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Ship Design Based on Extreme Waves

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KEYWORDS
Extreme Wave,
Freak Wave,
Ship Safety,
Design Criteria,
Dynamic Wave Impact

ABSTRACT – Recent studies have revealed that extreme waves (also known as freak waves), with heights ranging from 20 to 30 meters, occur more frequently than previously assumed. Over the past decades, numerous large commercial vessels have been lost due to incidents involving such anomalous wave phenomena. However, the current design criteria outlined in the 2022 BKI (Biro Klasifikasi Indonesia) Consolidation still consider significant wave heights of less than 11 meters, which is increasingly recognized as inadequate for modern oceanic conditions. This study aims to evaluate and propose ship design parameters that account for extreme wave conditions by incorporating significant wave heights of up to 30 meters into the safety analysis. The methodology involves a comparative analysis between the conventional design standards and a revised model that integrates dynamic wave impact forces as a crucial factor in determining the structural dimensions and stability of ships. The findings indicate that designing ships with consideration of extreme wave scenarios is not only feasible but also necessary to enhance vessel resilience and reduce the risk of capsizing and sinking. This research underscores the urgent need for updating maritime safety regulations and design frameworks in response to evolving oceanographic realities, thereby contributing to the development of safer and more robust marine transportation systems.

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INTRODUCTION

Ship design is a complex process governed by a set of prescriptive rules and both international and national standards [1,2]. These regulations are intended to ensure that the structural design of ships meets various operational requirements throughout their service life, including resilience against extreme environmental conditions encountered at sea [3,4]. In principle, these standards are formulated based on assumptions regarding the average operational conditions that vessels are likely to experience. One commonly applied approach in defining structural design criteria is to model the ship as a flexible beam, floating and supported by dynamic fluid pressure rather than by rigid supports [5,6]. In this context, dynamic loads generated by ocean waves—particularly due to the impact of high waves—represent a critical factor that must be incorporated into the safety and structural integrity analysis of ships [7]. Unfortunately, the current design criteria, as outlined in various regulations including the consolidated rules of BKI and other international standards, generally still consider a significant wave height of approximately 10.75 to 11 meters [8,9-11]. Based on recent studies and updated oceanographic data, this figure is increasingly regarded as insufficient to represent actual sea conditions, especially in regions characterized by extreme maritime dynamics.

There is thus a growing need to reassess existing ship design criteria, particularly by accounting for the occurrence of extreme or freak waves [12,13], which have been observed to reach heights of 20 to 30 meters. The MaxWave Project (2003) even revealed that such extreme waves occur more frequently than previously assumed [14]. The implications of this phenomenon are profound, affecting not only technical aspects of ship design but also maritime safety and global economic stability [15]. Empirical evidence indicates a significant rise in the number of large commercial vessels that have suffered accidents due to high waves over the past few decades [16]. Approximately 41% of these vessels sustained structural damage, 28.5% were lost due to collision, fire, or explosion, 28% ran aground, and 2.5% disappeared without a trace and are classified as "missing and presumed lost." This reality highlights the potential consequences of inadequate design approaches in anticipating extreme wave loads, which may lead to catastrophic accidents and disrupt global economic stability, particularly in the sectors of logistics and international trade.

Given this background, the present study aims to propose a more adaptive and resilient approach to ship design that can effectively accommodate extreme wave conditions. Through dynamic load analysis and a comprehensive reassessment of existing design criteria, this research seeks to develop a responsive design strategy that aligns with the future challenges posed by climate change and evolving ocean dynamics.

LITERACY DATA AND METHOD

Irregular Wave

The wave height parameters used in high wave early warning systems generally refer to the classification standards established by the World Meteorological Organization (WMO) through the Sea State Code [17]. According to this classification, sea waves are categorized into several severity levels, namely: moderate (1.25–2.5 meters), high (2.5–4.0 meters), and very high (4.0–6.0 meters) [18]. These categories are widely adopted by meteorological and climatological agencies around the world, including the Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG), to provide marine weather forecasts for sailors, fishermen, and other stakeholders in the maritime sector [19,20]. In the field of oceanography, marine weather forecasts typically report significant wave height (Hs), which is technically defined as the average height of the highest one-third of waves observed within a specific time interval. Hs is the most commonly used parameter for describing general sea surface conditions, as it represents the wave heights that pose the greatest impact on maritime operations, including ship design and offshore platform stability.

