

Environmental impacts caused by fire and explosion accidents in maritime activities: A review

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Abstract. Over the past few years, marine transportation accidents have decreased significantly. Marine transportation accidents are complex events often caused by multiple factors through the interaction of multiple parties. These accidents can cause loss of human life and property and ecological and environmental damage. They could disrupt the balance of the industrial and economic situation. This paper comprehensively reviews Fire and Explosion (F.E.) accidents in maritime activities. The subject is narrated through a brief history and the resulting impact on the surrounding marine ecosystem. Then, the study summarizes the policies and regulations derived from international maritime agencies that have governed prevention and countermeasures. Therefore, preliminary research on enhancing the safety and security of composite-based structures is summarized in this review to highlight protection and prevention programs in the maritime scope. Overall, this study covers the current state of the global maritime industry and the policies and regulations for protection from fire and explosion accidents.

1. Introduction

Maritime activities involve many dangerous risks. Many factors can trigger these risks, such as human error, faulty equipment, environmental conditions, regulatory violations, etc [1,2]. If one or more of these triggers is left unattended or unmaintained, it can lead to a significant disaster in the form of an accident. Accidents in maritime activities have many types. According to a report from Allianz in 2023, standard and frequent types of accidents include foundering (sunk, submerged), wrecked/stranded (grounded), Fire and Explosion (F.E.), collision, machinery damage/failure, and hull damage [3]. Fire accidents can be triggered by the emergence of tiny sparks in any ship location that are not immediately appropriately handled. Especially if the spark is in an area not far from flammable materials such as fuel, it can cause a more extensive fire and is often accompanied by an explosion [4,5]. Fire and explosion accidents often occur on ships transporting fuel, such as tankers, fuel carriers, etc. [6,7]. The impact of these accidents can cause serious environmental problems and threaten the existence of living things in the environment [8].

During fire and explosion accidents, many negative impacts are caused, ranging from loss of life and property to disruption of the environmental ecosystem [9,10]. Pollutants left in the environment without any remedial action can cause damage to the marine ecosystem and its surroundings. In order to keep the marine ecosystem sustainable, the International Maritime Organization (IMO) has made regulations on standardizing the design and design of shipbuilding structures [11]. In addition, researchers from mechanical engineering, shipping engineering, and construction engineering have researched to develop the design and design of shipbuilding structures and offshore installations so that the level of safety increases [12-14].

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The purpose of this paper is to present a comprehensive review of the impact of fire and explosion accidents on the environment. It is starting with past accidents and the losses incurred, such as property, human life, living things, and their environment. Then, the study continues by reviewing policies that regulate protection procedures as a preventive measure to overcome fire and explosion accidents that international organizations have made. Finally, it concludes with a summary of the prospects for research and cutting-edge technology in composites as part of components in maritime and offshore structures.

2. History of F.E. accidents: Impact on environmental sectors

Over the last ten years, fire and explosion incidents have seen a noticeable improvement, with a steady reduction in accident fatalities. According to a report issued by Allianz [3], from 2013 to 2022, a total of 807 marine accidents with total losses from ships with a gross tonnage (G.T.) of 100 or greater occurred worldwide (Figure 1a). In 2022, 38 total marine accidents (over 100 gross tonnages). Figure 1b shows that fire and explosion accidents ranked second most common, after foundered accidents, which accounted for about half of the total accidents, with a percentage of 21%. Nonetheless, over the previous ten years, these losses have dropped by 65% (with 109 thefts in total in 2013), demonstrating the beneficial impact of growing attention on safety precautions throughout time, including legislation, well-designed ships, and advancements in risk management and technology.

