Stability Barrier Management for Large Passenger Ships

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ABSTRACT

This paper deals with major accident risk related to stability on large passenger ships. The main scope of work is to investigate the impact stability related risk has on the total risk picture, and introduce barrier management as an approach to control stability related risk. The paper also addresses some main elements in stability management, highlights critical barriers and presents a case study on how stability barrier management may function in practise.

Keywords: *Stability barrier management, barrier management, stability management, safety management, passenger ships, cruise ships, bowtie*

1. MAJOR ACCIDENT RISK FOR PASSENGER VESSELS

Several definitions of major accident exist, as described by DNV GL and the Norwegian Ship-owners Association in the report “Good Practices - Barrier Management in Operation for the Rig Industry” [1]. Although somewhat different, they all have in common that they refer to large scale consequences, in terms of impact on life, property and the environment. They also indicate that the consequences may be immediate or delayed, suggesting that there is a potential for escalation. Further, major accidents are complicated by nature and hard to predict. They involve a complex risk picture, multi-linear chain of events, failure in several safety features, and with a potential for uncontrolled escalation.

Accidents related to ship damage stability have been shown to be a major risk contributor for passenger ships through the joint industry project Risk Acceptance Criteria and Risk-Based Damage Stability [2] and the Goal-Based Damage Stability project (GOALDS) [3] where annual accident frequencies for passenger ships were determined based on the IHS Fairplay. To increase the accuracy, the data was filtered according to several criteria and the following accident categories were selected for analysis: Collision, contact, grounding, (also designated wrecked/stranded) and fire/explosion

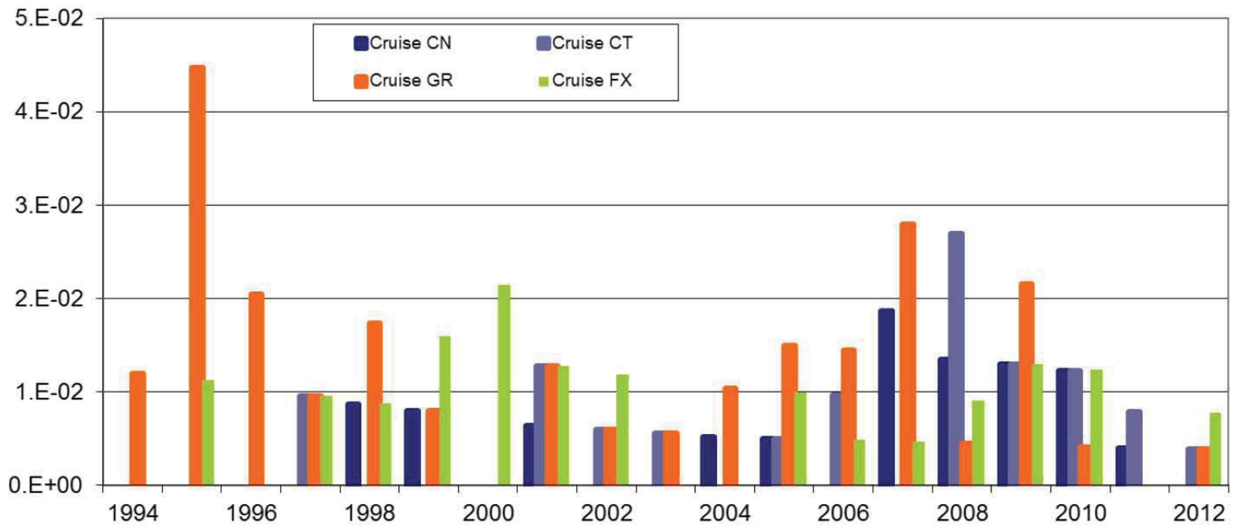

Figure 1: Annual accident frequencies for passenger ships (excluding ropax) **[2] [3]**

Explanation to figure:

- CN: Collision
- CT: Contact
- GR: Grounding (incl. Wrecked/Stranded)
- FX: Fire/explosion

The accident frequency statistics show that the main risk contributors for cruise ships are stability related. From 2000 to 2012, there were a total of 59 cruise ship casualties related to grounding, contact and collision and 21 to fire.

