Numerical simulation on Crashworthiness of 105000t LNG Carrier

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Abstract. It is of great significance to study the crashworthiness of LNG carrier to improve its crashresistance and enhance its operation safety. In this paper, the collision process between the bulbous bow of the container ship and the side structure of the LNG ship is analyzed by using nonlinear finite element numerical simulation. Collision performance of LNG carrier and collision indicators during the collision, the impact force, velocity and displacement and energy absorption in the process of collision by changing parameters of the major velocity, impact angle and impact location and others are studied. The relevant research results have a strong practical significance for analyzing the deformation, strengthening measures and structural repair of ship side structure impact damage.

1. Introduction

Under the background of trade globalization, the shipping industry has made great progress, the number of merchant ships has increased significantly, and the routes have become increasingly dense, but the collision accidents between ships also occur from time to time. According to incomplete statistics, more than 40% of the shipwrecks in the world are caused by ship collision. The marine transportation of liquefied natural gas (LNG) is also developing rapidly due to the increasing demand for LNG in the market. Because LNG ship is a dangerous goods ship, the collision between LNG ship and other ships is particularly important, which has been paid more and more attention by relevant authorities and scholars. Because the collision accident of LNG ship will not only lead to the damage of the hull structure, marine environmental pollution, but also may cause the leakage of LNG, which will lead to low temperature damage, explosion and personnel poisoning. Therefore, it is of great significance to study the crashworthiness of LNG carrier to improve its crashresistance and enhance its operation safety.

Generally, ship collision only occurs locally and in a very short time. The sudden application of huge impact force is a very complex nonlinear transient response process involving ship plastic deformation and fracture. The theoretical study of ship collision is very complex, which requires the comprehensive utilization of ship hydrodynamics, plastic mechanics, fracture mechanics and reliability knowledge, mainly including analytical method, empirical formula method, experimental research method and numerical simulation method. With the rapid development of nonlinear finite element technology and computer hardware, numerical simulation has gradually become the main means to study ship collision [1, 2]. In this paper, with the help of Patran and DYTRAN modules of large commercial finite element
software MSC, 3D nonlinear finite element numerical simulation method is used to simulate the collision of the side structure of a 105000 ton LNG ship, and the crashworthiness of the ship is studied.

2. Research methods of ship collision

2.1. Related parameters of the example
In this example, the LNG ship is impacted by a container ship, and the principal parameters of the two ships are shown in Table 1.

Table 1. Principal parameters of ships.

| Item                      | LNG carrier (collided ship A) | Container ship (impact ship B) |
|---------------------------|-------------------------------|-------------------------------|
| Length (L/m)              | 280                           | 245                           |
| Breadth (B/m)             | 45.8                          | 32.2                          |
| Depth (D/m)               | 23.95                         | 19.3                          |
| Draught (d/m)             | 11.5                          | 10                            |
| Displacement (Δ/t)        | 105000                        | 55000                         |
| Cb                        | 0.695                         | 0.680                         |
| Speed (V/m/s)             | 0                             | 2                             |

The two ships collided vertically. The impact position is located at 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 and 0.8 ship length in the longitudinal direction of the impacted ship, as shown in Figure 1.

2.2. Collision energy calculation
Considering the effect of fluid-structure interaction, the attached water coefficient depends on the hull shape and impact duration. For convenience, the attached water mass coefficient can be taken as:

\[
\begin{align*}
m_{a1} &= m_{b1} = 0.05 \quad \text{(Pitch)} \\
m_{a2} &= m_{b2} = 0.05 \quad \text{(Roll)} \\
J_a &= J_b = 0.21 \quad \text{(Yaw)}
\end{align*}
\]
The inertia radius of the ship is approximately: \( R = (0.19C_b + 0.11)L \), where \( C_b \) is the block coefficient and \( L \) is the length. In the example, the inertia radius of the ship is \( R_a = 58.604m \) and \( R_b = 67.78m \) respectively.

