Journal of the Korean Society of Marine Environment & Safety
Research Paper
Vol. 24, No. 3, pp. 319-324, May 31, 2018, ISSN 1229-3431(Print) / ISSN 2287-3341(Online) https://doi.org/10.7837/kosomes.2018.24.3.319

# Analysis of Marine Vessel Collision Risk based on Quantitative Risk Assessment

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Abstract : *The collision problem is one of the design factors that must be carefully considered for the risk of collision occurring during the operation of ships and offshore structures. This paper presents the main results of the ship collision study, and its main goal is to analyze potential crash scenarios that may occur in the FLNG (Floating Liquefied Natural Gas) considering the likelihood and outcome. Consideration being given to vessels visiting the FLNG and surrounding vessels navigating around, such as functionally supported vessels and offloading carriers. The scope includes vessels visiting the FLNG facility such as in-field support vessels and off-loading carriers, as well as third party passing vessels. In this study, based on QRA (quantitative risk assessment), basic research methods and information on collision are provided. Based on the assumptions and methodologies documented in this study, it has been possible to clarify the frequency of collision and the damage category according to the type of visiting ship. Based on these results, the risk assessment results related to the collision have been derived.*

Key Words : *Ship collision, QRA (Quantitative Risk Assessment), Risk assessment, Safety, Impact*

## 1. Introduction

When designing an offshore floating vessels and platforms, it is necessary to assess the collision resistance of the vessels against ship impacts. For example, for installations on the Norwegian Continental Shelf, it is required that the platform resists impact from supply vessels. Damage to the platform is allowed to occur as long as the damage does not lead to progressive collapse of the structures or prevent safe evacuation. The size and speed of the vessel can be determined by a risk analysis and the best estimate of a design impact event should not exceed an annual probability of occurrence of $10^{-4}$. The standard collision event over the past three decades is the impact from a supply vessel of a 5,000 ton displacement and a speed of 2 m/s. Considering the added mass, the obtained kinetic energy is 11 MJ (Mega Joule) and 14 MJ for bow/stern collisions and broad side impacts (NORSOK STANDARD, 2007), respectively. Recent collision events on the Norwegian Continental Shelf with energies in the 40-70 MJ range indicate that the current requirement for the standard design collision event is too low. A brief review is made in previous research works related to ship collisions.

Tian Chai et al. (2017) developed a quantitative risk assessment (QRA) model to evaluate the risk of ship collisions, taking into account the frequency and consequence of all possible accident scenarios. The proposed QRA model consists of a collision frequency estimation model, an event tree, and consequence estimation models. The event tree comprises five intermediate events, including ship type, ship size, loading conditions, hull damage and survivability. Considering the relatively high percentage of oil tankers involved in ship collisions and their severe consequences, focus should be placed on the tracking and management of oil tanker traffic.

Liu et al. (2017) compared two methods based on finite element simulations to assess the external dynamics and the internal mechanics in ship collisions. The two methods were compared to determine the differences in predicting the deformation and rupture of the collided ship structures and to assess the relationship between the structural deformation energy of the struck ship and the energy loss of the striking ship. The objective of the paper was to verify whether the decoupled method satisfies the predictions required for design appraisal assessments. The paper also illustrated the influence of the collision angle on the mechanics of ship collisions.

Mujeeb-Ahmed et al. (2018) carried out a probabilistic collision-risk analysis for offshore platforms exposed to powered collisions with passing vessels using an automatic identification system (AIS) database. The paper first describes the statistical distribution of the ship traffic under study and then considers how this information can be effectively used to estimate collision

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frequencies and impact energies across various categories of vessels, based on a simple probabilistic method. The effects of various collision mitigation measures, such as the use of enhanced collision alarming devices and the ability of platforms to rotate using thrusters, are considered in the frequency calculations. The risk method presented in this paper can be applied in the design and development phase of both new and existing platforms.

Liu et al. (2018) presented a review of experiments and calculation procedures for the resistances of ships' structural components that are subjected to impact loadings. The purpose of the paper was to highlight the importance of large-scale collision and grounding experiments and to discuss the technical difficulties and challenges in analytical, empirical and numerical ways.

## 2. Ship collision hazards

Ship collision has been identified as a Major Accident Hazard (MAH) with potential collision scenarios detailed in the Major Hazard Register and discussed further in Section 2.1.

### 2.1 Type of collision

Ship collisions with offshore installations may involve three different categories of colliding vessels.