However, under extreme sea conditions, waves can occur that are significantly higher than Hs. These are referred to as extreme waves or freak waves, and are defined as waves whose height exceeds 2.3 times the significant wave height (Hext > 2.3 × Hs). Although historically considered rare statistical anomalies, recent advances in oceanographic research and observational data from satellites and buoys have revealed that extreme waves occur more frequently than previously estimated, particularly in open sea regions affected by severe weather systems, large-scale storms, or complex wave interactions. The presence of such extreme waves poses serious challenges to ship safety, especially for vessels designed solely based on conventional Hs values. Therefore, it is imperative for naval architects and maritime industry stakeholders to incorporate the potential for extreme wave events into design criteria formulations, in order to ensure structural integrity and operational safety of vessels under future marine environmental conditions.

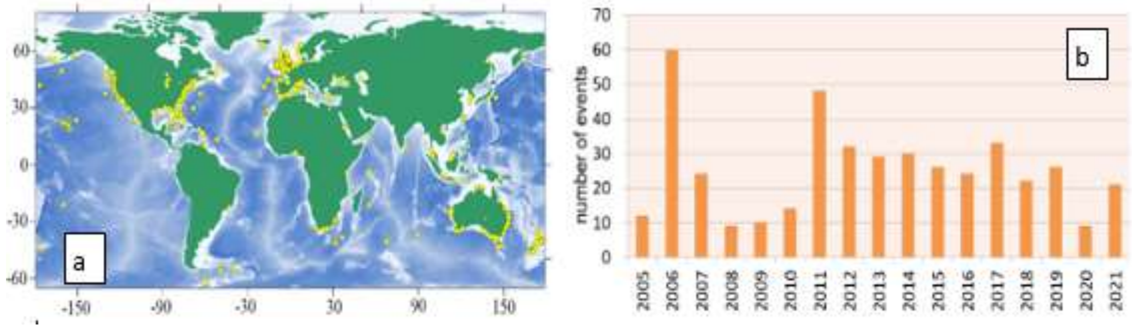

Figure 1. Freak Wafe. a) Freak wave occurrence map. b) Freak wave occurrence distribution

Stability Theory

Ship stability is one of the fundamental aspects in the field of naval architecture and marine engineering that critically determines maritime safety [21]. Conceptually, ship stability refers to the vessel's ability to return to its upright equilibrium position after being subjected to external disturbances such as rolling caused by waves, wind, currents, or cargo displacement [22]. This capability is closely related to mass distribution, hull shape, geometric configuration, and the value of the righting arm (GZ), which serves as a primary indicator of the ship's ability to recover from a given heel angle. Good stability is essential to prevent hazardous conditions such as capsizing or permanent listing, both of which can lead to serious maritime accidents. Factors influencing ship stability are generally divided into two categories: internal and external [23,24,25]. Internal factors include the ship's physical design, such as its principal dimensions, hull form, and cargo distribution. External factors encompass environmental influences such as waves, wind, currents, and storms. Based on its physical condition, ship stability is classified into two main types: intact stability and damage stability. Intact stability refers to the vessel's stability in an undamaged condition, without structural failure or flooding, and is assessed by calculating the righting arm (GZ) characteristics at various heel angles to ensure the ship's ability to recover under normal operational conditions [22].

In contrast, damage stability refers to the ship's ability to maintain stability after suffering structural damage, such as hull breaches that allow seawater to enter internal compartments. Evaluating damage stability is crucial to determine a vessel's survivability during emergencies, particularly for passenger ships, tankers, or vessels operating in high-risk environments, where loss of buoyancy and cargo redistribution due to flooding must be taken into account. Both types of stability must be rigorously assessed and calculated in accordance with international regulations such as SOLAS, the IMO IS Code, and classification society standards, in order to ensure structural integrity and operational safety under various sea conditions.

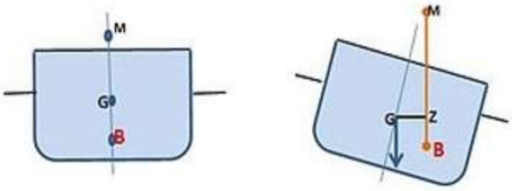

Figure 2. Key points of ship stability

RESULTS AND DISCUSSION

The dimensions and characteristics of a new vessel must be determined by taking into account its intended mission and the specific operational areas it will navigate. Other fundamental design considerations include ensuring good stability, minimizing hydrodynamic resistance, and achieving high propeller efficiency. Additionally, the vessel must operate under draft limitations as minimal as possible, all of which significantly influence the selection of the ship's principal dimensions and hull form. The structural design of the hull must be formulated based on these considerations.

Summary of the principal dimension determination:

Ship Length (L) = 310.5 m,

Ship Beam (B) = 34.5 m,

Ship Depth (H) = 20.7 m.

