of the vessel are shown in **Table 3**. As shown in **Fig. 3**, NSafe-Hull was applied to the top-side fuel oil tanks and the fuel oil tank in the engine compartment, as well as the hold hull. The vessel parts for which NSafe-Hull is used and the expected effects thereof are summarized in **Table 4**. It can be expected that the hold hull of NSafe-Hull will restrain the occurrence of fractures, prevent the cargo holds from flood, and protect the cargo in

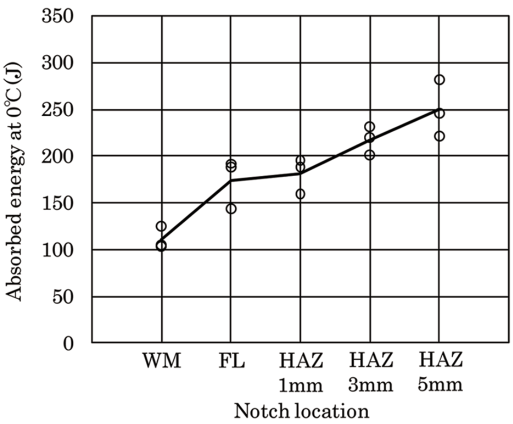


Fig. 2 Charpy impact test results of welded joint

Table 3 Outline of the bulk carrier with the world-first adoption of NSafe-Hull

Deadweight	206 600 tons
Length	299.94 m
Breadth	50.00 m
Depth	24.70 m
Shipping company	Mitsui O.S.K. Lines, Ltd.
Shipbuilding yard	Saijo Shipyard, Imabari Shipbuilding Co., Ltd.
Launch	2nd August, 2014
Amount of NSafe-Hull used	Approximately 3 000 tons

Photo 2 Launch of the bulk carrier with the world-first adoption of NSafe-Hull

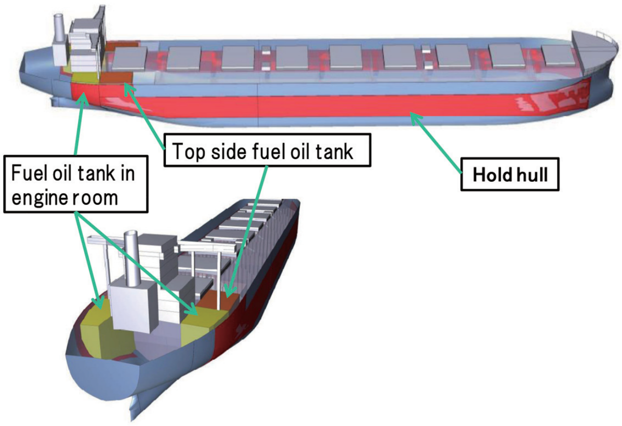


Fig. 3 Overview of parts for which NSafe-Hull is world-first used (courtesy of Imabari Shipbuilding Co., Ltd.)

Table 4 Parts for which NSafe-Hull is applied and its expected effects

Positions	Details of parts applied	Effects expected
Hold single hull	• Side shell plating • Hold Frames • Side longitudinal stiffeners	• Prevention of flooded cargo holds • Protection of cargo • Prevention of penetration by loading machine grab strike
Top side fuel oil tanks	• Side shell plating • Topside tank bottom plating • Fuel oil tank longitudinal bulkhead • Side longitudinal stiffeners	• Prevention of oil spill • Prevention of penetration by loading machine grab strike
Fuel oil tank in engine room	• Side shell • Fuel oil tank longitudinal bulkhead	• Prevention of oil spill

the event of a lateral collision. It will also help prevent the vessel side plates from penetration by the grab strike of loading machine while the vessel stays in port. In addition, the fuel tanks made of NSafe-Hull will restrain the occurrence of fractures in them and help prevent the spillage of oil that can cause serious damage to the environment if a strong impact of a collision is applied to them.