**Passing vessels** – such collisions involve shipping traffic where the voyage is not related to the FLNG installation activities.

- Impact by a passing vessel including merchant ships, passenger vessels, naval vessels, fishing boats and other offshore related traffic operating to/from other installations.

**Visiting offloading vessels** – such collisions involve large carriers approaching the installation to remove cargo products.

- Impact by an LNG offloading carrier in a side by side configuration;
- Impact by a condensate offtake tanker in a tandem configuration.

**In-field support vessels** – such collisions involve smaller vessels that serve the installation as standby vessels, tow vessels for offtake tankers, personnel transfers, and supply and maintenance activities. It is also possible to further categorize ship collisions with respect to how the colliding vessel is approaching at the time of the collision:

**Powered (head-on)** collisions occur when the colliding vessel is under the power of its engines when colliding with the installation and may be due to navigational/manoeuvring errors, watch keeping failure or poor visibility /ineffective radar use. The 'errant' vessel may be unaware of the proximity to the installation or in the case of visiting vessels, may fail to reduce its approach speed sufficiently to avoid a collision with the installation.

**Manoeuvring collisions** occur when the colliding vessel fails to reduce its speed sufficiently and impacts the installation while manoeuvring into position for transfer/offloading operations by supply vessel or carrier respectively.

**Drifting collisions** occur when the colliding vessel drifts into the installation due to a loss of propulsion, steering failure, mooring or towline failure or under the influence of environmental factors such as waves, currents and winds. Powered collisions typically occur at higher speeds than maneuvering collisions which in turn are at higher speeds that drifting collisions.

### 2.2 Cause of collision

The potential causes of ship collisions as identified in the Off-loading HAZID Report include (DNV, 1999):

Adverse weather conditions resulting in poor visibility or rough seas;

Mechanical failure of propulsion or steering systems;

HSE management failures including inappropriate procedures / procedural control of vessel movements;

Human errors including poor seamanship, inadequate planning, poor navigation, inadequate watch keeping, bad practices by negligence, etc.

## 3. Impact energy calculations

The total impact energy of a colliding vessel with a static installation is equal to the kinetic energy of the vessel immediately prior to impact. That is:

Impact Energy $E = 0.5\,kmv^2$ [kJ]

where:

$k$ = hydrodynamic added mass constant,

$m$ = the displacement in Tons of the colliding vessel,

$v$ = the velocity in m/s of the colliding vessel immediately prior to impact.

For an end-on (powered) collision; $k = 1.1$

For a broadside (drifting) collision: $k = 1.4$

The hydrodynamic added mass constant is a factor that accounts for the hydrodynamic forces acting on a vessel during a collision. This factor is affected by a number of parameters, however, the following simple approximations can be commonly adopted. The displacement of a vessel is the total mass of the vessel and its contents. This is equal to the volume of sea water displaced by the vessel multiplied by the density of sea water.

Some of the kinetic energy is absorbed by the colliding ship itself in elastic/plastic deformation resulting in damage, and the remainder can be absorbed by the hull structure of the FLNG facility again through elastic/plastic deformation. For glancing impacts, the colliding ship retains much of the kinetic energy after the collision and there might be less structural damages to the FLNG facility. For the purposes of this assessment, it is pessimistically assumed that the total kinetic energy associated with the collision is absorbed by the structure of the FLNG facility. In order to estimate the displacement of the colliding vessel, the deadweight tonnage is used. The deadweight tonnage of a ship is defined as the maximum mass of cargo and fuel that is carried, which can be derived from the vessel capacity. The displacement tonnage is calculated by dividing the deadweight tonnage by a factor specific to the content of the vessel.

### 3.1 Impact energies for passing vessel

In the absence of any specific field data regarding potential passing vessel sizes and speeds, a number of assumptions have been made regarding the passing vessel traffic. Representative merchant vessel size bands are given in Table 1 with the average size for each band considered as a representative size (OGP, 2010). The range of vessel sizes considered in the analysis is shown in Table 2. For the last ship size band, two representative vessel sizes have been assumed. The displacement tonnage for these vessel sizes has been estimated using the DWT coefficient for general cargo vessels of 0.7.

