

# The Application of Risk Based-Design (RBD) Methodology For LNG Carrier Under Varied Sea State

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**Abstract.** The energy transition issue is being pursued following the outcomes of the 22nd Summit by the G-20 group. The use of Liquefied Natural Gas (LNG) fuel has emerged as one of the solutions in addressing the energy transition challenge. In line with the issuance of the Ministry of Energy and Mineral Resources Decision in January 2022, the Indonesian Government will increase the utilization of natural gas in the form of LNG for the electricity generation sector. LNG fuel is considered to possess numerous advantages and is more environmentally friendly. The distribution of LNG fuel is often carried out by tanker ships equipped with cryogenic tanks called LNG carrier. However, challenges arise when ships operate in waters which has high sea state condition, where the vessel faces the risk of accidents such as sloshing, increased motion response, stability disruptions, and other. Therefore, this paper provide a comprehensive risk analysis to minimize the existing accident risks caused by varied sea state condition using Risk-Based Design (RBD). RBD is a structured and systematic method to ensure safety levels and cost-effectiveness and utilizing risk analysis.

## 1 Introduction

Use At the close of the year 2022, the G-20 group convened the 22nd High-Level Conference (HLC) held in Bali, Indonesia. The G-20 comprises 19 countries and one European Union institution, with Indonesia being one of them and having the privilege of hosting and presiding over the 22nd G-20. The three main issues that Indonesia, in its capacity as the President, is advocating for in the 22nd G-20 High-Level Conference are sustainable energy transition, digital transformation, and global health architecture [5].

Energy transition is the process of shifting from the use of environmentally unfriendly fossil-based energy sources to clean and eco-friendly energy sources. The energy transition is continuously promoted, including through the utilization of Indonesia's natural gas potential, specifically Liquefied Natural Gas (LNG), which is claimed to offer numerous advantages in both the power generation sectors and transportation sectors [1].

The provision of LNG as a fuel for power generation is predominantly carried out by large-sized vessels commonly known as LNG carriers. On these vessels, LNG storage tanks are typically installed either above or within the ship. However, challenges emerge in supplying LNG to remote and small archipelago regions, typically characterized by shallow water depths. The use of large-sized LNG carriers can potentially grounding due to the difference in draft between the vessel and water depth. The small LNG carrier scheme is one of the solutions to address this issue [9].

Another challenge is that LNG carriers are classified as Type 1G vessels, which means they are gas carriers that must remain intact even when faced with severe damage, and their cargo tanks must be located far from the ship's hull. This challenge is compounded by the maritime conditions in the Eastern Indonesian waters, which are prone to high waves where the vessel faces the risk of accidents such as sloshing, increased motion response, stability disruptions, and other [2][4].

One method that can be employed to address these issues is the Risk-Based Design (RBD) approach. Risk-Based Design is a design process that supports risk assessment or design based on the results of risk assessment. RBD is a structured and systematic method with the aim of ensuring safety performance and cost-effectiveness through the use of risk analysis and cost-benefit assessment.

## 2 Methodology

### 2.1 Small LNG Carrier

The small LNG carriers generally with volumes up to 10,000 m<sup>3</sup> have a configuration of 2 cargo tanks, and for sizes larger than 10,000 m<sup>3</sup> up to 20,000 m<sup>3</sup>, they typically have 3 cargo tanks. Meanwhile, a configuration of 4 tanks is found in ships with volumes ranging around 30,000 m<sup>3</sup>. [7]. These configurations are shown in the Figure 1 below. The LNG carrier volume taking into consideration is small LNG carrier with the cargo capacity below 1500 m<sup>3</sup>.

