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Causes and Effects of the Rapid Sinking of the Titanic

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Abstract

On April 14, 1912, the R.M.S. Titanic collided with a massive iceberg and sank in less than three hours. At the time, more than 2200 passengers and crew were aboard the Titanic for her maiden voyage to the United States. Only 705 survived. According to the builders of the Titanic, even in the worst possible accident at sea, the ship should have stayed afloat for two to three days. This article discusses the material failures and design flaws that contributed to the rapid sinking of the Titanic. In addition, the article addresses the changes that have been made in both the design of ships and the safety regulations governing ships at sea as a result of the Titanic disaster.

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Introduction

At the time of her construction, the Titanic was the largest ship ever built. She was nearly 900 feet long, stood 25 stories high, and weighed an incredible 46,000 tons [Division, 1997]. With turn-of-the-century design and technology, including sixteen major watertight compartments in her lower section that could easily be sealed off in the event of a punctured hull, the Titanic was deemed an unsinkable ship. According to her builders, even in the worst possible accident at sea, two ships colliding, the Titanic would stay afloat for two to three days, which would provide enough time for nearby ships to help [Gannon, 1995].

On April 14, 1912, however, the Titanic sideswiped a massive iceberg and sank in less than three hours. Damaging nearly 300 feet of the ship's hull, the collision allowed water to flood six of her sixteen major watertight compartments [Gannon, 1995]. She was on her maiden voyage to the United States, carrying more than 2200 passengers and crew, when she foundered. Only 705 of those aboard the Titanic ever reached their destination [Hill, 1996]. After what seemed like a minor collision with an iceberg, the largest ship ever built sank in a fraction of the time estimated for her worst possible accident at sea.

The purpose of this article is to explain the material failures and design flaws that contributed to the rapid sinking of the Titanic. Specifically, brittle fracture of the hull steel, failure of the rivets, and flaws in the watertight compartments will be analyzed. Human factors that contributed to the sinking will not be reviewed. In addition to the causes for the sinking, the effects of the disaster are reviewed. As a result of the Titanic disaster, changes were made in ship design, such as double hulls and taller bulkheads. Also, stricter standards for safety regulations governing ships at sea were implemented, including mandatory use of electronic communication, minimum lifeboat capacities, and the development of the ice patrol.

The first section of the article is a historical overview of the Titanic disaster. This section includes statistics on the Titanic and a time line of the disaster. The next section of the article is a discussion of the material failures and design flaws that contributed to the rapid sinking of the Titanic. In the last section, the design changes made to ships and the safety regulations that have been developed as a result of the Titanic disaster are explained. The article concludes with a review of the causes and effects of the rapid sinking of the Titanic. In addition, the conclusion provides a future perspective on the limitations of the shipbuilding industry.

Historical Overview

The Titanic was a White Star Line steamship built in the early nineteenth hundreds by Harland and Wolff of Belfast, Ireland. At the time of her construction, she was the largest moving object ever built. With a weight of more than 46,000 tons, a length of nearly 900 feet, and a height of more than 25 stories, she was the largest of three sister ships owned by the White Star Line [Division, 1997]. The Titanic was also equipped with the ultimate

in turn-of-the-century design and technology, including sixteen major watertight compartments in her lower section that could easily be sealed off in the event of a punctured hull. Because of her many safety features and a comment by her designer that she was nearly unsinkable, the Titanic was immediately deemed an unsinkable ship [Gannon, 1995].

On April 10, 1912, the Titanic commenced her maiden voyage from Southampton, England, to New York, with 2227 passengers and crew aboard [Division, 1997]. The passengers included some of the wealthiest and most prestigious people at that time. Captain Edward John Smith, one of the most experienced shipmasters on the Atlantic, was navigating the Titanic [Rogers and others, 1998]. On the night of April 14, although the wireless operators had received several ice warnings from others ships in the area, the Titanic continued to rush through the darkness at nearly full steam.