The events in the accident statistics above are all initial events considered to be serious, and could lead to a major accident with significant loss of life. For major accidents such as capsizing or sinking the risk is uncertain - we are still dependent on our perceptions to determine the risk. Exposure to some risk is unavoidable when operating a large passenger vessel in a seaway and it is not feasible for the industry to contemplate building and operating risk-free ships. The alternative would be a passenger ship never leaving port. The purpose of managing major accident risks is therefore not to eliminate the risk itself but to understand and control it so that risk can be managed in the most effective way.

2. INTRODUCTION TO BARRIER MANAGEMENT

The purpose of the barrier management approach to safety is to take into account the low frequency and high consequence major accidents by addressing the complexity of these scenarios. If a risk analysis predicts a major accident to occur once in a hundred years, it is hard to tell whether this happens tomorrow, in fifty years or in a hundred. Consequently, management of major accident risk requires good systems, which captures this complexity and reduces uncertainty. This is the main objective, or rationale, behind barrier management[1].

2.1 Bowties – the Foundation for Barrier Management

A common way to illustrate barriers is by James Reason's Swiss Cheese Model [4]:

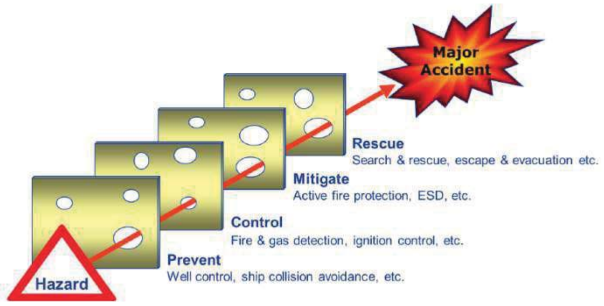

Figure 2: Swiss cheese model

As revealed by its name, the Swiss Cheese model illustrates an event sequence in which barriers are presented as cheese slices. The holes in the cheese slices represent barrier failure. Throughout the lifetime of a ship, holes in this model are expected to constantly move and change sizes depending on a multitude of causes, such as type of operation, condition of the ship, crew competence, to name but a few. For a major accident to happen, holes in the Swiss Cheese Model need to align, allowing for an accident trajectory.

Safety barriers are defined by making bowties, as has been defined by DNV GL and the Norwegian Shipowner's Association [1] to consist of the following elements:

- Hazard/Threat: Potential for human injury, damage to the environment, damage to property, or a combination of these (ISO 13702).
- Hazardous event: Incident which occurs when a hazard is realised (NORSOK Z-013; ISO 13702).
- Barriers: Barriers refer to measures established with an explicit purpose to (1) prevent a hazard from being realised, or (2) to mitigate the effects of a hazardous event.

A simplified presentation of the elements in the bowtie diagram is as follows:

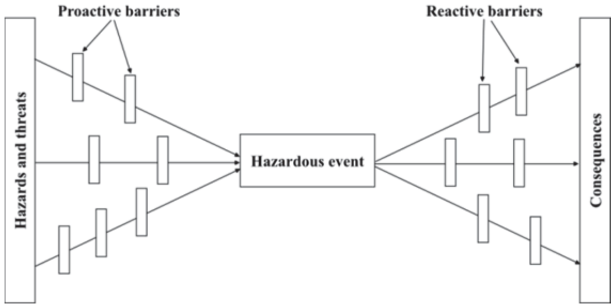

Figure 3: Simplified bowtie diagram **[5]**

An example for stability could be a ship sailing in a busy waterway in heavy fog (threat) leading to collision (hazardous event) that may lead, in turn, directly to loss of life (consequences).

The bowtie tool is flexible and standards vary between different companies depending on their needs and what the bowtie structure is used for. As an example, bowties for accident analysis may differ from bowties used to define barriers in a safety management system or bowties used for the purpose of regulatory development. DNV GL typically uses major accidents as defined in chapter 1 as hazardous events in the centre of the bowties [1]. Examples of such hazardous events are fire/explosion, capsizing, collision/grounding, loss of power generation, loss of propulsion /manoeuvring, terrorism and pollution to air/sea.

These hazardous events are selected to best capture the complexity of major accidents. The bowties are naturally interlinked, meaning that the same incident may be a hazardous event, consequence or a threat depending on how the operator decides to set up the bowtie. Likewise, the same incident may be a threat in one bowtie, and a consequence in another. As an example, a collision may lead to fire/explosion, capsizing, loss of power generation or pollution to sea. Likewise loss of power generation may lead to collision.

