Probabilistic Approach to Risk Assessment for Alternative Design of Hydrogen Fuel Tank Arrangements on Small Ships

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Abstract:
In order to reduce greenhouse gas emissions in the shipping sector, alternative fuels are being introduced, one of which is hydrogen. In Japan, the Ministry of Land, Infrastructure, Transport and Tourism revised the Safety Guidelines for Hydrogen Fuel Cell Ships in August 2021 to provide standards for the construction of hydrogen fuel cell ships for domestic voyages. The Safety Guidelines contain safety requirements which small ships are difficult to comply with. Based on this, the Safety Guidelines allow the use of alternative designs if equivalent safety is demonstrated by risk assessment, simulation or other methods.

However, there are not enough precedents for the selection of methods and the setting of calculation conditions to prove equivalent safety, and a standard method has not been established because technologies of alternative fuels have been developing. The authors have therefore developed a risk assessment method for the alternative design of fuel tank arrangement for a domestic compressed hydrogen fuel cell ship utilizing information on ship accidents.

The aim of this paper is to introduce the developed method for alternative design of fuel tank arrangement and to illustrate that the proposed method has the potential to place the fuel tank in a wider area using current statistical ship collision data. This paper first introduces the developed method for alternative design of fuel tank arrangement. Next, statistical collision data were obtained by aggregating the Japanese version of Marine Accident Investigation Reports published by the Japan Transport Safety Board. The statistical collision data show that it is not recommended to place a fuel tank in the front part of a ship from the standpoint of safety. Finally, a test calculation was conducted for a 499 Gross Tonnage cargo ship using the statistical collision data. The results show that the proposed method has the potential to place the fuel tank in a wider area than the areas decided by probabilistic and deterministic methods.

Keywords: Risk Assessment, Hydrogen Fuel Tank Arrangement, Small Ship, Alternative Design

1. INTRODUCTION

Efforts to reduce greenhouse gas emissions are underway worldwide and numerous countries have committed to achieve carbon neutrality. In the international shipping sector, the International Maritime Organization adopted its strategy on GHG emissions [1]. This strategy identifies ambitions, one of which is to reach net-zero GHG emissions by or around 2050. In the coastal shipping sector, GHG emissions are accounted for by each country. Subsequently, each country is required to develop measures on this issue. In response, Japan aims to achieve carbon neutral by 2050.

In light of these circumstances, alternative fuels are being introduced, one of which is hydrogen. In Japan, the Ministry of Land, Infrastructure, Transport and Tourism revised the Safety Guidelines for Hydrogen Fuel Cell Ships[2] (hereinafter, the Safety Guidelines) in August 2021 to provide a standard for the construction of hydrogen fuel cell ships for domestic voyages. However, the Safety Guidelines [2] were developed on the basis of the International Code of safety for ships using gases or other low-flashpoint fuels [3] (hereinafter the IGF Code), which mainly covers large ships using liquefied gas as fuel engaged in international voyages. Therefore, the Safety Guidelines [2] contain safety requirements for fire safety, explosion protection, tank arrangements, bunkering, and other aspects that small ships may find difficult to comply with. Based on this, the Safety Guidelines [2] allow the use of alternative designs if equivalent safety is proven by risk assessment, simulation or other methods.

However, there are not enough precedents for the selection of methods and the setting of calculation conditions to prove equivalent safety, and a standard method has not been established because technologies of alternative fuels have been developing. Therefore, the authors have developed a risk assessment method for the alternative design of fuel tank arrangements for a domestic compressed hydrogen fuel cell ship utilizing information on ship accidents [4].

The aim of this paper is to introduce the method developed for alternative design of fuel tank arrangements and to demonstrate, using current statistical ship collision data, that the proposed method can place fuel tank in a larger area than conventional methods. This paper first introduces the developed method. Next, the results of Japanese statistical data for recent years are presented in order to perform risk assessment using the developed method under practical conditions. Finally, a test calculation is conducted using the statistical collision data.

2. METHOD

In this section, the requirements for tank arrangements in the Safety Guidelines [2] are introduced, followed by the method developed to show equivalent safety to the requirements in the Safety Guidelines [2].

