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Why did *Endurance* sink?

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Research Article

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Abstract

Sir Ernest Shackleton's ship, *Endurance*, was crushed by Antarctic sea ice and sank in November 1915. Since then, it has been widely considered that *Endurance* was the strongest polar ship of its time and was lost because ice tore away the rudder. Based on expedition diaries, Shackleton's correspondence, and structural analysis, this paper shows that *Endurance* was not among the strongest ships of its time and that the rudder was not the main cause of the vessel sinking. While the final reason was tearing off the keel, *Endurance* sank because the vessel was simply crushed in compression by ice. This is not surprising, *Endurance* was not designed for compressive conditions in the Antarctic pack ice, but for easier conditions at the ice edge in the Arctic. The weakest part of its hull was the engine room area, which was not only larger than in other early Antarctic ships but also lacked beams to give strength against compression by ice. Comparison with other wooden polar ships is not favourable for *Endurance*: ships designed for compressive pack ice were stronger. It is also evident from archive research that Shackleton was well aware of the weaknesses of *Endurance* even before his expedition set sail for Antarctica.

Introduction

In December 1914, Sir Ernest Shackleton left Grytviken in South Georgia and sailed south with his ship *Endurance*. Shackleton's aim was to reach the Antarctic continent at Vahsel Bay, located at the southernmost edge of the Weddell Sea, and then cross the continent via the South Pole to the Ross Sea. The expedition was called the Imperial Trans-Antarctic Expedition, and it consisted of two parties: Weddell Sea party led by Shackleton himself and Ross Sea party led by Æneas Macintosh. The role of the Ross Sea party was supportive, to transport food depots on the Ross Ice Shelf for Shackleton and his group of men crossing the continent and to take them to New Zealand with the second ship of the expedition, *Aurora* (Shackleton, 1914a, 1920).

Famously, Shackleton did not achieve his goal. In January 1915, before reaching Vahsel Bay and the Antarctic continent, *Endurance* was beset by ice and started to drift northwards. The hull of *Endurance* was not strong enough to withstand the compressive forces caused by the moving ice, and in October 1915, the ship was leaking so badly that the expedition abandoned it and moved to a camp on the sea ice. On 21 November 1915, *Endurance* sank. Shackleton and his men continued drifting north on ice floes, reached Elephant Island on lifeboats in April 1916, and in the end, all 28 members of the Weddell Sea party survived and returned home. The Ross Sea party did not know the fate of *Endurance*, expected that Shackleton was on his way crossing the continent, and hauled food on the Ross Ice Shelf as planned. The chain of depots was ready in January 1916, but three men, including Æneas Macintosh, were lost (Shackleton, 1920).

The story of Shackleton and the *Endurance* expedition has been told numerous times. In addition to general Shackleton biographies and *Endurance* narratives (Mill, 1923; Fisher & Fisher, 1957; Lansing, 1959; Huntford, 1985; Alexander, 1998; Shackleton & MacKenna, 2002; Tyler-Lewis, 2007; Smith, 2014; Verlinden, 2017; Fiennes, 2021, Bound, 2022; Shears & Vincent, 2024), several different aspects of the expedition – leadership and heroism, navigation and ice conditions, lifeboat, cat – have been discussed (Morrell & Capparell, 2017; Barczewski, 2007; May & Lewis, 2015; Bergman, Mearns, & Stuart, 2022; de Vos et al. 2023; Burton & King, 2016; Dunnett, 1996; Alexander, 1997), but a structural analysis of *Endurance* as a ship has never been conducted. This is surprising, considering that the crushing of *Endurance*, and its structural strength, had a central role in the fate of the expedition.

The popular narrative of *Endurance* has two key themes. First, since its launch, it has been repeated many times that *Endurance* was maybe the strongest wooden ship of its time (e.g. Shackleton, 1920, p. 66; Fisher & Fisher, 1957, p. 321; Lansing, 1959, p. 20; Huntford, 1985, p. 370; Bryan, 2011, p. 278; Bound, 2022, p. 325), with very few questioning comments (Tyler-Lewis, 2007, p. 216; Tuhkuri, 2024, p. 320). Lansing's opinions may have been influential in popularising this narrative. His book on *Endurance* became well-known and has been translated into several languages. Lansing wrote: "By the time she was launched on December 17, 1912, she was the strongest wooden ship ever built in Norway – and probably anywhere else – with the possible exception of the *Fram*, the vessel used by Fridtjof Nansen, and later by Amundsen" (Lansing, 1959, p. 20). However, the narrative of *Endurance* as an exceptionally strong ship may already have been started by *The Times* in 1914. *Endurance* became the first ship insured for an

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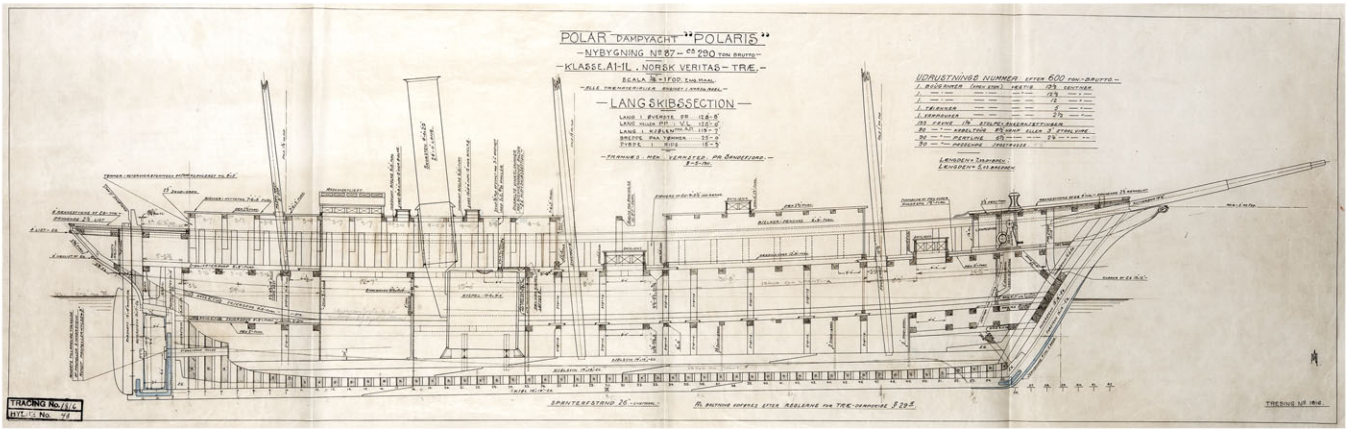

Figure 1. *Endurance*. Cross-section along the centre line, showing the hull structure (Framnæs Mekaniske Værksted, 1911). Reproduced by kind permission of the Vestfoldmuseene.

Antarctic voyage which, according to *The Times*, was not a surprise, because "although very severe pressure from ice is to be anticipated when the vessel is navigating in ice zone, it must be borne in mind that the vessel has been designed to meet it" (The Times, 1914). Newspapers tell us even today that *Endurance* was designed for the pressures in compressive pack ice (Flanagan, 2022; Fountain, 2022).

The other part of the *Endurance* narrative gives one major cause for the loss of the ship: the rudder was the Achilles' heel, and when ice tore away the rudder and the sternpost, *Endurance* was doomed. The rudder as an Achilles' heel was first mentioned by Shackleton in his book *South* (1920, p. 12), and more than hundred years later, the loss of the rudder is still given as the sole cause for the sinking of *Endurance* (Bound, 2022, p. 332).

Together, these two aspects of *Endurance* provide a simple and easily understood story: *Endurance* was as strong as an early polar ship could have been and was lost due to failure of one structural detail, the rudder. But how true is this story?

This paper describes how *Endurance* was crushed by compressive ice and compares its structural strength with other early polar ships. These topics are approached from three directions: (1) from diaries of the members of the *Endurance* expedition, (2) from Shackleton's correspondence and actions at the time, and (3) from a naval architectural analysis of *Endurance* in compressive ice. This kind of study has not been conducted before. It is shown that *Endurance* was not among the strongest polar ships of its time and that the rudder was not the main cause of the vessel sinking. The results are compared with the underwater images of the wreck of *Endurance*, which was found on 5 March 2022, at the depth of 3008 m in the Weddell Sea by the Endurance22 expedition (Bound, 2022; Shears & Vincent, 2024; Morelle & Francis, 2024; Addley, 2024). The underwater images give support to the conclusions of this study. The paper ends with a discussion on the parallel development of wooden polar expedition ships and steel icebreakers in the late 1800s and early 1900s.

