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Exposure, vulnerability and recoverability in relation to a ship's intact stability

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Abstract

Intact stability describes a ship's stability in waves to avoid incidents. Operational safety measures are an important aspect of a holistic safety approach for intact stability. The aim of this study is to provide a structure of the relationship between key elements of the intact stability risk concept. Such a structure has implications for risk assessment and risk management. The developed structure is discussed in relation to the proposed second generation intact stability criteria, which highlights how the measures relate to safety. The definitions are also analyzed in relation to seven incidents. Operational decisions and the human element are shown to have strong ties to exposure, vulnerability and recoverability. However, the results herein show that the interdependency between risk and operational decisions differ between the three areas; the effective measures are thus different. The actual exposure, vulnerability and recoverability for a ship is not known nor can it be fully assessed. However, all three aspects of intact stability safety must be considered in a structured manner to reach a cost effective intact stability.

Keywords: *Intact stability; operational stability management; reliability; safety measures*

1. Introduction

The intact stability of ships deals with a ship's stability in waves to avoid incidents such as sudden loss of stability in a wave crest (i.e., *pure loss of stability*), resonance phenomena (i.e., *parametric roll*), *broaching*, and *excessive accelerations*. These stability failure modes can lead to injury to personnel and to damage to the cargo and ship. These modes can also result in capsizing, which could result in the loss of a large part of the crew, the entire cargo and the ship. In 2001, the International Maritime Organization (IMO) launched the development of the second generation intact stability criteria. The existing intact stability code (IMO, 2008b) is based on a semiempirical criterion derived from casualty data now more than 50 years old. Therefore, "applicability of these existing criteria to current ships cannot be straightforwardly guaranteed". (Umeda and Francescutto, 2016)

Using the capsize of Finnbirch in 2006 as an example, the analysis of the accident identified that the ship had relatively poor stability and large variations in its stability in waves (Kluwe and Krüger, 2007). In combination with a cargo shift, this situation led to the capsize (Swedish Accident Investigation Authority, 2008). However, was the fact that the stability was sensitive to waves enough to render the ship unsafe, or does it need to be combined with cargo that is not sufficiently lashed? Liwång and Rosén (2018) propose a framework that distinguishes between intact stability vulnerability and recoverability to better capture the conditions and causes for 36 intact stability incidents. However, the proposed framework does not clearly distinguish between operational and design causes and does not cover measures that aim to reduce the probability of encountering hazardous conditions. To facilitate and further investigate the relation between intact stability safety measures and actual safety, this paper describes a more developed terminology for structuring intact stability safety measures and for discussing how adequate safety can be achieved. The analysis builds on the general definitions of intact stability vulnerability and recoverability proposed by Liwång and Rosén (2018). In this paper, the vulnerability and recoverability are further specified and put in relation to the term exposure. It is postulated that the consequences of intact stability issues on safety can only be fully understood if the ship's exposure, vulnerability and recoverability is understood.

The goal of this study is to provide a structure of the relation between key elements of the intact stability risk concept. Such a structure has implications for risk assessment and risk management and the safety level achieved with different actions. The structure developed will be discussed in relation to the proposed second generation intact stability criteria to highlight how the measures relate to safety. This is important because IMO aims to "be able to appreciate the effect of proposed regulatory changes in terms of benefits (e.g. expected reduction of lives lost…) and related costs incurred for the industry as a whole and for individual parties affected by the decision" with the risk based approach defined by the Formal Safety Assessment (FSA) (IMO, 2013b). With the FSA IMO aims to achieve "a balance between the various technical and operational issues, including the human element, and between maritime safety or protection of the marine environment and costs" (IMO, 2013b). This balance is what IMO defines as cost effectiveness. To meet these requirements put forward by the FSA the safety implications of the second generation intact stability criteria need to be possible to analyze.

In this study, the framework is developed based on earlier general work on exposure and vulnerability (Aven, 2012), specific but limited work on vulnerability and recoverability in relation to intact stability (Liwång and Rosén, 2018) and a qualitative study of seven stability incidents. These seven incidents are chosen to represent different stability challenges in relation to design and operations.

2. Theory

Safety is here the final risk during operation, independent on whether the safety barrier is implemented in technology, crew training or operations, i.e., as applied in the FSA (IMO, 2013b). FSA is an approach to investigate the risk level (and, implicitly, the safety level) in ship operations.

This study is based on a sociotechnology system perspective and focus on the *reliability of the safety system,* i.e., *the ability of the total set of safety measures, organizational as well as technology, to maintain a suitable level of safety (successful performance) during operation*[1]. Safety is here understood as the "ability of individuals or organizations to deal with risks and hazards to avoid damage or losses yet still achieve their goals" (Reason, 2000). Reason (2000) also found that effective safety work requires informed participants that can operate close to unacceptable danger without crossing over the edge. This perspective on safety is consistent with the IMO ambitions stated below:

- "risk and safety levels need to be assessed on a holistic basis, recognizing that high levels of operator training, comprehensive and thoroughly implemented procedures, high levels of automation and sophisticated software can all make significant contributions to risk reduction" (Sames, 2009), and
- "to take measures to implement the proactive policy … more actively than in the past… . In implementing this directive, Formal Safety Assessment should be used to the extent possible in any rule-making process" (IMO, 1999).

[1] This definition was developed from Andrews and Moss (2002b) with respect to the understanding of reliability and from Trist (1989) for the understanding of a socio-technical perspective, i.e., that an optimum condition in any one dimension does not necessarily result in optimum conditions for the system as a whole.

According to IMO (2013b) the "human element is one of the most important contributory aspects to the causation and avoidance of accidents". Human element issues throughout the integrated system, i.e., the system that includes the technical system, the personnel system, the organizational/management infrastructure, and the environmental context, should be systematically treated (IMO, 2013b).

Risk is one approach for measuring the absence of safety. Several different risk perspectives exist in current practice (Aven, 2012) and how to analyze risk depends on the risk perspective used. This study is performed with the risk perspective of the IMO FSA, where risk is described and understood as a measure of the combination of probability and the severity of adverse effects (consequences). This risk perspective is by Aven (2012) denoted as $Risk = C \,\&\, P$, where C are the consequences and P the probability. Furthermore, the risk perspective used in the FSA is here understood as a quantitative frequentist understanding of probabilities (i.e., "objective" probability).

The types of consequences to be measured depend on the case studied. The FSA focus is on fatalities and serious injuries (IMO, 2013b). The goal in risk management is most often to avoid unnecessary risks using cost-effective measures (IMO, 2013b). The FSA focus on safety during operation, including both proactive and reactive measures for risk reduction, illustrated by the bow tie diagram shown in Figure 1.

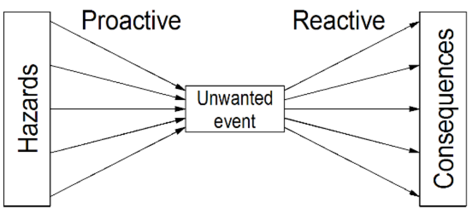

Figure 1. Bow tie diagram showing that risk controls can be applied proactively and reactively, developed from Rausand and Bouwer Utne (2009).