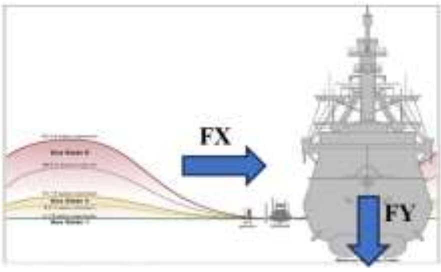

Figure 3. Comparison of Wave Height (Hs) with Ship Dimensions

This illustrates the comparison between significant wave height (Hs) and ship dimensions, which provides an overview of the interaction between wave force (FX) and stability moment (FY). The wave force (FX) induces rolling motion in the vessel, while the stability moment (FY) acts to restore the ship to its original upright position. When the value of FX is smaller than FY, the ship will return to its initial equilibrium state. However, if FX exceeds FY, the ship will lose its ability to recover and may capsize.

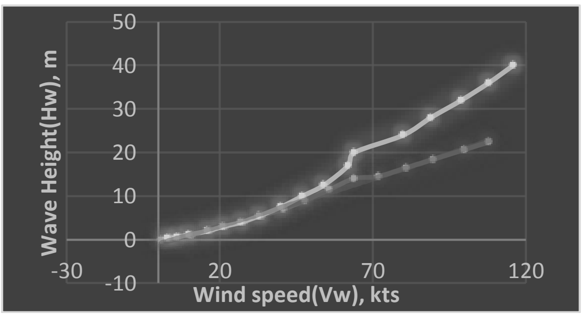

Figure 4. Graph of the relationship between wind speed (Vw) and wave height (Hw)

The graph illustrates the relationship between ship length (Ls) and wave height (Hw) for large vessels operating in sea areas with Sea State > 8, which is proposed as a preventive measure to mitigate frequent maritime accidents that could potentially impact global economic stability.

Table 1. Relationship between Beaufort Scale (BS) Wind Speed (Vw) and Wave Height (Hs)

BS	Vw	Hs	Low		High	
1	1–3 kts	0–0.3 m	1	0	3	0,3
2	4–6 kts	0.3–0.6 m	4	0,3	6	0,6
3	7–10 kts	0.6–1.2 m	7	0,6	10	1,2
4	11–16 kts	1–2 m	11	1	16	2
5	17–21 kts	2–3 m	17	2	21	3
6	22–27 kts	3–4 m	22	3	27	4
7	28–33 kts	4–5.5 m	28	4	33	5,5
8	34–40 kts	5.5–7.5 m	34	5,5	40	7,5
9	41–47 kts	7–10 m	41	7	47	10
10	48–55 kts	9–12.5 m	48	9	54	12,5
11	56–63 kts	11.5–16 m	56	11,5	62	17
12	≥ 64 kts	≥ 14 m	64	14	64	20
13	72–80 kts	?	72	14,5	80	24
14	81–89 kts	?	81	16,5	89	28
15	90–99 kts	?	90	18,5	99	32
16	100-108kt	?	100	20,6	108	36
17	> 108 kts	?	108	22,4	116	40

Table 1 illustrates the relationship between the Beaufort Scale (BS), wind speed (Vw), and significant wave height (Hs), which reflects the prevailing sea conditions around the world. Based on the question, “Is a wave height parameter of 10.75 meters sufficient?”, it appears that this parameter is not adequate. In fact, data shows that numerous large commercial vessels have been lost due to high-wave accidents.

The United States Navy has previously designed military vessels to withstand sea state 8 conditions, with significant wave heights reaching up to 14 meters [15]. The design criteria for military and commercial ships differ; for instance, military vessels are constructed to endure shock loads and excessive pressure, which commercial vessels are generally not capable of withstanding. Nevertheless, both types of ships share common operational criteria—particularly the need to account for the significant wave height of the waters they operate in. For commercial vessels, this wave height criterion becomes one of the most critical design considerations.

Table 2. The longest ship data in the world

No	Ship Name	Ls (m)	Hext (m)	Hs (m)	B (m)	H (m)	DISPL. (t)
1	USS Gerald R Ford	333	11,13	4,84	39,18	23,79	221748
2	Costa Smeralda	337	11,2	4,869	39,65	24,07	229777
3	Independence of the Seas	339	11,23	4,883	39,88	24,21	233833
4	P&O Iona	345	11,33	4,926	40,59	24,64	246511
5	Symphony of the Seas	361	11,59	5,039	42,47	25,79	282486
6	Allure of the Seas	362	11,61	5,046	42,59	25,86	284840
7	Harmony of the Seas	362,12	11,61	5,047	42,6	25,87	285112
8	TI-Class Supertanker	380	11,89	5,17	44,71	27,14	329424
9	Emma Maersk	397,71	12,17	5,289	46,79	28,41	377700
10	HMM Algeciras	399,9	12,2	5,304	47,05	28,56	383907
11	Pierre Guillaumat	414,22	12,41	5,398	48,73	29,59	426706
12	Batillus	414,22	12,41	5,398	48,73	29,59	426706
13	Seawise Giant	458,45	13,06	5,679	53,94	32,75	578590
14	Seawise Giant	458,46	13,06	5,679	53,94	32,75	578603
15	Prelude	488	13,48	5,859	57,41	34,86	697736

