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Extreme Waves and Ship Design

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Abstract

Recent research has demonstrated that extreme waves, waves with crest to trough heights of 20 to 30 meters, occur more frequently than previously thought. Also, over the past several decades, a surprising number of large commercial vessels have been lost in incidents involving extreme waves. Many of the victims were bulk carriers. Current design criteria generally consider significant wave heights less than 11 meters (36 feet). Based on what is known today, this criterion is inadequate and consideration should be given to designing for significant wave heights of 20 meters (65 feet), meanwhile recognizing that waves 30 meters (98 feet) high are not out of the question. The *dynamic* force of wave impacts should also be included in the structural analysis of the vessel, hatch covers and other vulnerable areas (as opposed to relying on static or quasi-dynamic analyses).

Keywords

Extreme waves; Rogue waves; Ship design; Ship losses; Sinking; Risk.

Nomenclature

CSR, Common structural rules
ft, foot, feet (0.305 m)
grt, Gross register ton
H_{ext}, Extreme wave height, m
H_S, Significant wave height, m
HTS, high strength steel
HY, high yield strength steel
IACS, International Association of Classification Societies
m, meter
N, Newton
Pa, Pascal (N/m^2)
psf, pounds force per square foot
psi, pounds force per square inch
SSC, Ship Structure committee

Introduction

Recent research by the European Community has demonstrated that extreme waves—waves with crest to trough heights of 20 to 30 meters—occur more frequently than previously thought (MaxWave Project, 2003). In addition, over the past several decades, a surprising number of large commercial vessels have been lost in incidents involving extreme waves. Many of the victims were bulk carriers that broke up so quickly that they sank before a distress message could be sent or the crew could be rescued.

There also have been a number of widely publicized events where passenger liners encountered large waves (20 meters or higher) that caused damage, injured passengers and crew members, but did not lead to loss of the vessel. This is not a new phenomenon; there are well-documented events dating back to at least the early 1940s.

These two facts, vessel losses combined with knowledge that waves larger than previously considered likely may be encountered, suggest that reviewing vessel design criteria may be necessary. (Smith, 2006).

Ocean Wave Environment

Marine weather forecasts report the significant wave height (H_S), which is defined as the average of the highest one-third of the wave heights. A working definition for an extreme wave is one with a height greater than 2.3 times the significant wave height. In mathematical terms, this is:

$$H_{ext} = 2.3 \times H_S \qquad (1)$$

Such waves are often referred to as rogue waves or freak waves, as their height lies at the extreme of what would be expected for a Rayleigh distribution of wave heights. Based on observations made by ship's crews and on limited data from offshore platform measurements and satellite observations, these waves are asymmetrical and have unusually steep faces. They may be preceded or followed by a deep trough.

Ship Design

Ship design is based on a set of prescriptive rules or standards. While this standardization ensures that designs meet operating requirements, it is important that these standardized requirements reflect the actual operating conditions that a ship will see during its service life. As a first approximation for structural design purposes, a seagoing vessel is considered to be a structural beam or girder. A fundamental difference is the fact that it is not connected to rigid supports, but rather is supported by fluid pressure. In addition, because a vessel is in constant motion, it is also subjected to dynamic forces.

Reduced to basic terms, the design of the vessel can be considered in two parts: first is the design of the hull as a girder capable of resisting the bending moments, shear forces, and torsion resulting from the cargo weight distribution and the forces of wind and wave. The second part is the detailed design of local structural elements such as hatch openings, hatch covers, engine and crane supports, bridge windows, and so on. The latter case is an important aspect of structural design whether for aircraft, civil structures, or ships. Failure often occurs at connections, local details, and other areas where stress concentrations can occur.

The reader is assumed to be familiar with ship design, so for conciseness I will not discuss it here. Readers interested in a general overview can consult my book (Smith, 2007), or for an excellent detailed discussion and comparison of ship design standards, see Kendrick and Daley (2007). Central to any design methodology is estimating the prevailing sea state and selecting a design wave height.