Endurance

Endurance was a wooden three-masted barquentine with a length of 43.9 m, beam of 7.6 m and draught of 3.5 m. The ship had also a 350 hp steam engine. *Endurance* was designed by Ole Aanderud Larsen and built at the Framnæs shipyard in Sandefjord, Norway, where Johan Jacobsen was responsible for the construction. The original name of the vessel was *Polaris*, given by Adrien de Gerlache and Lars Christensen, who were the first owners together with other investors. Construction of *Polaris* started in early 1911, and the ship was launched in December 1912 (Verlinden, 2017; Mitchener, 2015, p. 190).

The structure of *Polaris* is shown in Figures 1–3. The ship had three decks: Lower (tween) deck, main deck and, above those, a short bridge deck. Only the main deck covered the whole ship's length. The lower deck was interrupted at the machine room to make space for the steam engine and boiler. In Figure 1, the machine room can be located by the funnel and boiler, and in Figure 3, by the large open area on the lower deck drawing. In the machine room area, only one deck beam spanned the whole breadth of the ship, and five deck beams were discontinuous. The machine room area was, therefore, a weak part of the ship.

The keel was made of oak, four members on top of each other, making a total height of almost 1.5 m (Fig. 2). About 300 mm of the keel was below the hull planking. Frames were oak near the bottom and pine higher up. Planking was pine, sheathed with greenheart. Deck beams were also made of pine, and the connections of beams and frames were strengthened with knees; made of spruce for the main deck and of iron for the lower deck. The bow was strengthened with an iron rail and iron plates.

Polaris was designed and built for polar tourism, for hunting polar bears and walruses in the Arctic. Maybe due to the First World War looming, maybe because de Gerlache and Christense ran out of money, *Polaris* did not make a single voyage to the Arctic and in March 1914 was sold to Shackleton, who changed its name to *Endurance* (Verlinden, 2017).

Weddell Sea 1915

The events that led to the loss of *Endurance* in the Weddell Sea in 1915 are told below using the diaries and memoirs written by members of the expedition. This paper draws on the diaries of Frank Worsley (1916), Harry McNish (1916), Reginald James (1916), James Wordie (Smith, 2004), Frank Hurley (Dixon & Lee, 2011), Thomas Orde-Lees (Thompson, 2020), and Ernest Shackleton (1915), together with the memoirs of Worsley (1931) and Shackleton (1920). There are some differences in the stories, but no contradictions. Memoirs were also written by Frank Hurley (1925), Leonard Hussey (1949) and Frank Wild (Butler, 2011), but they do not add any relevant details to the account.

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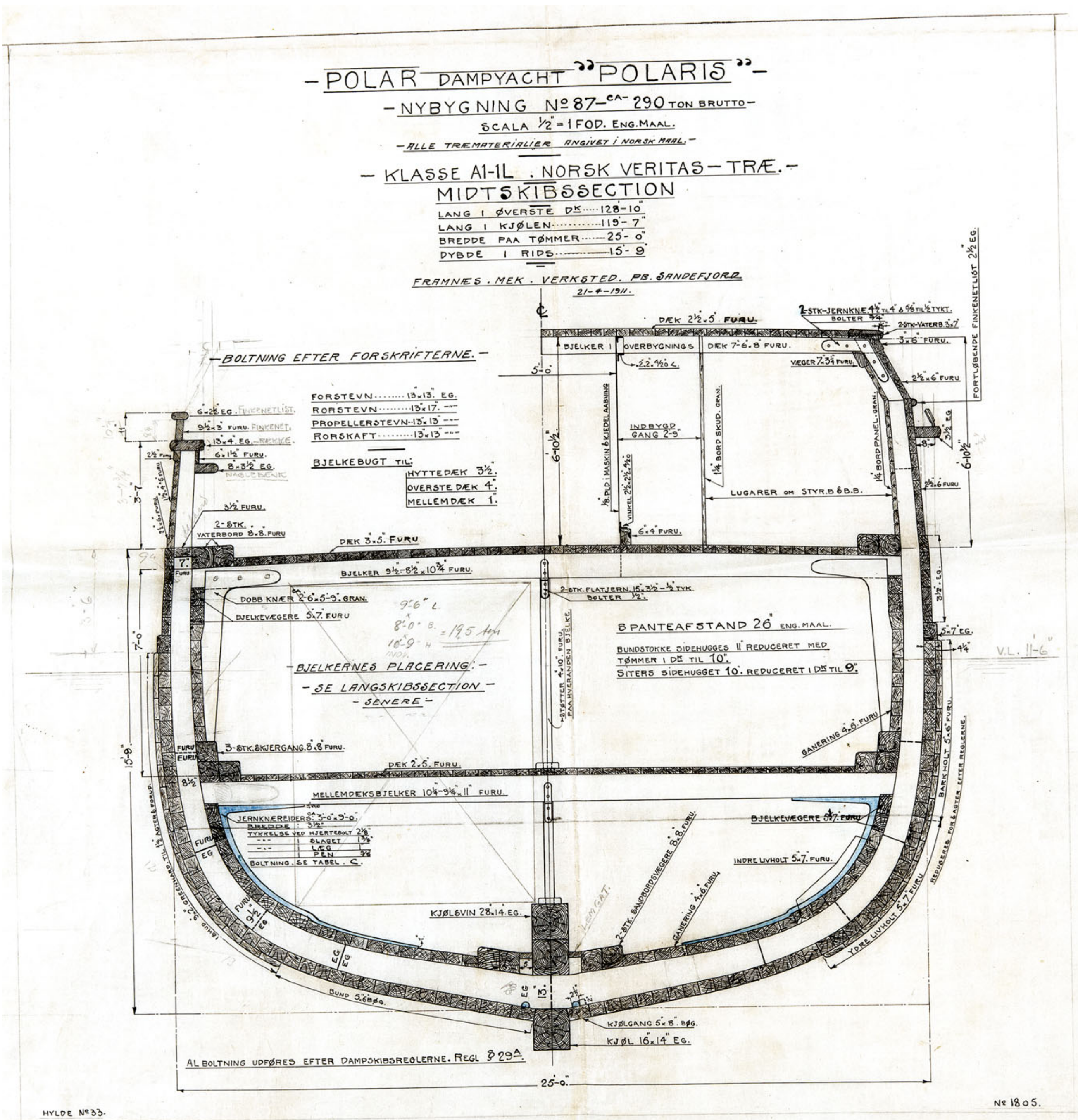

Figure 2. Midship cross-section of *Endurance* (Framnæs Mekaniske Værksted, 1911). Reproduced by kind permission of the Vestfoldmuseene.

Endurance became beset in sea ice in the Weddell Sea on 18 January 1915. A few attempts were made to free the ship, but on 24 February, watches were ceased and the ship became a floating research station drifting northwards with the ice (Worsley, 24.2.1915). Between February and October, when *Endurance* was finally crushed and abandoned, there were five serious events that could have sunk the ship, but the events ended before the forces involved grew too large.

The first serious event occurred on 4 April. Wordie, one of the scientists, heard loud rumbling noises: there was pressure in the ice and an ice ridge, about three metres high, formed near the ship. At the same time, *Endurance* was vibrating slightly. (Worsley, 4.4.1915; Wordie, 3.4.1915. Wordie's diary is occasionally out by one day, sometimes earlier and sometimes later than the other diaries.) If the sail, the above-water part of a ridge, is three metres high, the underwater part of the ridge reaches to a depth of more than ten metres. The vibration, in turn, suggests that ice was failing through a compressive failure process, crushing directly against the ship hull. Crushing of ice results in high ice loads on a small area, high enough to break ship structures.

The second noteworthy event started on 14 July when a violent snowstorm hit *Endurance,* and noises resembling the breaking of ice were heard below the ship. Ship's carpenter McNish rushed on deck but could not figure out where the noise was coming from.