The bow tie diagram in Figure 1 illustrates that there are safety issues that can be eliminated long before the event; however, some of the issues occur closer to the event and even after the unwanted event. In this study, *operational safety measures are understood as measures that reduce the probability of unwanted events and or the consequences of unwanted events during operations*.

Operational measures here include but are not limited to, operational guidance and operational limitations as discussed within the current body of work with the second generation intact stability criteria (W. Peters et al., 2011; Umeda and Francescutto, 2016).

When studying safety in a sociotechnical system, as in this study, the social aspects of safety, such as safety culture, and the technical aspects, such as hull design, all must be considered. Technical measures alone cannot create safety, i.e., their effectiveness is decided by the actions and the culture on board. A safety culture does not just emerge; it is the result of many aspects, particularly: formal regulations and processes; competence and training; and shared risk awareness throughout the organization (Parker et al., 2006). Therefore, the social aspects of safety are important components of the safety system.

2.1 The second generation intact stability criteria

The existing work on the second generation intact stability criteria is based on the three following alternative assessment procedures: level 1 vulnerability assessment, level 2 vulnerability assessment; and direct stability assessment. Compliance with levels 1, 2 or the direct stability assessment fulfils the requirements of the intact stability criteria. Alternatively, ship-specific operational limitations or operational guidance can be developed for conditions failing to fulfil the criteria (W. Peters et al., 2011; Umeda and Francescutto, 2016).

Research on the second generation intact stability criteria to date has focused on “passive” safety measures described by level 1 and 2 assessments (Bačkalov et al., 2015). Level 1 and 2 and the direct assessment are physics-based, i.e., the aim is to capture the physics (forces, motions and accelerations) of the ship (the physical ship) at sea when subjected to wind, waves and other possible important events. However, the operational environment and the operation itself is not static; therefore, passive design measures must be far-reaching to exclude unsafe operations. This is the motivation for introducing operational limitations or operational guidance within the second generation intact stability criteria.

Acceptable safety levels and operational aspects are implicitly addressed in the proposed criteria. For example, in the direct assessment a ship in a given loading condition fulfills the requirements if the average rate of stability failure is below 1×10^{-4} to 2.6×10^{-3} per ship year (final maximum rate not set) (IMO, 2018). The average rate of stability failure is calculated as a weighted average over relevant sea states. The final definition of a failure event is not decided; suggestions include (IMO, 2018):

- failure if roll exceeds 40 degrees or angle of vanishing stability in calm water or angle of submergence of unprotected openings in calm water; or if lateral acceleration of 9.81 m/s^2 or more (final definition of a failure event is not decided).
- failure if for parametric roll angle exceeds 25 degrees; for excessive acceleration lateral acceleration exceeds 9.81 m/s^2; for dead ship, broaching and pure loss of stability if roll angle exceeds 40 degrees, angle of vanishing stability in calm water or angle of submergence of unprotected openings in calm water (final definition of a failure event is not decided).

2.2 Acceptable safety level

Bačkalov et al. (2015) state that "the likelihood of an intact stability failure is typically required to be at acceptable probability levels, which can be very low". For example, acceptable probability levels for incidents have been developed by Bačkalov (2012) and A. Peters (2010). They both explicitly assume a relation between the safety level and the probability of capsize as defined by the probability of reaching a specific heel angle. Such a relation is not straightforward, as exemplified for cruise ships by Hinz (2015), where several consequences were often found to be the indirect, and possibly nonlinear. In addition, the Hofman and Bačkalov (2007) description of the incident with the ship Cougar Ace show that extreme heel angles can have high consequences to the operation (and cargo), but is not necessarily life-threatening to the crew.

The approaches discussed by Bačkalov and Peters assume that the probability of a specific heel angle is proportional to the risk posed by capsizing. However, there can be different reactive phenomena affecting the consequences and the resulting safety level. Belenky and Sevastianov (2007) found that the relation between the heel angle and a capsize event is not straightforward even for simplified cases.

The FSA define a negligible number of fatalities in relation to societal risk and individual risk, wherein risks below that level do not need to be reduced further (Skjong, 2002). For accidents with multiple fatalities, which is typically the case for a capsize, societal risk is the most relevant measure (Pedersen, 2010; Skjong, 2009). Negligible societal risk is a function of the value the activity presents to the society; therefore, the negligible level should be calculated based on the acceptable potential loss of life, given as the number of occupational fatalities per gross national product and the economic value of the activity. The negligible risk level is given by the number of fatalities and the upper limit of the possible number of fatalities (persons on board). For details of the calculations, see IMO (2013b) and Skjong (2009).

Using the IMO approach, *if* the fatalities associated with a capsize are known, the maximum negligible probability of a capsize can be calculated based on the negligible number of fatalities. If the capsize probability is lower than that level, there are no safety reasons for reducing it further. However, how the probability of capsize corresponds to the maximum annual large heel angle probability (such as discussed by A. Peters (2010)) depends on the system's recoverability after the occurrence of large heel angles. Therefore, to understand the intact stability risk, the mechanics of large-heel-angle incidents must be included in the analysis.

However, it may also be appropriate to improve the intact stability for operations with negligible levels of capsize risk. Some examples of other reasons to introduce operational measures and intact stability knowledge on board are presented by Huss (2016). Huss' example illustrates work on board with routing to reduce the probability of hazardous weather types and decision support on board to identify situations that are hazardous for pure car and truck carriers (PCTC). In this case, the aim is to create predictable transport without ship motions that could damage the cargo. Such measures that can reduce the frequency/probability of incidents is an important part of intact stability for many types of ships.

2.3 Operational aspects of safety

The safety level enjoyed today is, to a large extent, a function of the operational decisions taken on board and thus based on seamanship. The personnel must be able to make informed decisions. This includes avoiding surprises during operation (Cleary, 1975), such as sudden loss of stability without prior large ship motions (Mata-Álvarez-Santullano and Souto-Iglesias, 2014). From the definition of safety by Reason (2000), it follows that operating without incident is not proof of safe operation, especially for the types of rare events discussed here. In addition, crews sometimes underestimate risks in dangerous situations where they have been successful in the past (Schröder-Hinrichs et al., 2012). In these cases, more specific feedback is required to distinguish between safe and unsafe operation. The traditional prescriptive regimes typically do not inform the crew adequately (Kuo, 2007b). An operational measurement regime must therefore be designed to keep the crew informed.