As larger and larger ships have been built, alternate methods of determining the design wave height have been used. Current design criteria generally consider significant wave heights less than 11 meters (36 feet). For example, the International Association of Classification Societies (IACS) has issued standard wave data—called IACS Recommendation 34—for use in the design of cargo-carrying vessels in the North Atlantic. (IACS, 2001). Table 1 in the IACS document indicates that most waves (88%) will have periods of 7 to 14 seconds and significant heights of 1m to 10.9 m (3.3 to 35.7 ft) or less. Only 0.2% of these significant wave heights will fall in the range of 11m to 17 m (36 to 55.7 ft).

Ship design necessarily must consider many service conditions, wave height being but one. Military vessels, for example, are designed to withstand shock and overpressure loads not experienced by commercial vessels. Basic ship design considers the moments and shear forces imposed by hogging and sagging loads with the vessel supported on or between waves having the maximum expected height.

The United States Navy uses a design wave height based on the length of the vessel (Fee, 2005), as noted in (Eq. 2).

$$H = 1.1\,(L_s)^{0.5} \tag{2}$$

Here L_s is the length of the ship in feet. Thus, for a vessel 900 feet long, the design wave height would be (1.1)(30) = 33 feet high. Note: Converting the formula to metric units it becomes $H = 0.61\,(L_s)^{0.5}$, where now H and L_s are in meters. Historically, the U.S. Navy has taken the position that the largest wave likely to be encountered was 21.4 m (70 ft.) Based on more recent experiences the navy now believes that larger waves can occur, but that they are unstable and only last for a brief period. The possibility of extreme waves that are steeper and possibly do not have longer wavelengths is now recognized.

Once the loads are established, finite element methods are used to calculate the primary stresses in the ship's ribs, longitudinals, and other main structural elements, to ensure that the sizing of steel members is adequate for the expected loads. The navy's general criterion is built around a Sea State 8 condition. In Sea State 8, the significant wave height is about 14 m (45 ft). This is typical for most hurricanes. Hurricane Camille is one of the best recorded hurricanes, and the navy uses a wave scenario based on this hurricane in their ship models to check for dynamic stability and survivability. On the basis of other analyses, the navy has not had to make any fundamental changes in ship design as a result of the prospect of a wave greater than 21.4 m (70 ft). Naval vessels appear to already have sufficient strength built into them to survive an encounter with a larger wave using the existing criteria.

The energy carried by a wave is proportional to the square of its height. For this reason, a 30.5 meter (100 foot) high wave will hit a vessel with four times the force of a 15 meter (50 foot) high wave. If a high wave is traveling at 35 knots and a vessel traveling at 20 knots runs into it bow first, the combined velocity of the impact is 55 knots. The resulting slamming force has the potential to seriously damage the bow structure.

Consequently, other parts of the ship structure that may be subject to wave forces are also examined to ensure that they are sufficiently strong to resist the forces that will occur. The next step is the design of the deck plate for "deck wetness." Those areas subject to extreme deck wetness are the bow area and parts of the superstructure that encounter extreme wave loading due to wave slap and the dynamic load of large amounts of water pouring onto the deck in an extreme wave encounter. The basic design criterion is to assume a pressure of 24 kPa (500 psf) for any area that is prone to "green water" (wave slap). Most navy vessels are designed for at least 71.9 kPa (1500 psf), and some unique parts of a structure, such as the sponsons on an aircraft carrier, are designed for as high as 359 kPa (7,500 psf). In addition, a static head equivalent to a column of green water 2.4 to 3.1

meters (8 to 10 feet) high is designed in the forward part of the vessel that is likely to encounter waves. This is reduced linearly as you move aft from the bow of the vessel where a value of 30.6 kPa (640 psf) is used to a minimum value of 1.2 meters (4 feet) of head, equivalent to about 12.3 kPa (256 psf). Military vessels include additional design conservatism to account for the need to resist blast over pressure during combat operations.

Both military and commercial vessels are designed to stay afloat with one or more hull compartments flooded. In the case of commercial vessels, one or two flooded compartments is the norm, while for the navy it is three.

The military has progressed from using steel with a yield strength of 207 to 276 MPa (207 to 276 N/mm^2 or 30,000 to 40,000 psi) called HTS or high strength steel to using high yield strength steels (called HY steels) that have a yield strength of 551 MPa (80,000 psi). Submarines use 714 MPa (100,000 psi) HY steel. The norm for commercial ships is HTS at 276 MPa (40,000 psi). Further verification of ship designs is accomplished by carrying out model tests in wave tanks. Once the vessel is commissioned, it will undergo sea trials to verify performance and operational characteristics.