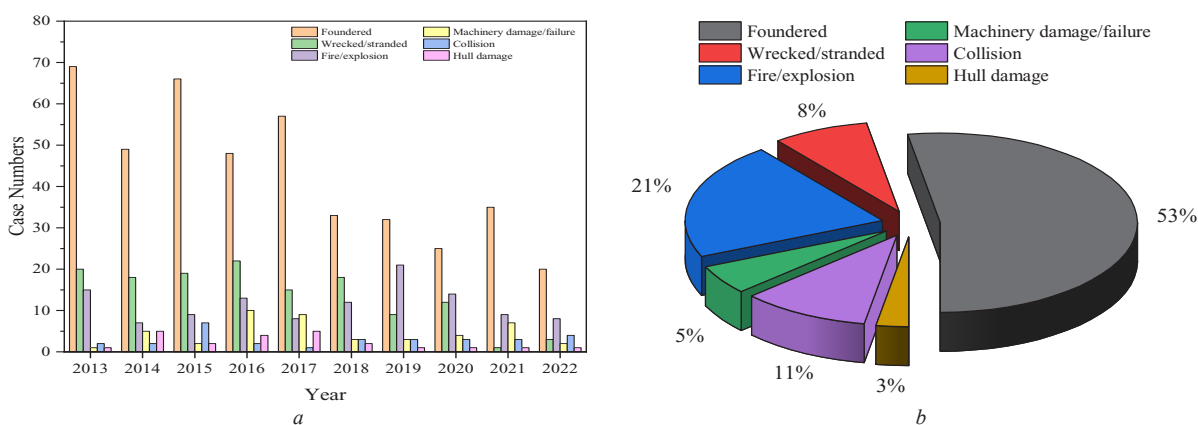


Fig. 1. Data on total losses on shipping activities [3]: (a) Line diagram showing accidents from 2013 to 2022; and (b) Pie chart of accidents only in 2022.

Although fire and explosion accidents have decreased significantly, in May 2021, the world was gripped by the horror of the X-Press Pearl, a new and modern container ship registered in Singapore, burning for 12 days and then sinking in the shallow waters of Sri Lanka, having entered service only three months before the accident occurred [15]. This event has been called the most significant marine ecological disaster in Sri Lanka [16]. This event brought unfavourable impacts such as the amount of toxic cargo, the spread of toxins and toxic burnt products, the receiving environment becoming unsustainable, and most likely becoming a bad legacy for the ecosystem. For instance, as Figure 2 illustrates, some sunken containers may leak extremely toxic chemicals, posing a serious threat to the nearby marine ecosystem; others may carry fossil fuels and cause substantial oil spills; still others may release everyday items, which may turn into marine debris that becomes problematic to dispose of because of the non-biodegradable materials.

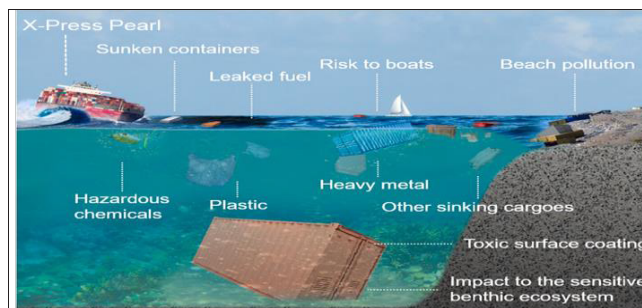


Fig. 2. Illustration of pollution and risks caused by container ship accidents, e.g., X-Press Pearl [17].

3. Regulation framework: An international scope

The incident on board the container ship X-Press Pearl serves as a reminder that security and safety measures need to be strengthened. Examining the current regulatory framework is one of the first things that should be done. All shipping companies must be aware of and abide by the international regulatory framework since it is crucial to the safety of crews and ships traveling the seven seas. The global to local regulatory levels of the maritime navigation safety and environmental management system are hierarchically shown in Fig. 3. The United Nations Convention on the Law of the Sea (UNCLOS) is the highest legal document that establishes the fundamental guidelines controlling all uses of the sea and its resources and offers a framework for the future development of particular legal provisions. The International Labour Organization (ILO) and the International Maritime Organization (IMO) share responsibility for maritime affairs; the ILO is in charge of legislation about maritime personnel, while the IMO is in charge of shipping, the environment, and security.

Table 1. Summary of SOLAS chapter II-2 [20].