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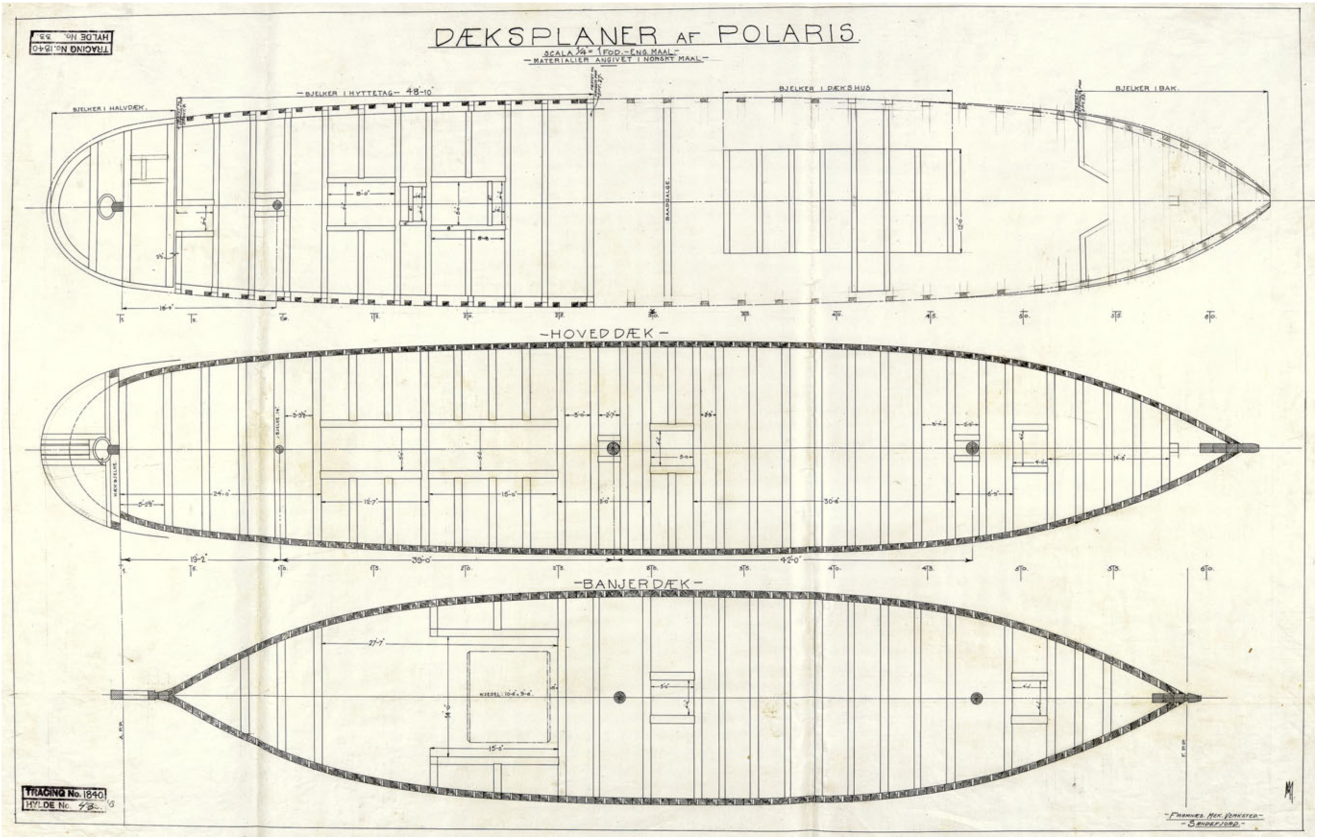

Figure 3. Decks of *Endurance*. From the top: bridge deck, main deck, and lower (tween) deck (Framnæs Mekaniske Værksted, 1911). Reproduced by kind permission of the Vestfoldmuseene.

According to Wordie, Shackleton was very nervous on that day and went several times on deck to check the situation. Boxes stored on deck were carried below, and the deck was cleaned of snow. Shackleton asked McNish to attach runners to a lifeboat. Over the next few days, pressure ridges kept forming in the one metre-thick ice around *Endurance*, and Shackleton, together with his second in command Frank Wild and ship's captain Frank Worsley, started four-hour watches on deck. Food, matches, oil, and other important items were collected on deck. McNish wrote in his diary on 24 July: "We have everything prepared for leaving the ship". (McNish 14.–24.7.1915; Wordie 14.7.1915)

The third dangerous event took place on 1 August. *Endurance* made an abrupt movement, and grinding sounds were heard under the ship. The expedition dogs were at once moved from the ice to the ship, and soon after, the ice floe fractured and ridges started to form near the ship. The ice piled under the ship, lifted it up and heeled first to starboard (right) and then to port. Deck beams buckled, and some of the trenails (wooden pegs) got started under the pressure from the moving ice. Shackleton encouraged everybody to rest as much as possible and to keep warm clothes either on or nearby. Captain Worsley packed his chronometers, sextants and tables, the scientists packed their notebooks, and carpenter McNish placed photos of his family between pages of a Bible, and the Bible into his bag. (James 1.8.1915; Worsley 1.8.1915; Wordie 1.8.1915; McNish 1.8.1915)

Compressive events came and went, and gradually the expedition members got used to them, until 30 September, when the situation escalated fast. Ice started crushing against the ship's hull, which experienced vibrations violent enough to shake the whole rigging and make boxes fall down from shelves. Frames were bent inwards, the tween deck was forced up, bulkheads inside the ship bulged, and linoleum on the floors buckled. It looked like *Endurance* "was going into pieces", as McNish put it, but then the loading ended. This was the fourth of the serious events. (James 30.9.1915; Orde-Lees 30.9.1915; McNish 30.9.1915)

The fifth dangerous ice loading event started on 17 October. Again, the ice piled under *Endurance*. The vessel rose up about a metre and heeled to port, it was possible to see about 20 cm of the propeller. At the same time, loud screeching noises were heard from the engine room where the iron plates on the floor buckled up and rafted over one another. Reginald James, one of the scientists, wrote that "for a time things were not good as the pressure was mostly along the region of the engine room where there are no beams of any strength" (James 17.10.1915). Captain Worsley noted on the same day that "engine room [was] the weakest part of the ship" (Worsley 18.10.1915). Both were right. In the afternoon the following day, events escalated. *Endurance* was still heeled to port and rested against a floe on the port side. At 4.45 p.m., the ice floe broke up, and *Endurance* heeled over to almost 30 degrees to port. At that stage, the keel was visible from the starboard side. Worsley admitted thinking that it was "possible for the floe to force us right over & even override us" (Worsley 18.10.1915). But at 7.45 p.m., the ice around the ship started to fracture and gradually *Endurance* come upright again. (James 17.10.1915; Worsley 17. & 18.10.1915)

The end of *Endurance* started in earnest after dinner on 24 October. The crew heard a loud crash, which was followed by a prolonged vibration of the whole ship. A floe coming from the starboard side had hit the stern and twisted the rudder and the

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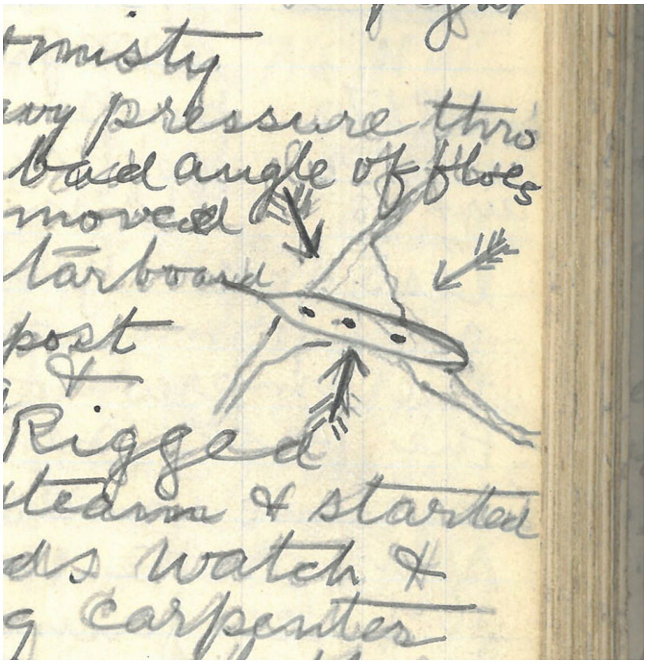

Figure 4. *Endurance* nipped by ice on 24 October 1915 (Worsley, 1916). Reproduced by kind permission of the University of Cambridge, Scott Polar Research Institute.

sternpost, with the result that planks parted from the sternpost on the starboard side. The ship started to leak. However, McNish was able to build a cofferdam in the aft section of the machine room and, together with pumps, it was fairly easy to keep the leak under control. (Worsley 24.10.1915, James 24.10.1915, Hurley 24.10.1915)

Worsley's diary from that day has a drawing of *Endurance* nipped by three ice floes, with arrows showing the motion of the ice. The drawing illustrates how the bow is held by one floe, another floe is loading the stern from the starboard side, while a third floe on the port side is loading *Endurance* at midships (Fig. 4). A drawing of the same event in Shackleton's book *South* (1920, p. 72) is similar, but a mirror image, with the stern loaded by an ice floe from the port side. The underwater images of the wreck of *Endurance* show the rudder at the sea bottom on the port side of the ship (Morelle & Francis, 2024; Addley, 2024), suggesting that the drawing in Worsley's diary is correct.