From a safety management perspective, the purpose of the bowtie is to define barriers that are the foundation of the management system.

The only way to control a major accident risk is by controlling the integrity of the barriers at all times. By spotting degradation of a barrier at an early stage, one can take necessary action before an accident trajectory opens in the Swiss cheese model. Further, there is a need to have a process in place that continuously analyses the barriers for improvement potential, either by strengthening the existing barriers or adding new ones.

Using the bowtie structure as a basis for barrier management also contributes to the understanding of major accident risk. If one understands the bowtie, one will also improve the understanding of the complexity of accident risk and the purpose of the different safety functions. For every item that is sorted and managed under a barrier, be it e.g., a job in a maintenance system, a procedure or a rule, the function and purpose of the item is self-explanatory - the bow-tie structure explains *why* the item is there. Likewise, the bowtie structure explains *how* we manage our barriers. A certain barrier is managed by the totalities of items beneath it in the structure. As the complexity of the passenger ship industry develops, the bowtie concept may be useful for handling a novel design, which requires a different approach to managing safety barriers than what is stipulated through regulation and conventional design processes, which more often than not lack structure and rationale.

2.2 Moving Beyond Compliance

Given the severe consequences of a major accident on a large passenger vessel, it is the opinion of the authors that a compliance- based safety culture is not sufficient. History has proven that the current international structure for rules and regulations cannot keep up with the pace in which the industry is developing. The aftermath of the Estonia and the Herald of Free Enterprise accidents are two examples where update of international regulations first came as a consequence of a major accident. Weaknesses in safety barriers must be addressed before an accident happens and this is one of the main purposes of a barrier management system. By systematically seeking improvements to barriers, the target goes from being in compliance to continuous improvement.

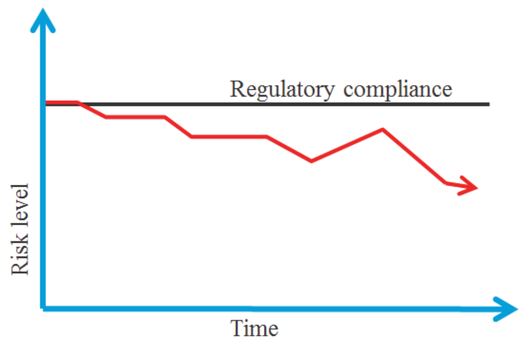

Figure 4: Targeting continuous improvement vs targeting compliance

Some operators of large passenger ships have taken steps beyond compliance on some aspects relating to stability. Examples are cruise ships designed to withstand more than three compartment damage, double skin at the engine room region of cruise ships, larger GM than the required value for compliance, enhanced damage response procedures, shore side training in damage control, increased drill frequencies, etc.

The next step for such companies could be to introduce a barrier management system that systemizes these initiatives and ensures that the improvements continue. However, simply placing a modern approach upon aging foundations will lead to increased long-term workload, frustration and a general hesitation towards acceptance of the modern approach. The transformation must not be done by adding work, but rather by working smarter, and it must be seen and understood as a means of delivering higher value.

3. STABILITY BARRIER MANAGEMENT

In 2012 Royal Caribbean Cruises Ltd and DNV GL worked together in defining a framework for enhanced stability management [6]. The focus on stability has continued and can be seen in the light of the following trends:

- Increasing size of passenger ships, which both increases the severity of the worst case consequences and increases the complexity of barriers related to e.g. evacuation.
- Manning and training. Finding competent crew is an increasing challenge, which makes training ever more important.
- Workload onboard ships.
- Operation in new areas and continual shifts in deployment strategy.
- New operators entering the market with little passenger ship experience.
- Ship revitalization projects and conversions whose scope impacts stability.
- Complexity of new approaches to ship stability: shift from deterministic to probabilistic stability regulations
- Increased level of automation.