2.1 Requirements for Fuel Tank Arrangements in the Safety Guidelines [2]

The Safety Guidelines [2] specify restrictions on the positioning of fuel tanks with the aim of protecting fuel tanks from collisions and groundings. These restrictions are specified by means of deterministic and probabilistic methods and designers can select one of them. The following paragraphs provide an overview of both methods.

2.1.1 Deterministic Method

Section 5.3.3 of the Safety Guidelines [2] specifies a deterministic method to determine areas where the fuel tank cannot be located. Detailed requirements are shown in Appendix A.1 to this paper, and the outline is illustrated in Figure 1. Fuel tanks cannot be located in the following areas, which are shaded in Figure 1:

(a) areas within a specified distance, which is determined solely by ship width, measured inboard from the ship side shell at right angles to the centerline at the level of the summer load line draught;

(b) areas where the distance to the ship shell is less than a specific distance determined by ship type (for passenger ships, a distance corresponding to the ship width; for cargo ships, a distance, which is determined by the volume of the fuel tanks); and

(c) areas where the vertical distance to the ship's bottom is lower than a specific distance corresponding to the ship width.

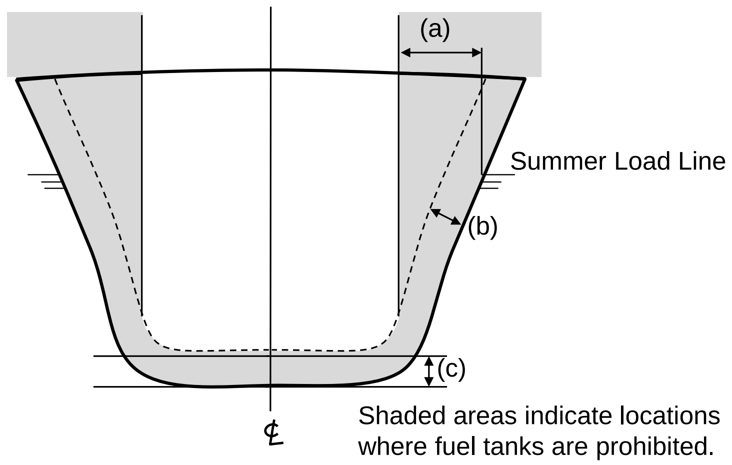

Figure 1. Prohibited Areas for Fuel Tanks (Prepared Based on IMO Resolution [5])

2.1.2 Probabilistic Method

Section 5.3.4 of the Safety Guidelines [2] specifies a probabilistic method, which is used to determine acceptable arrangements of fuel tanks, as an alternative to area (a), with reference to Section 5.3.4 of the IGF Code [3]. The IGF Code [3] requires the calculation a value of f_{CN}, an index corresponding to the probability that damage will reach the location of fuel tanks in the event of a collision. A tank arrangement is acceptable if the value f_{CN} is lower than the threshold value given for the ship type. Detailed requirements are summarized in Appendix A.2 to this paper. The dimensions of a ship required for calculating f_{CN} are shown in Table 1, and their relationships are illustrated in Figure 2.

Table 1. Dimensions of a Ship Required for Calculation of f_{CN}

	Symbol
Subdivision length of the ship	L_s
Width of the ship	B
Deepest subdivision draught	d
Distance to the aftermost boundary of the fuel tank from the aftermost boundary of the ship	x_1
Distance to the foremost boundary of the fuel tank from the aftermost boundary of the ship	x_2
Minimum transverse distance between fuel tank, and ship shell at the deepest subdivision draught	b
The vertical distance between the fuel tank and the bottom of the ship	H