According to the relevant references, the calculation formula of the energy released due to the compression of the hull structure when two ships A and B collide is as follows [3]:

Energy released along the direction \( \xi \): \[ E_\xi = \int_0^{\xi_{max}} F_\xi d\xi = \frac{1}{2} \frac{1}{D_\xi} \xi(0)^2 \]

Energy released along the direction \( \eta \): \[ E_\eta = \int_0^{\eta_{max}} F_\eta d\eta = \frac{1}{2} \frac{1}{D_\eta} \eta(0)^2 \]

Where \[ D_\xi = \frac{D_{\alpha\xi}}{M_a} + \frac{D_{\beta\xi}}{M_b}, \quad K_\xi = \frac{K_{\alpha\xi}}{M_a} + \frac{K_{\beta\xi}}{M_b}, \quad D_\eta = \frac{D_{\alpha\eta}}{M_a} + \frac{D_{\beta\eta}}{M_b}, \quad K_\eta = \frac{K_{\alpha\eta}}{M_a} + \frac{K_{\beta\eta}}{M_b} \]

\[ \mu = \frac{D_\xi \eta(0) - K_\xi \xi(0)(1 + e)}{K_\eta \eta(0)(1 + e) - D_\eta \eta(0)} \]

Because the collision between the two ships is vertical, the initial velocity along the \( \xi \) direction is \( \dot{\xi}(0) = 2m/s \), and the initial velocity along the \( \eta \) direction is \( \dot{\eta}(0) = 0m/s \), so \( E_\eta = 0 \). In addition, due to the complete plastic collision between the two ships, the coefficient of restitution \( e \) is 0.

In order to calculate the energy in direction \( \xi \), the above formula should be refined:

\[ D_{\alpha\xi} = \frac{1}{1+m_{a1}} \sin^2(\beta - \alpha) + \frac{1}{1+m_{a2}} \cos^2(\beta - \alpha) + \frac{1}{1+j_a} \left[ (y_c - y_a) \sin \alpha - (x_c - x_a) \cos \alpha \right]^2 \]

\[ D_{\beta\xi} = \frac{1}{1+m_{a1}} \sin^2 \alpha + \frac{1}{1+m_{a2}} \cos^2 \alpha + \frac{1}{1+j_b} \left[ y_c \sin \alpha - (x_c - x_a) \cos \alpha \right]^2 \]

\[ D_{\alpha\eta} = -\frac{1}{1+m_{a1}} \sin(\beta - \alpha) \cos(\beta - \alpha) + \frac{1}{1+m_{a2}} \sin(\beta - \alpha) \cos(\beta - \alpha) \]

\[ + \frac{1}{1+j_b} \left[ (y_c - y_a) \sin \alpha - (x_c - x_a) \cos \alpha \right]^2 \]

\[ D_{\beta\eta} = \frac{1}{1+m_{a1}} \sin \alpha \cos \alpha - \frac{1}{1+m_{a2}} \sin \alpha \cos \alpha + \frac{1}{1+j_b} \left[ y_c \sin \alpha - (x_c - x_a) \cos \alpha \right]^2 \]

Where

\[ K_{\alpha\xi} = -\frac{1}{1+m_{a1}} \sin(\beta - \alpha) \cos(\beta - \alpha) + \frac{1}{1+m_{a2}} \sin(\beta - \alpha) \cos(\beta - \alpha) \]

\[ + \frac{1}{1+j_a} \left[ (y_c - y_a) \sin \alpha - (x_c - x_a) \cos \alpha \right]^2 \]

\[ K_{\beta\xi} = \frac{1}{1+m_{a1}} \sin \alpha \cos \alpha + \frac{1}{1+m_{a2}} \sin \alpha \cos \alpha \]

\[ + \frac{1}{1+j_b} \left[ (y_c - y_a) \sin \alpha - (x_c - x_a) \cos \alpha \right]^2 \]
Based on the above formula, the collision parameters as shown in Table 2 can be obtained.