3.1 Stability Bowties

The following bowtie for Capsizing was created as a prototype by DNV GL in 2014:

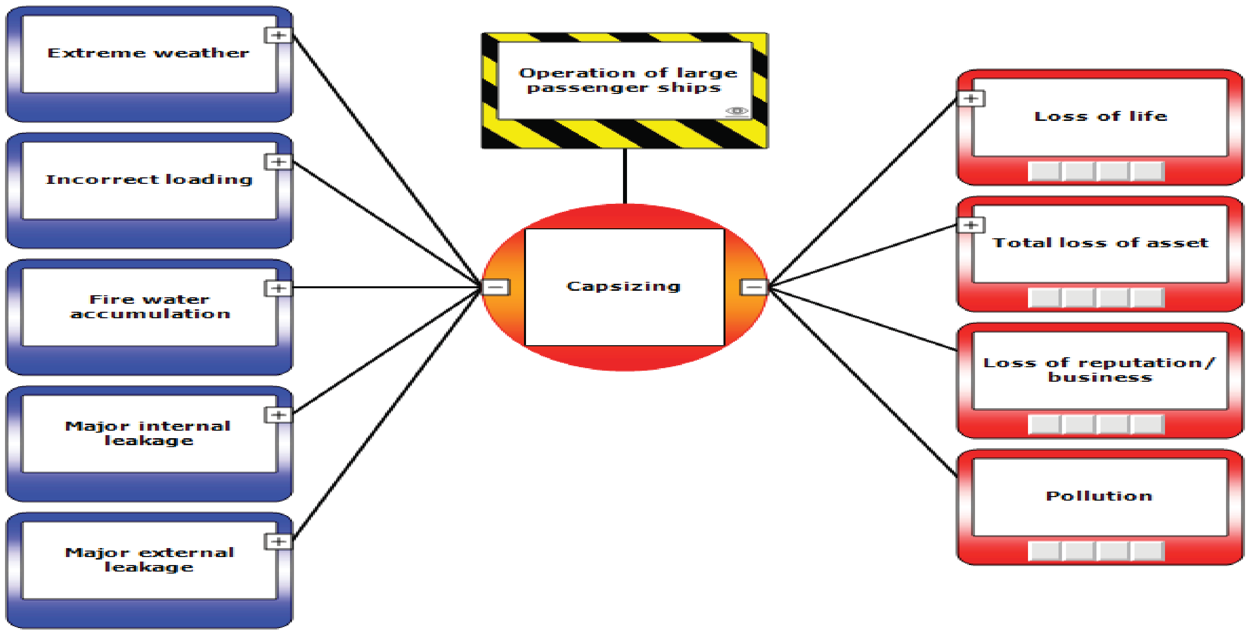

Figure 5: High level bowtie diagram, only showing threats and consequences.

To account for the complexity of the major accident, the bowtie diagram can be broken down into a number of elements. The following example is for the sub-function Detect Leakage.

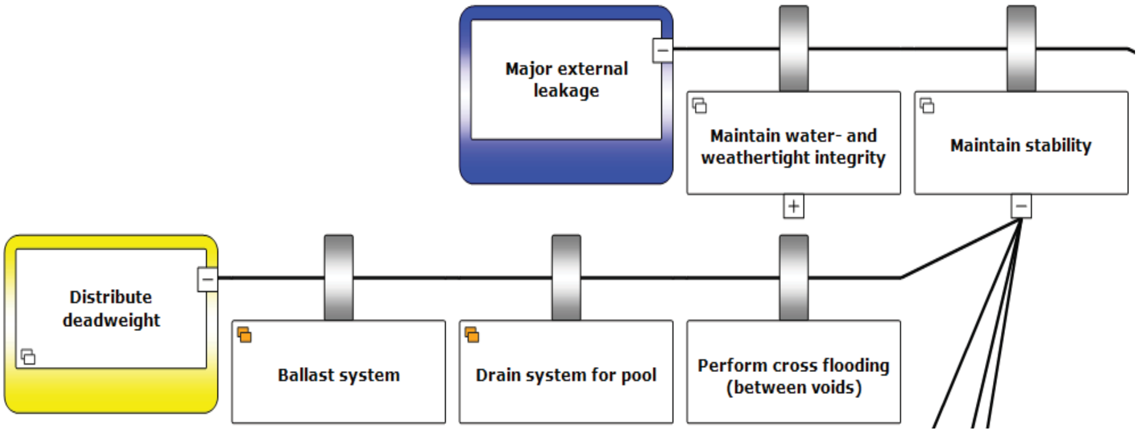

Figure 6: Elements in bowtie diagram

The bowtie diagram will typically consist of dozens of different barrier elements that all need to be considered in the barrier management system. While the full detail bowtie serves its purpose for designing the barrier management system and barrier analysis, it may be beneficial to simplify it for the purpose of day-to-day management. In the following example, four preventive barriers against capsizing have been designed for use in a stability barrier management system.