IACS Common Structural Rules

One of the vagaries of ship design is that there are no uniform codes or international standards as in the case of building design. Instead, ship design has evolved from centuries-old traditions where ship insurers inspected and classified vessels in accordance with the risks they perceived and the premiums they would impose. Over time this system evolved from vessel inspection to a classification system that stipulated design rules for a vessel to be eligible for rating in a specified class. Today there are more than 50 classification societies worldwide, each with different rules. The rules vary depending on the type of vessel as well.

In 1968 a group of classification societies formed the International Association of Classification Societies (IACS). Today the IACS membership consists of 10 classification societies representing China, France, Germany, Italy, Japan, Korea, Norway, Russia, United Kingdom, and United States. The IACS claims that its members collectively class more than 90 percent of all commercial tonnage involved in international trade. Historically IACS resolutions have not been mandatory for implementation by member organizations, which have been free to develop their own rules for ship design.

In response to growing discontent by ship owners concerned about the fact that ships being built today are less robust, three classification societies announced in 2001 that they would work together to establish common design criteria for standard ship types, beginning with tankers. Subsequently, a task force was formed to develop common structural rules for bulk carriers (IACS, 2006). As part of this effort, vessel inspection reports were reviewed to assess problem areas. The IACS reported that the majority of bulk carriers lost were more than 15 years old, were carrying iron ore at the time, and failed as the result of corrosion and cracking of the structure within cargo spaces, and as a result overstressing by incorrect cargo loading and cargo discharging operations. (IACS 1997). Curiously, there was no mention of extreme waves or rough seas as a cause of failure. The *Derbyshire*, only 4 years old, likely sank when 20+m (70 ft) high waves collapsed hatch covers (Tarman and Heitman, no date). Incidentally, bulk carriers continue to sink, the most recent example being May 2006 when 190,000 gt *M/V Alexandros T* broke up off the coast of South Africa in an area noted for extreme waves.

In 2004, the chairman of the IACS council, Ugo Salerno, issued a letter reporting on the status of common rules for oil tankers and bulk carriers. (IACS, 2004). Salerno stated that IACS's objective is that the new rules will be adopted and applied uniformly by all IACS members. The new ship design criteria—called *Common Structural Rules*—were released in April 2006, and will apply to tankers and bulk carriers designed and constructed after that date. The design wave loads in the new rules will be based on IACS Recommendation 34, described previously.

Should Design Loads be Increased?

Although the IACS Common Structural Rules (CSR) for bulk carriers state that they are based on IACS Recommendation No. 34, "Standard Wave Data," the relationship is not obvious. (IACS 2001). The CSR (see Chapter 1 page 17) defines a "wave parameter" C that is a function of vessel length and has a maximum value (dimensionless) of 10.75. The CSR rules specify material properties and design calculations that are required for vessel classification. The rules also contain a number of "check values" that stipulate certain minimum parameters, such as minimum hull plate thickness, that must be met by the design. In other words, the designer can use his or her own methods to size structural members but must ensure that results meet or exceed the checking criteria.

To get a feel for applying the CSR, I made a series of calculations for a hypothetical bulk carrier based on these parameters:

Rule length L = equal to 275 m (900 feet)
Breadth B = 45 m (147.5 feet)
Depth D = 23.8 m (78 feet) depth.
Draught T = 17.5 m (57.4 feet) displacement.
Displacement Δ = 161,000 metric tons

Here the nomenclature is as given in the CSR chapter 1 page 16.

Applying the CSR formula in this example gives a wave parameter of C = 10.625. (The maximum value of C = 10.75 is to be used for vessels 300 to 350 meters in length.) The wave parameter is used in various formulas in the CSR to calculate the bending moment and shear forces at various positions along the length and height of the hull and also in determining the hydrodynamic pressure at various locations. The procedures consider hogging and sagging as well as various sea states, such as bow-on, following seas, beam seas, et cetera.

In the CSR formulation the wave parameter is dimensionless but has a numerical value very close to the design wave height determined by the US Navy criteria (Eq. 2), i.e., $C = 0.61 (L)^{0.5} = 10.56$ meters when L = 300 meters.