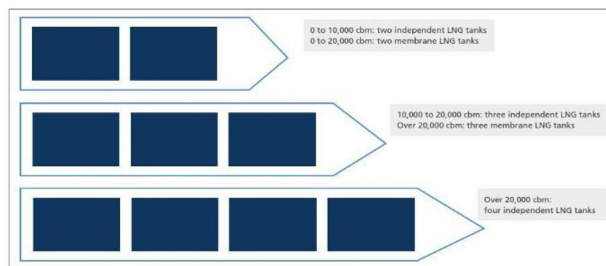


Fig. 1. Small LNG Carrier Configuration

### 2.2 Indonesia Sea State

The determination of sea states in Indonesian waters is conducted to understand the distribution of areas prone to high waves. Sea state data is obtained from BMKG based on the distribution of the highest wave data [4]. The wave conditions are classified as extreme, with an annual wave distribution having a significant wave height reaching up to 3 meters. When compared to sea state data distribution as indicated in Table 1 below, the waters in the eastern regions of Indonesia have a sea state range from sea state 0 to sea state 7.

**Table 1.** Sea State Distribution [3]

Sea State	0	1	2	3	4	5	6	7	8	9
Wind Vel. (m/s)	1.029	4.373	6.945	8.231	9.774	12.347	13.376	25.208	27.780	30.609
Wave Height (m)	0.03	0.488	1.006	1.433	2.012	3.200	4.359	8.870	16.185	22.708
Average Periode (Sec)	0.5	2.3	3.6	4.3	5.1	6.4	7	10.7	14.5	15.9
Average Wave Length (m)	0.254	0.508	1.321	1.803	2.515	4.064	4.775	11.176	20.574	25.019
Minimum Duration (hr)	0.30	1.7	4.8	6.6	9.2	14	17	42	81	101

### 2.3 Risk Based-Design

Risk-Based Design (RBD) for ships is a relatively new field of knowledge and engineering that has been developed in relation to ship design, construction, operation, and regulation. RBD, or Risk-Based Design, is a design process that supports risk assessment or design based on the results of risk assessment. RBD is a structured and systematic method with the objective of ensuring safety performance and cost-effectiveness through the use of risk analysis [6].

### 2.4 Functional and Failure Identification

The process of functional identification is carried out with the aim of detailing the functions of main component of Small LNG carrier. This process begins at the system level, then breaks down to the subsystem level, and finally reaches the minimum level that needs to be achieved. This step allows for a deep understanding of the roles and contributions of each component of Small LNG Carrier. By detailing these functions, a comprehensive understanding of the relationships between parts can be built, facilitating the identification of potential failure modes, and aiding in the planning of effective maintenance strategies [8].

### 2.5 FMEA (Failure Mode and Effect Analysis)

The Failure Mode and Effect Analysis (FMEA) analysis begins by defining the failure modes of a component. Subsequently, the impact of each potential failure mode is identified. Recommendations for corrective actions are also proposed to address or prevent these failures. During the analysis, the Residual Risk Priority Number (RPN) is calculated to provide a better understanding of the risk level and the necessary priority of improvements for that component. The Risk Priority Number is determined by three factors: severity, occurrence, and detection levels [3]. These factors are described in Table 2, Table 3 and Table 4. It's will help assess the seriousness of the potential failure, the likelihood of its occurrence, and the ability to detect it before it causes significant consequences. The calculated RPN serves as a quantitative measure to prioritize and guide the implementation of corrective actions, emphasizing components with higher risk level.

**Table 2.** Severity Level

<b>Severity Level</b>	<b>Criteria</b>	<b>Level</b>
Most Hazardous	Ship damage cause an accident suddenly and endanger safety Work	10
Very Hazardous	Ship damage cause an accident work and the ship doesn't operational but there are warning/early detection	9
Very High	Ship damage causing the engine to stop and loss of function mainly	8
High	Ship damage causing the system to shut down but the ship still operate	7
Moderate	Ship damage resulting in system performance decreased drastically however the machine still works operate	6
Low	Ship damage resulting in system performance decreases gradually with the ship still available operate	5
Very Low	Ship damage cause influence small impact on system performance with the engine still operates perfectly	4
Unharmd	Ship performance decreased but the system still running perfectly	3
Very Unharmd	Ship are seen as bad but component performance still good and the system as well the machine is still running perfect	2
No Hazard	No influence	1

