Brittle Fracture in Ships – A Lingering Problem

Introduction

The Lake Carling is a conventional “Handy-sized” bulk carrier with bridge, accommodations and engine room located aft of the five cargo holds. The vessel, constructed in Turkey in 1992 to DNV 1A1 and Polish Registry specifications, is strengthened for the carriage of heavy bulk cargoes including alternate loading arrangements such that holds 2 and 4 may be kept empty. Additionally, the vessel was constructed to DNV ice class 1C specifications. In shipbuilding, grade A steel is often used in the majority of the hull structure, and this is indeed the case for the Lake Carling. The shear strake and strength deck are, however, as per current best practices, of grade E steel.

In the early morning hours of 18 March 2002, after berthing at Seven Islands (Quebec, Canada), loading of iron ore pellets in holds 1, 3 and 5 was commenced. Loading was accomplished according to the alternate hold loading plan in the vessel’s loading manual. The loading and de-ballasting sequence was conducted to keep the bending moments and shear stresses below the harbour limits, as set out in the vessel’s loading manual, and the sequence was verified on the vessel’s loading instrument. In the early afternoon that same day loading was completed, with the vessel’s draughts now at 9.7 meters (m) forward and 10.08m aft. According to the loading instrument, the greatest seagoing Still Water Bending Moments (SWBM) were located at frames 85 (hold 4) and 154 (hold 2), and were 90% and 86% of maximum approved SWBM respectively. By 1400, the Lake Carling was underway.

The initial hours of the voyage were uneventful. The vessel was making approximately 13.5 knots while transiting the Gulf of St. Lawrence with winds generally from the north or northeast between 10 and 20 knots. The next day, when the hatch cover of hold 4 was opened for routine maintenance, the ship’s personnel discovered all was not well with their ship. They could observe a wall of water streaming in on the port side of the hold through a fracture approximately 6 m in length. The ship’s position at this time was 48°16'.8N; 061°21'.5W, approximately 38 nautical miles (nm) north of the Magdalen Islands. Winds were from the north at 20 knots, air temperature was -6° C and water temperature was near 0° C. Sea state was not documented by the crew but, by all accounts, was unexceptional. Calculations and historical data support a wave height of between 1.5 and 2.5 m and a wavelength of approximately 56 m.

On 20 March, shelter was sought to the northeast of the Magdalen Islands as winds were now shifting to the southeast. Continuous pumping had stabilized the water level in hold 4 at about 3250m3.

By 22 March a specialized rescue tug had arrived on scene and the hold had been pumped dry. Bracing work was being fitted to the inside of the fracture to reduce water ingress further. Later in the day winds shifted to the west southwest and increased to 40 knots, with 3 m swells. The decision was made to proceed to the protected waters of the Bay of Gaspé. The transit to the Bay of Gaspé was not without risks, as freezing spray was causing ice accretion on the forward third of the vessel, thus increasing the SWBM. By the late afternoon of 23 March, the Lake Carling had arrived in calmer waters and was safely anchored in the Bay of Gaspé. Once the weather had cleared the vessel was conducted to the port of Quebec City to unload a portion of the cargo and carry out repairs.

Pre-existing cracks

One year earlier, the Lake Carling had undergone an extensive re-fit and dry-docking at Gdansk

(Poland). All holds were carefully scrutinized at that time and no cracks had been documented in hold 4. During the post accident survey, apart from the principal fracture, five other cracks were observed at the bottoms of the side shell frames in this hold – and were clustered between frames 85 and 96. A study of all cargo operations since leaving dry-dock, as recorded by the vessel's crew and the vessel's loading instrument, revealed an overstress event some four months prior to the fracture. The overstress had occurred at the maximum SWBM locations between frames 86 and 91 and was at least 103% of the approved seagoing allowable limit. This event was retained by the Transportation Safety Board of Canada as the most probable genesis of the cracks in hold 4 – culminating in the eventual brittle fracture at frame 91 (TSB 2003).

Steel Tests

The steel in way of the fracture was removed in order to affect repairs and was subsequently examined by the TSB under its mandate to advance transportation safety. During testing, Charpy Vee Notch (CVN) energies were found to be relatively low, as seen in the table below. Fracture mechanics calculations demonstrate that even if the initial crack had been in the order of 10 cm in length just prior to the brittle fracture, a length similar to other pre-existing cracks in hold 4, it would experience brittle fracture when exposed to approximately 11 ksi – a value well below the material's ultimate tensile strength (TSB 2002). In 2003, a sister ship to the Lake Carling, the Ziemia Gornoslaska, called at the port of Montreal to repair small cracks discovered in the side shell. This steel was also tested by the TSB and CVN energies were found to be even less than that found with the Lake Carling steel (TSB 2004).