Table 1 summarizes the results of my sample calculations. The notation "min or max" in the table means that this is a check value and the actual value calculated by the ship designer must be greater than or less than this value.

Table 1: CSR Sample Calculations

Material = AH steel with minimum yield stress 315 N/mm^2 and k= 0.78

Vertical wave bending moment, midship, deck level

- Hogging 4.98×10^6 kNm
- Sagging 5.68×10^6 kNm

Vertical wave shear force = 56,200 kN

Hydrostatic pressure, 8.75 m below waterline = 88 kN/m^2

Hydrodynamic pressure = 122 kN/m^2

Pressure on exposed decks and hatch covers = 35.8 kN/m^2

Normal stress due to vertical bending = 315 N/mm^2 (max value)

Shear stress = 154 N/mm^2 (max value)

Material thicknesses:

- Cargo area hull plate thickness, 22.6 mm
- Bow area, intact condition, 27.8 mm
- Bottom, inner bottom, 13.75 mm (min value)
- Weather strength deck, 10.0 mm (min value)
- Side shell, bilge, 14.1 mm (min value)
- Hatch cover plate thickness, 10 mm (calculated)
- Hatch cover plate thickness, 5-6 mm (min value)
- Note: thicknesses are “net” and must have a corrosion allowance of 2 to 4 mm added.

Lateral pressure, side of superstructure 29.9 kN/m^2

Pressure on exposed deck at superstructure level, 22.4 kN/m^2. Toughened window glass, 8 mm (min value).

The effort to develop the CSR is laudable, and hopefully will lead to greater consistency in the design of new vessels. One question is whether or not a maximum wave parameter of 10.75 is adequate.

Ship Failure Modes

There are several ways in which a large vessel could conceivably founder under the impact of wind and wave. Typically it is a chain of occurrences rather than a single event. For example, due to wave damage, a vessel could lose power or sustain rudder failure, which might then cause it to wallow in beam seas, in turn causing the cargo to shift and the vessel to list, take on water, and capsize. Or, wave damage to hatch covers, hatch coamings, deck equipment, or the hull itself could lead to flooding of holds or compartments, loss of freeboard, and eventual sinking.

Failure of structural integrity is common to several loss scenarios so it is of interest to estimate the order of magnitude of stresses imposed by large waves. Such stresses can be considered in three categories: hydrostatic loads, hydrodynamic loads, and impulse loads.

In Table 2 I compiled the hydrostatic force of a column of sea water of various heights. This could be considered the deck or hatch cover static load caused by green water flowing over the vessel (keep in mind that the actual load would be greater due to hydrodynamic forces acting in addition to the static load). The table also includes the original design criteria for the Derbyshire hatch covers, the Derbyshire hatch load at failure (as determined by SSC), typical deck and hatch loads using the CSR methodology (Chap. 4 pg. 23, Chap. 5, p.29) and some of the United States Navy guidelines mentioned above.

Table 2: Hydrostatic Load Points

Static Head (m)	Static pressure psi	Static pressure kN/m^2	Notes
1.0	1.46	10.1	
1.7	2.48	17.1	(1)
2.0	2.92	20.1	
2.38	3.47	23.9	(2)
3.0	4.37	30.2	
3.56	5.19	35.8	(3)
5.0	5.29	50.3	
5.32	7.76	53.49	(4)
6.0	8.75	60.3	
7.15	14.4	71.9	(5)
10	14.6	100	
15	21.9	151	
20	29.2	201	(6)
25	36.5	251	

Notes:

1. *Derbyshire* DnV design load.
2. USN 500 psf criteria.
3. CSR design load, decks, hatches.
4. *Derbyshire* hatch load at ultimate Stress (3.125 x design), (Tarman and Heitman).
5. USN 1,500 psf criteria.
6. *Derbyshire* hatch load likely during

Typhoon Orchid, (Tarman and Heitman).