Passing vessel collisions may be either of the powered or drifting type. According to data presented in Table 2, only 3.5 % of such collisions are of the drifting type, which typically occur at low speeds of less than 1 m/s (approximately 2 knots). However, powered, passing vessel collisions are likely to occur at up to the typical cruising speed of the vessel. A speed of 12 knots is commonly used as a representative value for powered merchant vessel collisions (DNV, 1999). Due to the absence of specific field data, the following representative collision speeds are assumed:

Table 1. Passing vessel displacement

| Vessel size (DWT) | Average size (DWT) | Average displacement | |
|---|---|---|---|
| | | Ton | Kg |
| 0-1500 | 750 | 1,071 | 1,071,429 |
| 1500-5000 | 3,250 | 4,643 | 4,642,857 |
| 5000-15000 | 10,000 | 14,286 | 14,285,714 |
| 15000-40000 | 27,500 | 39,286 | 39,285,714 |
| > 40000 | 50,000 | 71,429 | 71,428,571 |
| | 100,000 | 142,857 | 142,857,143 |

Passing vessel under power = 8 and 12 knots

Passing vessel while drifting = 2 knots

The above range of vessel displacements and collision speeds has been considered in the analysis in order to get an idea of the potential impact energies. The results are shown in Table 2.

For drifting collisions at 2 knots, the damage level is insignificant or minor for vessel displacement sizes up to 70,000 tonnes. For the 140,000 tonne vessel displacement size, the damage level increases to significant / severe.

In the case of powered drifting collisions, the damage is at the insignificant level for displacement of 4,643 tonnes with speeds at 8 and 12 knots respectively. The minor level represents a vessel displacement of 4643 tonnes, while the severe level represents a 14,286 tonnes. If these conditions are exceeded, it is difficult to consider in terms of RISK management within a HAZARD matrix.

For all larger vessel sizes, the damage category for powered collisions is a total loss of integrity.

### 3.2 Impact energies for off-loading carrier

For a 216,000 $m^3$ capacity LNG export carrier, the deadweight tonnage would be 97,200 tonnes assuming an LNG density of approximately 450 $kg/m^3$. The loaded displacement of an LNG carrier is typically approximately 1.6 times its deadweight tonnage and would therefore amount to approximately 156,800 tonnes. Its light-weight displacement would be around 59,600 tonnes (156,800-97,200).

Table 2. Impact energies for passing vessel collisions

| Vessel displacement (Ton) | Scenario | Speed (m/sec) | Impact energy (MJ: Mega Joule) | | Damage category |
|---|---|---|---|---|---|
| | | | End-on (power) | Broadside (drifting) | |
| 1,071 | Drifting | 1.0 | - | 1 | Insignificant |
| | Powered | 4.1 | 10 | - | Insignificant |
| | Powered | 6.2 | 22 | - | Minor |
| 4,643 | Drifting | 1.0 | - | 3 | Insignificant |
| | Powered | 4.1 | 43 | - | Minor |
| | Powered | 6.2 | 97 | - | Significant |
| 14,286 | Drifting | 1.0 | - | 11 | Insignificant |
| | Powered | 4.1 | 133 | - | Severe |
| | Powered | 6.2 | 299 | - | Total loss |
| 39,286 | Drifting | 1.0 | - | 29 | Minor |
| | Powered | 4.1 | 365 | - | Total loss |
| | Powered | 6.2 | 822 | - | Minor |
| 71,429 | Drifting | 1.0 | - | 53 | Significant |
| | Powered | 4.1 | 664 | - | Total loss |
| | Powered | 6.2 | 1,495 | - | Total loss |
| 142,857 | Drifting | 1.0 | - | 106 | Severe |
| | Powered | 4.1 | 1,495 | - | Total loss |
| | Powered | 6.2 | 2,989 | - | Total loss |

Table 3. Impact energies for LNG off-loading carrier collision

| Collision scenario | Displace-ment (Ton) | Speed (m/sec) | Impact energy (MJ) | | Damage category |
|---|---|---|---|---|---|
| | | | End-on | Broadside | |
| Powered on arrival | 59,600 | 2.6 | 216 | - | Total loss |
| Manoeuvring on arrival | 59,600 | 1 | - | 44 | Minor |
| | 59,600 | 0.5 | - | 11 | Insignificant |
| Manoeuvring on departure | 156,800 | 0.5 | - | 29 | Minor |

The following observations may be made with regards to the above results:

- The impact energy of a powered on arrival collision of 5 knots is predicted the worst scenario to an operating FLNG facility. In this case, mitigation plans are needed to reduce the speed of approaching ships.
- The impact energy of the maneuvering collisions for the unloading LNG carrier is predicted to cause insignificant to minor damage to the FLNG facility when approaching speed is limited to 1-2 knots.
- The impact energy of maneuvering on departure collisions, for the fully laden LNG carrier, is predicted to cause minor damage to the FLNG facility with an impact speed of 1 knot.