Part-Name	Regulations	Summary of Content
Part A – General	Regulations 1 – 3	Regulations 1 through 3 in Part A describe the "Application" of this chapter on shipbuilding. The goal and functional requirements of this chapter, as well as the "Definition" of several terminology used in it, are explained in these regulations.
Part B – Prevention of Fire and Explosion	Regulations 4 – 6	Part B of this chapter outlines the requirements for preventing fire and explosion on cargo ships, including tankers. Regulation 4 describes the procedures and restrictions on the use of fuel and lubricant oils on board, as well as the measures taken to avoid fires in the tanker ship's cargo sections to prevent the ignition of a combustible source that may be present on boats. Cutting any one side of the fire triangle is one way to comply with Regulation 5's obligation to stop the spread of fire in various areas of the ship. Furthermore, the goal of Regulation 6 in this section is to lessen the risks to human life posed by smoke and harmful gases released by-products (such as paint, varnish, etc.).
Part C – Suppression of Fire	Regulations 7 – 11	Part C of this chapter consists of five regulations (Regulations 7 – 11) addressing the need to extinguish a fire as quickly as possible. These regulations address the need for smoke and flame detection and control, containment requirements, maintaining the structural integrity of the area to prevent the spread of the fire, and the use of firefighting systems and equipment on ships' machinery, passenger accommodations, and cargo areas.
Part D – Escape	Regulations 12 – 13	Part D concerns how passengers or sailors should flee in the event of a fire or other emergency. Regulation 13 explains the requirements for methods of escape for various ship types (cargo, passenger, RoRo, etc.) and the tools and systems that aid in escaping from hazardous environments.
Part E – Operational Requirements	Regulations 14 – 16	Regulations 14 through 16 in Part E of Chapter II-2 provide details on maintaining the fire detection, fighting, and control systems aboard cargo ships, including tankers and passenger ships. It also explains why fire safety drills and instruction are necessary on-board ships. The fire safety pamphlet is the subject of Regulation 16, which states that all ships must have one on board.
Part F – Alternative Design and Arrangements	Regulation 17	Part F of this chapter describes the alternate layout and design for the ship's fire safety following Regulation 17.
Part G – Special Requirements	Regulations 18 – 23	Part G provides specific requirements for operations performed on tanker and bulk carrier ships, including helicopters (Regulation 18). These requirements include information on various construction, safety, and firefighting arrangements. Safety precautions are outlined in Regulation 19 for transporting hazardous materials in bulk, tanker, and Roro ships. Regulation 20 addresses the prevention, detection, and containment of fire aboard ships transporting vehicles as cargo and passengers. Passenger-focused regulations 21, 22, and 23 outline the procedures a passenger ship must adhere to in the event of an aboard fire to protect the passengers and the ship from a serious mishap.

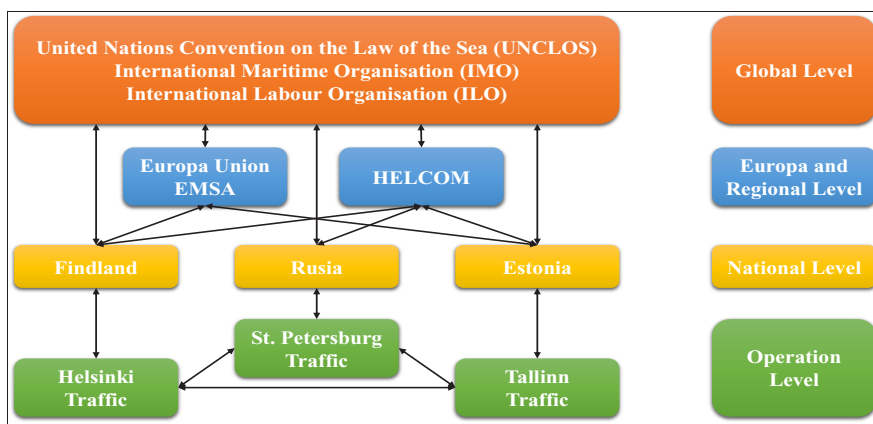


Fig. 3. Marine transport safety regulations are arranged hierarchically, with an arrow signifying the two-way information flow between the various regulatory tiers. (Redefined from [18,19]).