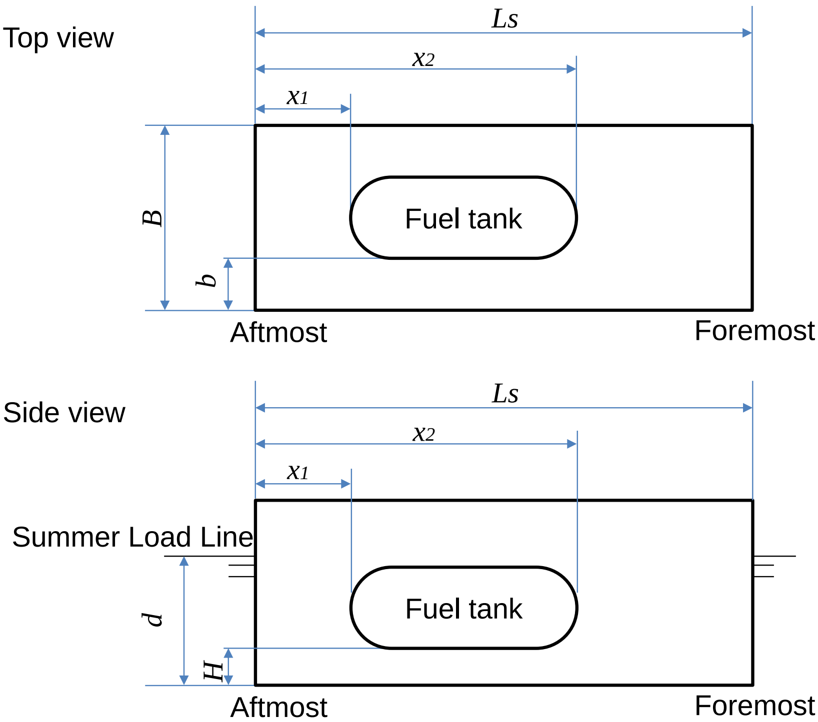

Figure 2. Relationships of Dimensions Required for Calculation of Probabilistic Method

As shown in Equation 1, f_{CN} is defined as the product of probabilities in the length, width and height directions,

$$f_{CN}=f_l \times f_t \times f_v, \tag{1}$$

where:

- f_l reflects the probability that the damage includes the position of the fuel tank in the longitudinal direction,
- f_t reflects the probability that the damage penetrates beyond the outer boundary of the fuel tank in the transverse direction,
- f_v reflects the probability that the damage is extending vertically above the lowermost boundary of the fuel tank.

The equations for the calculation of f_l, f_t and f_v are specified in the SOLAS Convention [6], as referred to in the IGF Code [3]. Input values for the calculation of f_l, f_t and f_v are summarized in Table 2.

Table 2. Input Values for Calculation

	Necessary input values
f_l	L_s and (x_2-x_1)
f_t	L_s, B, b and f_l
f_v	H-d

2.2 Proposed Method for Alternative Design

The Safety Guidelines [2] also allow the use of alternative methods if these methods can demonstrate equivalency to the above methods. For small ships, further design possibilities regarding fuel tank arrangements are desired, because the arrangements of fuel tanks may be limited due to their small size. The IGF Code [3] mainly addresses large ships using liquefied gas as fuel and engaged in international voyages.

The probabilistic method in the Safety Guidelines [2] is an approach that restricts the probability of certain damage to below a specified level. This method can be interpreted as a performance standard. The authors have developed an alternative method using the same assumptions and criteria. The proposed method calculates the value of f_l using statistical ship collision data [4] instead of using the equations specified in the IGF Code [3]. Therefore, the proposed method is equivalent to the probabilistic method in terms of probability.

In the proposed method, if the longitudinal damage areas are classified into three parts, i.e., aft, mid and fore, the value of f_l is calculated by Equation 2. The relationship of L and l is shown in Figure 3.

$$f_l = P_{aft} \times \frac{l_{aft}}{L_{aft}} + P_{mid} \times \frac{l_{mid}}{L_{mid}} + P_{fore} \times \frac{l_{fore}}{L_{fore}} , \tag{2}$$

where:

P is the probability of damage occurring in the relevant part, obtained from statistical ship collision data.
l is the tank length placed in the relevant part.
L is the length of the relevant part.

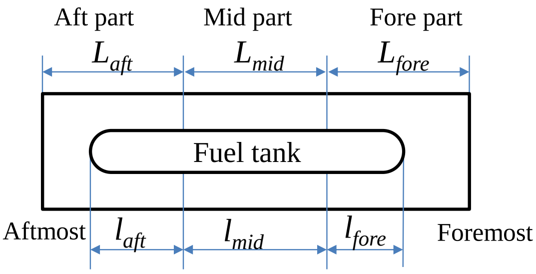

Figure 3. Relationships of L and l

The number of ship lengths to be separated and the length of each part is determined based on statistical collision data. The equations for f_t and f_v are the same as those used in the probabilistic method specified in the Safety Guidelines [2].