Operational limitations prescribe a safe combinations of aspects such as sea state, heading and speed. Operational guidance dynamically introduces limitations (Bačkalov et al., 2015), often with onboard computers that assess the situation and the forecast, typically aimed towards avoiding hazards, i.e., to create inherently safe operations. (Perera and Soares, 2017)

Increased system reliability can be achieved with redundancy, segregation and diversity (Möller and Hansson, 2008). Redundancy and segregation are important concepts in designing for intact stability. However, typical engineering redundancy and segregation require the operational conditions to be within the design conditions; therefore, the diversity of the design can be low. Operational measures introduce possibilities other than designed engineering solutions and therefore increase the diversity of the safety system, i.e., solutions that “avoid common cause failures” (Möller and Hansson, 2008). Operational measures have the power to change the operational conditions. This means that operational safety measures add reliability, i.e., they reduce uncertainty in the system as a whole, even though there are uncertainties in the measure itself (Andrews and Moss, 2002a; Möller and Hansson, 2008). Operational measures are specifically important for operations with large uncertainties, where procedural safeguards are ineffective (Oltedal, 2018).

IMO (2013a) describe that in general, to produce valid results for risk assessment, it is necessary to assess the contribution of the human element to system failure. IMO also found that on board ships, the crew often have a great "degree of freedom to disrupt system performance" (IMO, 2013b). Therefore, human actions can affect the system on a high-level and disrupt the intended operation. Safety cannot be assessed without capturing these types of effects.

2.4 Existing discussion on vulnerability and recoverability in relation to intact stability

Liwång and Rosén (2018) argue that, based on 36 studied incidents, the conditions for operational measures differ between ship types as a result of different types of operations and different conditions for implementing the measures on board. Therefore, they proposed that there is an important distinction between a ship's general likelihood for intact stability incidents (*vulnerability* to intact stability failures) and the ability of a ship to return to a safe mode when it experiences an intact stability incident (*recoverability* after intact stability failures). Vulnerability is then, according to the authors, typically a result of ship design, whereas recoverability, in addition to ship design, can be a result of operational aspects, such as decisions taken on board in relation to loading or unclosed hatches.

The second-generation intact stability criteria primarily apply to the general vulnerability to intact stability failure for ships operating within the operational conditions. However, according to Liwång and Rosén (2018), it has not been shown that high vulnerability alone is enough to introduce severe safety problems according to the IMO definitions of safety.

According to Liwång and Rosén (2018), ships with high vulnerability and high recoverability include, for example, modern PCTC with possible good control over cargo, specialized hull forms (that lead to vulnerability to specific intact stability failure modes) and superstructures that can contribute to high recoverability after experiencing large heel angles (Hofman and Bačkalov, 2007). For these ships, high-end onboard simulations can be an effective method to support the master's decisions about routing as well as maneuvers to avoid intact stability incidents. However, such onboard operational guidance is not necessarily needed for PCTC's to meet the FSA IMO required safety levels on such ships. The operational safety measures are motivated by the goal of increased effectiveness and quality of service, i.e., to limit any escalation of an incident as well as reduce injuries to personnel and damages to cargo during an incident.

For ships with moderate recoverability and moderate to high vulnerability, Liwång and Rosén (2018) suggest that an effective approach can be found in dealing with the recoverability uncertainties with respect to, for example, the cargo, and putting effort into tending to the problems before or while the cargo is loaded on board. For ships with low recoverability, such as workboats and fishing vessels, and moderate to high vulnerability, the uncertainty of the effectiveness of engineering solutions is high. The effective approach is most likely found in ensuring that the risk drivers, such as open hatches and overloading, are reduced, especially in situations when the ship is more vulnerable to intact stability incidents. In such situations, decision support, such as operational guidance, can be ineffective because of the limited possibility use the information offered (Oltedal and Lützhöft, 2018). Identifying and tending to risk drivers is work that must be performed by the entire crew by strengthening risk knowledge and risk awareness on board through safety management.

The framework presented by Liwång and Rosén (2018) illustrates how the different conditions and varying uncertainties affect the consequences of the incidents, the need for operational measures and the requirements on those measures. However, the framework includes neither exposure nor a specific distinction between vulnerability and recoverability. Additionally, the proposed framework is only discussed in relation to accident types in relation to operational conditions.

3. Data

Liwång and Rosén (2018) present 36 intact stability incidents at sea. Most of the incidents described were serious accidents, i.e., leading to one or more fatalities, damage to the vessel that interrupts service or a lost vessel, see IMO (2008a) for definition of serious accidents. The data from Liwång and Rosén (2018) are summarized in Table 1. Several of these accidents are not in a strict sense intact stability incidents and very few directly relate to one and only one of the five identified intact stability modes in the proposed second generation intact stability criteria. However, they are included in the data because they all relate to stability failures with intact hulls, i.e., no unintended damage to the hull.

Table 1. Summary of documented causes for the identified and documented 36 intact stability incidents studied by Liwång and Rosén (2018).

Cause	Number of times represented as a cause in the 36 incidents
Water on the deck	13
Over loaded/loaded incorrectly	9
Poor stability in design conditions	9
Cargo shifting	9
Down flooding	8
Stability sensitive to waves	7
Rudder forces	5
Design flaw	5
Parametric rolling	4
Free surface in tanks	2
Technical error	1
Forced oscillation combined with low damping	1
Limited knowledge of the cargo’s dynamic behavior	1

The 36 incidents are summarized in Table 1 with a total of more than 408 fatalities. The median number of persons on board was 14, and the median number of fatalities per accident was 3 (13 and 6, respectively, if the ship capsized or sunk). In all but 11 cases, the ship was lost as a result of the accident (Liwång and Rosén, 2018). The incidents can most often be contributed to a combination of causes and for many of the accidents the cause is uncertain. Many of the studied incidents (approximately 20 out of 36) were incidents where the operational conditions and the state of the ship were not according to design or outside the intended operational conditions, e.g., vessels that were over-loaded and/or operated in heavy weather with the hatches open. Cargo shift is also common. These conditions are not typically captured in intact stability vulnerability assessment procedures.

Seven incidents from Liwång and Rosén (2018) were selected for an in-depth qualitative study of exposure, vulnerability and recoverability. The incidents were chosen based on the classification of causes performed by Liwång and Rosén to include different causes and operational conditions. The incidents are described in Table 2 and a short introduction to each of the seven accidents is presented below.

Table 2. Summary of the seven incidents qualitatively studied in this research.

Year	Vessel name	Vessel type	Crew + pass.	Fatalities	Other consequences	Sea state/ weather	Causes	Reference
1987	Herald of Free Enterprise	RoPax	≈590	193	Ship lost	Calm	Down-flooding and water on deck	(Department of Transport, 1987; Hua & Rutgersson, 1994)
2006	Cougar Ace	PCTC	≈20	0	Cargo and ship Damaged	Moderate	Over loaded/ loaded incorrect	(Hofman & Bačkalov, 2007)
2006	Finnbirch	RoRo	14	2	Ship lost	Severe	Cargo shift, poor stability in design condition and stability sensitive to waves*	(Swedish Accident Investigation Authority, 2008)
2008	Chicago Express	Container vessel	35	1	5 injured	Severe/ extreme	Forced oscillations and low damping*	(BSU, 2009)
2008	Wallenius vessel	PCTC	-	0	-	Moderate	Parametric rolling	(Huss, 2016)
2013	No.38 Sankyo Maru	Tug boat	3	2	Ship lost	Severe	Design Flaw	(Taguchi, Haraguchi, Minami, & Houtani, 2015)
2015	Hoegh Osaka	PCTC	24	0	1 injured, cargo and ship damaged	Calm	Over loaded/ loaded incorrect	(MAIB, 2016)

*) The causes of the accidents are summarized based on the accident descriptions studied. The five intact stability failure modes were not found to be suitable categories for describing the causes of the accidents.