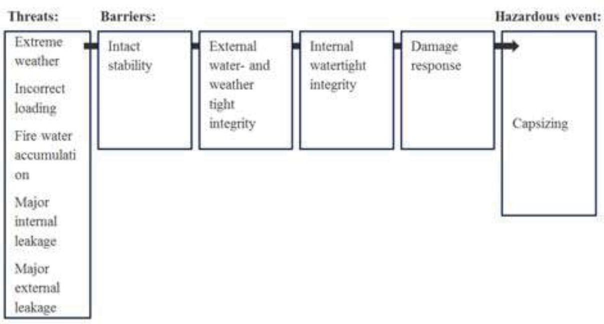

Figure 7: Example of preventive barriers against capsizing, for use in a stability management system.

Besides the four barriers above, there are several other barriers that may be relevant for stability barrier management. A bowtie with Collision/Grounding as the Hazardous Event is interesting with regards to the accident statistics, which highlights this as the major risk contributor for passenger vessels. The Collision/grounding and Capsizing bowties would be interlinked, as they can be seen as threats/causes and consequences for each other (collision can be a cause for capsizing, and capsizing a consequence in collision). In the bowtie above, collision/grounding is included in the threat “Major external leakage”. Having Collision/grounding and Capsizing as hazardous events in separate bowties, will allow for a better risk presentation as it will capture the other threats for capsizing and the other consequences of collision/grounding.

The following main areas are seeing the most attention in the industry:

- Barriers related to Navigation, i.e preventing collision/grounding/contact.
- Watertight doors, which is a part of the barrier Internal Watertight Integrity, i.e preventing capsizing or sinking.
- Damage response: Detection, assessment and mitigation of a damage.

And as with most barriers, the challenges with ensuring the integrity are all related to people, processes and technical systems.

Navigation is an important barrier as it is far most to the left in the accident scenario described above. Controlling this barrier and preventing an accident from happening in an early stage is of course preferable to mitigation after e.g., grounding. At the same time it is a complicated barrier, involving management of people, processes and advanced systems. There have been significant investments into navigation systems and training over the last years, but still the shipping industry as a whole has not seen a reduction of navigational accidents.

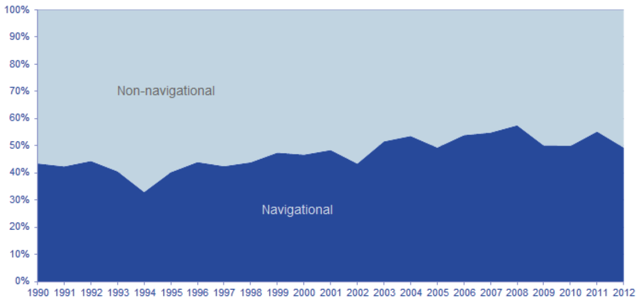

Figure 8: Distribution of navigational vs non-navigational accidents, 1990-2012 (All vessels, excluding fishing and miscellaneous categories). Source: IHS Fairplay

Watertight doors are a critical system for maintaining internal watertight integrity of the ship. The watertight doors stand out from other watertight bulkhead penetrations because of the following:

- The size of the opening. The bilge systems on dry side of the bulkhead may handle small leaks but not the flow rate through an open watertight door.
- The possibility that the door is open at the time of the accident and will depend on the combination people, processes and technical systems in order to be closed.
- The water tight doors may frequently be in use and thereby over time be prone to failure.

Watertight doors are used as a case study in chapter 4.

3.2 Main Elements of Stability Barrier Management

The total robustness of a safety barrier can be seen as the sum of the inherent robustness, which is latent in the ship design and the robustness, which needs to be managed during operation. Therefore, the ship design sets the bar and the operation of the vessel can be seen as the ability to keep the bar as close to the design intent. Having said this, interventional or active measures (e.g., counterballast post damage, use of inflatable devices, active foam, etc.), may with time and technological innovation change this norm. This is outlined further in the following.