A time line of the events that followed is shown in Table 1. At 11:35 p.m., the lookouts spotted a massive iceberg less than a quarter of a mile off the bow of the ship. Immediately, the engines were thrown into reverse and the rudder turned hard left. Because of the tremendous mass of the ship, slowing and turning took an incredible distance, more than that available. At 11:40, without enough distance to alter her course, the Titanic sideswiped the iceberg, damaging nearly 300 feet of the right side of the hull above and below the waterline [Gannon, 1995].

Table 1. Timeline of the Sinking of the Titanic [Gannon, 1995].

Time	Event
11:35 p.m.	Lookouts spot the iceberg 1/4 mile ahead.
11:40	The Titanic sideswipes the iceberg, damaging nearly 300 feet of the hull.
Midnight	Watertight compartments are filling; water begins to spill over the tops of the transverse bulkheads.
1:20 a.m.	The bow pitches; water floods through anchor-chain holes.
2:00	The bow continues to submerge; propellers lift out of the water.
2:10	The Titanic tilts 45 degrees or more; the upper structure steel disintegrates.
2:12	The stern raises up out of the water; the bow, filling with water, grows heavier.
2:18	Weighing 16,000 tons, the bow rips loose; the stern rises to almost vertical.
2:20	The stern slips beneath the surface.
2:29	Coasting at about 13 mph, the bow strikes the ocean floor.
2:56	Falling at about 4 mph, the stern strikes the ocean floor.

The damage caused by the collision allowed water to flood six of the sixteen major watertight compartments. As water rushed into the starboard side of the ship's bow, the ship began to tilt down in front and slightly to the right. By midnight, water in the damaged compartments began to spill over into others because the compartments were watertight only horizontally and the walls extended only a few feet above waterline.

By 1:20 a.m., water began flooding through anchor-chain holes. Around 2:00, as the bow continued submerging, the propellers in the stern were lifted out of the water. Flooding progressed until roughly 2:10; the bow of the ship was under water and the stern was lifted out of the water almost 45 degrees.

Because of the tremendous weight of the three large propellers in the stern of the ship, the stresses in the ship's midsection increased immensely as the stern was lifted out of the water. At an angle of 45 degrees or more, the stresses in the midsection exceeded the ultimate stresses of the steel and the steel failed [Garzke and others, 1994]. Stresses at failure were estimated at nearly 15 tons per square inch [Gannon, 1995].

What survivors of the disaster then described was a loud noise that sounded like breaking china or falling equipment [Hill, 1996]. This noise can be attributed to the tearing and disintegration of the Titanic's upper structure. By 2:12, with the bow and stern attached by only the inner bottom structure, the stern angled high out of the water. The bow, dangling beneath, continued to fill with water. At 2:18, when the bow reached a weight of about 16,000 tons, it ripped loose from the stern.

Free from the weight of the bow, the stern rose again sharply to an almost vertical position. Slowly filling with water, the stern began to sink into the water. At 2:20, the stern slid beneath the surface. Meanwhile, the bow had been coasting down at about 13 miles per hour (mph). At 2:29, the bow struck the bottom of the ocean. Falling nearly vertical at about 4 mph, the stern crashed into the ocean floor 27 minutes later.

The two pieces of the Titanic lie 2,000 feet apart, pointing in opposite directions beneath 12,500 feet of water. The bow section remains mostly intact, although the damaged portion of the hull is covered with a 35-foot high wall of silt and mud that plowed up when the Titanic hit bottom, so the point of fracture can not be seen. The stern section is a tangled wreck, as implosions occurred during the descent due to air trapped within the structure succumbing to the increased water pressure at greater depths. Between the two sections is a wide field of debris [Hill, 1996].

For 73 years, the Titanic remained undisturbed on the ocean floor. On September 1, 1985, oceanographer Bob Ballard and his crew discovered the wreck of the Titanic about 350 miles southeast of Newfoundland, Canada [Gannon, 1995]. Since then, four more expeditions have visited the Titanic. In 1991, the first purely scientific team visited the site. The dive was called the Imax dive because the purpose was to create a film for Imax theaters. The Soviet submersibles used in the dive were capable of staying submerged for twenty hours and were equipped with 110,000-lumen lamps. With this equipment, scientists were able to take pictures of the Titanic wreck and eventually uncover new evidence into the cause of the Titanic disaster.