3. CONDITIONS OF TEST CALCULATION

3.1 Target Ship

In this paper, a cargo ship of 499 gross tonnage was used as the target ship for the test calculations. Table 3 shows the average dimensions of such a cargo ship [7]. In this paper, the subdivision length and the deepest subdivision draught were considered to be the same as the overall length and deepest draught of the ship, respectively.

Table 3. Average Dimensions of a Cargo Ship of 499 Gross Tonnage [7]

Particular	Value
Length (m)	70
Width (m)	12
Draught (m)	5

The following conditions were adopted:

- The minimum distance from a fuel tank to the ship's shell is 1.0 meters, as described for area (b) in Section 2.1.1.
- The vertical distance between a fuel tank and the bottom of the ship (*H*) is equal to the draught (*d*).
- The arrangement is symmetrical in the width direction of a ship.
- Tank length (x_2-x_1) is 10 meters.

Therefore, the minimum value of x_2 is 11 meters when the tank is installed in its most rearward position. This is obtained by adding the minimum distance to the ship shell of 1 meter and the tank length of 10 meters. The maximum value of x_2 is 69 meters when the tank is installed in its most forward position. This is obtained by subtracting the minimum distance to the ship shell of 1 meter from the ship's subdivision length of 70 meters.

3.2 Statistical Ship Collision Data

In this paper, statistical ship collision data are obtained by aggregating the Japanese version of Marine Accident Investigation Reports [8] published by the Japan Transport Safety Board for the following reasons.

- Almost all the reports cover maritime casualties that occurred in the vicinity of Japan.
- The reports contain information on the damaged areas.
- The reports have been published for over a decade and contain recent data.

The aggregation conditions for the statistical ship collision data are shown in Table 4.

Table 4. Aggregation Conditions for Statistical Ship Collision Data

	Condition
Published year of reports	2022 to 2023
Size of ship	20 to 499 Gross Tonnage
Accident type	Collision

Damage area data were obtained from the 'Damage to vessels' section of the reports. Most of the reports provide three distinct descriptions of the damaged area. This paper adopts a three-part classification, namely aft, mid and fore. The lengths of each part are considered to be equal.

4. RESULTS AND DISCUSSION

Statistical collision data under the conditions specified in Table 4 are shown in Table 5. More than half of the ships were damaged in the fore part. Consequently, from the standpoint of safety, it is not recommended to place a fuel tank in the fore part.

As illustrated in Table 5, the mid part has the lowest probability of damage. However, fuel tank arrangements in the mid part can be restricted because this part is used as cargo space on most cargo ships.

Table 5. Historical Collision Data

	Number of ships	Probability
Fore	96	0.64
Mid	14	0.094
Aft	41	0.28

The results of the tank arrangements with a fixed tank length of 10 meters are presented in Figure 5. The ordinate represents *b*, the minimum transverse distance between the fuel tank and the ship shell, and the abscissa represents x_2, the position of the foremost boundary of the fuel tank. The upper portion of the graph represents the area where the design is deemed acceptable.

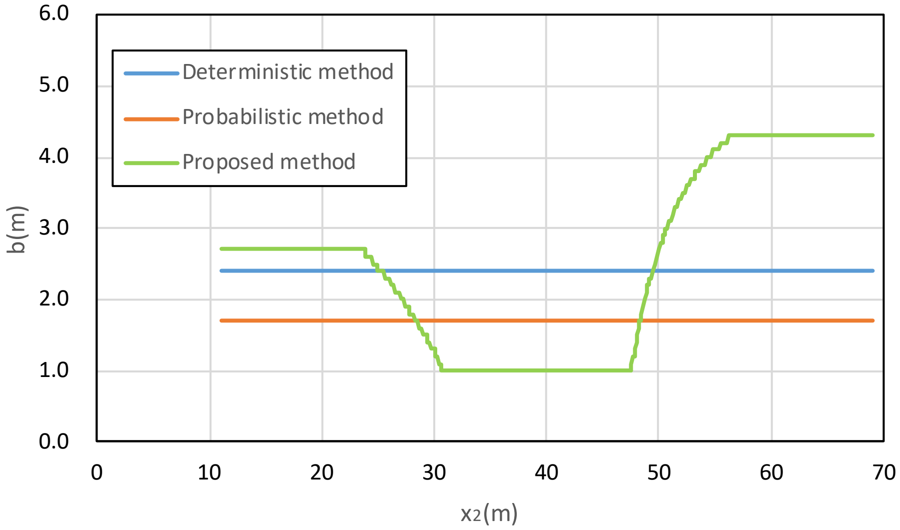

Figure 5. Calculation Results with a Fixed Tank Length

For the deterministic method, b is a constant value of 2.4 meters because area (a) only depends on the ship width, as shown in Section 2.1.1.