The RoPax ship Herald of Free Enterprise, capsized and sank, 1987: The capsize and sinking of the Herald of Free Enterprise was a result of down-flooding through unclosed inner and outer bow doors. This was the result of an onboard safety culture that allowed a single mistake to lead to large safety issues (Department of Transport, 1987; Hua and Rutgersson, 1994).

The PCTC Cougar Ace, large permanent list, 2006: The Cougar Ace heeled heavily at sea as a result of errors during the ballast discharge that reduced the righting lever to very low values and allowed the ship to heel over by swell and wind and then stay heeled. The accident also showed that the superstructure was watertight enough to avoid a capsize (Hofman and Bačkalov, 2007).

The RoRo ship Finnbirch, capsized and sank, 2006: The large heel/roll angles and subsequent capsize of the Finnbirch was a result of a stability sensitive to following seas, the crew being unaware of the sensitivity and how to reduce it, and the cargo not being lashed sufficiently (Swedish Accident Investigation Authority, 2008). The incident may have been avoided by reducing any of these three limitations. However, given the sensitivity to waves and the state of the cargo lashing, it would have been challenging (and perhaps not feasible) to perform this specific voyage based on active speed and heading actions alone.

The container ship Chicago Express, large vertical accelerations, 2008: The vessel left Hong Kong port as a result of instructions from the local port authority because of an approaching typhoon. The ship encountered heavy weather at sea and experienced large roll motions and large vertical accelerations, resulting in injuries to the crew and the subsequent fatalities of one person. The accident was identified as caused by very strong excitation moments from large waves in combination with low roll damping as a result of the low speed. Lower stability would not have reduced the roll period but would have reduced the transversal accelerations. However, cargo to reduce the stability sufficiently was not available before departure from Hong Kong (BSU, 2009).

The Wallenius large car and truck carrier (LCTC), parametric rolling, 2008: This relatively new LCTC experienced heavy parametric rolling with a maximum amplitude greater than 30° in following seas. The significant wave height was just slightly more than 4 m. The vessel avoided resonance by changing course and speed. The onboard live warning system was not active at the time; however, it would most likely not have identified the situation as critical because of the moderate wave height. (Huss, 2016) This is probably a common type of accident. However, it is not mandatory to investigate and report these incidents.

The tug boat No. 38 Sankyo Maru capsized and sank in 2013: The tug boat is assumed to have capsized as a result of an outward heeling moment induced by starboard steering in combination with wave-induced rolling to starboard that caused immersion of the bulwark and allowed subsequent waves to capsize the vessel. It was therefore concluded that the accident was a result of the specific operational conditions that made the vessel sensitive to rudder angles when operating without a box barge (a common, but not typical operational situation) (Taguchi et al., 2015).

The PCTC Hoegh Osaka, large permanent list, 2015: Hoegh Osaka heeled heavily while turning as a result of having left port with “inadequate stability”. The inadequate stability was a result of the full upper vehicle decks in combination with lightly loaded lower vehicle decks, a low level of bunker fuel oil and no additional ballast prior to departure. The accident investigation also found that no departure stability calculation had been performed and that "unsafe practices had become the norm" (MAIB, 2016).

4. Analysis

4.1 Exposure, vulnerability and recoverability

In this section, a theoretical description of exposure, vulnerability and recoverability in relation to intact stability is presented. In the following sections, the description is further specified in relation to actual ship conditions.

Generally, safety depends on a combination of choices and external factors. Important decisions are made at the time of the initiating event, as well as long before and after the initiating event. A generic theoretical description of exposure and vulnerability is presented by Aven (2012). Aven's description is used in combination with the risk understanding used here and presented in Section 2, i.e., that *Risk* = *C* & *P*.

Component I: Exposure, the probability of exposing the ship to an external risk source and or to a specific event. In this step, the magnitude, frequency and duration of exposure to a specific condition in terms of sea state, wind, speed, heading in combination with a specific ship condition is described. Exposure means that "the system is subject to the risk source or hazard/threat" (Aven, 2012). Exposure is divided in two sub types, sub *type a*: Exposure to a condition in general (defined by wind and sea state), a risk source (*RS*) and sub *type b*: exposure to a hazard/threat, herein called an event, e.g., a specific wave crest or a specific set of consecutive wave crests.

Component II: Vulnerability, the measure of how vulnerable the vessel is to the condition of exposure. "Vulnerability given a specific risk source (*RS*) or hazard/threat (*A*) refers to the pair (i) consequences of the system being exposed to *RS*/*A* (the exposure is known/given) and (ii) the associated probabilities".

Component III: Recoverability, the measure of the extent that the system (vessel, crew and cargo) can return to its intended operation after an event and/or the extent that subsequent consequences can be reduced (represents passive and active recoverability, respectively).

For a ship to suffer negative consequences, the system during operation has to at least be exposed and vulnerable. However, the total consequences can only be assessed if the recoverability is also assessed.

The vulnerability assessed by the proposed second generation intact stability criteria is a theoretical simplified vulnerability for a given theoretical representation of the exposure.

Measures to reduce *component I, exposure*, have strong ties to an operational version of the design principle *Inherently Safe Design* (Möller and Hansson, 2008), *Inherently Safe Operations*, which provides operational limitations as well as measures such as weather routing to avoid expected weather systems. The exposure is also affected by operational decisions. This is, for example, highlighted by the UK Navy's changed exposure to high waves in the North Atlantic as a result of the ending of the Cold War and the subsequent operational changes (A. Peters, 2010). Operational limitations limit exposure type a and actions onboard also affect exposure type b.

Component II, vulnerability, if seen in general terms, i.e., the ships generic vulnerability when operated according to theoretical/documented and intended load cases. This vulnerability is assessed in the second generation intact stability. The vulnerability is to the *general* risk source or event, or $V(RS/A)$. However, risk takes the form (RS', A', P, $V(RS', A')$, $R(C_1)$, K), where RS' and A' are the *specific* risk source and event, $R(C_1)$ is the recoverability with respect to the consequences C_1 and K is the background knowledge (Aven, 2012) as illustrated by Figure 2.