Causes of the Rapid Sinking

On an expedition in 1991 to the Titanic wreck, scientists discovered a chunk of metal lying on the ocean floor that once was a part of the Titanic's hull. The Frisbee sized piece of steel was an inch thick with three rivet holes, each 1.25 inches in diameter [Gannon, 1995]. Since the retrieval of this piece of steel, extensive research has been done to uncover additional clues to the cause of the rapid sinking of the Titanic. The following is a discussion of the material failures and design flaws that contributed to the disaster.

Material Failures

When the Titanic collided with the iceberg, the hull steel and the wrought iron rivets failed because of brittle fracture. A type of catastrophic failure in structural materials, brittle fracture occurs without prior plastic deformation and at extremely high speeds. The causes of brittle fracture include low temperature, high impact loading, and high sulphur content. On the night of the Titanic disaster, each of these three factors was present: The water temperature was below freezing, the Titanic was traveling at a high speed on impact with the iceberg, and the hull steel contained high levels of sulphur.

The Hull Steel. The first hint that brittle fracture of the hull steel contributed to the Titanic disaster came following the recovery of a piece of the hull steel from the Titanic wreck. After cleaning the piece of steel, the scientists noted the condition of the edges. Jagged and sharp, the edges of the piece of steel appeared almost shattered, like broken china. Also, the metal showed no evidence bending or deformation. Typical high-quality ship steel is more ductile and deforms rather than breaks [Gannon, 1995].

Similar behavior was found in the damaged hull steel of the Titanic's sister ship, Olympic, after a collision while leaving harbor on September 20, 1911. A 36-foot high opening was torn into the starboard side of the Olympic's hull when a British cruiser broadsided her. Failure of the riveted joints and ripping of the hull plates were apparent in the area of impact. However, the plate tears exhibited little plastic deformation and the edges were unusually sharp, having the appearance of brittle fractures [Garzke and others, 1994].

Further evidence of the brittle fracture of the hull steel was found when a cigarette-sized coupon of the steel taken from the Titanic wreck was subjected to a Charpy test. Used to measure the brittleness of a material, the Charpy test is run by holding the coupon against a steel backing and striking the coupon with a 67 pound pendulum on a 2.5-foot-long arm.

The pendulum's point of contact is instrumented, with a readout of forces electronically recorded in millisecond detail. A piece of modern high-quality steel was tested along with the coupon from the hull steel. Both coupons were placed in a bath of alcohol at -1°C to simulate the conditions on the night of the Titanic disaster.

When the coupon of the modern steel was tested, the pendulum swung down and halted with a thud; the test piece had bent into a "V." However, when the coupon of the Titanic steel was tested, the pendulum struck the coupon with a sharp "ping," barely slowed, and continued up on its swing; the sample, broken into two pieces, sailed across the room [Gannon, 1995]. Pictures of the two coupons following the Charpy test are shown in Figure 1. What the test showed, and the readout confirmed, is the brittleness of the Titanic's hull steel. When the Titanic struck the iceberg, the hull plates did not deform. They fractured.

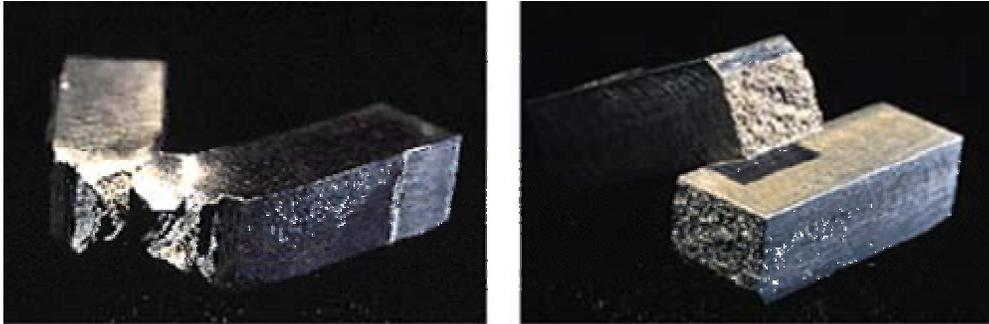


Figure 1. Results of the Charpy test for modern steel and Titanic steel [Gannon, 1995]. When a pendulum struck the modern steel, on the left, with a large force, the sample bent without breaking into pieces; it was ductile. Under the same impact loading, the Titanic steel, on the right, was extremely brittle; it broke in two pieces with little deformation.