Table 2 Showcasing the longest ships in the world designed with wave height (Hw) parameters exceeding 10.75 meters, a standard initially pioneered by the United States Navy. These vessels, in addition to being constructed in alignment with their specific missions and operational visions, were also developed as a proactive measure to mitigate the risks of maritime accidents caused by extreme waves and operational failures.

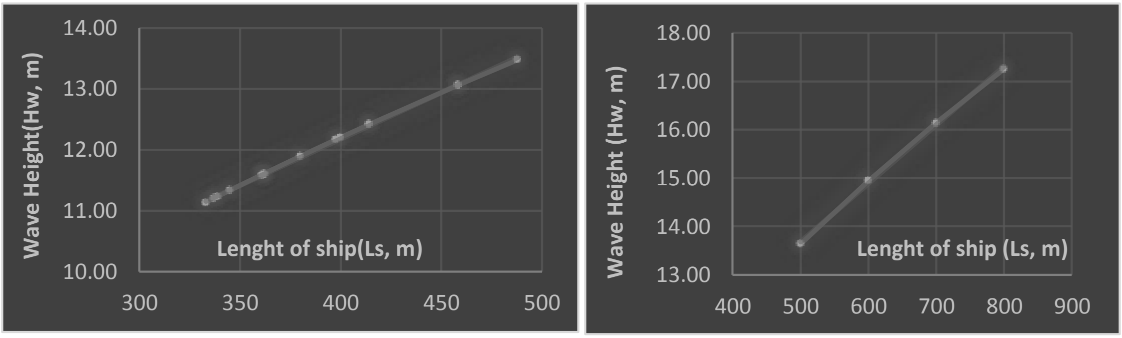

Figure 5. Graph of the relationship between ship length (Ls) and wave height (Hw)

The graph on the left illustrates the relationship between ship length (Ls) and wave height (Hw) as expressed by mathematical Equation (2), serving as a design parameter that has already been applied in the construction of large vessels currently in operation worldwide. Future developments aim to accommodate large ships with lengths (Ls) ranging from 500 to 800 meters, taking into account wave height (Hw) parameters between 13.8 and 17.5 meters. Meanwhile, the graph on the right shows the relationship between Ls and Hw for large ships operating in sea areas with Sea State > 8, proposed as a preventive measure to reduce the risk of frequent maritime accidents that could threaten the balance of the global economy.

Table 3. Ship design data based on wave height > Sea state 8 proposed

No	The proposed ship	Ls (m)	Hext (m)	Hs (m)	B (m)	H (m)	DISPL. (t)
1	K1	500	13,64	5,93	58,82	35,71	750311
2	K2	600	14,94	6,50	70,59	42,86	1296890
3	K3	700	16,14	7,02	82,35	50	2059151
4	K4	800	17,25	7,50	94,12	57,14	3073752

Table 3 Presenting ship design data that considers wave heights exceeding Sea State 8, as proposed to support and ensure the resilience of global maritime economic activities. These design standards aim to enhance the structural integrity and operational safety of commercial vessels navigating in high-seas conditions. By adopting criteria based on extreme wave environments, such ship designs are better equipped to withstand harsh oceanographic conditions, reduce the risk of maritime disasters, and maintain the continuity of international trade routes vital to the global economy.

CONCLUSION

Every ship to be constructed—particularly large vessels intended for international operations—is typically designed based on the operational vision and mission outlined in the *Terms of Reference (TOR)* or *Term of Requirement (ToR)*, which serve as the primary foundation for ship development. These documents define the ship's intended function, operational area, cargo characteristics, and required speed. However, in light of global climate change and the increasing frequency of extreme wave events, ship dimension planning can no longer rely solely on functional requirements. It must also incorporate safety considerations regarding structural resilience in harsh marine environments. Therefore, it is strongly recommended that maximum wave height (*Hw*) be adopted as a critical design parameter in determining a vessel's principal dimensions. By integrating *Hw* into the design framework, ships will not only fulfill their operational mandates but also possess sufficient structural integrity and stability to withstand high-sea conditions, thereby reducing the risk of maritime accidents caused by extreme wave events.

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