Hull Structures with Newly Developed Highly Ductile Steel to Mitigate Impact Damage and Cargo Loss in Ship to Ship Collision

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Abstract

Since the authors developed a new steel material called Highly Ductile Steel (HDS) that offers significantly greater plastic deformability than conventional steel, HDS has recently been used in the main structure of capesize bulk carriers. The aim of using HDS is to take advantage of its high deformability to improve hull safety and prevent cargo leakage in the event of a collision, and in specific terms, by offering a reduced likelihood of cracking occurring in the hull and smaller hollow depth. Other mechanical properties and workability of HDS are exactly the same as conventional steel, meaning it can be used without requiring any change to structural design. This research was conducted on very large crude carriers (VLCC) that could cause great harm to the environment if they sustain damage, and we used collision simulations to analyze the effect of HDS. The analysis assumed collisions between fully loaded VLCCs. The collision angle and speed were varied, and the lowest speed of the striking ship before cracking occurred in the inner shell of the struck ship was calculated, as well as the amount of energy absorbed. For example, in a right-angle collision (the most severe angle possible), a ship that used HDS absorbed three times as much energy as a ship that used conventional steel. In terms of the lowest speed of the striking ship for cracking to appear in the inner shell, the lowest speed for the ship with HDS was at least 12 knots compared with five to six knots for conventional steel.

1. Introduction

One of the most important issues concerning VLCCs is the prevention of leakage of crude oil, as it is not just a matter of crew safety and loss of cargo, but also has a large impact on the environment.

Double hulls are a very effective method to prevent leakage of crude oil, but incidents of leakage have still occurred in double hull vessels. As such, an expanded width of a double hulls, depths of double bottom and an increased number of cargo tanks have all been investigated, but it is clear that all led to a decrease in shipping efficiency and an increase in construction and operating costs. Since we developed a new steel material called Highly Ductile Steel (HDS), that offers significantly greater plastic deformability than conventional steel, HDS has recently been used in the main structure of capesize bulk carriers. HDS can be manufactured with a strength equivalent to that of mild steel and high-tensile steel, and its mechanical properties as well as its weldability and other aspects of its workability are the same as conventional steel so there is no need to alter structural designs. This research focused on VLCCs, for which cargo leakage has the most serious impact, and we conducted analysis of ship-to-ship collisions involving fully loaded VLCCs. We used the non-linear finite element (FE) code LS-DYNA and varied the speed and angle of the collision, and then calculated the energy absorbed before cracking occurred in the inner shell (Ecr) and the minimum speed of the striking ship in such cases (Vcr) in order to investigate the effect of HDS.

2. What is HDS?

Fig. 1 shows an example of stress-strain curves for a steel plate. After an elastic deformation, a permanent deformation starts at the yield point and the plate ruptures after work hardening.

The total deformation HDS can be at least 1.5 times the value demanded by the Rules and Regulations for the Classification of Ships, and as the strength is the same as that of conventional steel, the amount of energy that can be absorbed before it ruptures is larger than for conventional steel. As discussed later, the time until rupture occurs is also greater, so the plastic area expands and energy absorption increases further. As such, the following effects can be expected.

1) Cracking is less likely to occur in a struck ship, or in other words it is hard for the ship to be pierced, thus reducing the risk of oil leakage and sinking.
2) The hollow depth of a struck ship is smaller, thus repairs in transverse direction can be reduced.

HDS is already being applied to actual ships. The ships are 200,000 DWT bulk carriers and each ship uses approximately 3,000 tons of HDS for its side shell and around its fuel tanks. Two such ships have already been completed, and serial construction is planned further. The steel plates are manufactured using the same procedure as recent conventional steel plates meaning there is no difference in terms of usage with conventional steel whatsoever. This means that when using HDS, as there is no need to alter the design or usage of the steel plates when compared with conventional steel, the benefits of HDS can be obtained simply by changing the steel plates.