A microstructural analysis of the Titanic steel also showed the plausibility of brittle fracture of the hull steel. The test showed high levels of both oxygen and sulphur, which implies that the steel was semi-killed low carbon steel, made using the open-hearth process. High oxygen content leads to an increased ductile-to-brittle transition temperature, which was determined as 25 to 35°C for the Titanic steel.

Most modern steels would need to be chilled below -60°C before they exhibited similar behavior. High sulphur content increases the brittleness of steel by disrupting the grain structure. The sulphur combines with magnesium in the steel to form stringers of magnesium sulphide, which act as "highways" for crack propagation. Although most of the steel used for shipbuilding in the early 1900s had a relatively high sulphur content, the Titanic's steel was high even for the times [Hill, 1996].

The Rivets. The wrought iron rivets that fastened the hull plates to the Titanic's main structure also failed because of brittle fracture from the high impact loading of the collision with the iceberg and the low temperature water on the night of the disaster. Figure 2 shows the Titanic during her construction, with the riveted hull plates of her stern visible. With the ship traveling at nearly 25 mph, the contact with the iceberg was probably a series of impacts that caused the rivets to fail either in shear or by elongation [Garzke and others, 1994].

As the iceberg scraped along sections of the Titanic's hull, the rivets were sheared off, which opened up riveted seams. Also, because of the tremendous forces created on

impact with the iceberg, the rivet heads in the areas of contact were simply popped off, which caused more seams to open up. Normally, the rivets would have deformed before failing because of their ductility, but with water temperatures below freezing, the rivets had become extremely brittle.

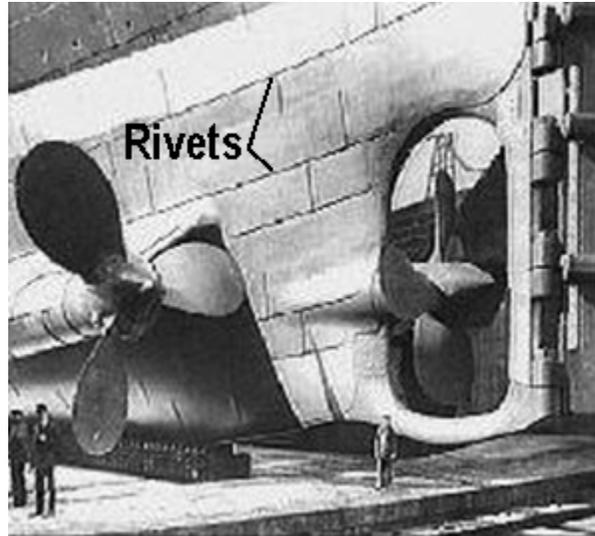


Figure 2. The Titanic in the shipyard during her construction [Refrigerator, 1998]. Note the hull plates, fastened on all sides to the ship's main structure by thousands of rivets.

When the iceberg tore through the hull plates, huge holes were created that allowed water to flood the hull of the ship. As a result, rivets not in the area of contact with the iceberg were also subjected to incredible forces. Like a giant lever, the hull plates transferred the inward forces, applied to the edges of the cracked plates by the water rushing into the hull, to the rivets along the plate seams. The rivets were then either elongated or snapped in two, which broke the caulking along the seams and provided another inlet for water to flood the ship.

Design Flaws

Along with the material failures, poor design of the watertight compartments in the Titanic's lower section was a factor in the disaster. The lower section of the Titanic was divided into sixteen major watertight compartments that could easily be sealed off if part of the hull was punctured and leaking water. After the collision with the iceberg, the hull portion of six of these sixteen compartments was damaged, as shown in Figure 3. Sealing off the compartments was completed immediately after the damage was realized, but as the bow of the ship began to pitch forward from the weight of the water in that area of the ship, the water in some of the compartments began to spill over into adjacent compartments.