The significant / critical damage (50 MJ) and severe damage (100 MJ) levels can be reached for the approaching LNGC at approximate speeds of 2 and 3 knots, respectively for side on collisions. For the departing LNGC, these damage levels can be reached at speeds of around 1.2 and 1.8 knots respectively. In order to efficiently control the collision during unloading of LNG as mentioned in Table 3, it is necessary to prepare reasonable guidelines to control the approaching speed in MPVs.

The frequency of passing vessels has been calculated, based on the OGP database of shipping movements in the vicinity of the field over a calendar year as indicated in Table 2 and 3. The analysis then used statistical techniques to predict the probability that these vessels may impact a facility located in East-Asia. This analysis takes into account the likely type of vessels in the area, the cruising speed of the vessels, the ability of the facility or a Standby Vessel to alert an incoming ship and the size of the facility to predict the combination of frequency and collision energy for vessels passing through the area.

### 3.3 Impact energies for MPV (multi-purpose vessels)

The MPVs serve two main functions:

- Personnel transfer for offloading operations;
- Provision of supplies

The MPVs are assumed to have a DWT in the range from 1,000 to 1,800 tonnes. The vast majority of collisions between visiting vessels serving an offshore installation occur when the vessel is berthing alongside the installation. The cause is normally human error and the consequence is typically a low energy impact (bump). For powered collisions on arrival, the sparse historical data confirms that collisions have indeed occurred at the full transit speed of the visiting vessel. However, in some cases a “last-minute emergency stop” has been made in an attempt to reduce the vessel speed, with the historical data showing that one out of two collisions occurred at the vessel’s full speed.

In order to avoid being overly pessimistic, it is therefore assumed that 50 % of collisions on arrival are at the full cruising speed of 10 knots and 50 % are at 5 knots. For all powered collisions on arrival, the point of impact is likely to be the bow of the visiting vessel with any part of the hull of the FLNG facility. Powered collisions on arrival may occur as a result of watch-keeping or mechanical problems. It is assumed that such collisions have an equal likelyhood of impacting anywhere on the hull of the FLNG facility.

Impact speeds of powered, manoeuvring collisions involving support vessels are typically in the range 0-6 knots (0-3 m/s). For drifting collisions, the vessel speed depends upon a number of factors including the above-water form of the vessel, the wind speed, currents and, in particular, the wave-induced motions related to the wave height. Past experience indicates that a reasonable (maximum) collision speed for drifting collisions involving in-field support vessels is approximately 2 knots (1 m/s).

## 4. Assessment of collision risk

The results by vessel type and damage category are summarized in Table 4 and they are shown graphically in Figure 1 and Figure 2. The majority (97 %) of ship collisions are expected to have an impact energy of less than 14 MJ. That leaves only 3 % of collisions expected to have an impact energy of 15 to 49 MJ and a remaining 0.02 % of ship collisions are expected to have an impact energy greater than 50 MJ. Note that a logarithmic scale has been used in the charts to show clearer distinction of the low frequency events.

Figure 2 illustrates that the majority (96.0 %) of collisions with the FLNG facility are assessed to occur with MPVs, 3 % with LNG carriers, and 1.0 % with condensate carriers. The frequency of passing vessel collisions is estimated to be only 0.01 % of the total.

In order to benchmark these figures against industry standard values, the data for the worldwide and UK Continental Shelf (UKCS) values are presented here for comparison. These are taken from OGP data, which are in turn based on the Worldwide Offshore Accident Databank. Table 5 presents the historical collision frequencies per installation year.

Assuming that the “Total Loss” category corresponds with the 200 MJ impact and the “Severe”category corresponds with the 100MJ impact, then a coarse comparison can be made between the calculated data and the historical data from OGP is as shown in Table 6.