The operational part can further be broken down into strategic, operational and emergency stability management [6]

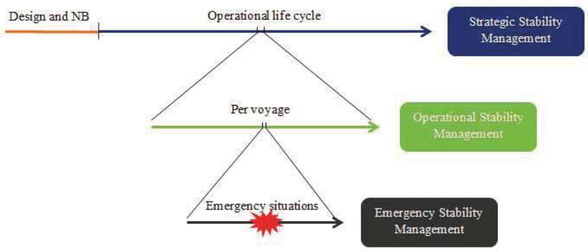

Figure 9: Main Elements of Stability Management

- Ship design and new building: The management process ensuring that the ship is designed and built with an inherent level of safety and sufficient margins as a result of current regulation and a company's safety culture, addressing aspects such as layout constraints, number of bulkheads, tank arrangement, steel weight, centre of gravity, WTD arrangement and deck openings.
- Strategic stability management - operational life cycle perspective: shore side barrier management processes that ensure fleet-wide control over barriers, continuous improvement and allows for long term planning of stability enhancing measures based on data and operator feedback.
- Operational stability management - per voyage perspective: On board barrier management processes that control barriers and react to important factors and parameters to ensure that the voyage is safe, efficient, in compliance and according to company policy. The operational level of stability management is strongly linked to strategic management

and is a key predicator for effective strategic management.

- Emergency stability management – emergency situations: Both on board and shore side emergency response procedures that give a structured and clear response to ensure full barrier integrity and thereby preventing loss of stability.

The inherent robustness in passenger ship design with regards to stability has developed significantly in the last decade, in particular with the transition from deterministic to probabilistic rules for stability. In addition some ship owners have introduced own standards, such as designing ships with double skin.

However, for the industry as a whole, it is the claim of the authors that the traditionally design focused culture for stability management must be shifted to one where the operation is seen as integral player to maintaining barrier integrity. Examples on how stability management in operations can be improved have been demonstrated by Royal Caribbean Cruises Ltd who since 2012 have enhanced their damage response procedures, increased the shore side training on damage control, introduced data tracking of opening hours of watertight doors and increased damage response drill frequencies [6] to name but a few of the many initiatives.

4. CASE STUDY: WATERTIGHT DOORS

In this chapter we are using a barrier defined as Internal Watertight Integrity and the sub-function Watertight Doors as an example on how barrier management may function in practice. The chapter exemplifies how the barrier can be managed by cooperation between the shore side and ship side of an organization.

The following figure shows how watertight doors can be represented as a sub-function in a simplified bowtie.

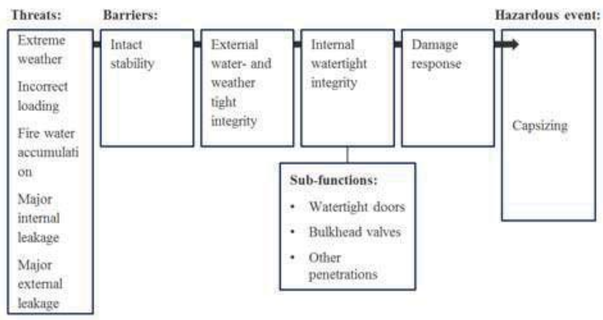

Figure 10: Simplified bowtie, including internal watertight integrity and watertight doors.

With a barrier management system, the operator knows why watertight doors are important, knows the condition and takes necessary action to ensure maximum integrity to the safety barrier. A person with knowledge about the bowtie structure will also know why watertight doors are important, so the chapter focuses on how a company could know the condition of the watertight doors and take necessary action.

While watertight doors are chosen as an example in this paper, it is important to highlight the need for also managing the other sub-functions in the barrier to ensure that there are no holes in the Swiss cheese. Time and resources should be distributed according to the importance of the sub-functions, and with the bowtie as a basis there are possibilities to do a risk calculation for each barrier, which can be used as input for concentrating resources to the most critical areas.

Besides being an important function, watertight doors are interesting as an example for the following reasons:

- It is possible to measure data which may be available via the watertight door control system or the VDR. Further, the data can be aggregated to ship class and fleet level and be used for analytics. This is already being done by some operators. There is also a possibility of live data streaming of this data from ship to shore and provide shore side with a live feed on the status of the barrier.

- There is a certain degree of complexity to the watertight doors as a sub-function. It has elements related to the people, processes and technical systems.
- Watertight doors must be managed in all elements of stability management: Design, strategic, operational and emergency. It thereby also requires active participation from both ship side and shore side.