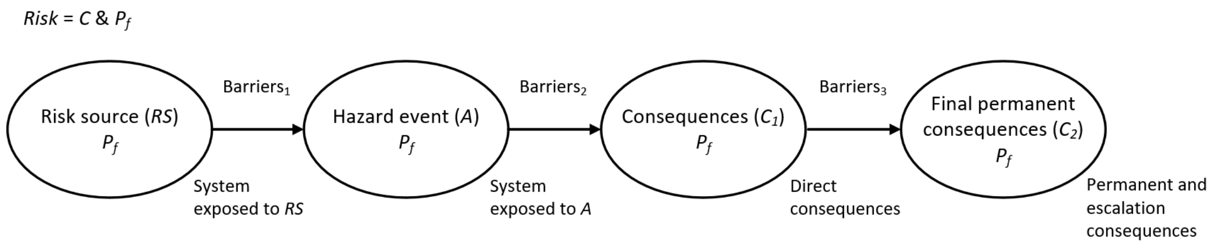

Figure 2. Primary features of exposure and recoverability leading to consequences. P_f = "objective probability" (frequentist probability). Developed from Aven (2012).

The consequences to the event *A*, C_1, can, to some extent, be de-escalated by recovery efforts. However, there can also be escalation to severer consequences. Therefore, the set of consequences defined by *C1* and *C2* according to Figure 3 have the following relation to escalation and de-escalation:

- The de-escalation is defined by the consequences of C_1 that not are a part of C_2, hence the de-escalated consequences are given by $C_1 \setminus C_2$.
- Escalation is defined by the consequences of C_2 that not are a part of C_1, hence the escalated consequences are given by $C_2 \setminus C_1$.

Therefore, recoverability limits escalation and promotes de-escalation.

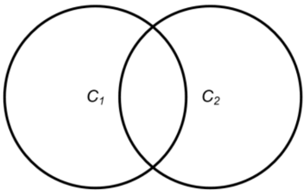

Figure 3. Venn diagram of the set of consequences. The consequences of the event, C_1, and the final permanent consequences C_2.

Exposure to *RS* or *A* does not deterministically lead to consequences. The risk effect of the source on the system (at any specific instance) is unknown; however, it could be assumed to be assessable by a probabilistic analysis using a physics-based approach.

4.2 Intact stability exposure

In this study, exposure is the probability of exposing the ship to a specific sea condition. An analysis of the seven incidents shows that the sea conditions need not be severe to produce intact stability incidents. Herald of Free Enterprise, Hoegh Osaka and Cougar Ace should not have been at sea at all, given the condition of the ship at the time of the incident. Exposure is therefore also about the condition of the ship. In these three accidents it is thus not meaningful to distinguish between the risk source and the event, i.e., the important risk source (RS) is the general combination of ship state and sea condition. For the Herald of Free Enterprise, this meant that the ship should not have gone to sea under the given ship conditions (open bow doors). Hoegh Osaka should not have left port without lowering the center of gravity and Cougar Ace should have used another ballast discharge order. However, for the tug boat No. 38 Sankyo Maru it is important to distinguish between the risk source and the event. In this case, it was the exposure to the risk source (operating without a barge) in combination with a specific event (a combination of rudder forces, heading and waves) that led to the incident and subsequent capsize.

Reducing exposure to external conditions is not necessarily a relevant option. However, for the three incidents that occurred during severe weather, reducing the exposure to the weather could have been a relevant safety measure. For Chicago Express, limiting excessive acceleration when unloaded with design solutions, i.e., limiting the stability, could limit the ship's cargo capacity. Therefore, it may be more effective to limit the exposure to the risk source, i.e., limit the operational profile while unloaded.

In total, this means that exposure will be affected by route and scheduling as well as by more detailed decisions onboard, in relation to speed and heading in general but also the actual steering over a wave crest, etc. (see Tug boat No. 38 Sankyo Maru). These operational decisions must always be viewed in relation to the ship's condition as well as to uncertainties in relation to the ship's condition. The exposure will also be limited/affected by regulatory operational limitations and operational guidance.

Some ship conditions are always dangerous; others are only dangerous at specific external conditions. There are external conditions that are dangerous for all ship conditions. The master (with support from the crew) is the only system component that can be tasked with distinguishing between these ship-specific situations. Additionally, an onboard operational guidance system must have good data on the condition of the ship, i.e., the loading and ballast conditions must be correct; otherwise, the allowable exposure cannot be correctly assessed and the guidance will be wrong. Such uncertainties had a large effect on at least the accidents involving Herald of Free Enterprise, Cougar Ace, Finnbirch, No. 38 Sankyo Maru and Hoegh Osaka.

General conditions (*RS*) that are not suitable for operation, such as those exemplified by the Herald of Free Enterprise accident, are easier to identify compared to specific events (*A'*), such as those exemplified by the Tug Boat No. 38 Sankyo Maru. Such specific events demand very specific analyses and are, if they are identified, also not necessarily straightforward to communicate to the crew. In addition, the routing of ships is not a stochastic process; rather, it is a process of weighing different values, risks and prognoses with respect to the future. On some ships, this is a very systematic process, on others it is unstructured. Therefore, the relevant exposure to use as input in a vulnerability analysis is not necessarily an even distribution of headings and sea states.

The second generation intact stability criteria state that the results of the direct assessment should be presented for a weighted average over relevant sea states. However, there are no explicit considerations taken in relation to operational conditions, i.e., exposure, other than that the "the loading and environmental conditions chosen for the direct stability assessment must be representative for the intended service of the ship", also the phrase "anticipated loading conditions" is used (IMO, 2018). From the analysis above it is clear that actual loading conditions at accidents, intended loading conditions and anticipated loading conditions differ, or at least could differ, substantially. There is also a difference between the prescribed "relevant" environmental conditions and the proposed use of standardized scatter diagrams because most ships do not chose heading randomly.

Today, given an increased availability of weather data and onboard routing tools, the proposed use of standardized scatter diagrams can be considered to create an on average conservative estimation of the exposure because ships often, but not necessarily always, will be trying to avoid bad weather. However, this is not the case in all situations and for example for ship with wind assisted propulsion, that may route deliberately into windy situations, standardized scatter diagrams may be underestimating the exposure to bad weather.

4.3 Intact stability vulnerability

The vulnerability is relevant if it is based on correct exposure to risk sources (*RS*) and events (*A*). The vulnerability at sea is probabilistic and depends on the actual ship's state. The estimated vulnerability (based on design) should be a relevant approximation of the actual vulnerability that creates conservative safety measures. Ideally, at least the conceptual difference between the estimated vulnerability and the actual vulnerability should be known and described. Therefore, effective tools to evaluate vulnerability and suitable operational conditions that correspond to the actual operations are both required. An example of a probabilistic difference between the estimated vulnerability and the actual vulnerability, $V(RS', A')$, is the difference between an idealized distribution of wave headings used for assessment and the actual wave heading distribution.

Another important issue when assessing vulnerability is how and to what extent, to include the vulnerability to operational conditions outside the planned operational envelope, such as overloading and open hatches and bow doors. These are common specific risk sources and events.