Worsley's diary has other important information from that day. Together with officers Lionel Greenstreet and Hubert Hudson, Worsley went down to the hold of *Endurance* to clear the ice and dirt from the bilges; the pumps were not working as the pipes were frozen up. The men succeeded in their task, but the work in the cold and darkness was terrifying, and they were relieved when they got back in the open air. A part of the unpleasant experience was the noise within the ship's hull. In his diary Worsley wrote that "...this is not a pleasant job...with the beams & timbers groaning & cracking all round us like pistol shots", and later, in his memoirs say that "we continually expected the ship was going to collapse on top of us and bury us alive" (Worsley, 24.10.1915; Worsley, 1931, p 15). From this, it is evident that, at this stage, *Endurance* was breaking up below the tween deck at midships; not only at the stern near the waterline, where the sternpost and planks met and where the leak was.

The next day, 25 October, was uneventful, but on 26 October, the ice pressure returned. Pressure ridges were forming near *Endurance,* and gradually the active ice failure zone reached the ship. *Endurance* was bent like a bow, the bulwark at midships broke in, windows splintered, deck beams bent, ends of planking on the starboard side opened more than 10 cm, the sides of the ship were bent inwards, and masts were shaking as the tension in the stays varied with the deforming ship. Ice pushed under the ship and lifted it up, which reduced the leak somewhat. (Worsley 25.10.1915; James 25.10.1915; Hurley 25.10.1915; Shackleton, 1920, p. 71–72)

Wednesday, 27 October 1915, was a sunny day on the Weddell Sea. There was pressure in the almost 1.5-metre-thick ice all day, but at 4 p.m., the pressure intensified, raising first the bow and then the stern more than a metre out of the water. *Endurance* was heavily listed to starboard, and a large part of the bottom was exposed from the port side. "The rudder and propeller were buried in a maze of pressure blocks", as James Wordie put it (Wordie 27.10.1915). *Endurance* had become a part of a pressure ridge, and rubble was up to the bulwark level on the starboard side. Then the rudder, sternpost, and part of the keel were torn off; deck beams and decks broke up; the side planking fractured. As a result of all this damage, *Endurance* was filling rapidly with water, and Shackleton ordered the crew to abandon ship, and they got off onto a nearby ice floe. (Worsley 27.10.1915; McNish 27.10.1915; James 27.10.1915; Hurley 27.10.1915; Wordie 27.10.1915; Shackleton, 1915; Shackleton, 1920, p. 76; Worsley, 1931, 17–19)

The expedition abandoned *Endurance* on 27 October, but it was not until 21 November that the vessel sank (Shackleton, 1915). During those weeks, *Endurance* was full of water, but was held on the surface by the buoyancy of the ice rubble under the ship and by the frictional forces maintained by the compressive ice. This was well understood and described by carpenter McNish: "she is down level with the decks now but there is a lot of ice under her & when the floe opens we expect she will sink as she is broken in two halfs" (McNish 9.11.1915). The last six words in his note are important.

The structural damage to *Endurance* can be categorised into four groups, according to their location on the ship:

1. *The rudder and the sternpost*. They were torn off, which is mentioned in all the diaries and is also confirmed by the underwater images from the wreck site (Morelle & Francis, 2024; Addley, 2024). The rudder is at the bottom, on the port side of the stern, in one piece. Beside the rudder is a partly buried beam, which could be the sternpost, based on the location and dimensions as compared to the rudder.
2. *The keel.* McNish wrote in his diary on 27 October that "the keel was ripped off" (McNish 27.10.1915). His observation is mentioned on the same day by Wordie, who shared a tent with the carpenter: "Chippy tells me from his bag that the keel went during the pressure" (Wordie 27.10.1915). Captain Worsley made the same observation as McNish and wrote later in his book: "... part of the keel was driven upwards by the ice" (Worsley, 1931, p. 17). As the ship was heavily listed to starboard, *driving the keel upwards* presumably means driving the keel along the ship's bottom on the port side. The note by McNish, that *Endurance* was broken into two halves (McNish 9.11.1915), is a logical consequence of the failure of the keel. The underwater images show, at some distance forward from the rudder, on the port side, something that could be the end of a displaced part of the keel sticking up from under the ship (Morelle & Francis, 2024; Addley, 2024). The dimensions are similar to those of the beam that was suggested above to be the sternpost. The location on the port side is logical considering the chain of events described above.

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3. *Deck beams*. Buckling and breaking of deck beams are mentioned in all the diaries. This is due to compressive loads on the hull and is well described by Shackleton: "Just before leaving [the ship], I looked down the engine-room skylight as I stood on the quivering deck, and saw the engines dropping sideways as the stays and bed-plates gave way" (Shackleton, 1920, p. 76). The engine room was a large open space without beams and, as Captain Worsley acknowledged, the weakest part of the ship (Worsley 17.10.1915).
4. *Ship's sides*. "The ice has cut clean through the ship", wrote McNish in his diary on 28 October (McNish 28.10.1915). The same was reported by Worsley: "Great spikes of ice were now forcing their way through the ship's sides" (Worsley, 1931, p. 18–19). The underwater images of the wreck of *Endurance* do not show great holes in the sides, but those mentioned by McNish and Worsley may well be buried in the mud on the seabed. On 27 October, *Endurance* was heavily listed and the bottom was exposed. There may be damage there, but we may never know.

The idea of the rudder as the Achilles' heel, as the sole or main reason for the loss of *Endurance*, is not supported by the diaries or memoirs of the expedition members. They had seen their ship demolished by the pressure of the Weddell Sea ice and had described it in detail. What happened to *Endurance* on 27 October 1915 can be summarised by the words of Shackleton: "I cannot describe the impression of relentless destruction that was forced upon me as I looked ... around. The floes ... were simply annihilating the ship" (Shackleton, 1920, p. 76).

What did Shackleton know before the expedition?

What did Shackleton think of the strength of *Endurance* and of its suitability for the Weddell Sea before the expedition? In his book *South*, Shackleton wrote that in building *Endurance*, "shipwrights had never done sounder and better work", and continued: "... no ship ever built by man could live if taken fairly in the grip of the floes and prevented from rising to the surface of the grinding ice" (Shackleton, 1920, p. 66 & 62), giving support to the narrative of an exceptionally strong ship that faced an insurmountable natural force, the Weddell Sea ice. However, as will be explained below, Shackleton was fully aware of the weaknesses of *Endurance* and the risks involved when sailing into the Antarctic pack ice.

Antarctic, Scotia*, and* Deutschland

Endurance was the fourth research vessel to sail into the Weddell Sea. *Antarctic*, the ship of the Swedish expedition led by Otto Nordenskjöld, was caught in compressive ice in November 1902 and sank in February 1903. The story of *Antarctic* is very similar to that of *Endurance*. After *Antarctic* sank, the men moved onto an ice floe, sailed with a lifeboat to a remote island, built a hut from rocks and the lifeboat, and in the end, everybody was saved. The two ships were also crushed by ice in the same way: they were lifted up by the compressive ice, heeled over, vibrating due to the ice crushing on the ship sides; beams buckled, planking broke, rudder and sternpost were damaged and, finally, the end came when the keel was ripped off by an advancing ice floe sliding along the bottom and hitting it. All this is vividly described in the book written by the Swedish expedition (Nordenskjöld et al., 1904). The book also has two interesting notes (Nordenskjöld et al., 1904, Part II, p. 423): "All ships designed for the Arctic Ocean would presumably get damaged in Antarctic waters", and "In short, if *Antarctic* did not have such a [protruding] keel, she would still be sailing the oceans".