An all-encompassing regulatory framework for shipping, including important conventions, is the goal of the International marine Organization (IMO). This regulatory framework will address marine security, safety, environmental concerns, legal matters, and technical collaboration. A significant agreement that outlines minimum security arrangements for ships, ports, and governments and assigns duties to governments, shipping companies, ship personnel, and port/facility personnel is the International Ship and Port Facility Security (ISPS) Code, which is an amendment to the Safety of Life at Sea (SOLAS) convention. Since July 1, 2002, SOLAS has implemented regulations aimed at ensuring the following three aspects: (1) fires are detected quickly; (2) they can be contained and extinguished; and (3) fires are first prevented from occurring by, for example, enforcing strict controls over materials like carpets and wall coverings to reduce the risk of fire. An essential aspect of this chapter is ship design that guarantees staff and passenger access to evacuation routes. SOLAS chapter II-2, which deals with fire prevention, detection, and extinguishment on ships, is summed up in Table 1.

4. Requirements for fire safety of maritime composites

The utilization of composite materials in maritime structures can be applied starting from superstructures, propellers, propulsion shafts, bow planes, fins, and rudders, until the secondary structures of machinery and engine components. A description of all these applications along with their benefits has been summarized by Tran, Nguyen and Lau [21]. Furthermore, the summary performance of maritime structures against fire will be addressed in the subsections below.

4.1 Laboratory experiments in naval composite performance

Both commercial and military surface ships have fiber-reinforced composites on board, which are well-designed to operate well in typical operational environments. High-temperature gradients produced by typical fires, particularly those involving hydrocarbons, are known to alter composites' structural performance dramatically. According to Tran, Nguyen and Lau [21], marine composites' typical burning/ignition temperature is between 300 and 500°C. However, some composite materials like polyester or vinyl ester used in ship structures have a relatively low glass transition temperature of 120°C, which might cause the composite's performance to deteriorate significantly earlier due to a loss of strength after the glass transition point [22,23].

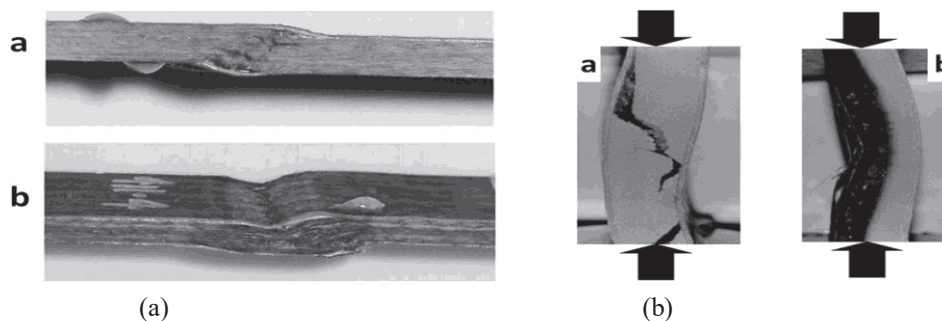


Fig. 4. Failure mode of composite materials: (a) glass fiber composite [23], (b) sandwich composite [24].

The failure mechanism of composite laminates at more significant heat fluxes was significantly influenced by the glass transition temperature, which occurs when the temperature through the laminate thickness approaches to exceed the glass transition point. Diffusion processes in temperature and glass transition point have not governed creep; exposure to lower heat fluxes has induced failure. Figure 4a [23] shows the typical failure modes of glass fiber composites under compression loads and fire. In the meantime, Mouritz and Gardiner [24] have investigated the mechanical behavior of sandwich composites (see Figure 4b) with an emphasis on failure modes in order to comprehend the risk of large heat fluxes involving oil fires (up to 100 kW/m² or more).