**Table 3.** Occurrence Level

<b>Occurance Level</b>	<b>Criteria</b>	<b>Level</b>
Very often happened until no damage can be avoided	Almost all the time happens within less than 1-2 times operation	10
Very often	Very high occurs within less time from 3-4 operations	9
Often (1)	High occurs within less time than 5-8 of operation	8
Often (2)	Quite high within less time than 9-20 of operation	7
Rare (1)	Intermediate occurs within less time than 21-80 of operation	6
Rare (2)	Low occurs within less time than 81- 400 of operations	5
Rare (3)	Rarely occurs within less time than 401- 2000 of operations	4
Very Rare (1)	Rarely occurs within less time than 2001- 15000 of operations	3
Very Rare (2)	Almost never happens in more than 15001 operations	2
None	Never happened	1

**Table 4.** Detection Level

Detection Level	Criteria	Level
Impossible to be detected	It won't be controlled and/or detected there is a cause potential failure as well as damage furthermore	10
Very difficult to be detected	Very difficult to control change to detect potential causes and type of failure furthermore	9
Difficult to be detected	Difficult to control changes to detect the cause potential and type subsequent failure	8
Very low to be detected	Very low for detect the cause potential and type subsequent failure	7
Low to be detected	Low for detect the cause potential and type subsequent failure	6
Moderate to be detected	Hard to detect potential causes and type of failure furthermore	5
Currently to be detected	It's almost easy to detect the cause potential and type subsequent failure	4
Easy to be detected	Easy to control for detect the cause potential and type subsequent failure	3
Very easy to be detected	Very easy controlled for detect the cause potential and type subsequent failure	2
Detection is possible done with bare eye	It can be expected happens frequently resulting in detection on potential causes and events	1

### 3 Result and Discussion

The result of risk based design is to provide design requirement from identified failure effect for Small LNG Carrier components on each sea state condition. The design requirement will determined based on the value of risk priority number (RPN) for each failure effect as simulated in the Table 5 below.

**Table 5.** The Simulation Between Risk and Ship Design

Sea State	Failure Effect	Ave. RPN	Ship Design Requirement	Ship Operational Requirement
A	Failure 1	0-100	Design requirement A	Operational requirement A
B	Failure 2	100 – 200	Design requirement B	Operational requirement B
C	Failure 3	200 - 500	Design requirement C	Operational requirement C

#### 3.1 Risk Identification

The failure mode will be achieved after the risk identification is determined. The risk identification is regarding to Small LNG Carrier when operated under varied sea state conditions. These risks will lead to several failure conditions of ship depend on the main component. The selected main component are the LNG tank and hull ship, its are because these two components have significant role when Small LNG Carrier is being operated. The result of risk identification is indicated in Table 6 below.

**Table 6.** Risk Identification

No	Component	Function	Risk Identification
1	LNG Tank	The storage equipment of LNG	Sloshing
2	Ship Hull	The source of buoyancy force	Increasing of stress and bending moment in the midship area
			Ship speed reduction
			Bottom slamming
			Deck wetness
			Increasing of capsizing effect

### 3.2 Failure Mechanics

Every identified hazard is analysed to understand the mechanisms through which failure may occur when each main component is at risk. The failure mechanisms typically consist of failure modes, the effects of failure, and how failure can be detected. Failure mechanisms are identified based on each hazard risk that occurs in each main component. The results are presented in Table 7 below.