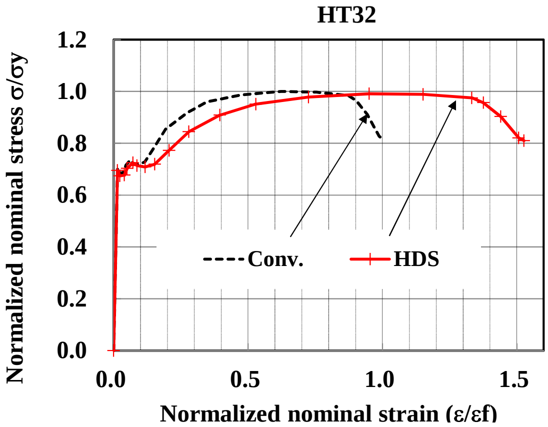


Fig. 1 Stress-strain curves (Yamada et al. 2015)

3. Results of collision simulation

The trial collision simulation “Simulation 1” (S1) was first attempted followed by much finer and detailed one identified as “Simulation 2” (S2) in this paper. S1 was indeed necessary before proceeding the further major but expensive and exhausting simulation, “S2”. The main conditions for these simulations are shown in Table 1. The deformation areas were the bow of the striking ship and the middle of the struck ship, and as indicated in Fig. 2, one tank was modeled elasto-plasticity in S1 whereas S2 had nine tanks with elasto-plasticity. In S1, we made the elasto-plasticity area smaller in order to optimise calculations and make it useful for conservative evaluation. The motion of both ships was considered in both simulations. Table 2 shows the dimensions of the struck ship and striking ship, and Table 3 shows the number of nodes, elements, and parts. Table 4 shows a summary of the areas where HDS was applied. Both ships were the same type of VLCC, had a double-hull structure, and collided with each other in the fully loaded condition. S1 used limited conditions in order to investigate the rough state of the deformation, and we investigated the difference in energy absorbed upon collision and the hollow depth. In S2, we assumed a collision between actual ships and varied the angle and speed of the collision to investigate the *Vcr* and *Ecr*. In S2, nine tanks were modeled elasto-plasticity to complement the accuracy of the extent modeled in S1 because in the case of a large deformation (i.e. a high speed of collision), the extent of the deformation is large and exceeds one tank.

Table 1 Colliding conditions.

Collision conditions	Simulation 1	Simulation 2
Loading condition	Both ships full loaded 310,084DWT	Both ships full loaded 310,084DWT
Striking area	Midship betwee transverse BHD. and swash BHD.	Midship betwee transverse BHD. and swash BHD.
Ship speed (striking)	12knot	2-12knot
(struck)	Still	Still
Collision angle	90deg.	30-150deg.
Motion of struck ship	Considered	Considered
Horizontal bending	Not considered	Considered
Deformation area(elastic-plastic)	1tank	9 tanks

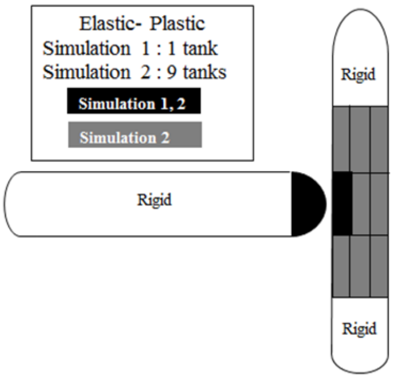


Fig. 2 Finite elements model and analysis condition

Table 2 Dimension of ships

Length O.A.[m]	333
Length B.P.[m]	324
Breadth [m]	60
Depth [m]	29
Draft [m]	21.1
DWT [ton]	310,084

Table 3 Number of nodes, elements and parts

		Node	Element	Part
Simulation 1	Struck	651,444	773,930	756
	Striking	157,543	168,109	357
Simulation 2	Struck	669,110	825,299	2,165
	Striking	157,543	168,109	357

Table 4 Application area of HDS

HDS application pattern		Outer shell	Inner shell	Outer shell stiffener	Inner shell stiffener	Other members
Simulation 1	Applied	○	○	–	–	–
Simulation 2	Full applied	○	○	○	○	○
	Partial applied	○	○	○	–	–
Simulation 1,2	Conventional	–	–	–	–	–