**Table 2. Collision parameters.**

| Collision locations | Collisions parameters | K\(_m\) | K\(_n\) | K\(_a\) | K\(_t\) | D\(_m\) | D\(_n\) | D\(_a\) | D\(_t\) | \(\mu\) | E\(_z\)/MJ |
|---------------------|-----------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|----------|
| 0.20                | -84.0                 | 3.85   | 84.0   | 1.04   | -0.261 | 0      | -2.48\times10^4 7.95\times10^4 | 1.73 | 0.952 | -0.261 | 0 | 3.38\times10^4 -2.48\times10^4 0.031 | 15.6 |
| 0.30                | -56.0                 | 3.85   | 56.0   | 1.04   | -0.174 | 0      | -1.66\times10^4 7.95\times10^4 | 1.07 | 0.952 | -0.174 | 0 | 2.75\times10^4 -1.66\times10^4 0.021 | 18.2 |
| 0.40                | -28.0                 | 3.85   | 28.0   | 1.04   | -0.087 | 0      | -8.28\times10^4 7.95\times10^4 | 0.673 | 0.952 | -0.087 | 0 | 2.37\times10^4 -8.28\times10^4 0.010 | 21.1 |
| 0.50                | 0.00                  | 3.85   | 0.00   | 1.04   | 0.000  | 0      | 7.95\times10^4 0.541 | 0.952 | 0.000 | 0   | 2.25\times10^4 0.000 | 0.000 | 22.5 |
| 0.60                | 28.0                  | 3.85   | 28.0   | 1.04   | 0.087  | 0      | 8.28\times10^4 7.95\times10^4 | 0.673 | 0.952 | 0.087 | 0 | 2.37\times10^4 8.28\times10^4 -0.010 | 21.1 |
| 0.70                | 56.0                  | 3.85   | 56.0   | 1.04   | 0.174  | 0      | 1.66\times10^4 7.95\times10^4 | 1.07 | 0.952 | 0.174 | 0 | 2.75\times10^4 1.66\times10^4 -0.021 | 18.2 |
| 0.80                | 84.0                  | 3.85   | 84.0   | 1.04   | 0.261  | 0      | 2.48\times10^4 7.95\times10^4 | 1.73 | 0.952 | 0.261 | 0 | 3.38\times10^4 2.48\times10^4 -0.031 | 15.6 |

It can be seen from the calculation results in Table 2 that the maximum collision energy is in the middle of the ship. Therefore, the most dangerous state of ship collision is usually that the bow of the striking ship is striking the middle side of the struck ship. In this kind of collision scenario, because the stiffness of the bow of the striking ship is significantly greater than that of the side of the struck ship, most of the impact energy is absorbed by the side structure of the struck ship.

### 3. Collision strength analysis of LNG carrier based on MSC / DYTRAN

For the external dynamics of collision, the research focuses on the overall motion, force and energy dissipation of the ship, and the internal structure of the ship in the collision model can be greatly simplified [4, 5]. Considering the attached water mass of ship collision, the density of ship material is increased to make the model mass equal to the sum of ship displacement and attached water mass. For the internal mechanics of collision, the damage, deformation, stress and energy dissipation of the local structure of the ship in the collision area are mainly studied. It is not necessary to establish the finite element model of the whole structure for the numerical simulation of the internal mechanics of impact, but only the local structure of the impact contact area [6]. For ship to ship collision, the mass of the ship's bow can be enlarged to make its impulse equal to that of the whole.

#### 3.1. Model of collision structure

In order to better study the crashworthiness of LNG ship, the middle cabin structure of LNG ship and the bulbous bow of container ship are selected for collision analysis.

The middle cabin structure of LNG ship is selected, with a length of 50.1m. Figure 2 shows the cross section of the ship. Bulbous bow can be seen as a rigid body.
Figure 2. Schematic diagram of transverse section of LNG ship.

The finite element model of the impact structure is shown in Figure 3 to Figure 5, the number of elements and nodes is up to 160000.

Figure 3. Finite element model of LNG cabin section structure.

Figure 4. Internal finite element model of LNG ship.
3.2. Related parameters and material properties of ABAQUS model

ElasPlas (DMATEP) model with linear strengthening is selected as the material [7]. The material density is 7850 kg/m$^3$, the yield stress is 235 MPa, the elastic modulus is 201 GPa, the Poisson ratio is 0.3, the maximum plastic failure strain is 0.2 and friction coefficient is 0.1.

3.3. Determination of collision scheme

Through the understanding and analysis of Lagrange and Euler solver in the software, the setting of relevant parameters is determined. It is assumed that there is an initial distance of 10 mm between vessels. The impact time was set at 3.5s [8]. At the same time, the influence of attached water and friction is also considered. The collision scheme of LNG carrier in the process of collision includes collision speed, collision position and collision angle. Therefore, four collision schemes are selected in this paper, as shown in Table 3.

| Item            | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 |
|-----------------|----------|----------|----------|----------|
| Initial speed   | 2 m/s    | 1 m/s    | 2 m/s    | 2 m/s    |
| Collision location | between strong frames | between strong frames | on strong frame | between strong frames |
| Collision angle | 90°      | 90°      | 90°      | 60°      |