For the probabilistic method, b is a constant value of 1.7 meters because the index of f_{CN} depends on the value of x_2-x_1, which represents the length of the fuel tank, and the value of x_2-x_1 is kept constant in this calculation.

For the proposed method, a correlation can be observed between the probability of damage to the area and the value of b. When x_2 exceeds 70/3 meters, the value of f_l is lower because a portion of the tank enters the mid part of the target ship where the probability of collision is lower than in the aft part. Consequently, a larger f_t is permitted because the graph represents the point at which the value of f_{CN} is constant and because f_v is a constant value due to the constant value of H-d. Finally, a lower f_t allows for a lower value of b.

Figure 5 illustrates that the value of b in the proposed method is less than that of the deterministic and probabilistic methods in the x_2 range of 28.6 to 48.2 meters. This indicates that the restrictions on the fuel tank arrangement are more relaxed. In other words, the utilization of the proposed method has the potential to allow fuel tanks to be placed in a larger area than the areas decided by probabilistic and deterministic methods.

5. CONCLUSION

This paper introduced a method for alternative design of fuel tank arrangements. Statistical collision data were obtained by aggregating the reports from the Japanese version of Marine Accident and Incident Reports published by the Japan Transport Safety Board. The statistical collision data show that it is not recommended to place a fuel tank in the fore part, from the standpoint of safety. Test calculation was conducted for a 499 Gross Tonnage cargo ship using the statistical collision data. The results show that the proposed method has the potential to allow fuel tanks placed in a larger area than the area currently prescribed by probabilistic and deterministic methods.

Acknowledgments

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APPENDIX REQUIREMENTS FOR CALCULATION OF TANK ARRANGEMENTS

Requirements for the calculation of tank arrangements are summarized in the following paragraphs.

A.1 Deterministic Method

Paragraph 5.3.3.1 of the IGF Code [3] is definition of area (a) and shown below:

> "The fuel tanks shall be located at a minimum distance of *B*/5 or 11.5 m, whichever is less, measured inboard from the ship side at right angles to the centreline at the level of the summer load line draught:"

Paragraph 5.3.3.4 of the IGF Code [3] is definition of area (b) and shown below:

> "In no case shall the boundary of the fuel tank be located closer to the shell plating or aft terminal of the ship than as follows:
>
> .1 For passenger ships: *B*/10 but in no case less than 0.8 m. However, this distance need not be greater than *B*/15 or 2 m whichever is less where the shell plating is located inboard of *B*/5 or 11.5 m, whichever is less, as required by 5.3.3.1.
>
> .2 For cargo ships:
>
> .1 for V_c below or equal 1,000 m^3, 0.8 m;
> .2 for 1,000 m^3 < V_c < 5,000 m^3, 0.75 + V_c × 0.2 / 4,000 m;
> .3 for 5,000 m^3 ≤ V_c < 30,000 m^3, 0.8 + V_c / 25,000 m; and
> .4 for V_c ≥ 30,000 m^3, 2 m,
>
> where:
> V_c corresponds to 100% of the gross design volume of the individual fuel tank at 20°C, including domes and appendages."

Paragraph 5.3.3.5 of the IGF Code [3] is definition of area (c) and shown below:

> "The lowermost boundary of the fuel tank(s) shall be located above the minimum distance of *B*/15 or 2.0 m, whichever is less, measured from the moulded line of the bottom shell plating at the centreline."

A.2 Probabilistic Method

The value f_{CN} calculated as described in Equation 1 shall be less than 0.02 for passenger ships and 0.04 for cargo ships in accordance with paragraph 5.3.4.2 of the IGF Code [3].

f_l is calculated by the following equations in accordance with the SOLAS Convention [6].