Hydrodynamic loads ("wave slap") can impose greater stresses on marine structures than the hydrostatic load of green water. In heavy seas, an envelope of operating conditions bounded by predominant wave periods of 7 to 18 seconds, wave lengths of 50 to 250 meters, wave heights of 10 to 30 meters, and wave crest velocities of 10 to 35 meters/seconds would encompass dangerous conditions. Using Bernoulli's equation, the hydrodynamic loads for typical conditions can be found as noted in Table 3 using Eq. 3.

$$P_d = \tfrac{1}{2} C_p \rho v^2 \qquad (3)$$

Where P_d is the hydrodynamic pressure in N/m^2, C_p is a factor to account for concentrated loads, ρ is sea water density, 1,025 kg/m^3, and v is velocity, m/sec. C_p is given the value of 3 for global loadings and 9 for local, concentrated loads. (Faulkner, 2001).

Table 3: Hydrodynamic Loads

Velocity m/sec	Pressures, kN/m^2	Global	Local
	C_p =1	C_p =3	C_p =9
10	51.3	154	461
15	115	346	1,040
20	205	615	1,850
25	320	961	2,880
30	461	1,380	4,150
35	628	1,880	5,650

In addition to the dynamic loads estimated above, plunging or breaking waves can cause short-lived impulse pressure spikes called Gifle peaks. These can reach pressures of 200 kN/m^2 or more for milliseconds, leading to brittle fracture of mild steel. Evidence for this type of failure was found when *Derbyshire's* wreckage was surveyed. (Faulkner, 2001).

As noted above in Table 2, the CSR design load for hatches is a static head of 3.6 m corresponding to a pressure of 35.8 kN/m^2. This value would be exceeded by waves 4 m high or by waves with an incident velocity of 10 m/sec. But would the hatch fail?

Are the CSR design criteria adequate?

The IACS CSR design criteria are intended to insure that stresses remain less than the yield stress of the selected material. This being the case, the expectation is that there is a safety factor of around 3 before the ultimate stress is exceeded and failure occurs. In the case of exposed decks and hatch covers this value corresponds to a wave 10.7 meters high or a pressure of 107 kN/m^2. Considering that the hatch covers, deck, and hull are structures fabricated of plates supported by beams and stiffeners, failure could occur by bending or shear.

In bending, the plate deforms elastically until some point reaches the yield point. In the case of a plate rigidly supported at the edges and uniformly loaded, yielding occurs at the center and edges. Plastic failure occurs when yielding and resulting plastic flow propagates throughout the section. This is known as a three-hinge plastic collapse because the three yield points at the center and edges act as hinges and allow the plate to collapse under the applied load.

To fail in shear, the applied load has to be considerably greater, sufficient to exceed the ultimate shear strength at the edge supports.

To check hatch failure for the hypothetical vessel described above, I made two further assumptions: hatch plate material thickness 12 mm (10 mm + corrosion allowance of 2 mm) and unsupported span distance b of 600 mm. Material is still AH steel with a minimum yield stress σ of 315 N/mm^2. Shear yield stress is taken as $\tau = \sigma/(3)^{1/2}$. Two potential failure modes to consider are the three-hinge plastic collapse and the edge shear yield.

The three-hinge plastic collapse pressure P_c in kN/m^2 can be found from equation 4 and the edge shear yield pressure P_e from equation 5. (Faulkner, 2001).

$$P_c = 4.5\, \sigma\, (t/b)^2 = 423\ kN/m^2 \qquad (4)$$

$$P_e = 2\, \tau\, (t/b) = 5{,}430\ kN/m^2 \qquad (5)$$

These results indicate that a large, fast moving wave (v ≥ 35 m/sec) could possibly cause edge shear failure for a hatch designed in accordance with the CSR. However, and more importantly, plastic collapse would most likely occur first, either from the impact of a wave crest traveling at 20 to 30 m/sec or from the combined load of a slower moving wave with a head of 10 meters or so.

No doubt it can be argued that more sophisticated analyses can be made. Nonlinear finite element models of hatch covers can be developed and subjected to time-dependent wave loadings that more realistically simulate actual sea conditions. For example, in heavy seas, a vessel would be pitching up and down and the freeboard would not be constant. Also, if the vessel is underway, the impact velocity is the sum of the vessel velocity and the incident wave velocity. For a vessel underway at 16 knots and struck by a single rogue wave (as opposed to a vessel hove to in a storm) this velocity difference can be significant.

However, for the purposes of this study these refinements are not important.