Shackleton knew the fate of *Antarctic* very well. He had been involved in the rescue operation, and the book of the Swedish expedition, translated into English, was in the library on board *Endurance*. Shackleton even took the book with him when *Endurance* sank (Shackleton, 1920, p. 229).

In February 1903, at the same time as the ice was crushing the *Antarctic*, a Scottish expedition led by William Speirs Bruce was trying to reach the Antarctic continent on the eastern side of the Weddell Sea. Bruce was careful not to let his ship, *Scotia*, get nipped by ice, and returned north for winter. The following year, ice conditions were easier, and in March 1904, *Scotia* reached the ice shelf. This time, *Scotia* could not escape compressive ice and ice blocks piled against its sides, some ending on the deck. The ice piled up also under the ship, and it was lifted up about a metre. When the compressive situation ended and the ship was freed, Bruce sailed north and escaped from the ice. (Day, 2013, p. 122; Bryan, 2011, p. 190)

Deutschland was the third expedition ship that sailed to the Weddell Sea. Originally called *Bjørn*, the ship was built in 1905 for whaling and sealing in the Arctic. Shackleton had considered buying *Bjørn* for his 1907–1909 Antarctic expedition, but did not have enough funds and ended up buying the cheaper *Nimrod* (Riffenburgh, 2004, pp. 121–123). In 1910, Wilhelm Filchner bought *Bjørn* for the second German South Polar Expedition, renamed the ship *Deutschland*, and took it for modifications to the Framnæs shipyard in Sandefjord, Norway. From there, in February 1911, *Deutschland* sailed to Hamburg, Germany, for final modifications before going south (Filchner, 1922).

Shackleton helped Filchner in his preparations for the expedition (Mill, 1923, p. 185). In early 1911, Shackleton visited Sandefjord while *Deutschland* was there and advised Filchner to strengthen the ship's hull for the Weddell Sea ice by adding diagonal beams to the ship (Filchner, 1922, p. 26). Filchner followed that advice; the modified hull structure of *Deutschland* is shown in Figure 5.

Another important event took place while *Deutschland* was in the Framnæs shipyard. In January 1911, the shipyard signed a contract to build *Polaris*, which would later become *Endurance* (Verlinden, 2017).

Filchner and his expedition reached the southern extremity of the Weddell Sea, the ice shelf that is now called the Filchner-Ronne ice shelf, in early 1912. In March, the expedition headed north, but *Deutschland* got beset in ice. The ice crushed against the hull, and the ship vibrated the same way as *Antarctic* had ten years earlier and *Endurance* would three years later. For eight months, *Deutschland* drifted with the ice, but finally broke free and sailed home.

The crucial difference between *Antarctic* and *Endurance*, which were crushed by the Weddell Sea ice and sank, and *Deutschland*, which survived the compressive ice, were the diagonal supports added in Sandefjord into *Deutschland*. It is noteworthy that this strengthening was planned in accordance with advice from Shackleton and was carried out by the Framnæs shipyard, which was in the process of building *Endurance*. Therefore, both Shackleton and the shipyard knew how to take compressive sea ice into account in ship design, and after *Deutschland* returned

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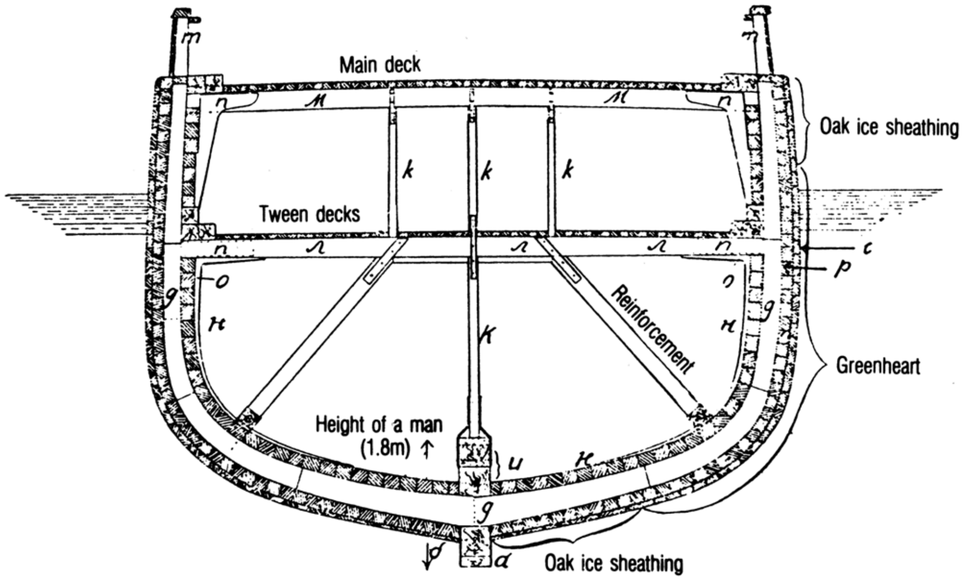

Figure 5. *Deutschland*. Midship cross-section after modifications suggested by Shackleton (Filchner, 1922/1994). Reproduced by kind permission of the Erskine Press.

from the Weddell Sea, both knew that the design had been successful. Why then the hull of *Endurance* was not strengthened in a similar way, after Shackleton had bought the ship in March 1914, is not known.

A letter to Emily Shackleton

Considering that Shackleton had suggested modifications to strengthen *Deutschland*, it is not a surprise that he was monitoring the structural behaviour of *Endurance*. From Buenos Aires, before sailing towards South Georgia and the Weddell Sea, Shackleton wrote to his wife Emily (Shackleton, 1914b):

> "... this ship is not as strong as the *Nimrod* constructionally this I have seen from her way of behaving when in a gale pressing against the dock wall here though there is nothing to be scared of as I think she will go through ice all right only I would exchange her for the old *Nimrod* any day now except for comfort."

Nimrod was the ship Shackleton used on his 1907–1909 expedition. From the letter, it can be assumed that *Endurance* was not stiff enough. Maybe Shackleton had seen its decks and/or sides deflecting under the wind load. Or if he was using the word "strong" the same way as strength is today understood in engineering mechanics, maybe joints between structural members, or some members themselves, had been cracking. Either way, it is clear that wind load on a ship in harbour is smaller than the compressive load from sea ice. For Emily Shackleton, there definitely was something to be scared of.

John King Davis

In 1914, John King Davis was one of the most experienced captains to take a ship to the Antarctic. He had been the first mate of *Nimrod* during Shackleton's 1907–1909 expedition and the captain of *Aurora* during Mawson's 1911–1914 expedition. Shackleton asked Davis to join his expedition to the Weddell Sea as the master of *Endurance*, but Davis declined, and Shackleton chose Frank Worsley instead. In two polite letters to Shackleton, Davis explained that he would not like to commit himself to a long expedition immediately after returning from Antarctica with *Aurora* (Davis, 1914a), but also expressed his doubts about the expedition plans, personnel – and ship (Davis, 1914b). Davis wrote that "no man would embark in a serious enterprise without personally discussing ... what sort of vessel the one chosen would prove to be ..." (Davis, 1914b).

While the letters do not directly comment on the strength of *Endurance*, they show that Davis wanted to discuss the importance of the ship with Shackleton. Two years later, Davis made his opinion clear. In April 1916, when news of the fate of *Endurance* had not yet reached London, Davis met with Douglas Freshfield, president of the Royal Geographical Society, and expressed his fears for the fate of *Endurance*. Davis assumed that *Endurance* had been crushed by the ice pressure. To him, *Aurora* was the strong ship: "unlike the *Endurance*, the *Aurora* was a stoutly build old Dundee whaler" (as cited in Tyler-Lewis, 2007, p. 216). This comment is in line with what Shackleton had written to his wife, that *Nimrod*, another old whaler, was stronger than *Endurance* (Shackleton, 1914b). Both Davis and Shackleton seem to have understood that *Endurance* was a different kind of ship than the wooden whalers, which were often used in early polar expeditions. In his memoirs, Davis continued with this comparison: "... modern engines, fine cabins and good laboratories for the scientists could not compensate for lighter scantlings if she [*Endurance*] met with ice conditions similar or worse than those recently encountered by the *Aurora*" (Davis, 1962, p. 236–237).