3.1 Results of analysis of Simulation 1

In S1 we assumed severe conditions in which the striking ship and the struck ship were both fully loaded (310,084 DWT) and the angle of the collision was 90°, and set the speed of the striking ship to be 12 knots. As shown in Fig.3, the simulation was implemented under conditions in which HDS was used only for the outer shell (OS) and the inner shell (IS), and other conditions were the same as for conventional steel. Fig. 4 shows the change in contact force during the collision. The collision itself lasted for approximately six seconds. The contact force for both an OS and IS rupture was approximately 30% higher for HDS. The contact force rapidly decreased after the IS ruptured. Once the cracking began to extend, no particular difference is seen between conventional steel and HDS. With conventional steel, the OS ruptured in 0.45 seconds and the IS ruptured in 0.87 seconds, whereas with HDS, the time until rupture increased to 0.65 seconds and 1.81 seconds, respectively. Calculation of *Ecr* revealed that it was 478MJ and 1393MJ for conventional steel and HDS, respectively, i.e. if HDS is used, it absorbs approximately three times as much energy as conventional steel. This is not simply because greater ductility in HDS, but also because the plastic deformation area expands as it takes longer to rupture, which is a significant secondary effect. Table 5 shows a summary of the timing of ruptures, as well as *Ecr* and *Vcr.* The *Vcr* for conventional steel was 5.1 knots, whereas for HDS it was 8.7 knots. However, with regards to *Vcr,* S2 offered more accuracy as it had a deformation area expanded to nine tanks and increased precision.

Fig. 5 shows the results of analysis of the IS hollow depth. With conventional steel, the hollow depth for a 12 knot collision was approximately 20 m, but with HDS it did not exceed approximately 10 m (around half), thus revealing that the extent of the damage was also smaller. This analysis did not take into account the motion of the struck ship.

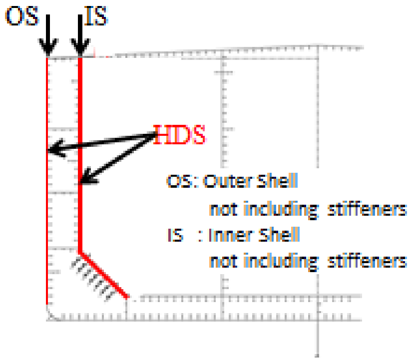


Fig. 3 HDS application area of Simulation 1

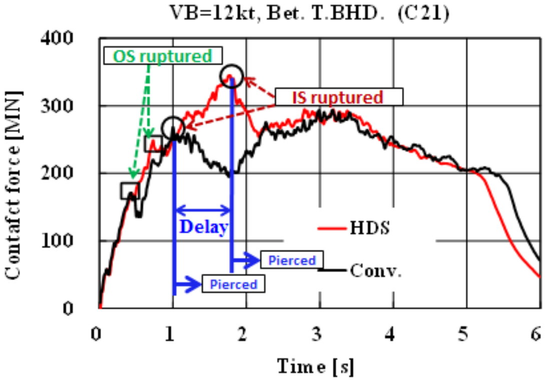


Fig. 4 Time histories of contact force

Table 5 Rupture time, *Ecr* and *Vcr*

Steel	OS rupture time [s]	IS rupture time [s]	Ecr [MJ]	Vcr [kt]
Conv.	0.45	0.87	1,393	5.1
HDS	0.65	1.81	478	8.7

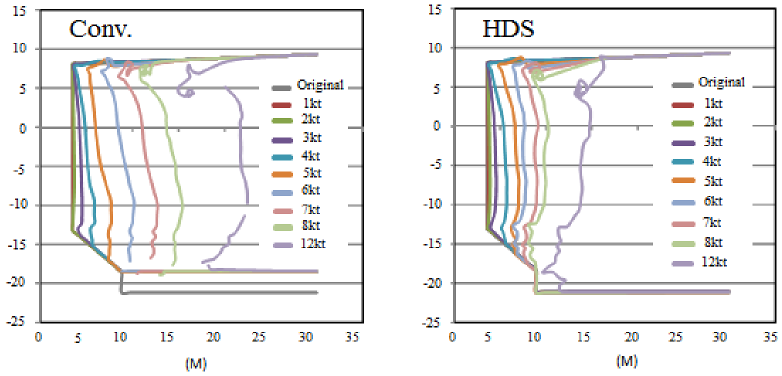


Fig. 5 Deformation while collision (motion of struck ship is not considered, (Yamada et al. 2016b)

3.2 Results of analysis of Simulation 2

As the effect of HDS largely became apparent in S1, here we conducted a simulation with a range of collision speeds and angles, as well as an expanded deformation area to increase accuracy. Fig. 6 shows the areas in which HDS was applied. In full application, all materials including stiffeners used HDS, and in partial application, only the OS, IS, and stiffeners attached to the OS used HSD. Table 6 shows the implementation variables for the simulation. The collision angle for conventional steel was varied greatly from 30° to 150°, and the collision speed was varied from two to 12 knots. As HDS has a higher performance than conventional steel, the collision speed was fixed at 12 knots, and the collision angle was set in the vicinity of 90°. The *Vcr* was obtained based on the calculations below. This is the same as Simulation 1.