From the vulnerability analysis, there must be a relevant description of the consequences, C_1, as a result of different situations. Only for tug boat No. 38 Sankyo Maru was the direct consequences of the incident a capsize. Therefore, the consequences are probably more correctly described by both direct fatalities, damages and the effect on the ship as well as the rate of down-flooding, the heel angles and the accelerations. This information is needed to understand what requirements the direct consequences put on recoverability preparations, recoverability design and recoverability procedures or if the incident must be avoided by changing the exposure or by reducing the vulnerability.

The proposed standardized failure events within the second generation intact stability criteria described in Section 2.1 do not necessarily correspond to consequences and they do not take operational aspects of vulnerability into account.

4.4 Intact stability recoverability

Examples of ship conditions that affect vulnerability include unlatched cargo, open hatches and bow doors, etc. (Liwång and Rosén, 2018). These are conditions that if the ship experiences excessive motions or accelerations, will increase the probability of consequence escalation.

Recoverability is mostly a case of bringing the ship back to a condition where the consequences to crew and cargo are less probable. Instant consequences (C_1) to crew and cargo are seldom possible to de-escalate. The instant consequences that are not possible to de-escalate are often a result of large (lateral) accelerations, as illustrated by Chicago Express; thus, it is more important to reduce accelerations by limiting exposure and vulnerability than reduce large heel angles. The description of the Wallenius PCTC (Huss, 2016) indicated that stability issues and parametric rolling, for ships with high built-in recoverability and onboard preparations for large roll angles can, based on relevant onboard knowledge, be handled with reactive measures alone. This is because they do not directly lead to any substantial consequences.

On board Finnbirch, the consequences become severe as a result of limited recoverability from the cargo shift. The cargo shift was a result of insufficient lashing. The consequence level was therefore a function of the recoverability preparations, the fact that the personnel on board had limited knowledge of the substandard lashing, the ship's sensitivity to waves, and how these uncertainties combine to increase risk when exposed to the specific sea conditions.

Recoverability in general and therefore also the difference in recoverability between ship types and specific ships is not all covered in the proposed second generation intact stability criteria. This means that there is no link between the proposed uniform rate of stability failure and the resulting safety level.

4.5 The findings in relation to the proposed second generation intact stability criteria

It is clear from the analysis that the physical modeling of the ships vulnerability to different intact stability phenomena is central in the ships intact stability safety. Also, the vulnerability is the aspect with the strongest link to the design of the ship. However, the actual vulnerability at sea also has strong ties to operational decisions. Therefore, based on the analysis above it can be identified that the proposed second generation intact stability criteria do not provide for the safety level to be assessed on a holistic basis including aspects such as operator training, onboard procedures etc.

However, it is not necessary that the criteria them self achieve this holistic basis as long as the effect of the proposed criteria can be analyzed on a holistic basis when deciding on if and how the criteria are to be implemented. Therefore, the here suggested framework aims at contributing to the possibility to analyze and assess the safety effect of the proposed criteria. First after such an analysis will it be fruitful to propose to what extent operational aspects of exposure, vulnerability and recoverability must be included in new codes or criteria.

Based on the analysis here performed it is identified that the proposed second generation intact stability criteria directly and indirectly account for some operational aspects of vulnerability and to some extent aims at having the possibility to limit Exposure type a. Also, the difference between exposure type a and type b is indirectly addressed when the proposed criteria discuss how simulations results should be interpreted. The proposed criteria also make several implicit assumptions on the operational aspects of exposure, vulnerability and recoverability. Based on the findings here it is proposed that these aspects and assumptions are more explicitly accounted for in the criteria. Such clarifications will aid in the assessment of the safety level achieved with the criteria, but also be a strength when developing approaches and methods for direct stability assessment.

Therefore, in sum, a framework like the one here proposed:

- is needed when the safety effects of the second generation intact stability criteria should be assessed and discussed, when assessing the sensitivity of the criteria to different conditions, and when assessing the safety margin the criteria offer and how that margin depends on ship type in relation to operational conditions and decision. For example, in relation to cargo lashing, ballast procedures, operating out of the typical operating conditions etc.
- could also be used to document and structure the aspects of exposure, the effect of operational conditions on vulnerability and the aspects of recoverability that today are included in the second generation intact stability criteria in order to make these aspects explicit. This would help to apply the criteria to ship types that fall outside the such types that are considered today. For example, the effect and reliability of routing procedures for different types of ships including sail assisted ships.

By comparing the findings to similar research in relation to damage stability it is also identified that the general knowledge within fields such as human reliability analysis (IMO, 2013a), or human system integration frameworks (Kuo, 2007a; Oltedal, 2018; Oltedal and Lützhöft, 2018) is not enough to the understand or describe the operational effects on intact stability incidents. The operational aspects related to exposure to damage stability, see for example Pedersen (2010) and Goerlandt et al. (2012), are different from the ones found here for intact stability as a result of the specific couplings to the vulnerability under study. Therefore, in combination with the fact that the human element has a large effect on several intact stability incidents (Liwång and Rosén, 2018), there is a need for a *specific* understanding of how operational aspects relate to intact stability.

5. Discussion

Human errors have strong ties to accidents. In addition, intact stability accidents, to a large extent, can be explained by the crew’s inability to handle complex situations. Therefore, such ability must be strengthened. IMO (2013a) identified that the crew on a ship can disrupt the system performance, and the quantitative analysis in Liwång and Rosén (2018) and the qualitative analysis in Section 4.2 show a strong relation between the intact stability consequences and operational conditions not covered by a general vulnerability analysis. Therefore, it is important to meet the FSA IMO requirement that safety measures should be relevant also from a human element perspective. Operational decisions and the human element have strong ties to exposure, vulnerability and recoverability. However, as shown in this study, the interdependency between risk and operational decisions differ among the three analysis aspects and the effective measures are therefore different. The actual exposure, vulnerability and recoverability for a ship is not known nor can it be fully assessed. However, all three aspects of intact stability safety must be considered in a structured manner to achieve a cost-effective intact stability.

Regulatory criteria also must be well-defined and possible to implement. Therefore, it is not necessary that aspects of exposure and vulnerability should be a part of the criteria. The IMO FSA put no such requirements on codes or criteria. However, these aspects need to be a part of the evaluation of aspects such as effects, conservativeness, and sensitivity of the proposed criteria.

The frequency of different ship motions given a ship’s state and exposure to specific risk sources and events can be assessed with the methods and tools from second generation intact stability research.

The challenge is to put values to the exposure levels in relation to specific ship states, especially the ship states that were not envisioned (or simply not defined) during design.

A wider understanding of the terms for operational measures is needed. They cannot be judged in the same way as passive engineering solutions for safety. Such a view takes away the strength of safety solutions in the ship operation. However, the acceptable level of uncertainty varies between types of ships and especially with the ship's recoverability after stability incidents.