Overall normalized max damage length:	J_{max} = 10/33
Knuckle point in the distribution:	J_{kn} = 5/33
Cumulative probability at J_{kn}:	p_k = 11/12
Maximum absolute damage length:	l_{max} = 60 m
Length where normalized distribution ends:	L^* = 260 m

$$f_l = p\left(x_1, x_2\right), \tag{A-1}$$

$$b_0 = \left(\frac{p_k}{J_{kn}} - \frac{1-p_k}{J_{\max} - J_{kn}}\right). \tag{A-2}$$

If $Ls \le L^*$:

$$J_m = \min\left\{J_{\max}, \frac{l_{\max}}{Ls}\right\}, \tag{A-3}$$

$$J_k = \frac{J_m}{2} + \frac{1 - \sqrt{1 + (1 - 2p_k) b_0 J_m + \frac{1}{4} b_0^2 J_m^2}}{b_0}. \quad \text{(A-4)}$$

$$b_{12} = b_0, \quad \text{(A-5)}$$

If $Ls > L^*$:

$$J_m^* = \min\left\{ J_{\max}, \frac{l_{\max}}{L^*} \right\}, \quad \text{(A-6)}$$

$$J_k^* = \frac{J_m^*}{2} + \frac{1 - \sqrt{1 + (1 - 2p_k) b_0 J_m^* + \frac{1}{4} b_0 J_m^{*2}}}{b_0}, \quad \text{(A-7)}$$

$$J_m = \frac{J_m^* \bullet L^*}{Ls}, \quad \text{(A-8)}$$

$$J_k = \frac{J_k^* \bullet L^*}{Ls}, \quad \text{(A-9)}$$

$$b_{12} = 2\left(\frac{p_k}{J_k} - \frac{1 - p_k}{J_m - J_k} \right), \quad \text{(A-10)}$$

$$b_{11} = 4\frac{1 - p_k}{(J_m - J_k) J_k} - 2\frac{p_k}{J_k^2}, \quad \text{(A-11)}$$

$$b_{21} = -2\frac{1 - p_k}{(J_m - J_k)^2}, \quad \text{(A-12)}$$

$$b_{22} = -b_{21} J_m, \quad \text{(A-13)}$$

$$J = \frac{x_2 - x_1}{Ls}, \quad \text{(A-14)}$$

$$J_n = \min(J, J_m), \quad \text{(A-15)}$$

If $J \le J_k$:

$$p(x_1, x_2) = \frac{1}{6} J^2 (b_{11} J + 3b_{12}). \quad \text{(A-16)}$$

If $J > J_k$:

$$p(x_1, x_2) = -\frac{1}{3} b_{11} J_k^3 + \frac{1}{2}(b_{11} J - b_{12}) J_k^2 + b_{12} J J_k - \frac{1}{3} b_{21}(J_n^3 - J_k^3) + \frac{1}{2}(b_{21} J - b_{22})(J_n^2 - J_k^2) + b_{22} J (J_n - J_k). \quad \text{(A-17)}$$

f_t is calculated by the following equations in accordance with SOLAS Convention [6].

$$f_t = (1 - C)\left[1 - \frac{G}{f_l} \right], \quad \text{(A-18)}$$

$$C = 12 \cdot J_b (-45 \cdot J_b + 4), \quad \text{(A-19)}$$

$$J_b = \frac{b}{15 \cdot B}, \quad \text{(A-20)}$$

$$G = -\frac{1}{3} b_{11} J_0^3 + \frac{1}{2}(b_{11} J - b_{12}) J_0^2 + b_{12} J J_0, \quad \text{(A-21)}$$

$$J_0 = \min(J, J_b), \quad \text{(A-22)}$$

f_v is calculated by the following equations in accordance with paragraph 5.3.4.2 of the IGF Code [3].

If (H-d) ≤ 7.8:

$$f_v = 1.0 - 0.8\left(\frac{H-d}{7.8}\right), \tag{A-23}$$

If (H-d) > 7.8:

$$f_v = 0.2 - \left(\frac{0.2\left(\left(H-d\right)-7.8\right)}{4.7}\right). \tag{A-24}$$

However, f_v shall not be less than 0 or greater than 1.