The wave loads developed above suggest that vessels designed in accordance with CSR minimum values may in fact be vulnerable to high waves that can reasonably be expected in a 25 year service life. My conclusion is that the current design criteria spelled out in the CSR are inadequate and need to be increased. Specifically, hatch covers, coamings, wheel house windows and deck and bow structures and equipment subject to direct wave impacts should be designed to withstand the impact of fast moving waves 20 meters (66 feet) high.

Evidence for Higher Waves

Today there is considerable evidence for the existence of higher waves. In addition to observations by mariners at sea, there are measurements based on buoys, subsurface pressure transducers, wave height measuring instruments on offshore platforms, and satellite-based radar altimeters. Researchers are looking at installation of ship board wave height measuring instruments to gather more comprehensive data under actual conditions at sea. See Table 4 for examples ranging from 24 to 40 meters (80 to 140 feet).

Table 4: Some Evidence for Extreme Waves

Description and Location (Year)	Wave heights (m) Significant	Extreme
Sydney-Hobart Race (1998)	12-18	43 (M)
Weather ship data ca. 1980:		
Atlantic	13-23	40 (C)
Pacific	11-20	36 (C)
Offshore platforms		
North Sea	--	34 (C)
USS *Ramapo* N. Pacific 1933	--	34 (M)
East Dellwood N. Pacific 1993	12	31 (M)
Ocean Ranger N. Atlantic 1982	--	31 (E)
SS *Bremen S.* Atlantic 2001	--	30 (E)
Submarine *Grouper*, Atlantic	Calm seas	30 (M)
Caledonian Star S. Atlantic 2001	--	30 (E)
Athene Indian Ocean 1977	--	30 (E)
Queen Elizabeth 2 N. Atlantic 1995	--	29 (E)
Hurricane *Ivan* Atlantic 2004	--	28 (M)
Queen Elizabeth N. Atlantic 1943	--	27 (E)
Draupner platform N. Sea 1995	12	26 (M)
Esso Nederland Agulhas	--	25 (E)
MaxWave satellite study 2001	--	24+(M)

Notes: M= Measured, C=Calculated, E=Estimated
Source: Smith (2006) p. 215

Historic Ship Losses

A few decades ago, commercial vessels were lost at the rate of one per day somewhere in the world. Not all of these losses were attributed to heavy seas or extreme waves; the statistics indicated that 41% were wrecked, 28.5 % were lost to collisions, fire or explosion, 28 % foundered, and 2.5% simply disappeared and were never found, "missing and presumed lost." (Bascom, 1980). Today the size of the global merchant fleet is only about half the number of vessels that existed in 1980, but the cargo carrying capacity is actually increased through the use of larger vessels.

While many improvements have been made in vessel safety through improved operations, better weather forecasts, improved radar, and satellite navigation techniques, a surprisingly large number of vessels are still lost each year. For example, in 2006, a total of 261 vessels sank. Of this total, 75 were over 500 gross tons. These numbers are based on data that I have been able to gather; the actual losses are probably greater. Of the 75 vessels that sank, 25% were lost due to the effects of wind and wave. There were at least 10 rogue wave incidents reported in 2006, along with 15 other "large wave" incidents. I cite the following examples to show that the risks are real.

In May, 2006, bulk carrier *Alexandros T*, carrying iron ore from Brazil to China, broke up off the coast of Port Alfred, South Africa, a notorious location for rogue waves. Of the crew of 33, only 5 persons made it to life rafts before the vessel sank. A fishing vessel called *Super Suds II* capsized off shore from South Carolina after taking a big wave on the starboard bow, but the five crew members were rescued. Also in May, a large ferry, the *M/V Pont-Aven*, with 1,100 passengers on board, was hit by a rogue wave, breaking windows, flooding berths, and injuring 5 passengers. It was on its way from Plymouth, England to Santander, Spain, traversing the Bay of Biscay, another rogue wave hot spot. In August, the fishing vessel *Challenger* was swamped by a sudden, unexpected large wave and driven onto the rocks at the west end of Hoy, Orkney Islands, Northern Scotland. The two crewmen were saved. In November 2006, an offshore utility vessel called *M/V Hawk* disappeared off the east coast of South Africa, with no sign of the 4 crewmen. An empty life raft was later discovered. Its condition suggested that it was torn from the boat before any of the crew could get in, and they are lost and presumed drowned. November saw a large tanker, *M/T FR8 Venture*, with a load of crude oil from Scapa Flow, Orkney Islands, and headed for Houston, take a huge wave over the bow off the east coast of Scotland. Two seamen were killed and a third injured. Also in November, the German fishing vessel *Hohe Weg* was capsized by a huge wave in the North Sea, north of Bremerhaven. There was no time for the two crew members to escape; a month later their bodies washed ashore. A fishing vessel named *Joe Green* was hit by a rogue wave in the Atlantic Ocean off the coast of South Carolina, smashing bridge windows and damaging electronic gear, but the boat and crew survived. In November, a cargo ship 440 feet long, the *Westwood Pomona*, was hit by a wave 70 feet high that smashed in the windows on the bridge, damaged essential electronics, and forced the vessel to seek shelter in Coos Bay, Oregon for repairs. In December, a large wave came out of nowhere and smashed the tug *M/V Kathleen* in the Gulf of Mexico while it was offshore from Padre Island, Texas. It lost power and suffered one injured crewman, but was able to recover. Finally, in December the tall ship *Picton Castle* sailing from Nova Scotia to the Caribbean was hit by a rogue wave that washed a female crew member over board to her death in the Atlantic.