The effect of application of NSafe-Hull on the crashworthiness and absorbed energy of a vessel to which a strong impact is applied is described below. **Figure 4** schematically shows a collision between two vessels. Here, as shown in **Fig. 5** (a) (plan) and Fig. 5 (b) (front view), it is assumed that vessel B (large oil tanker) with speed vector $\vec{V}_B$ hits against the side of bulk carrier A with speed vector $\vec{V}_A$ to which NSafe-Hull is applied. The collision was simulated by the nonlinear finite element method (FEM). In the simulation, only the three sections near the center of the hull of bulk carrier A were assumed as variable conditions: the front and rear ends (parts marked "Fix" in Fig. 5 (a)) were handled as fixed conditions. (For bulk carrier A, that shall be a safer assumption.) **Figure 6** shows the downward view of the model of bulk carrier A from the striking vessel side.

A comparison was made between the fracture situation of a hole when an ordinary steel plate having the elongation specified in the NK rules & inspection procedure was applied to certain hull members (shown in red in **Fig. 7**) and the fracture situation condition when NSafe-Hull was applied to those hull members. The angle formed by $\vec{V}_A$ and $\vec{V}_B$ is 90°. Namely, $|\vec{V}_B|$ is the collision speed and $|\vec{V}_A| = 0$ knots. $|\vec{V}_B|$ was assumed to be 12 knots. The reason for this is that 12 knots is the maximum speed within the Japanese seaways

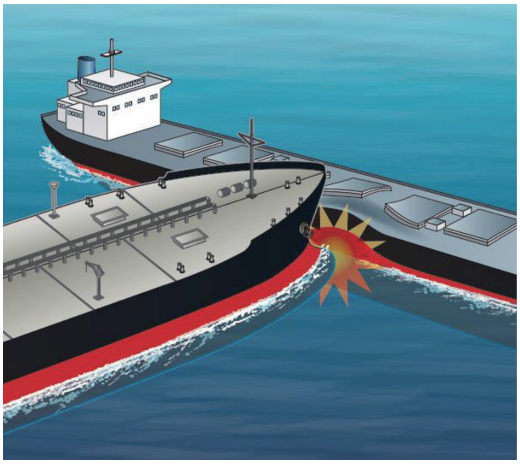
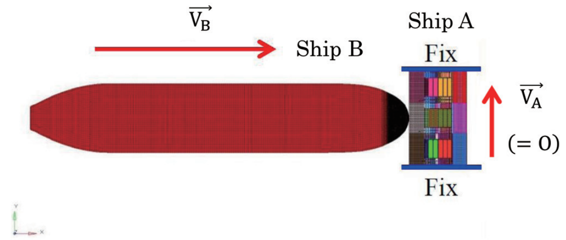
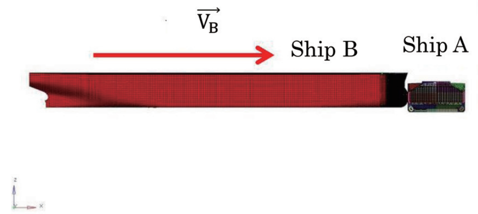


Fig. 4 Ship side-collision (schematic)



(a)



(b)

Fig. 5 Side-collision model for bulk carrier (courtesy of National Maritime Research Institute) (a) Plan view, (b) Front view

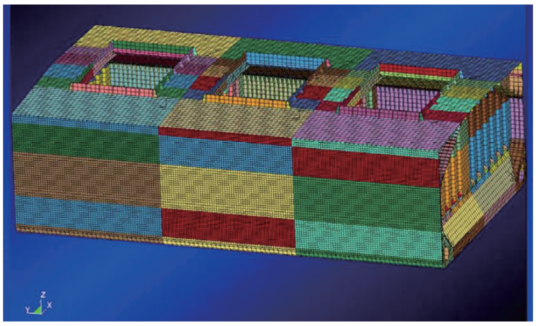


Fig. 6 FEM model of struck ship used (courtesy of National Maritime Research Institute)

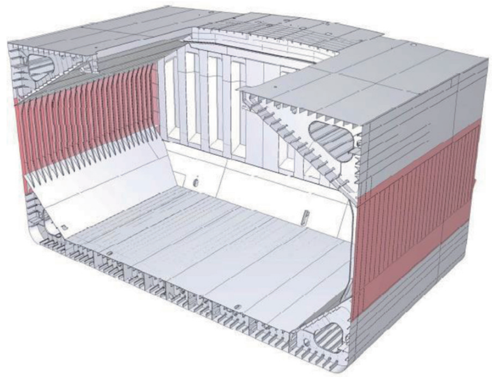


Fig. 7 Sectioned view of parts for which NSafe-Hull is used (parts in red)

set by the Regulations for the Enforcement of the Marine Traffic Safety Act (Ordinance No. 9 of the Ministry of Transport, dated March 27, 1973) and that Yamada and Kinko who studied the speeds of vessel collisions on the basis of tribunal records of the Marine Accident Inquiry Agency found that the majority of vessel collisions had occurred at speeds 10 to 11 knots per hour.[10] Thus, the assumed collision speed of 12 knots as $|\vec{V_B}|$ is considered quite rational.