3.4. Calculation results

The calculation results of impact force, bow impact displacement and energy of the four schemes are shown in Table 4, and the energy absorption of each component is shown in Table 5. Due to the limited space, only the overall and local stress and deformation diagrams of scheme 1 are listed here, as shown in Figure 6 ~ Figure 9.

| Scheme   | Speed (m/s) | Impact force (MN) | collision displacement (m) | kinetic energy consumption (MJ) | deformation energy (MJ) | Energy absorption ratio (%) |
|----------|-------------|-------------------|-----------------------------|---------------------------------|-------------------------|-----------------------------|
| Scheme1  | 2           | 26                | 3.15                        | 25                              | 18.03                   | 72.12                       |
| Scheme2  | 1           | 7                 | 1.61                        | 8                               | 6.62                    | 82.75                       |
| Scheme3  | 2           | 29                | 3.08                        | 37                              | 25.02                   | 67.62                       |
| Scheme4  | 2           | 32                | 2.84                        | 57                              | 27.70                   | 48.60                       |
Table 5. Energy absorption summary of each component.

| Item                  | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 |
|-----------------------|----------|----------|----------|----------|
|                       | Energy absorption (MJ) | Proportion (%) | Energy absorption (MJ) | Proportion (%) | Energy absorption (MJ) | Proportion (%) | Energy absorption (MJ) | Proportion (%) |
| Side shell            | 9.05     | 50       | 4.30     | 65       | 9.65     | 39       | 14.92     | 54       |
| Side Longitudinal     | 3.38     | 19       | 1.62     | 24       | 2.44     | 10       | 3.88      | 14       |
| Inner shell plate     | 1.84     | 10       | 0.1      | 2        | 2.55     | 10       | 0.20      | 1        |
| Inner shell longitudinal | 1.86    | 10       | 0.1      | 2        | 1.13     | 4        | 0.20      | 1        |
| Transverse frame      | 1.90     | 11       | 0.50     | 7        | 9.43     | 37       | 8.50      | 30       |
| Total absorbed energy | 18.03    | 100      | 6.62     | 100      | 25.02    | 100      | 27.70     | 100      |

Figure 6. Integral damage diagram.

Figure 7. Damage deformation diagram of internal frame.
4. Conclusion
In this paper, the collision process between the bulbous bow of the container ship and the side structure of the LNG ship is simulated through the collision velocity, collision position and collision angle. Furthermore, some collision indexes in the collision process are analyzed, such as damage and deformation, velocity and displacement of the container ship and the LNG ship, collision force and energy absorption. The results of the above calculation and the analysis of the data can be concluded as follows:
(1) Speed factor. The scheme 2 is that the container ship impacts the LNG ship at the speed of 1 m/s, and the outer side shell of the LNG ship is damaged at the end of the collision, while the inner shell plate is not damaged. By comparing the energy absorption of different internal components of the hit ship, it can be concluded that the energy absorption of the side shell is the largest, followed by the side longitudinal, accounting for 50% and 19% of the total energy respectively. In the other three schemes, the speed of the container ship is 2m/s, and the outer and inner shell plates of the LNG ship are damaged at the end of the collision. Through the comparison of the energy absorption of different internal components of the hit ship, it can be concluded that the energy absorption of the side shell is the largest, followed by the transverse frame, and the specific proportion of different schemes is different.

(2) Location factor. The other parameters of scheme 1 and scheme 3 are the same except for the impact position. In the scheme 1, the speed, displacement, deformation energy and maximum impact force are 1.73m/s, 3.15m, 18MJ and 2.6×10⁷N respectively. In the scheme 3, the velocity is 1.64m/s, the displacement is 3.08m, the deformation energy is 25MJ, the maximum impact force is 2.9×10⁷N, and the hull damage is more serious.

(3) Angle factor. In scheme 4, the collision angle is 60° and the kinetic energy of the container ship is 57MJ at the end of collision, the deformation energy of the LNG ship is 27.7MJ and the energy absorption ratio is 48%. The maximum collision force between the container ship and the side structure of the LNG ship is 3.2×10⁷N and the collision force is 1.7×10⁷N when the side shell fails. In scheme 1, the kinetic energy of the container ship is 25MJ at the end of collision and the deformation energy of the LNG ship is 25MJ the collision force is 1.0×10⁷N when the side shell plate fails.

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