Table 4. Results by vessel type and damage category

| Type of vessel | Insignificant 0-14MJ | Mionr 15-49MJ | Significant 50-99MJ | Severe >100MJ | Total Loss >200MJ | % |
|---|---|---|---|---|---|---|
| Passing vessel | 7.46E-06 | 4.39E-06 | 3.51E-06 | 1.32E-06 | 1.32E-06 | 0.0 |
| LNG carriers | 1.71E-03 | 5.13E-03 | - | - | 1.04E-05 | 3.0 |
| Condensate offtake tankers | 5.70E-04 | 1.71E-03 | - | 3.48E-06 | - | 1.0 |
| MPVs (1000DWT) | 1.05E-01 | 1.39E-04 | - | - | - | 46.1 |
| MPVs (1800DWT) | 1.14E-01 | 1.51E-04 | - | - | - | 50.0 |
| TOTAL | 2.21E-01 | 7.13E-03 | 3.51E-06 | 1.18E-05 | 1.18E-05 | - |
| Percentage (%) | 96.9 | 3.1 | 0.0015 | 0.0052 | 0.0052 | 100.0 |

## 5. Conclusions

To investigate the risk of collision between visiting vessels and passing vessels, the current paper proposes a specific risk analysis framework with relevant analysis methods.

In the paper, collision consequences are analyzed based on historical data and experience led assumptions. The results can be summarized as follows:

- The estimated risk of high energy (> 100 MJ) offloading vessel (LNG and condensate) collisions resulting in severe or total loss of integrity of the FLNG facility is approximately $1.4 \times 10^{-5}$
- The majority of the in-field support vessel collision risks fall into the insignificant damage category ($2.2 \times 10^{-1}$ per year). These vessels are assumed to be subject to less strict approach controls than the export carriers.
- The remaining collisions fall into the minor damage category ($2.9 \times 10^{-4}$ per year) and comprise the high speed powered on arrival collisions.
- The frequency of high energy (>100 MJ) passing vessel collisions resulting in severe or total loss of integrity of the FLNG facility has been estimated as $9.7 \times 10^{-6}$ per year, using generic worldwide data, with a reduction factor for being located well away from any major shipping lanes.

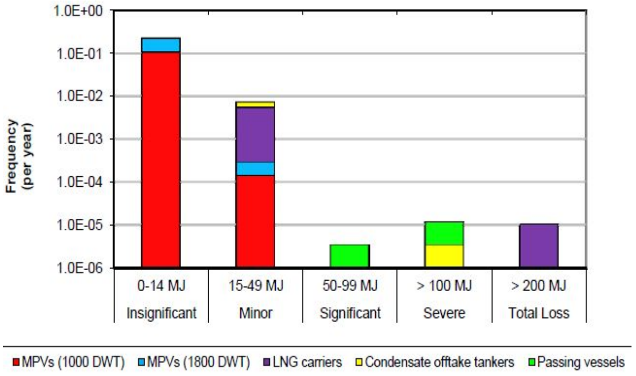


Fig. 1. Results by damage category.

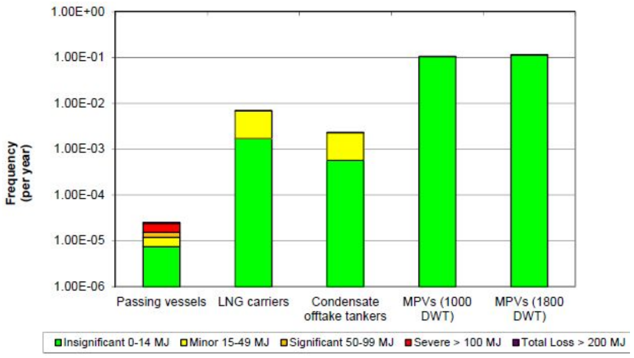


Fig. 2. Results by vessel type.

Table 5. Collision frequency data

| Vessel type | Collision frequency-world wide (1990-2002) | Collision frequency-UKCS (1999-2005) |
|---|---|---|
| Passing | $2.5\times10^{-4}$ | $2.2\times10^{-3}$ |
| Infield | $8.8\times10^{-4}$ | $4.6\times10^{-2}$ |

Table 6. Collision severity frequency

| Collision severity | Collision frequency-world wide (1990-2002) | Collision frequency-UKCS (1999-2005) |
|---|---|---|
| Total loss | $1.7\times10^{-5}$ | $3.4\times10^{-4}$ |
| Severe | $1.5\times10^{-4}$ | $4.4\times10^{-3}$ |

Again, it is necessary to adopt strict operational procedures and controls into the FLNG facility in order to manage the risk of passing vessel collisions. Specific location passing vessel traffic could be assessed during detailed design research to ensure that used worldwide generic data is representative.

## Acknowledgment

This research was supported by Changwon National University in 2017～2018.

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Received : 2018. 04. 23.
Revised : 2018. 05. 25.
Accepted : 2018. 05. 29.