Ships in compressive ice – a comparison

Endurance was not built for Weddell Sea pack ice conditions, or for polar winter at all. *Endurance* was built to take tourists to the Greenland Sea, Svalbard, Novaya Zemlya and Jan Mayen during the Arctic summer, from June to September (Verlinden, 2017). The ice conditions at the edge of the polar pack in the Arctic are very different to those deep inside the pack ice in the Antarctic. At the ice edge, ships are mostly dealing with collisions with ice floes. *Endurance* was designed for this kind of ice conditions, and its planking and frames were thick and strong enough for that task. However, in pack ice conditions, where compression from the ice

Table 1. Main dimensions of early Antarctic ships. L is the length, B is the breadth, L_M is the length of machine room area with discontinuous tween deck, and N is the number of stanchions supporting deck beams, see Figure 6 (Bryan, 2011; Mitchener, 2015). For *Aurora*, N is not known. The midship cross-section of *Belgica* (de Gerlache, 1938) does not show a single stanchion, but other drawings of the ship suggest the decks had some support.

Ship	Built	L [m]	B [m]	L/B	L_M [m]	L_M/L [%]	N
Scotia	1872	42.68	8.77	4.9	7.9	19	1
Aurora	1876	50.36	9.33	5.4	4.6	9	–
Belgica	1884	35.97	7.62	4.7	3.8	11	1
Fram	1893	39.00	11.00	3.5	n.a.	0	3
Gauss	1901	46.00	11.27	4.1	n.a.	0	3
Discovery	1901	52.54	10.37	5.1	5.0	9	1
Deutschland	1905	48.50	9.02	5.4	6.8	14	3
Endurance	1913	43.90	7.62	5.8	8.4	22	1

needs to be taken into account, deck beams become of key importance. It is the deck beams that keep the two ship sides apart and maintain the shape of a ship. Without strong enough deck beams, a vessel gets crushed by compressive ice, more-or-less irrespective of the thickness of planking and frames. This is where *Endurance* was not on a par with other early polar ships. There were also other design details that challenge the view that *Endurance* was a particularly strong ship.

Table 1 shows a list of early Antarctic ships. As mentioned above, *Scotia* was used by William Speirs Bruce in his 1902–1904 expedition. *Scotia* was built as a whaler, and before sailing south, it went through significant modifications planned by G.L. Watson. *Aurora* was also built as a whaler and was refitted for the 1911–1914 Australasian Antarctic Expedition led by Douglas Mawson. The refitting was supervised by John King Davis, who became the captain of the ship.

The first ship to winter in Antarctica, *Belgica*, was built in 1884 and used in whaling before being purchased and refitted by Adrien de Gerlache for the 1897–1899 Belgian expedition. *Belgica* has interesting connections to *Endurance*. *Belgica* was designed and constructed in Selvik, Norway and refitted for the expedition in Framnæs shipyard in Sandefjord. In both shipyards, the work was led by Johan Jacobsen. About ten years later, de Gerlache designed *Polaris,* which was built in Sandefjord under the leadership of Jacobsen and later sold to Shackleton, as mentioned above. According to Kjær (2005), "the design of *Polaris* was based on de Gerlache's experience with *Belgica"*. This is easy to understand by looking at the drawings of the two ships, they are very similar in construction. Maybe de Gerlache wanted *Polaris* to be an updated, luxury version of *Belgica*.

Fram, *Gauss* and *Discovery* were all designed and built for polar exploration. *Discovery* was built for the British 1901–1904 expedition led by Robert Falcon Scott. Although a purpose-built expedition ship, the design of *Discovery* followed more-or-less the tradition of whalers and sealers. *Fram* and *Gauss* were altogether a different kind of polar ships.

Fram was designed by Fridtjof Nansen and Colin Archer for pack ice, to survive when nipped in compressive ice. *Fram* was first used by Nansen in his 1893–1896 attempt to reach the North Pole by drifting with the ice, and then by Roald Amundsen in his 1910–1912 Antarctic expedition. In the construction of *Fram*, Nansen and Archer understood two important features: (1) The shape and size of the ship should be such that it will rise when the ice presses against its sides; (2) The vessel should be made strong enough to withstand the greatest possible pressure from ice, from any direction whatsoever (Nansen, 1897, p. 60). *Fram* was successful and showed that a wooden ship can be designed for compressive ice. The design was then followed in construction of *Gauss*, used by Erich von Drygalski in his 1901–1903 Antarctic expedition (Drygalski, 1904).

Hull shape and size

Table 1 shows the dimensions of *Endurance* and some other early Antarctic ships. The length (L) over breadth (B) ratio, L/B, describes the waterline shape of a ship. An ideal shape for compressive ice would be an oval, with no straight parts for the ice to get a grip, that is, no parallel midbody. *Endurance* had a higher L/B than any other of the early polar ships. For *Endurance*, $L/B = 5.8$, while for *Fram*, $L/B = 3.5$ and for *Gauss*, $L/B = 4.1$. Modern Baltic icebreakers have an L/B of about *4.5*. *Polarstern*, a polar research vessel built in 1982, also has an L/B of about 4.5. But while a low L/B is good in ice, it is less so in open water. Both *Fram* and *Gauss* were notoriously slow and rolled easily in open water.

Another aspect of hull shape is the inclination of the sides. *Fram*, a ship designed for compressive ice, had inclined sides so that compressive ice would lift the ship up, rather than crush it. Inclined sides have another benefit. Compressive ice fails in bending against inclined structures as opposed to crushing against vertical structures. The forces due to bending of ice are lower than those related to crushing. However, the inclination of the sides may be an overstated effect. *Endurance* had straight sides but was still lifted up by the ice and also made to heel. In heavy ice conditions, ships often heel and thus the sides become inclined, even if straight when not heeled.

In addition to the shape of a hull, the size of a ship also matters. It is easier for ice to lift a smaller and therefore lighter ship up, allowing the moving ice to slide below the vessel, and not to break against its sides.

Deck beams

Figure 6 shows two idealised cross-sections of early Antarctic ships under compressive loading from ice. The deck beams carry the horizontal load and are themselves supported by vertical supports, stanchions. For a beam in compression, the height (h) and width (b) of the beam cross-section, as well as the span (ℓ), are important. The compressive force F_B that makes a beam buckle is related to h, b and ℓ as follows:

$$F_B \sim \frac{bh^3}{\ell^2} \tag{1}$$

Scotia, Discovery, and *Endurance* were of the design shown in Figure 6(a), and the dimensions of their deck beams are compared in Table 2. The midship cross-sections of these ships show one stanchion at midships and thus $\ell \approx B/2$, where B is the ship breadth. In addition to their dimensions, the number of the deck beams also matters. Table 2 shows the number of beams per metre (N/L). By using $N/L \times bh^3/\ell^2$ as a proxy for the compressive load a ship can sustain, it can be calculated that *Scotia* carried about 2.7 times higher load than *Endurance*. *Discovery*, with higher ℓ, was about 10% weaker than *Endurance* in this respect. The midship

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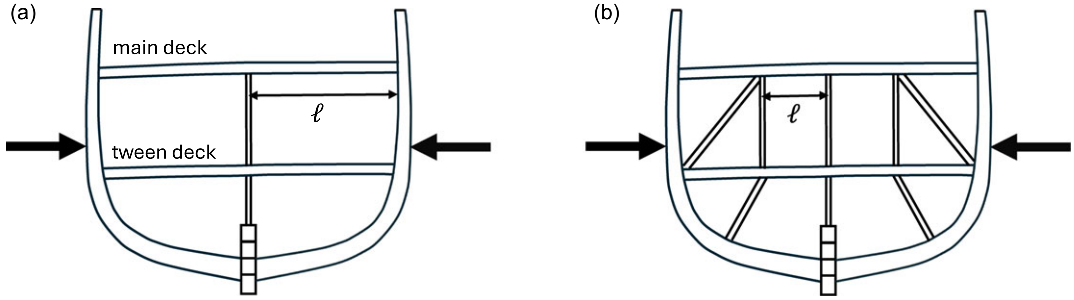

Figure 6. Idealised cross-sections of early Antarctic ships. Thick arrows represent compressive ice load. *Endurance*, *Discovery, Belgica, Scotia,* and presumably *Aurora*, were of the type (a); *Fram*, *Gauss* and *Deutschland* were of the type (b).