Although the compartments were called watertight, they were actually only watertight horizontally; their tops were open and the walls extended only a few feet above the

waterline [Hill, 1996]. If the transverse bulkheads (the walls of the watertight compartments that are positioned across the width of the ship) had been a few feet taller, the water would have been better contained within the damaged compartments. Consequently, the sinking would have been slowed, possibly allowing enough time for nearby ships to help. However, because of the extensive flooding of the bow compartments and the subsequent flooding of the entire ship, the Titanic was gradually pulled below the waterline.

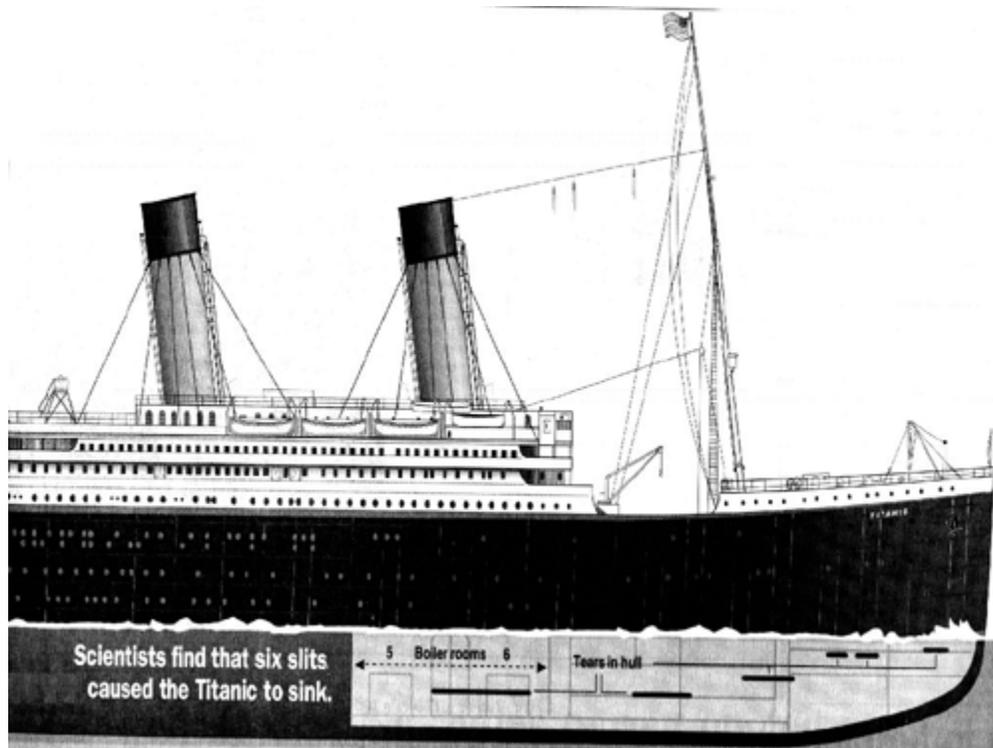


Figure 3. A layout of the watertight compartments and the damage from the collision [Refrigerator, 1998]. The thick black lines below the waterline indicate the approximate locations of the damage to the hull.

The watertight compartments were useless to countering the damage done by the collision with the iceberg. Some of the scientists studying the disaster have even concluded that the watertight compartments contributed to the disaster by keeping the flood waters in the bow of the ship.

If there had been no compartments at all, the incoming water would have spread out, and the Titanic would have remained horizontal. Eventually, the ship would have sunk, but she would have remained afloat for another six hours before foundering [Gannon, 1995]. This amount of time would have been sufficient for nearby ships to reach the Titanic's location so all of her passengers and crew could have been saved.

Effects of the Disaster

In an effort to prevent repeating their mistakes, the White Star Line modified several of their existing ships following the Titanic disaster. The changes were based on the design flaws that were assumed to have contributed to the disaster. Along with these design changes, the White Star Line, and all shipbuilding companies at the time, had newly established safety regulations, agreed upon by both the British and American governments, that they had to follow. Developing safety regulations for ships at sea was another attempt to avoid accidents similar to the Titanic. The following is a discussion of the changes made in the design of ships and the safety regulations implemented as a result of the Titanic disaster.