As an index for quantitatively analyzing the safety of a struck vessel in a collision, the critical collision speed was used. The critical collision speed can be calculated by the following equation using energy E_{cr} absorbed by the hull nonkinetically until the occurrence of a fracture.[11]

$$v_{B,cr} = \sqrt{2E_{cr}\frac{M_A + M_B}{M_A M_B}} \quad (1)$$

Where, M_A and M_B denote the displacement including the mass of added water for the struck vessel and striking vessel, respectively. As the front- and rear-end bulkheads of the struck vessel are assumed as fixed conditions, M_A is sufficiently large as to permit assuming $M_A \to \infty$. Therefore, Equation (1) can be approximated as follows.

$$v_{B,cr} = \sqrt{\frac{2E_{cr}}{M_B}} \quad (2)$$

The value of E_{cr} was calculated by FEM and $v_{B,cr}$ was obtained from Equation (2).

First, the results of FEM calculation of the change in condition of damage to the struck vessel with the lapse of time are shown. When an ordinary steel plate is used for the ship hull, a large vertical tear occurs 1.4 seconds after collision at a speed of 12 knots (**Fig. 8** (a)). On the other hand, when NSafe-Hull is applied, such a hole does not occur in the same period of time (Fig. 8 (b)). Ultimately, when striking vessel B almost stopped relative to struck vessel A (6 seconds after the collision), the crack reached the bottom of the vessel using the ordinary steel plate for the hull, indicating that the damage to the struck vessel was conspicuous (Fig. 8 (c)). By contrast, when NSafe-Hull was used, the crack was very small and the damage to the struck vessel was slight (Fig. 8 (d)). If the crack can be kept small in size, it should be possible to restrain the flood and thereby reduce the risk of foundering of the vessel. In the present analysis, it was assumed that the impact of collision was applied to the side of the cargo hold in the center of the vessel. Even if the impact of collision is applied to the fuel oil tank at the rear end of the vessel, NSafe-Hull will be able to restrain the occurrence of a hole in the tank and thereby help prevent the spillage of oil.

Figure 9 shows the results of a comparison of absorbed energy between ordinary steel and NSafe-Hull. It was found that when NSafe-Hull was used for the parts shown in red in Fig. 7 in place of