$E0$ = Initial kinetic energy of striking ship

= $Et + Er + Ea$

Et : Translational kinetic energy after collision

Er : Rotational kinetic energy after collision

Ea : Absorbed energy other than ship motion (mainly deformation and sliding energy) by the time of IS rupture

As shown in Fig. 7, for HDS, in collision angles ranging from 75° to 105° degrees and a collision speed of 12 knots, in both full and partial application, the results obtained showed that cracking did not occur in the IS, and neither did it occur in the OS. For conventional steel, however, cracking occurred at an angle of 45° to 135° degrees at a speed of 12 knots or less, and the *Vcr* for the IS in a collision in the vicinity of 90° was five to six knots while the value for the OS at the same angle was around three knots. For 30° and 150°, cracking did not occur at 12 knots, but this was due to the shallow angle, making it an incident of slipping contact. From this *Vcr* comparison, the *Ecr* for HDS under S2 conditions can be estimated to be more than four times that of conventional steel. Fig. 8 shows an example of the state of deformation after a collision.

In S1, the *Vcr* for HDS was 8.7 knots, but in S2 it exceeded 12 knots. The reasons for this are a) the deformation area in S2 was large, and deformations that exceeded over one tank were included in the analysis, and b) it may be that in contrast to S1, the range of application of HDS in S2 was expanded to stiffeners and other areas, but the details are still under analysis.

It should be mentioned that in these analysis of FEM, existences of weld metal and heat affected zone may be negligible and thus are not assumed in the present study. It can be rationalized by the fact that the volume fractions of such elements are fairly small (only few percent in a total collided ship) and thus their influence on the absorbed energy on collision can be relatively small as well.

ClassNK is planning to assign a class notation of “Hull Protection by Highly Ductile Steel” (HP-HDS) for such ships that use such steel plates with superior ductility, and to mention in the descriptive note the steel grade of ductility and the areas in which it is used.

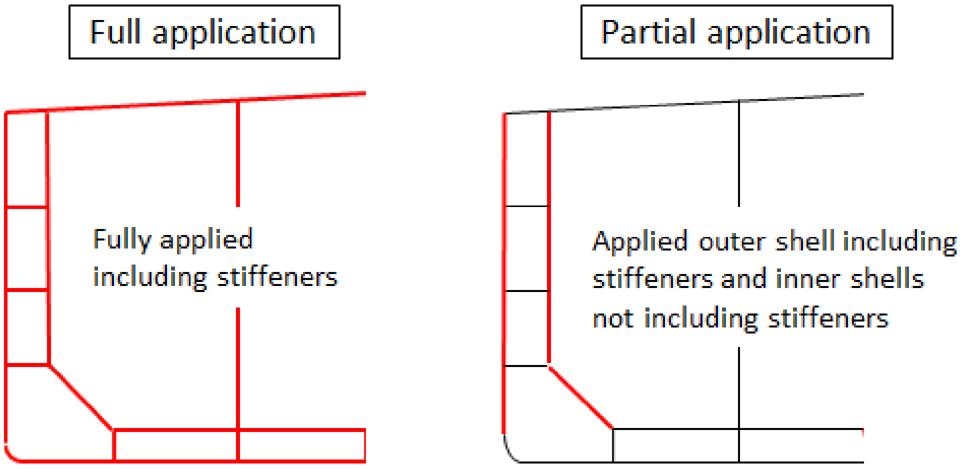


Fig. 6 HDS application area of Simulation 2

Table 6 Analysis matrix of Simulation 2

Velocity / Angle (deg)	12	10	9	8	7	6	5	4	3	2
30	N				N	N	N			
60					N	N	N	N		
75	F,P,N					N	N	N		
90	F,P,N	N		N		N	N	N	N	
105	F,P,N				N	N	N	N		N
120	N				N	N	N	N		
135	N	N	N	N		N	N	N		
150	N				N	N	N			