4.2 Numerical modelling to predict behaviours

Marine composite structure fire testing is costly, time-consuming, and technically challenging [25,26]. A numerical analysis of composite structure fire performance has been established to forecast composite behavior during fire and post-fire exposure. This subsection will present the modeled fire reaction characteristics and structural response.

Some computational fluid dynamics (CFD) models have been created to forecast the fire behavior of fiber-reinforced polymer composites [26-28]. The pyrolysis of composite material under a 50 kW/m² heat flux and Large Eddy Simulations (LES) combustion [29] are used to create the fire reaction model. Every volumetric element in the simulated zone contains a mixture of air, fuel materials, and combustion products, and the LES model determines the combustion rate. When the oxidizing agent and fuel material are combined at the proper temperature and concentration, combustion begins at the ignition point. When subjected to the necessary heat flow, the solid composite's chemical reaction [30-40] is simulated by the pyrolysis model.

This CFD simulation uses an example of an organoclay-filled composite to show how the computation is done. The resin and organoclay are combined before being infused into the reinforced glass fiber. The S3 composite is the result of curing. A curve representing the degree of breakdown (α) versus temperature for every material is recorded and displayed in Figure 5a. Three samples—the resin, the organoclay, and sample S3—are examined using thermogravimetry analysis (TGA). Next, using Kissinger's approach to calculate the reaction order n , the maximum reaction rate happens at the critical temperature T_m (see Figure 5b).

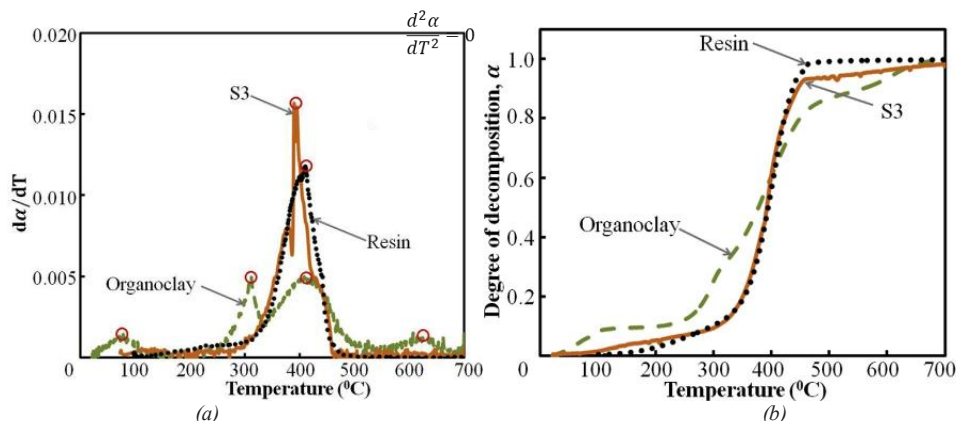


Fig. 5. TGA testing sample curves for resin, organoclay, S3: (a) Change in degree of decomposition α concerning temperature, (b) determination of critical temperature T_m based on each reaction to temperature.

5. Conclusions

A series of comprehensive reviews of the phenomenon of fire and explosion accidents, along with a summary of the effects on the environment, relevant regulations, and some research, have been conducted. According to the data obtained from the open literature, the number of fire and explosion accidents has decreased quite dramatically. However, regulatory updates and research still need to be pursued. IMO, one of the world's organizations, has made regulations to detect fire and prevent accidents in all maritime activities. One of the crucial points of the regulation is to cut off all kinds of potential that can cause the connection of the fire triangle, namely oxygen, heat, and fuel. If this can be resolved quickly and precisely, the potential for explosive phenomena will be reduced. Several research results using experimental methods and numerical approaches have also been added. Some composite materials, such as polyester or vinyl ester, have a glass temperature that can cause the composite performance to deteriorate significantly earlier due to the loss of strength after the glass transition point. Meanwhile, some research using the computational fluid dynamics approach has been conducted. The results show that S3 material has the highest reaction maximum when compared to resin and organoclay, with the highest point at about 400°C.

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