**Table 7.** Risk Identification

No	Risk Identification	Failure Mode	Failure Mechanism	Failure Effect
1	Sloshing	Crack in the LNG tank structure	Exceed the allowance deformation	LNG liquid leakage
				Environmental pollution
				Explosion
				Fire Hazard
2	Increasing of stress and bending moment in the midship area	Crack in the midship structure	Exceed the allowance deformation	Hull leakage
				Sink
				Ship bottom fracture
3	Ship speed reduction	Increasing of fuel consumption	Increasing of ship pitching	Anchoring
4	Bottom slamming	Crack in the bow structure	Increasing of ship pitching	Bow fracture
5	Deck wetness	Corrosion on deck	Sea water exposed to main deck	Crack on ship deck
6	Increasing of capsizing effect	Loss stability force	Increasing of ship rolling	Ship turns over

### 3.3 Failure Mitigations

Failure mitigation is a method used to reduce the potential for failure when an LNG ship faces existing hazard risks. Failure mitigation will be used as a reference in small LNG ship design activities. The results are presented in Table 8 below.

**Table 8.** Risk Identification

No	Risk Identification	Failure Effect	Risk Reducing Measure
1	Sloshing	LNG liquid leakage	Minimize the free surface area effect*
			Wheater forecast and re-routing*
		Environmental pollution	Transversal bulkhead in LNG Tank
			Baffle system
		Explosion	Reducing ship speed
		Fire Hazard	Material selection for LNG Tank Structure
Emergency shutdown procedures*			
2	Increasing of stress and bending moment in the midship area	Hull leakage	Wheater forecast and re-routing*
		Sink	Dynamic positioning system
		Ship bottom fracture	Water ballast adjustment*
			Material selection for hull structure
3	Ship speed reduction	Anchoring	Wheater forecast and re-routing*
4	Bottom slamming	Bow fracture	Wheater forecast and re-routing*
			Material selection for bow structure
			Reducing ship speed*
			Dynamic positioning system
			Water ballast adjusment*
			Anti slamming device
5	Deck wetness	Crack on ship deck	Bow structure design
			Wheater forecast and re-routing*
			Material selection for deck plate
			Reducing ship speed*
			Bow design
			Freeboard design
			Coating specification
6	Increasing of capsizing effect	Ship turns over	Deck drainage design system
			Wheater forecast and re-routing*
			Anti rolling system
			Reducing ship speed*
			Dynamic Stability Control system

\*Operational mitigation

### 3.4 RPN Value

Risk Priority Number (RPN) is utilized to determine the criticality of ship components concerning the occurrence of failures. The RPN value is the result of multiplication from severity x occurrence x detection of each failure effect. The results of the RPN assessment for ship components under each sea state in Indonesian waters are presented in Table 9 and Table 10 below.

**Table 9.** RPN Value Sea State 0 to 4

No	Risk Identification	Failure Effect	0	1	2	3	4
			RPN	RPN	RPN	RPN	RPN
1	Sloshing	LNG liquid leakage	32	32	96	96	128
		Environmental pollution	8	8	24	24	32
		Explosion	40	40	120	120	160

No	Risk Identification	Failure Effect	0	1	2	3	4
			RPN	RPN	RPN	RPN	RPN
2	Increasing of stress and bending moment in the midship area	Fire Hazard	40	40	120	120	160
		Hull leakage	56	56	112	112	168
		Sink	70	70	70	140	140
		Ship bottom fracture	70	70	140	140	210
3	Ship speed reduction	Anchoring	28	28	28	28	112
4	Bottom slamming	Bow fracture	40	40	80	80	120
5	Deck wetness	Crack on ship deck	4	4	16	20	24
6	Increasing of capsizing effect	Ship turns over	30	30	30	60	90
<b>Total Average</b>			<b>38</b>	<b>38</b>	<b>76</b>	<b>85.45</b>	<b>122.18</b>