Table 2. Dimensions of deck beams (main deck) and frames in *Scotia*, *Belgica*, *Discovery*, and *Endurance*. h is the beam/frame height, b is the beam width, ℓ is the beam span (distance between supports), N is the number of beams on the ship, and L is the ship length (Bryan, 2011; de Gerlache, 1938; Framnæs Mekaniske Værksted, 1911). f_{DB} and f_{FR} indicate the relative ability to carry horizontal loads for deck beams and frames, respectively, normalised to give unity to *Endurance*; $f_{DB} \sim N/L \times bh^3/\ell^2$, $f_{FR} \sim h^2$.

	Deck beams					Frames	
Ship	h [mm]	b [mm]	ℓ [m]	N/L [1/m]	f_{DB}	h [mm]	f_{FR}
Scotia	381	305	4.4	1.05	2.75	305	1.60
Belgica	292	254	3.8	1.28	1.25	288	1.42
Discovery	279	279	5.2	1.33	0.90	305	1.60
Endurance	279	254	3.8	1.05	1.00	241	1.00

cross-section of *Belgica* (de Gerlache, 1938) does not show a single stanchion, but other drawings of the ship suggest that at least some of the deck beams were supported at midships. By using $\ell \approx B/2$ for *Belgica* also, it can be estimated that *Belgica* carried about 1.7 times higher load than *Endurance*. However, if the deck beams of *Belgica* were unsupported, their strength would have been less than half of the strength of deck beams in *Endurance*. Presumably, *Aurora* also had the kind of hull shown in Figure 6(a), but drawings showing its midship cross-section were not found. It is assumed in these comparisons that the material properties of the wood used in the different ships were similar.

Fram, *Gauss* and *Deutschland* were of the design illustrated in Figure 6(b). These ships had three stanchions and diagonal supportive beams. Both the additional stanchions and the diagonal supports are very effective in stiffening and strengthening a ship hull.

The importance of the stanchions comes through the support they give to the deck beams. The modifications suggested by Shackleton to *Deutschland* decreased the deck beam span (ℓ) and more than doubled the strength under compressive loading. By using $1/\ell^2$ to compare ships with different designs, it can be calculated that, due to shorter deck beam spans only, *Fram* and *Gauss* would have carried about two times, and *Deutschland* more than one and half times larger forces than *Endurance*. This comparison considers the effect of deck beam span only and ignores all other dimensions. In addition to shorter beam spans, *Fram* and *Gauss* had more than 1.4 beams per metre, compared to 1.05 in *Endurance*.

The importance of the diagonal supports comes through their ability to resist distortion of a ship hull. A compressive loading is symmetric only when the forces act on both sides at the same height, and a ship is not heeled. However, an ice load becomes easily non-symmetric: it is enough that the ice piles against a ship hull on one side in a different way than on the other side. Such a non-symmetric compressive loading makes a ship heel, but more importantly for this analysis, it distorts the hull. When this happens, the diagonal supports in Figure 6(b) become very effective and make a ship significantly stiffer and stronger than a ship without any diagonal supports.

Frames

Table 2 also compares dimensions of the frames of *Endurance*, *Scotia, Belgica,* and *Discovery*. As ship frames are loaded in bending, the strength is related to h^2, where h is the frame height. From this perspective, the frames of *Scotia* and *Discovery* were 60% and the frames of *Belgica* were 40% stronger than the frames of *Endurance*.

Engine room

Due to the size of the engine and the boiler, many early polar ships, *Endurance* included, lacked a tween deck in the engine room. This created a large open space which, in the longitudinal direction, was defined by a bulkhead in front of the engine room and another behind it. In the vertical direction, the open space was defined by the main deck and the keel. From a structural point of view, the missing tween deck is a challenge, as illustrated in Figure 7. First, with the tween deck missing, all the compressive loading is carried by the main deck, and the strength of the hull is reduced by roughly half. Second, it is difficult to arrange stanchions in an engine room. This increases the span of the deck beams, and thus decreases their strength. Third, the frames lack all the support in the area limited by the main deck and the keel in the vertical direction. The larger the open engine room is, the weaker a ship is.

Table 1 gives the length of the machine room for the ships studied. At 8.4 m, 22% of the ship's length, the machine room of *Endurance* is the longest of all the early Antarctic ships, both in metres and in percentage of the ship length. Figures 1 and 3 show

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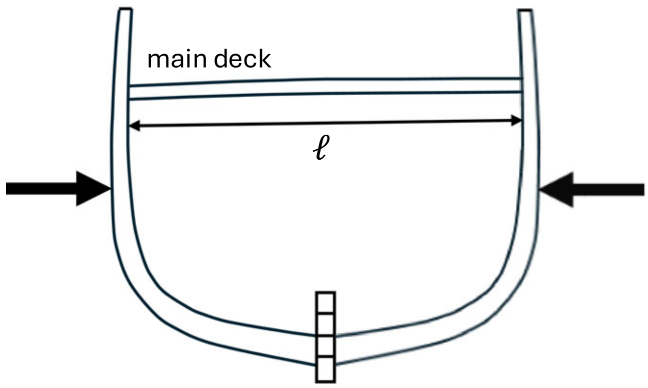

Figure 7. Idealised ship cross-section from a machine room area. Note the lacking tween deck. Compared with the cross-sections illustrated in Figure 6, both the deck span and the frame spans have increased.

the structure of *Endurance* in the machine room area. In addition to the missing tween deck, the main deck has only one continuous deck beam for the whole 8.4 m machine room length. In *Fram* and *Gauss*, the machine room problem is avoided by squeezing the engine and boiler between the decks, allowing the tween decks to extend the whole ship length.

Rudder and keel

Finally, how much is the rudder to blame for the loss of *Endurance*? All appendages in a ship – rudder, propeller, and keel – are in danger when sailing in ice. An ideal hull shape would be that of an egg, with nothing for the ice to get a grip on, nothing to prevent the ice from sliding under the hull. In *Endurance*, about 300 mm of the keel was below the hull planking; in *Fram,* less than 80 mm (Fig. 2; Nansen, 1897, p. 67). *Fram*, *Gauss*, *Discovery,* and *Belgica* had rudders and propellers that could be raised out of the water. *Endurance* had not, and ice tore off its rudder, sternpost and keel.

However, as described above in detail, *Endurance* had several structural deficiencies compared with other early Antarctic ships: the deck beams and frames were weaker than those of the other ships, the machine compartment was longer, leading to serious weakening in a significant part of the hull, and there were no diagonal beams to strengthen the hull. All these aspects caused problems in compressive ice, not only the rudder or the keel.

The simple structural analysis presented above does not support the narrative of *Endurance* as the strongest wooden ship of its time, or even as an especially strong polar ship. If a ranking of the ships discussed is made, *Fram* and *Gauss* are clear overall winners, followed by *Deutschland*. These ships had hulls designed for compressive ice, with well-supported deck beams and additional diagonal supports. Both *Scotia* and *Belgica* had sturdier deck beams and frames, *Discovery* had slightly weaker deck beams but stronger frames, than *Endurance*. All the seven ships discussed in this analysis had a shorter machine room than *Endurance*, making them stronger in that critical area.

Discussion

From a structural point of view, polar ships of the late 1800s and early 1900s can be categorised into three types: (1) wooden ships following the tradition of whalers, (2) wooden expedition ships built for pack ice conditions, and (3) icebreakers and other icebreaking ships made from steel.

Endurance, launched in 1912, is an example of the first type. While *Endurance* was built for polar expeditions, it was one of the last polar ships – if not the last – that followed in the tradition of wooden whalers and sealers. These ships were designed to operate at the ice edge, because that is where whales and seals could be found. The ships had thick and strong sides to cope with collisions with individual ice floes, but were not designed to deal with the compression from moving ice.