The vulnerability can largely be classified based on ship dynamics and the work performed with the second generation intact stability criteria has taken important steps towards this. However, the tools available for investigating exposure and recoverability are not as developed. Therefore, multidisciplinary studies are needed, especially in relation to areas such as routing, operational stability management and safety culture during challenging operational conditions. It is likely that intact stability must be addressed with efforts and regulations both in relation to ship dynamics and in relation to safety management in more general terms.

The proposed framework where different aspects of intact stability can be investigated and discussed in more detail opens up the possibility to specify explicitly what can be done and what should be done within different areas. For example, it introduces the question of whether the risk reduction is fully exchangeable between different types of measures, or if is there a need for the following:

- a minimum level of design measures,
- a minimum level of passive measures, or
- a minimum level of seamanship.

There are strong interconnections between operation, rules, regulations and design. Some risk sources must be limited even without introducing specific operational limitations, i.e., solely based on an expectation of a basic level of seamanship and common sense; others can be limited with operational limitations. Events caused by *permitted* risk sources cannot be deterministically decided. They occur as a result of the stochastic character of the sea, knowledge limitations and limitations on what can be controlled on board. If a traditional RoRo vessel, a PCTC vessel and a fishing vessel are compared, the conditions for controlling the vessel's exposure, vulnerability and recoverability differ substantially. For a PCTC, a high vulnerability could be allowed if the recoverability is very high as a result of good control over cargo lashing. From a safety perspective, such a ship could possibly reach a sufficient level of safety with intact stability vulnerability without operational limitations and operational guidance. For an opportunistically operated fishing vessel, the intact stability risks could be high, independent of the vulnerability level of the design.

Vulnerability investigations must consider the ship-specific recoverability for each operational situation considered. The recoverability is neither constant nor given by design. The ship's recoverability also defines the consequences to consider, focusing on fatalities and environmental consequences. In a commercial setting, damage to cargo and the level of operationally of the ship after the incident must also be considered. Without first answering the question *Vulnerability to what and when?*, the actual vulnerability cannot be assessed. Most important is that the ship can, preferably by itself, return to a safe condition. However, recoverability is also safe fail instructions and processes, i.e., processes that may save the crew even if it is not possible to safe the ship (see Möller and Hansson (2008) on the difference between fail-safe and the process of safe fail). In current understanding, the link to the consequences is weak. There is a limited knowledge on how different ship intact stability incidents connect to different consequences. Efforts to limit exposure and vulnerability should focus on the consequences of the incidents that cannot be de-escalated ($C_1 \cup C_2$). This at least means a focus on accelerations, without which different risk reduction measures cannot be prioritized.

The framework identifies that strengthening the onboard competence should be a prioritized operational safety measure approach that also increases the reliability of the safety work as it affects operational aspects that cannot be affected by design. However, this cannot be done without further knowledge about the human element aspects involved (Kuo, 2007b; Oltedal and Lützhöft, 2018). The traditional prescriptive regimes typically do not adequately inform the crew (Kuo, 2007b). Therefore, the development also must include processes and tools for knowledge transfer from design and analysis to onboard personnel.

In summary, when performing simplified analysis approaches for intact stability safety, such as the intact stability criteria, based on an analysis of a ship's vulnerability to intact stability incidents, there are important aspects related to the probability and consequences of such incidents that are omitted. The following aspects are particularly notable:

- The analysis lacks plausible but unintended operational conditions contributing to the number of risk sources (such as open hatches or undefined loading conditions). This results in the analysis underestimating the exposure to risk sources.
- The analysis has difficulty capturing specific and uncommon hazardous events with significant effects on the probability of an incident. This results in a failure to analyze exposure to specific hazard scenarios.
- The analysis cannot capture the link between the incidents and the consequences because there is no knowledge on how operational conditions affect the probability of de-escalation (recoverability).

Therefore, a specific vulnerability will have different safety implications, depending on the ship type, the operation type and the operation standard. It is likely that safety margins introduced in the assessment of vulnerability suitable for one area of shipping can be too restrictive or too lenient in other areas.

The second generation of intact stability criteria suggest that operational limitations and operational guidance (onboard decision support) are to be implemented if the ship does not meet the survivability criteria. Both these measures address the exposure, primarily the risk source exposure, for ships with survivability limitations. However, other operational conditions should be included both in the theoretical description of the exposure used in the vulnerability analysis and in the post analysis assessment of the consequences of an incident as well as in other operational aspects, such as cargo lashing.

6. Conclusions

Safety in general depends on a combination of choices and external factors. Important decisions are taken at the time of the initiating event and also long before and after the initiating event.

Exposure is the probability of exposing the ship to an external risk source and/or to a specific event. It is used to describe the magnitude, frequency and duration of exposure to a specific condition in terms of the sea state, the wind, the speed, and the heading, which must be considered in combination with a specific ship condition.

Vulnerability is the measure of how vulnerable the vessel is to the condition of exposure.

Recoverability is the measure of to what extent the system (vessel, crew and cargo) can return to its intended operation or a safe operation after an event and/or to what extent subsequent consequences can be reduced (represents passive and active recoverability, respectively).

Operational decisions and the human element have strong ties to exposure, vulnerability and recoverability. However, as shown herein, the interdependency between risk and operational decisions differ among the three areas, and the effective measures are therefore different. Consequently, the actual exposure, vulnerability and recoverability for a ship is not known nor can it be fully assessed. However, all three aspects of intact stability safety must be considered in a structured manner to find a cost-effective intact stability. Specific vulnerabilities thus have different safety implications that are dependent on the ship type, operation type and operation standard. It is likely that safety margins introduced in the assessment of vulnerability suitable for one area of shipping can be too restrictive or too lenient for other areas of shipping.

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References

Andrews, J. D., Moss, T. R., 2002a. Common cause failures. In Reliability and risk assessment (Second ed., pp. 267-285). Professional Engineering Publishing Limited, London.

Andrews, J. D., Moss, T. R., 2002b. An introduction to reliability and risk assessment. In Reliability and risk assessment (Second ed., pp. 1-20). Professional Engineering Publishing Limited, London.

Aven, T., 2012. On the link between risk and exposure. Reliab. Eng. Syst. Saf. 106, 191-199.

Bačkalov, I., 2012. A probabilistic analysis of stability regulations for river-sea ships. Paper presented at the 11th International Conference on the stability of ships and ocean vehicles (STAB 2012), Athens.

Bačkalov, I., Bulian, G., Rosén, A., Shigunov, V., Themelis, N., 2015. Ship stability & safety in intact condition through operational measures. Paper presented at the 12th International Conference on the Stability of Ships and Ocean Vehicles (STAB 2015), Glasgow, UK.

Belenky, V. L., Sevastianov, N. B., 2007. Philosophy of probabilistic evaluation of stability and safety. In Stability and safety of ships, Risk of capsizing (pp. 3-29). The Society of Naval Architects and Marine Engineers (SNAME), Jersy City, NJ.