Ship Design

Following the Titanic disaster, the White Star Line modified the design of the Titanic's sister ships in two ways: the double bottoms were extended up the sides of the hull and the transverse bulkheads of the watertight compartments were raised. The double bottom on ships is constructed by taking two layers of steel that span the length of the ship and separating them by five feet of space [Garzke and others, 1994]. When a ship runs aground or strikes something in the water, the bottom plate of the hull can be punctured without damage incurred to the top plate.

With a double bottom, the chance that a punctured hull would allow water into the watertight compartments is minimized. By extending the double bottoms up the sides of the hull, which adds another layer of steel to the sides of the ship, a similar event can be prevented. If an iceberg, or a collision with another ship, barely punctures the hull, only the space between the inner and outer sidewalls would flood with water. The watertight compartments would remain undamaged.

The ends of the transverse bulkheads of the watertight compartments were raised to prevent a tragedy similar to the Titanic. When the hull of the Titanic was torn open in the collision with the iceberg, water began to flood the damaged compartments in the bow. As the ship pitched forward under the weight of the water in the bow compartments, water began to spill over the tops of the bulkheads into adjacent, undamaged compartments.

Although called watertight, the watertight compartments were actually only watertight horizontally; their tops were open and the walls extended only a few feet above the waterline. By raising the ends of the transverse bulkheads, if a ship were taking in water through the bow compartments and the ship began to pitch forward, the water in the compartments could not flow over the tops of the bulkheads into the next compartments. As a result, flooding of the damaged compartments could be controlled and isolated to only the damaged sections [Gannon, 1995].

At the 1948 Convention on Safety of Life at Sea, specifications for the orientation, length, and number of watertight compartments in passenger ships were established. The

watertight compartments, which improve a ship's ability to withstand the effects of underwater damage, are used to control flooding in the hull of the ship. To maintain a nearly level position, the walls of the watertight compartments are to be oriented horizontally, or across the width of the ship, rather than vertically. If one side of the hull is damaged, the water that fills the hull will even out across the width of the ship.

With vertical walls, the water in the hull would remain on the damaged side of the ship, causing the ship to lean to that side. The length of the watertight compartments is determined by the length of the ship. Shorter ships should have shorter compartments while longer ships should have longer compartments. The number of compartments is also determined by the size of the ship. One criteria that must be met, however, is that the ship must remain afloat with two of the watertight compartments flooded [Muckle, 1951].

Safety Regulations

Along with the changes in ship design that resulted from the Titanic disaster, safety regulations were established to govern passenger ships while at sea. Many of these regulations were established at the 1948 Convention on Safety of Life at Sea. The mandatory use of the wireless, the increased lifeboat capacity, and the implementation of the ice patrol—each of these was developed to prevent accidents similar to the sinking of the Titanic [Garzke and others, 1994].

Wireless is the means of communication for ships at sea. The regulations require that ships exceeding 1600 tons be equipped with wireless apparatus. Use of the wireless is beneficial for ships because they are able to receive weather reports, check their positions, and call for help in emergencies [Society, 1977]. On the night of the Titanic disaster, several warnings were called in to the Titanic from ships aware of her position. Following her collision with the iceberg, the Titanic was able to send out distress signals to other ships with her position and the status of her damage so help was on the way immediately.

Although there was room on deck for twice as many lifeboats, the Titanic carried lifeboats for just over half of the passengers and crew on board. The designer of the Titanic had allowed room on deck for two rows of lifeboats, but one row was removed before the voyage began to make the deck more aesthetically pleasing [Rogers and others, 1998]. With outdated British Board of Trade regulations, the Titanic's twenty lifeboats actually exceeded requirements by 10 percent capacity [Refrigerator, 1998].

The new safety regulations increased the required number of lifeboats to a number that would accommodate all passengers and crew aboard the ship. Based on the length of the ship, a given number of davits, which are the mechanism used to raise and lower the lifeboats, are mounted along the perimeter of the lower deck.