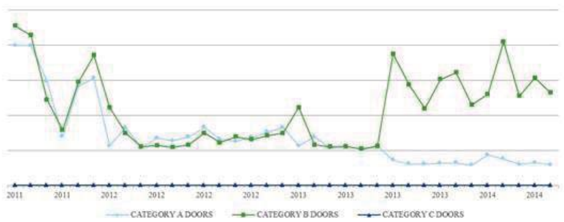

Figure 11: Example: Trending of opening hours for watertight doors

4.1 Ship side barrier management, watertight doors

Ship side will perform a barrier analysis for their ship, and their input for determining the status of the watertight doors will typically be the following:

- Tests and inspections
- Maintenance
- Drills
- Data monitoring of opening hours of the ship's watertight doors over time. This data may be measured against pre-defined targets.
- Partners or third party inspections, typically class, port state control or maker of systems. Ideally the partners report in the same barrier management structure as the operator.
- The 'last barrier analysis'. How has the status progressed since last time?

A combination of colour coding and pre-defined acceptance criteria is a common method for reporting the status.

Based on the barrier assessment, the officers will perform the following actions:

- Report the status of the safety barriers to shore side for further analysis in a ship class and fleet perspective
- If needed, perform any necessary action on the ship's watertight doors. These actions may be related to people, processes or technical systems.

4.2 Shore side barrier management, watertight doors

Shore side personnel will perform a barrier analysis for the fleet and for different ship classes. The barrier structure will be identical as the on-board analysis, but the perspective and number of units will differ. Their input for determining the status of the watertight doors will typically be the following:

- Barrier analysis for individual ships, reported by each ship. Are the reported deficiencies systematic in their nature, or is it a one-off?
- Maintenance records aggregated to fleet level
- Data monitoring of opening hours of the fleet's watertight doors over time. This data may be measured against pre-defined targets.
- Partners or third party inspections, typically class, port state control or maker of systems.
- The last barrier analysis. How has the status progressed over time?

Based on the barrier assessment, the shore side personnel may perform actions toward the ships related to people, processes or the technical systems. They may take immediate action against individual ships if needed, but the main task of the shore side management is to provide instructions, guidance and training to enable the ship's crew and officers to manage the watertight doors in operation and emergency situations.

Another important task of shore side management is to assess the confidence of the barrier assessment, asking if enough information is available in order to confidently set a status on a barrier, or if more sources of information are needed. This may for instance lead to changes in maintenance/test/inspection intervals for watertight doors or setting up systems for tracking and trending opening hours. Likewise, the acceptance criteria for the barrier assessment should be reviewed at regular intervals; this is where both shore side and ship side has the opportunity of raising the bar by setting new targets and thereby ensuring continuous improvement and concentrate resources on the most critical elements.

Shore side management will also be responsible for bringing relevant findings from the barrier analysis to the design phase, ensuring that the next generations of passenger ships are modified to strengthen the barrier. If a flooding situation occurs and one or more watertight doors are open, the survivability of the ship is most likely significantly reduced as expressed by the attained index A calculated in accordance with SOLAS. The designers must find solutions to reach an equivalent level of safety. In such a setting, input from strategic and operational stability management may be valuable, as has already been proven by some operators. By tracking and trending opening hours of watertight doors, one can pinpoint which doors have the biggest effect on survivability and the operation, and redesign accordingly.

5. CONCLUSIONS

Collision or grounding leading to water ingress and capsizing or sinking have been shown to be a major risk contributor for passenger ships. Given the severe consequences of a major accident on a large passenger vessel, it is the opinion of the authors that a compliance based safety culture is not sufficient. Moving beyond compliance means explicitly addressing risks and risk mitigation.

The introduction of barrier management can be an effective way of systemizing both prevention and mitigation in order to reduce risk and ensure continuous improvement. Barrier management must address people, processes and technological systems. Whilst the ship is designed and built with an inherent level of safety, it is necessary to address the important elements of stability in holistic view and over time. Watertight doors represent a good example of barrier management addressing all elements of stability management: Design, strategic, operational and emergency.

Proper stability management addressing all four phases of stability management using a barrier management system will in the opinion of the authors contribute to reducing the risk of large scale accidents involving major loss of life.

6. ACKNOWLEDMENTS

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