F: HDS Full applied
P: HDS Partial applied
N: HDS Not applied

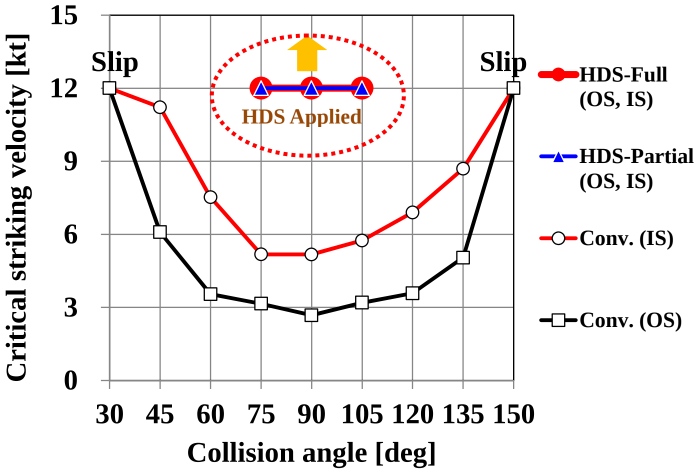
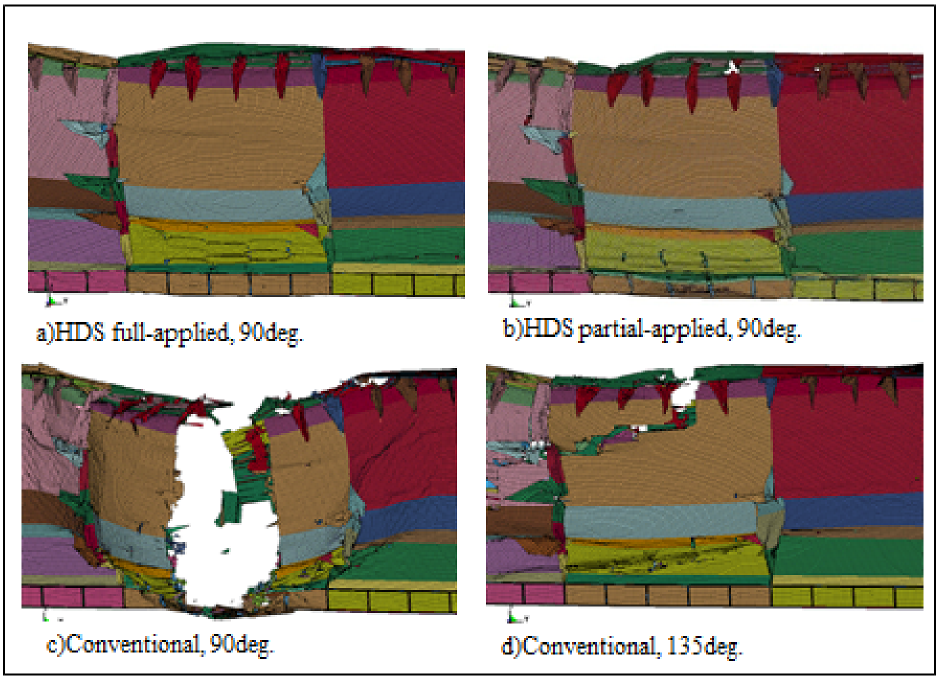


Fig. 7 Rupture limit curves (Yamada et al. 2016a)


a)HDS full-applied, 90deg.

b)HDS partial-applied, 90deg.

c)Conventional, 90deg.

d)Conventional, 135deg.

Fig. 8 Examples of simulation (IS after collision)

4. Summary

In this research, we investigated the application of highly ductile steel to VLCCs that would have a great environmental impact if a cargo leakage occurs, and analyzed simulated collisions. The following shows what we have identified through these activities.

1) From the most important perspective of the prevention and reduction of oil leakage, the collision energy that was absorbed prior to the rupturing of the IS (*Ecr)* was three times higher for HDS than conventional steel.

2) The results of implementing simulations with various collision angles revealed that the minimum speed of the striking ship to cause a rupture in the IS (*Vcr*) was at least 12 knots with HDS, which was more than twice that of the five to six knots for conventional steel.

3) It was revealed that the hollow depth after a collision was smaller with HDS than that with conventional steel. As an example, in the case of a collision at a speed of 12 knot and an angle of 90°, the IS hollow depth with conventional steel was around 20 m, whereas with HDS it was around 10 m.

4) ClassNK is planning to assign a class notation if highly ductile steel is used for a ship's hull.

5. Acknowledgments

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