Risk-Benefit Considerations

Let's assume that the design lifetime of a new vessel is 25 years or 1300 weeks. During this period of time, we can anticipate at least five haul outs, each lasting four weeks. Assume that an average ocean crossing trip (Atlantic or Pacific) has a duration of three weeks with a one-week layover at each end. This corresponds to 75% sea time and 25% port time. The equivalent lifetime sea time for the vessel is 960 weeks or 581 million seconds.

Then assume that the vessel experiences waves with periods in the range of 7 to 14 seconds. On average during its lifetime, it would experience approximately 55 million waves. According to IACS Bulletin 34, Table 1, 99.8% of these waves would have a significant height less than 11 m (36 feet), and only 0.2% of these waves would fall in the category of 11 to 17 m in height. This suggests that 110,000 waves over 11 m in height could be encountered during the life of a vessel plying North Atlantic waters. The probability of waves over 17 m in height is not given.

The trend today is to make commercial vessels bigger and bigger. The *Maersk Emma*, reportedly the world's largest container ship at 397 m (1300 ft) long and 170,000 grt, is an example. Orders are in place to build more than ten additional container ships this size. Passenger ships keep getting bigger and bigger, with the new Royal Caribbean Line's *Freedom of the Seas* (339 m, 1,112 ft) and a 4,000 passenger capacity outpacing the *Queen Mary 2* (3,000 passengers). The largest double-hull tanker is the *Hellespont Fairfax*, at 380 m (1,246 ft); the largest bulker is the *Berge Stahl*, at 343 m (1,125 ft).

It would be of interest to see a comparative study demonstrating how these longer vessels fare in large, long wavelength waves, compared to vessels 200 to 250 meters long.

In the last several decades emphasis has been placed on increasing the cost effectiveness of vessels. More sophisticated computer design tools and the use of high strength steel alloys has enabled ship designers to reduce the quantity of structural steel per ton of cargo capacity. Using more advanced design techniques designers have also reduced areas of design uncertainty with the consequence that safety margins have also been reduced. The use of thinner plates and structural elements is advantageous, because it not only reduces shipbuilding costs but improves fuel economy. Improved corrosion protection methods and coatings have been developed that in theory reduce the likelihood of wastage of structural metal due to corrosion. However, with thinner sections, rigorous inspection and maintenance takes on an even greater importance, since there is less margin for error.

New vessel construction costs range from approximately $1,000/grt for container ships to $5,000/grt for cruise ships like the *Freedom of the Seas*. Designing for higher waves will mandate the use of more steel in critical structural components, increasing the cost of construction. The benefit of increased vessel reliability and a reduced risk of damage to the vessel and cargo, or of the loss of the vessel and its crew, must be weighed against this added cost. At first glance the incremental cost appears to be small, the benefit, huge.

Consider the cost of losing a *Maersk Emma* or a *Freedom of the Seas*. For the container ship, the value of vessel and cargo could easily exceed one billion dollars. For a giant cruise ship such as *Freedom of the Seas*, the vessel alone reportedly costs $800 million; the loss of thousands of passengers has an incalculable cost. In either case the damage to the marine insurance industry and the loss of public confidence in marine transport would lead to bankruptcies and increased government regulation.