Temperature (°C)	CVN (Joules)	
	Longitudinal	Transverse
+20	33	29
+10	26	31
0	18	15
-10	10	8
-20	7	7

Historical Overview of Brittle Fracture in Ships

Although the relationship between CVN energy and fracture toughness is not necessarily straightforward, this test has been used with relative success by all of the major classification societies for many years by providing a qualitative estimate of material toughness. There are, however, no requirements to use steel of a given CVN energy in way of the ship's side shell, which is usually grade A steel. According to the IACS Unified Rules, grade A steel less than 50 mm thick (and grade B 25 mm or less in thickness) does not have to demonstrate a minimum CVN. Nonetheless, cargo vessels may be called on to trade in zones where ambient temperatures are close to, or below, zero and these low temperatures generally tend to reduce the ability of the steel to resist crack growth. Cracks are relatively common at one time or another in a vessel's history; hence the desirability of having side shells constructed with steel of known and sufficient toughness to ensure adequate fracture toughness and damage tolerance in all operational conditions, including temperatures down to zero degrees Celsius.

Historically, brittle fracture in ships has been a concern since the spectacular structural failures of the Liberty ships and T-2 tankers during and subsequent to World War II. By the mid-seventies standards had risen but brittle fractures in ships were still occurring even though ship design and crack arrester strategies, in addition to the fracture toughness of some (although not all) steel, had been adopted in an attempt to achieve fracture-safe performance. Recently, Lloyd's Register (1999) carried out tests of grade A steel from steelmakers worldwide due to the continuing concerns about the susceptibility of this steel to brittle fracture. The results of these tests concluded that there has been a significant improvement in steel quality over the past 40 years. However, the Lake Carling and her sister ship the Ziemia Gornoslaska are indications that, insofar as toughness is concerned, there are still sub-standard steels in use for ship side shells. A recent evaluation by IACS of risk control options (RCO) in respect of the side shell integrity of bulk carriers identified 15 RCOs, 11 of which were put forward for further investigation. Although one option called for the requirement to use notch toughened steel and associated welding consumables for frame brackets, toughness of the metal used in the side shell was not addressed or identified as an RCO.

Brittle Fracture in Ships – an Underestimated Phenomenon

It is well known that side shell failure is the cause of many vessel losses. Although it has been assumed that wastage is responsible for many of the side shell failures, many losses have never been properly investigated, so the true root causes of the failures have remained hidden. Additionally, there are many vessel losses that have simply been left as unexplained, again due to a lack of proper investigation. It is hard to find any other industry that has such a critical void of knowledge as to the causes of so many of its' serious failures. On the other hand, the challenges to investigators in this industry are greater than most due to the difficult task of simply finding the wrecks, or, once found, gaining access to them. The Derbyshire and the Prestige investigations have demonstrated, however, that where there is a will, there is a way. Finding the root cause of a failure is the fundamental principal behind advancing safety. Even in an industry such as railway transportation, where every failure can potentially be studied in detail, the stubborn deficiency of low toughness steel has only recently been revived. After the derailment and subsequent release of anhydrous ammonia near Minot (ND, U.S.A.) in 2002, the National Transportation Safety Board recommended design-specific fracture toughness standards for steel pressure tank cars used to transport certain hazardous materials (NTSB 2004).

Based on the number of documented brittle fractures, industry has been slow to move toward a toughness standard for side shell steel. Identifying brittle fracture as a risk for vessels is not easily deduced from statistics nor is it necessarily intuitive. The nexus of the TSB concern, however, is leveraged from an inductive analysis of the Lake Carling occurrence. Many of the known instances of brittle fracture, like the Lake Carling, have occurred in relatively benign conditions, thereby contributing in large measure to the vessel's survival.

Present day strategies to prevent crack propagation throughout the cross section, such as fracture hardened materials on the strength deck, sheer and stringer strakes have thus appeared to work. This has had the two-fold effect of producing a low numerical count and only moderate consequences associated with this type of failure. However, given the substantial number of vessel losses where the root cause has not been determined (classed as "unknown", but also those losses under "weather" or "various"), it would appear logical to attribute brittle fracture as a root cause to a certain proportion of these losses, especially those that occurred in cold water. It is not unreasonable to state that if a significant brittle fracture is suffered far from a port of refuge during bad weather, the vessel will be lost. This is exactly what happened to the Flare as reported in TSB (2000). It is postulated that losses due to this phenomena have, for the most part, gone undocumented, a heretofore invisible sub-set of the "unknown", "weather" or "various" categories of vessel losses.