Fram was the first expedition ship to deviate from the tradition of whalers. It was specifically designed for compressive ice conditions and was launched in 1893. *Gauss* followed this line of design nine years later. Both *Fram* and *Gauss* had a number of important features: inclined sides, no parallel midbody, retractable rudders and propellers, and diagonal supports to strengthen the hulls.

The benefit of the diagonal supports in compressive ice is so obvious that they were added to several ships that were modified for polar voyages. The strengthening of *Deutschland*, which was conducted in 1911 following the recommendation of Shackleton as mentioned above, was not the first. *Janette*, the ship used by George De Long in his ill-fated attempt to reach the North Pole in 1879, was strengthened with very heavy X-shaped braces, but only at the midbody (de Long, 1884, p. 59). Diagonal supports also were added to *Pourquoi-Pas?*, which in 1908 took a French expedition led by Jean-Baptiste Charcot to the Antarctic (Mitchener, 2015, p. 162).

As the danger of moving ice and compressive loads – as well as how to design a ship for such conditions – was well understood before *Endurance* sailed south, it is fair to ask why Shackleton chose a ship that was not strengthened for compressive ice. We do not know, but when he announced in December 1913 (Shackleton, 1913) that he was going to lead an expedition to the Antarctic the following year, he had neither a ship nor enough funding, and only about six months for all the preparations (Shackleton, 1914a). Maybe he was ready to take a risk in such a situation, even though he knew very well the dangers and understood that *Endurance* was not among the strongest of polar ships. Anyway, not all ships that went to the Weddell Sea had been crushed. Compression in pack ice is never uniform, but concentrated and local. It is not correct to say that *Endurance* had bad luck, but maybe it ran out of good luck in the end. After all, *Endurance* did survive a number of serious ice events before the final crushing on 27 October 1915.

The third type of early polar ships is those built from steel. (Only a few were built by using iron.) When *Endurance* was built, there was a belief that polar expedition ships must be made from wood, not from iron or steel. Mitchener (2015, p. xv) mentions that rivets get sheared off in ice, and Huntford (1985, p. 35) mentions that wooden ships were needed "for elasticity, to avoid being crushed in the ice." Both comments make sense, but do not recognise that, parallel to the construction and use of wooden polar ships like *Endurance*, icebreakers were being designed and built in steel. The transition from wood to steel was slow, but it was taking place.

This development had started in 1868, when A. E. Nordenskiöld sailed with *Sofia*, built in Sweden from iron, to 81° 4' North in Svalbard. In 1878, when Nordenskiöld headed to the Northeast Passage, he had a steel support ship, *Lena*. The first steel icebreaker was *Eisbrecher I*, built in 1871 in Germany, and the first steel icebreaker to visit the Arctic Ocean was the Russian *Yermak*, which in 1901 sailed to Franz Josef Land. In 1912, the year when *Endurance* was launched, Finland had already three steel icebreakers. (Ramsay, 1947)

If the whalers and sealers for polar work were based on tradition and experience, the development of steel ships for icebreaking was supported by scientific work. In 1889, more than twenty years before *Endurance*, Robert Runeberg published a scientific paper on the design of icebreaking ships (Runeberg, 1889). He considered the hull shape, power needed to break ice, details of construction, equipment – and the danger of compressive ice. He wrote: "... [a] ship should always carry a supply of strong timbers of suitable lengths which could be provisionally applied between the sides when the vessel is caught in moving ice. In such a case, if the sides are sufficiently stayed to prevent collapsing, the pressure of ice under the bilges will lift the vessel to some extent out of the water, and the ice, meeting under the keel, will take a part of the thrust, and thus diminish the danger of the situation" (Runeberg, 1889). Runeberg recommended also that an icebreaking ship should have as many watertight bulkheads as possible, and that "the vessel should be able to remain afloat with any two adjoining compartments open to the sea" (Runeberg, 1889). *Endurance* was not divided into watertight compartments at all; *Fram* had three (Nansen, 1897, p. 71).

Could Shackleton and his men have done something differently? Could *Endurance* have been saved? When the Weddell Sea ice was compressing the hull of *Endurance*, the expedition members attempted to relieve the pressure by digging trenches around the ship with picks and shovels, as Thomas Orde-Lees wrote in his diary on 17 October 1915 (Thompson, 2020). Any relief obtained must have been for a short time only, as moving ice would close any trench quickly.

Instead of digging trenches, the expedition could have tried to make the ice floe around *Endurance* stronger by pumping water on the ice and thus making it thicker. Such an ice embankment around the ship would have protected it from high local ice loads; the moving ice would have crushed and piled against the ice embankment, not against *Endurance*. Further, to strengthen the embankment against cracking, the expedition could have frozen ropes into the ice. Such ice would have been similar to pykrete, ice strengthened with wood fibres, developed during the Second World War for potential use as large floating vessels (Gold, 1993).

The underwater images of the wreck of *Endurance* show the ship in one piece and without major holes. *Endurance* looks settled on the sea bottom, its position resembling that of a sailing ship: slightly inclined and the ship bottom under the mud of the seabed (Morelle & Francis, 2024; Addley, 2024; Shears & Vincent, 2024). Are these images in contradiction with the analysis presented in this paper? No, they are not. The images show the rudder and sternpost, maybe also part of the keel, torn off just as described in the expedition diaries. Losing a part of the keel is a major damage that splits the hull into to two halves, even if held together by the remaining structural members. Similarly, buckling and breaking of deck beams are serious damage, even though the hull has not collapsed. That is not surprising, as *Endurance* was still a strongly built ship in the end, if not as strong as other early polar ships. It should also be noted that the underwater images show the hull of *Endurance* roughly from the waterline up, and, therefore, we cannot see the state of the hull in the area where the largest ice loads acted - below the waterline.

This paper has analysed the crushing and sinking of *Endurance* from a structural point of view, by concentrating on the structural geometry and dimensions. In the analysis, simple relations between the dimensions and strength of different structural members (deck beams, frames) were used. A more detailed analysis of the strength of *Endurance* would require modelling larger sections of the ship, one whole deck or several frames, for example. Such a detailed analysis would require information on the ice loads on the hull, which depend on both the ship parameters and the ice and weather conditions around the ship. A recent study by Fogt, Ziegler, King, & Jones (2025) on the role of weather on the fate of *Endurance* is a first step in that direction. In addition, a detailed analysis of the images of the wreck of *Endurance* could increase the understanding of how the ship sank, although it may be challenging to tell apart the damages that occurred before 27 October 1915, when *Endurance* was abandoned, from those that happened after that date.

Conclusions

Why did *Endurance* sink? The popular explanation, given most often since the sinking in 1915, is that the rudder was the Achilles' heel, and when ice tore it off, the ship was doomed. Another part of the popular narrative tells us that *Endurance* was an exceptionally strong wooden ship, maybe the strongest ever built. However, this narrative of *Endurance* as a particularly strong ship that sank due to a single point failure of the rudder is not supported by diaries of the expedition members, other written documents of the time, or structural comparison with other early polar ships.

Endurance did lose its rudder, but that did not sink the ship. *Endurance* would have sunk even if it did not have a rudder at all. If just one simple reason must be given for the loss of *Endurance*, it was tearing of the keel, which broke the ship into two halves, which was fatal. Nor was the rudder the weakest part of the ship. The weakest part was the engine room area, which lacked beams and thus strength against compression from the ice. A more correct explanation would be that *Endurance* was crushed by ice – simply annihilated, as Shackleton (1920, p. 76) put it – without naming a single reason for the sinking.

A comparison with other early Antarctic ships does not show *Endurance* in a favourable light. There is no single aspect where *Endurance* was stronger than the other polar ships of its time. This is not surprising, considering that *Endurance* was not designed to carry compressive loads caused by moving ice floes, as some of its contemporaries were. The deck beams and frames of *Endurance* were weaker than those of the other ships, it did not have diagonal beams, and it had no beams in the machine room area, leading to serious weakening in a significant part of the hull. Maybe *Endurance* was a strong and heroic ship in a poetic sense; in an engineering sense, unfortunately, it was not.

Finally, there is clear evidence that, before sailing towards the Weddell Sea, Shackleton knew that compressive ice loading should be expected, he knew how a ship should be designed for compressive ice, and he knew that *Endurance* was not that kind of a ship. Shackleton was well aware of the risks related to the strength of *Endurance*, but chose to use it anyway.

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