**Table 10.** RPN Value Sea State 5 to 7

No	Risk Identification	Failure Effect	5	6	7
			RPN	RPN	RPN
1	Sloshing	LNG liquid leakage	160	224	288
		Environmental pollution	40	56	72
		Explosion	200	280	360
		Fire Hazard	200	280	360
2	Increasing of stress and bending moment in the midship area	Hull leakage	280	392	448
		Sink	210	490	560
		Ship bottom fracture	280	490	560
3	Ship speed reduction	Anchoring	168	252	280
4	Bottom slamming	Bow fracture	240	280	320
5	Deck wetness	Crack on ship deck	32	28	32
6	Increasing of capsizing effect	Ship turns over	120	210	240
<b>Total average</b>			<b>175.45</b>	<b>271.09</b>	<b>320</b>

The result of RPN value show in line with the increasing of sea state conditions. The highest Total average RPN value occurs in the sea state 7 with 320. Among of all failure effect, Sink and Ship bottom fracture had the highest value of RPN with 560. These failure effect caused by the increasing of wave height that will lead to risk of the increasing of stress and bending moment in the midship area.

### 3.5 The Relationship Between Risk and Ship Design

The relationship between risk and ship design is a crucial aspect of naval engineering and management. Ship design involves creating vessels that meet specific operational requirements while minimizing various risks associated with their construction, operation, and lifecycle. In the other words, in the way of increasing of sea state condition the Small

LNG Carrier will have more specific requirement to prevent the failure effect of each sea state condition. This relationship tabulated in Table 11 below.

**Table 11.** The Relation Ship Between Risk and Ship Design

Sea State	Ave. RPN	Ship Design Requirement	Ship Operational Requirement
0	38	No Special Requirement	No Special Requirement
1	38	No Special Requirement	No Special Requirement
2	76	No Special Requirement	Minimize the free surface area effect
3	85.45	No Special Requirement	Minimize the free surface area effect
4	122.18	1. Baffle System on LNG Tank	1. Reducing Ship Speed
		2. Dynamic positioning system	
		3. Anti slamming device	2. Emergency Shutdown Procedures
		4. Bow construction	
5	175.45	5. Bow design	3. Anchoring
		6. Freeboard Design	
		7. Coating Specification	4. Water ballast adjustment
		8. Deck Drainage system	
		9. Anti rolling system	5. Weather forecasting
		10. Dynamic control stability system	
6	271.1	1. Baffle System on LNG Tank	. 1. Wheather forecasting and re-routing
		2. Dynamic positioning system	
		3. Anti slamming device	
		4. Bow construction	
		5. Bow design	
		6. Freeboard Design	
		7. Coating Specification	
7	320	8. Deck Drainage system	
		9. Anti rolling system	
		10. Dynamic control stability system	
		11. Material selection on deck	
		12. Material selection on midship body	
		13. Material selection on bow	

The ship design requirements are divided into 3 group based on the result of total average RPN Value. The 1<sup>st</sup> group is consisting of sea state 0 into 3 where the total average RPN is under 100. In this group, there is no design requirement for the Small LNG Carrier. Except in sea state 3 and 4, the surface area effect must be considered to minimize the failure effect.

The 2<sup>nd</sup> group is consisting of sea state 4 and 5 where the total average RPN is between 100 and 200. There are many design and operational requirements shall be considered to minimize the failure effect. In the 3<sup>rd</sup> group is consist of sea state 6 and 7 where the total average RPN is above 200. In this group, the material selection is considered as special design requirement to minimize the failure effect. It is because if the vessel face higher wave so the material to construct also has higher strength limit. But if these design requirements is not able for small LNG carrier to operate in sea state 6 and 7, re-routing based on weather forecasts is the best way to avoid the risk of failure effect.

## 4 Conclusion

The small LNG carrier has several design requirements to operate under varied sea stated conditions. The occurrence of failure getting higher in the way of the sea state condition. The highest RPN are failure on sink and bottom fracture where it is the priority risk shall be considered. The failure that affects the whole system of ship are sink, bottom fracture, bow

fracture and ship turn over. These cases have high occurrence in the sea state 6 & sea state 7. Hence, the Small LNG carrier design is very hazardous to operate under sea state 6 and 7.

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