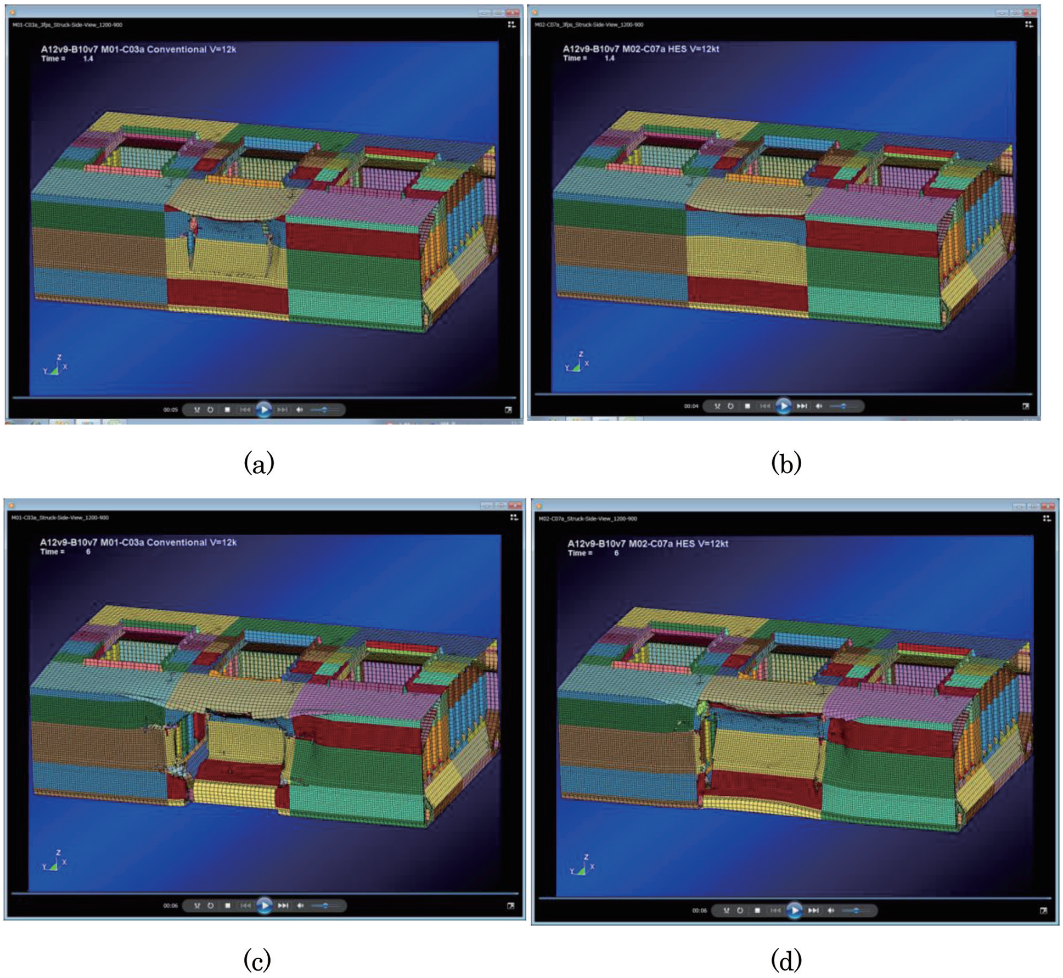


Fig. 8 Comparisons of damage in struck (at 12 knots) ship with conventional steel and NSafe-Hull in hull structure
(a) 1.4 seconds after collision with conventional steel, (b) 1.4 seconds after collision with NSafe-Hull, (c) 6 seconds after collision with conventional steel, (d) 6 seconds after collision with NSafe-Hull

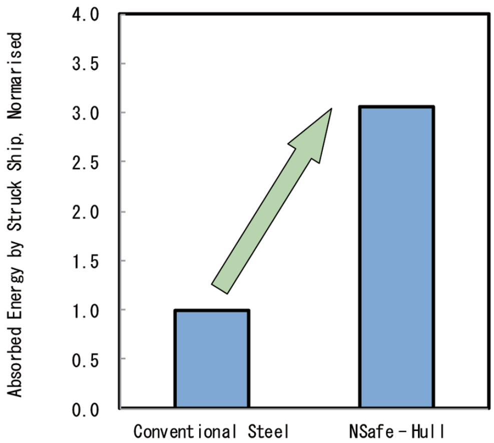


Fig. 9 Absorbed energy by struck ship, normalised by value of case with conventional steel

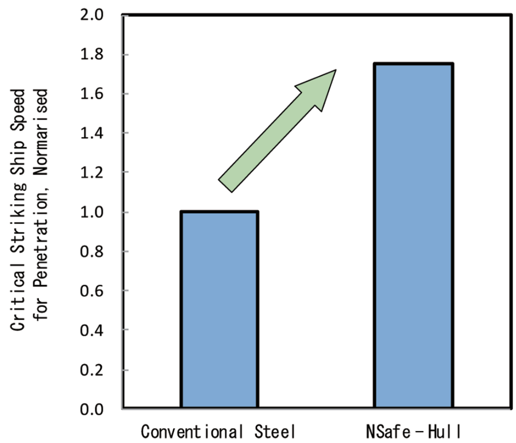


Fig. 10 Critical striking ship speed for penetration, normalised by value of case with conventional steel

the ordinary steel, the amount of energy absorbed until the occurrence of a fracture in the hull became approximately three times larger. In addition, a similar comparison between the ordinary steel and NSafe-Hull in terms of the critical collision speed showed that NSafe-Hull was 1.75 times higher (**Fig. 10**).