BSU, 2009. Fatal accident on board the CMV Chicago Express during Typhoon "Hagupit" on 24 September 2008 off the coast of Hong Kong. Bundsstelle für Seeunfalluntersuchung, Hamburg.

Cleary, W. A. J., 1975. Marine Stability Criteria. Paper presented at the International Conference on Stability of Ships and Ocean Vehicles (STAB 1975), Glasgow.

Department of Transport, 1987. MV Herald of Free Enterprise, Report of court no. 8074 formal investigation. Department of Transport, London.

Goerlandt, F., Ståhlberg, K., Kujala, P., 2012. Influence of impact scenario models on collision risk analysis. Ocean Eng. 47(0), 74-87.

Hinz, T., 2015. Risk analysis of a stability failure for the dead ship condition. Paper presented at the 12th International Conference on the Stability of Ships and Ocean Vehicles (STAB 2015), Glasgow.

Hofman, M., Bačkalov, I., 2007. Cougar Ace: the tipping point. Nav. Architect April, 10-11.

Hua, J., Rutgersson, O., 1994. A study of the dynamic stability of a RO-RO ship in waves. Paper presented at the 5th International Conference on Stability of Ships and Ocean Vehicles (STAB 1994), Melbourne, FL.

Huss, M., 2016. Operational stability beyond rule compliance. Paper presented at the 15th International Ship Stability Workshop (ISSW 2016), Stockholm.

IMO, 1999. Objectives of the organization in the 2000s (RESOLUTION A.900(21)). International Maritime Organization, London.

IMO, 2008a. FSA - RoPax ships, Submitted by Denmark (MSC 85/17/2). International Maritime Organization, London.

IMO, 2008b. International Code on Intact Stability, 2008 (2008 IS Code). International Maritime Organization, London.

IMO, 2013a. Guidance on human reliability analysis (HRA). Appendix 1 to Revised guidelines for formal safety assessment (FSA) for use in the IMO rule-making process (MSC-MEPC.2/Circ.12 Appendix 1). International Maritime Organization, London.

IMO, 2013b. Revised guidelines for formal safety assessment (FSA) for use in the IMO rule-making process (MSC-MEPC.2/Circ.12). International Maritime Organization, London.

IMO, 2018. Summary of questionnaire survey on draft guidelines of direct stability assessment procedures for use with the second generation intact stability criteria. Annex 1 to Finalization of second generation intact stability criteria, Information collected by the correspondence group on intact stability (SDC 6/INF.3 Annex 1). International Maritime Organization, London.

Kluwe, F., Krüger, S., 2007. Using full-scale capsizing accidents for the validation of numerical seakeeping simulations. Paper presented at the 9th International Ship Stability Workshop (ISSW 2007), Hamburg.

Kuo, C., 2007a. Human factors and safety. In Safety management and its maritime application (pp. 171-185). The Nautical Institute, London.

Kuo, C., 2007b. Safety management and its maritime application. The Nautical Institute, London.

Liwång, H., Rosén, A., 2018. A framework for investigating the potential for operational measures in relation to intact stability. Paper presented at the 13th International Conference on the Stability of Ships and Ocean Vehicles (STAB2018), Kobe.

MAIB, 2016. Report on the investigation into the listing, flooding and grounding of Hoegh Osaka Bramble Bank, The Solent, UK on 3 January 2015 (REPORT NO 6/2016). Marine Accident Investigation Branch, Southampton.

Mata-Álvarez-Santullano, F., Souto-Iglesias, A., 2014. Stability, safety and operability of small fishing vessels Ocean Eng. 79, 81-91.

Möller, N., Hansson, S. O., 2008. Principles of engineering safety: Risk and uncertainty reduction. Reliab. Eng. Syst. Saf. 93(6), 798-805.

Oltedal, H. A., 2018. Setting the stage for maritime safety management. In H. A. Oltedal & M. Lützhöft (Eds.), Maritime safety management (pp. 1-15). Routledge, Abingdon.

Oltedal, H. A., Lützhöft, M., 2018. The human contribution. In H. A. Oltedal & M. Lützhöft (Eds.), Maritime safety management (pp. 71-90). Routledge, Abingdon.

Parker, D., Lawrie, M., Hudson, P., 2006. A framework for understanding the development of organisational safety culture. Saf. Sci. 44(6), 551-562.

Pedersen, P. T., 2010. Review and application of ship collision and grounding analysis procedures. Mar. Struct. 23(3), 241-262.

Perera, L. P., Soares, C. G., 2017. Weather routing and safe ship handling in the future of shipping. Ocean Eng. 130, 684-695.

Peters, A., 2010. Tolerable capsize risk of a naval vessel. Paper presented at the 11th International Ship Stability Workshop (ISSW 2010), Wageningen.

Peters, W., Belenky, V., Bassler, C., Spyrou, K., Umeda, N., Bulian, G., Altmayer, B., 2011. The second generation intact stability criteria: An overview of development. T. Soc. Nav. Arch. Marine Eng. 121.

Rausand, M., Bouwer Utne, I., 2009. Risikoanalyse - teori og metod [Risk analysis - theory and method]. Tapir Akademiske Forlag, Trondheim.

Reason, J., 2000. Safety paradoxes and safety culture. Int. J. Inj. Prev. Saf. Prom. 7(1), 3-14.

Sames, P. C., 2009. Introduction to risk-based approaches in the maritime industry. In A. D. Papanikolaou (Ed.), Risk-based ship design (pp. 1-15). Springer-Verlag, Berlin.

Schröder-Hinrichs, J.-U., Hollnagel, E., Baldauf, M., 2012. From Titanic to Costa Concordia—a century of lessons not learned. WMU J. Marit. Aff. 11(2), 151-167.

Skjong, R., 2002. Risk acceptance criteria: current proposals and IMO position. Paper presented at the Surface transport technologies for sustainable development, Valencia.

Skjong, R., 2009. Regulatory framework. In A. D. Papanikolaou (Ed.), Risk-based ship design (pp. 97-151). Springer-Verlag, Berlin.

Swedish Accident Investigation Authority, 2008. Handelsfartyget FINNBIRCHs förlisning mellan Öland och Gotland, den 1 november 2006 (Rapport RM 2008:03) [The foundering of the ship FINNBIRCH between Öland and Gotland, 1 November 2006 (Report 2008:03)]. The Swedish Accident Investigation Authority, Stockholm.

Taguchi, H., Haraguchi, T., Minami, M., Houtani, H., 2015. An investigation into the capsizing accident of a pusher tug boat. Paper presented at the 12th International Conference on the Stability of Ships and Ocean Vehicles (STAB 2015), Glasgow.

Trist, E., 1989. The assumptions of ordinariness as a denial mechanism: Innovation and conflict in a coal mine. Hum. Resour. Manage. 28(2), 253-264.

Umeda, N., Francescutto, A., 2016. Current state of the second generation intact stability criteria - achievements and remaining issues. Paper presented at the 15th International Ship Stability Workshop (ISSW 2016), Stockholm.