Ship Losses and Vulnerability

Review of ship accident reports and US Coast Guard casualty reports indicates a number of areas where ships have been vulnerable to rogue wave damage. These areas should have priority for improved design. For bulk carriers, as discussed above, hatch covers and deck penetrations are extremely important, since they represent a potential path for seas to enter the vessel. In addition to the static load of green water on hatch covers, they should be designed to withstand the dynamic load of the impact of the design wave breaking on the vessel.

Consideration should also be given to installing seawater intrusion detection systems in forward sections of the vessel, as well as pumps that can be activated remotely from the bridge in the event leaks are detected.

In many of the reported rogue wave incidents, the wave smashed bridge windows and flooded instrument panels, disabling critical instruments and in a number of cases caused a complete loss of power. The obvious solution is to strengthen bridge windows. Less obvious is to weather-proof critical instrumentation systems within the bridge. Waves have also ripped lifeboats from their davits, suggesting that safety systems must be especially rugged.

Findings

I believe there is sufficient evidence to conclude that significant wave heights of 20 meters (66 feet) can be experienced in the 25-year lifetime of oceangoing vessels, and that 30 meter (98 foot) high waves are less likely, but not out of the question. Therefore, a design criterion based on an 11 meter (36 feet) high significant wave seems inadequate when risk of losing crew and cargo is considered. This is particularly true for large vessels that are intended for service in areas where extreme waves are likely to be encountered. IACS Recommendation 34 should be modified so the *minimum* significant wave height for design is at least

20 meters. The *dynamic* force of wave impacts should also be included in a dynamic structural analysis of the vessel, hatch covers and other vulnerable areas (as opposed to relying on static or quasi-dynamic analyses).

After selecting design loads, further steps are necessary to complete a ship design. An overall structural arrangement has to be selected; methods have to chosen to calculate the response of the structure (prescriptive rules, computer simulations, linear vs. non-linear analyses, et cetera); and finally the designer has to decide what are stress or deformations are acceptable, including determination of how much yielding or plastic response is allowable. Different classification societies take different approaches, with wide variation in results and safety factors. (Kendrick and Daley, 2007). This lack of consistency should be alarming to ship owners, insurers, passengers, and ship's crews.

Dedication

This paper is dedicated to the more than 2,700 merchant seaman, sailors, and passengers who lost their lives in marine disasters during 2006.

References

Bascom, Willard (1980). *Waves and Beaches*, Anchor/Doubleday, New York, p. 158.

Faulkner, Douglas (2001). "An Analytical Assessment of the Sinking of the M.V. Derbyshire," *Transactions*, Royal Institution of Naval Architects.

Fee, Captain Jerry, USN Ret (2005). Personal communication with Craig B. Smith.

The International Association of Classification Societies (2006). *Common Structural Rules forBulk Carriers*, January.

The International Association of Classification Societies (2004). Letter to shipping and shipbuilding associations, et cetera, from Ugo Salerno. Subject: *IACS common rules for oil tankers and bulk carriers.* Genoa: May 17.

The International Association of Classification Societies (1997). Recommendation No.46, *Bulk Carriers—Guidance on Bulk Cargo Loading and Discharging to Reduce the Likelihood of Over-Stressing the Hull Structure*, p. 1.

The International Association of Classification Societies (2001). Recommendation No. 34, *Standard Wave Data*, p. 2. (See IACS website at www.iacs.org.uk.)

Kendrick, A. and Daley, C. (2007). *Comparative Study of Naval and Commercial Ship Structure Design Standards*, Report No. SSC-446, Ship Structure Committee: Washington, D.C.

MaxWave Project (2003). Research project no. EVK: 3-2000-00544. Bergen: Commission of the European Communities. Available at: http://w3gkss.de/projects/maxwave.

Smith, Craig B. (2006). *Extreme Waves*, Joseph Henry Press: Washington D.C., pp 238-239.

Tarman, Daniel, and Heitmann, Edgar. (No date.) "Case Study II. *Derbyshire*—Loss of a Bulk Carrier." *Ship Structure Committee.*, pp 1-18. http:www.shipstructure.org/derby.shtml.