Vessel Side Shells at Risk

In a major review of a vast amount of available literature concerning the fracture properties of grade A ship plate, Bannister et al (1997) concluded that "...the crack arrest ability of grade A plate is poor and probably inadequate for most ship applications".
Sumpter & Caudry (1995) have suggested that a Fracture Appearance Transition Temperature (FATT50%- Charpy fracture surface is 50% cleavage and 50% tearing) below 0 degrees Celsius is necessary to ensure sufficient fracture toughness for a ship's hull.

In the Lloyd's Register study (1999), nearly 13% of the samples demonstrated a FATT50% above 0 degrees Celsius. Notwithstanding the average high quality of ship plate inferred by this study, these data may also indicate that a significant proportion of steel being produced and used in ship's side shells is of questionable suitability for colder conditions.

Cracks in ships, be they from greater than approved service loads, fatigue, loading/unloading equipment or other sources, are a fact of life in the marine world. All ships operating in cold waters and having their side shell of steel with characteristics similar to those of the Lake Carling are potentially at risk. The damage tolerance could be less than adequate and cracks could remain unnoticed or discounted as insignificant, yet they could still pose a significant risk when exposed to low temperatures. Given the uncertainties and variability of fracture toughness for some grade A and B steels, it would appear that residual risks for unstable brittle fracture are still present in vessels with side shells constructed with these steels, particularly within the critical 0.4L amidships section, and especially when operating in colder climates. Because there are no IACS Unified Requirements to use steel of a certified toughness or minimum FATT in way of a ship's side shell, this safety deficiency shall also remain in a significant proportion of new buildings.

Developments

In February 2005, Canada submitted an information paper at the IMO (Sub-Committee On Ship Design And Equipment, DE 48/24) bringing to light, anew, the lack of toughness standards for steel in way of vessel side shells. The paper opined the desirability of a "goal-based" standard that would ensure steel vessels be constructed such that their side shells are of qualified toughness. The toughness of the steel would be adequate under all expected circumstances such that a reasonable damage tolerance can be predicted and relied upon. The capacity of the IMO to incite change in this regard is, however, very limited. Classification societies, under the auspices of IACS, retain the real ability to affect change in this respect. Needless to say, much work has been undertaken by this body in the past 18 months to unify and consolidate classification rules. Although this will probably result in, among others, marginally more steel during construction, it appears unlikely toughness criteria will be set for vessel side shells.

In a communication sent to the TSB in response to this concern, IACS indicated its intention to carry out critical crack length calculations taking into account the actual material characteristics included in the Lake Carling report. Based on the results of this analysis, IACS would consider whether "to introduce screening of the material properties of shell plating in way of the single skin areas of the cargo and machinery region in ships with ice strengthening." However, low toughness steel in way of the side shell can critically affect a vessel, be it single or double hulled, ice strengthened or not. This approach, even if adopted, may therefore be inadequate to address the safety deficiency.

Concluding Remarks

Because of the insidious nature of low toughness steel, brittle fracture can happen at any time during a vessel's life. Unlike wastage or physical damage, which can be seen or easily measured, low toughness steel manifests no obvious indications of its state. Given the right conditions brittle fracture can strike without warning. Because, generally speaking, grade A ship steel is fine grained and has high CVN energy, this sets a defacto standard - ship owners, ship constructors, and classification societies all expect and depend upon this steel having a fracture toughness that is sufficient for all operational conditions. However, without actual standards, expectations are not always enough to ensure adequate fracture toughness and damage tolerance.

If brittle fracture is to occur there must be a coincidence of several factors, the principal ones being cold temperatures, pre-existing cracks, and low toughness steel. Given one of the over-arching qualitative standards being envisioned by the classification societies is “North Atlantic 25 years” (IACS 2005), then surely minimum toughness criteria for ship side shells must be set sooner or later – hopefully sooner - as the cold oceans have already claimed too many lives.

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* See complete TSB report of the Lake Carling Fracure at;
http://www.tsb.gc.ca/en/reports/marine/2002/m02l0021/m02l0021.asp

This is an electronic version of an article published in Ships and Offshore Structures, Volume 1 No. 3, 2006. Ships and Offshore Structures is available online at informaworld at;
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