As has been described above, it was confirmed that by applying NSafe-Hull—a high-strength, highly ductile steel—to the appropriate parts of a vessel, it would be possible to dramatically reduce the damage caused by a collision if it may occur.

6. Conclusion

Nippon Steel & Sumitomo Metal has come up with NSafe-Hull that has superior strength and ductility. NSafe-Hull that is comparable in strength to the conventional KD36 steel, it has much higher ductility with superior weldability and HAZ toughness allowing for welding with a high heat input. It was confirmed by FEM simulations that by arranging NSafe-Hull steel plate in the appropriate parts of a vessel, it was possible to restrain the occurrence of cracks in the hull even if a collision with another vessel occurs.

In future, we have plans to conduct a more sophisticated analysis with the backing of NK's scheme "Joint Research based on the demands from the Industry." NK is also planning to promote the improvement of ship safety by defining a "notation" (identification mark) to ships which have improved in safety, like the ones applying NSafe-Hull.

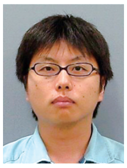
Through expansion of the application of NSafe-Hull to vessels, the company continues striving to contribute to the materialization of safer and more reliable maritime transportation.

Acknowledgments

We wish to express our heartfelt thanks to Dr. Shigeru Tozawa, Senior Director for Research at the National Maritime Research Institute and Mr. Kenji Kamita, Group Leader at the Hull Design Group, Marugame Headquarters Imabari Shipbuilding Co., Ltd. for their generous cooperation in our putting NSafe-Hull into practical application.

References

1) Japan Coast Guard: Present Situations of Marine Accidents and Preventive Measures. 2012 (in Japanese).
2) Nataro, G. et al.: Proceedings of 6th International Conference on Collision and Grounding of Ships and Offshore Structures, ICCGS. Trondheim, Norway, 17–19 June, 2013, p. 85
3) Schöttelndreyer, M. et al.: Proceedings of 6th International Conference on Collision and Grounding of Ships and Offshore Structures, ICCGS. Trondheim, Norway, 17–19 June, 2013, p. 101
4) Rudan, S. et al.: Proceedings of 6th International Conference on Collision and Grounding of Ships and Offshore Structures, ICCGS. Trondheim, Norway, 17–19 June, 2013, p. 331
5) Nippon Steel Corporation: Tetsu no Usuita-Astuita ga Wakaru Hon. Tokyo, Nihon-Jitsugyo-Shuppan-Sha, 2009 (in Japanese)
6) Terada, Y. et al.: Nippon Steel Technical Report. (90), 88 (2004)
7) Tsuji, N.: Tetsu-to-Hagané. 88 (7), 359 (2002)
8) Uchiyama, I. et al.: Tetsu-to-Hagané. 57 (13), 1897 (1971)
9) Kozashi, I.: Tetsu-to-Hagané. 61 (14), 2998 (1975)
10) Yamada, Y. et al.: Conference Proceedings, The Japan Society of Naval Architects and Ocean Engineers. (17), 175 (2013)
11) Yamada, Y. et al.: International Journal of Offshore and Polar Engineering. 18 (2), 1 (2008)



Teppei OKAWA
Researcher, Dr.Eng.
Oita R&D Lab.
1 Oaza-Nishinosu, Oita City, Oita Pref. 870-0992

Kazutoshi ICHIKAWA
Senior Researcher, Ph.D.
Plate & Shape Research Lab.
Steel Research Laboratories

Kazuhisa YANAGITA
Plate Quality Control Dept.
Quality Management Div.
Oita Works

Hiroyuki SHIRAHATA
Senior Researcher
Oita R&D Lab.

Akinori INAMI
Senior Manager
Plate Products Technical Service & Solution Dept.
Plate Technology Div.
Plate Unit

Kohji ISHIDA
Head of Dept.
Plate Quality Control Dept.
Quality Management Div.
Oita Works

Yasuhira YAMADA
Senior Researcher, Ph.D.
Structural Analysis Research Group
Structural Strength Evaluation Department &
Maritime Accident Analysis Center (MAAC)
National Maritime Research Institute

Tomoaki INAI
Assistant to Team Leader
Hull Design Team
Marugame Headquarters
Imabari Shipbuilding Co., Ltd.