Figure 4 shows the davits and lifeboats on the deck of the Titanic. If the minimum lifeboat capacity is not met, additional lifeboats must be stowed under other boats. Regulations also specify that each of the lifeboats must carry oars, sails, a compass,

signaling devices, food, and water. In addition, for large ships, two of the boats need to be motorboats [Manning, 1956].



Figure 4. The deck of the Titanic [Refrigerator, 1998]. The davits and lifeboats are on the left. The people are walking through the extra space on the deck that was designed to hold the additional lifeboats.

The United States Government began the ice patrol so that ships traveling between England and the United States could be alerted of approaching ice fields. The ice patrol studies and observes the ice conditions in the North Atlantic in order to keep track of where the ice fields are in relation to nearby ships [Society, 1977].

Ice fields, large expanses of floating ice that are more than five miles in their greatest dimension, shift around depending on weather conditions. Therefore, without the ice patrol, ships would need to constantly monitor the positions of the ice fields. For the Titanic, the ice patrol could have informed the captain of the ice fields and surrounding icebergs and instructed him to stop the ship until morning.

Conclusion

The sinking of the Titanic has become one of the most well known disasters in history. Because of the terrible loss of life and the demise of what everyone believed was an "unsinkable" ship, people are intrigued and curious about what caused the rapid sinking of the Titanic. Several theories have developed since the sinking to explain the events that occurred on that fateful night. This article has presented the most probable theory, which has become dominant as a result of evidence acquired during several expeditions to the Titanic site.

The failure of the hull steel resulted from brittle fractures caused by the high sulphur content of the steel, the low temperature water on the night of the disaster, and the high impact loading of the collision with the iceberg. When the Titanic hit the iceberg, the hull plates split open and continued cracking as the water flooded the ship. Low water temperatures and high impact loading also caused the brittle failure of the rivets used to fasten the hull plates to the ship's main structure.

On impact, the rivets were either sheared off or the heads popped off because of excessive loading, which opened up riveted seams. Also, the rivets around the perimeter of the plates elongated due to the stresses applied by the water, which broke the caulking and provided another inlet for the water.

The rapid sinking of the Titanic was worsened by the poor design of the transverse bulkheads of the watertight compartments. As water flooded the damaged compartments of the hull, the ship began to pitch forward, and water in the damaged compartments was able to spill over into adjacent compartments. Not only did the compartments not control the flooding, but they also contained the water in the bow, which increased the rate of sinking.

Following the Titanic disaster, double-sided hulls were added to ships to prevent minor hull punctures from causing major damage. Also, the transverse bulkheads of the watertight compartments were raised so that water could not spill over the tops if the ship were pitched at a slight angle. Safety regulations established after the sinking include the mandatory use of the wireless for large ships, the minimum lifeboat capacity equal to the number of passengers and crew aboard, and the implementation of the ice patrol to warn ships of nearby ice fields.

Understanding the causes for the rapid sinking of the Titanic is necessary to prevent similar accidents in the future. The changes made in ship design and safety regulations following the disaster were effective in decreasing the casualties of accidents at sea.

Examples include the successful rescues of 1600 passengers and crew from the Andrea Doria in 1956, 700 passengers from the Prinsendam in 1980, and all the passengers and crew from Mikhail Lermontov in 1986 and the Oceanos in 1992 [Garzke and others, 1994]. Other lessons need to be learned, however.

Just because shipbuilding companies have the technology to build something does not mean that they should. In the case of the Titanic disaster, the causes for the sinking indicate that shipbuilding technology was far more advanced than the understanding which engineers had of the materials they were using to build the ships.

Glossary

bow: the front section of a ship.

bulkheads: the upright partitions dividing a ship into compartments.

Charpy test: a common test of brittleness in structural materials. A Charpy test is run by placing a specimen against a steel backing and striking it with a large pendulum.

coupon: a cigarette-sized sample of material. Coupons are the test specimens used with the Charpy test.

davits: the small cranes that project over the side of a ship and are used to raise and lower lifeboats.

grain structure: the arrangement or pattern of the particles composing a substance.

ice field: a large, level expanse of floating ice that is more than 5 miles in its greatest dimension.

lumen: the unit of luminous flux equal to the light given off by one candle.

stern: the rear section of a ship.

wireless: a radio telegraph or radiotelephone system.

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