# FORENSIC ENGINEERING INVESTIGATIONS ON MARINE CASUALTIES

*A Thesis*

*Submitted By*

**AJIT NAIR**

*For the award of the degree*

*of*

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**COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY**

**KOCHI -682022**

**MAY 2018**

## DEDICATION

*To the Angels on Earth who guide me always*

## DECLARATION

This is to certify that the thesis entitled **"FORENSIC ENGINEERING INVESTIGATIONS ON MARINE CASUALTIES"** submitted to the Cochin University of Science and Technology in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy is a bonafide record of research work carried out by me. The contents of this thesis have not been submitted and will not be submitted to any other University or Institute for the award of any degree.

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# CERTIFICATE

This is to certify that the thesis entitled **"FORENSIC ENGINEERING INVESTIGATIONS ON MARINE CASUALTIES"** submitted by Ajit Nair to the Cochin University of Science and Technology in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy is a bonafide record of research work carried out by him under my supervision. The contents of this thesis have not been submitted and will not be submitted to any other University or Institute for the award of any degree.

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This is to certify that all relevant corrections and modifications suggested by the audience during the pre-synopsis seminar and recommended by the Doctoral Committee of Ajit Nair have been incorporated in the thesis.

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# ABSTRACT

The shipping industry has a fairly good safety record comparable to any other transportation mode. While the frequency and severity of marine casualty may have reduced considerably in recent years, statistics indicate a considerable number of ships still involved in casualties leading to ship loss, structural damages, environmental pollution and/or loss of lives. The thesis has approached marine casualties from three perspectives viz., human factor issues, engineering issues and inspection issues. The human factor approach is with the intent to prevent the recurrence of marine casualties as a result of human errors and poor performance issues, while the engineering issues and inspection issues approach is to mitigate the extent of damage sustained to the ship hull structure in the event of a marine casualty.

Ships are operated by humans and human factor issues leading to errors and performance issues dominate over all other causes leading to marine casualties. In the last few decades there has been a greater emphasis on understanding human factor issues in ship operations and manning. The use of advanced navigational equipment onboard ships, improved crew training and crew comfort, minimum manning requirements etc., are some of the noticeable changes made to alleviate the occurrence of marine casualties as a result of human errors and performance issues. However, marine casualties have continued to occur for the very same reasons that were identified earlier and apparently assumed to be resolved through incorporation of these changes. One of the shortcomings identified in this study is the lack of emphasis on the area based issues and navigation and infrastructure issues in the geographical area of marine casualty and how it influences the human factor issues.

Besides addressing this shortcoming, this study advances a novel approach for resolving the human factor issues in a specific geographical area of the marine casualty through a relationship established between the human factor issues, area based issues and navigation and infrastructure issues pertaining to this area of casualty. The analysis of these issues based on the established relationship form the *best practices* approach for resolving the identified human factor issues and this is illustrated with a hypothetical case study. Templates to input the data together with a

detailed procedure is also developed for conducting the analysis based on the *best practices* in this study.

The environmental impact of global warming has resulted in increase in wave heights in certain regions of the oceans and seas world over and so has there been an increase noted in the frequency of freak or rogue waves. Classification rules, International Maritime Organization (IMO), and International Association of Classification Societies (IACS) guidelines do not capture the requirements for deflection limits for damages sustained to the side shell plating as a result of the wave induced loads i.e. Hungry Horse Deflections (HHD). Corrosion on the hull structure further weakens the strength and energy absorbing capacity of the deformed hull structure in the event of a collision or allision casualty. Furthermore, it is evidenced that marine casualty investigations involving collision and allision casualties are not truly performed from an engineering perspective. These investigations shed little information on any existing damages to the hull structure and how these initial imperfections contributed to the escalation of the damage sustained as a result of the subsequent casualty.

On the backdrop of these issues, the need for a marine casualty investigation from an engineering perspective is espoused in this study. The criteria for assessment identified in this study is Hungry Horse Deflection (HHD), which individually and along with corrosion can influence the ability of the side shell plating to resist the impact forces during a collision or allision casualty. To facilitate a forensic engineering investigation for the identified criteria for assessment, a procedure is developed in this study which provides guidelines on gathering or recording physical evidence, selection of the appropriate marine casualties and analysis.

Crack initiation or formation in the ship hull structure appears inevitable in present day ships because of their complex designs and size, use of welding as the only joining technique, fabrication and workmanship issues, material selection, and fatigue and corrosion issues. These cracks can develop at a very early stage in the operational life of the ship and propagate rapidly leading to failure when subject to impact loads typically associated with collision, allision and NASF. Inspection of cracks poses a challenge as they are not easily detectable and when detected and rectified, it may resurface again if the correct crack inducement factor is not identified. Furthermore, a majority of the studies identify crack inducement factors from a fatigue condition perspective.

An age based crack assessment criteria is developed in this study to facilitate the inspection of the hull structure for cracks at a very early stage in the operational life. The intent here is to prevent the cracks from being the reason for escalation of damage sustained to the ship in the event of a marine casualty. A state of art diagram using the circular data visualization technique is used to represent the age based crack assessment criteria together with the inspection findings and validation methods available. The use of the state of art age based crack assessment criteria diagram is presented with a hypothetical case study.

In all the three objectives addressed in this thesis, the purpose of adopting a forensic engineering based investigation approach has been to prevent the future occurrence of similar failures by identifying the product and/or procedural shortcomings and to translate these findings to improve the design, construction, survey or operational systems of ships.

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## ABBREVIATIONS

| Symbol | Definition |
|---|---|
| ABS | American Bureau of Shipping |
| AIS | Automatic Identification System |
| ARPA | Automatic Radar Plotting Aid |
| BV | Bureau Veritas |
| CASMET | Casualty Analysis Methodology for Maritime Operations |
| CREAM | Cognitive Reliability Error Analysis Method |
| DNV | Det Norske Veritas |
| DWT | Deadweight |
| ECDIS | Electronic Chart Display and Information System |
| EMCIP | European Marine Casualty Information Platform |
| EMSA | European Maritime Safety Agency |
| FEA | Finite Element Analysis |
| FTA | Fault Tree Analysis |
| GCM | General Circulation Model |
| GEV | Generalized Extreme Values |
| GIS | Geographical Information System |
| GISIS | Global Integrated Shipping Information System |
| GL | Germanischer Lloyd |
| GWS | Global Wave Statistics |
| HFACS | Human Factor Analysis and Classification System |
| HHD | Hungry Horse Deflections |
| HK | Marine Department, The Government of the Hong Kong Special Admin. Dept. |
| IACS | International Association of Classification Societies |
| ICOADS | International Comprehensive Ocean-Atmosphere Data Sets |
| IMO | International Maritime Organization |
| ISM | International Safety Management |
| JTSB | Japan Transport Safety Board |

| | |
|---|---|
| LNG | Liquefied Natural Gas |
| LOWI | Loss of Watertight Integrity |
| LR | Lloyds Register of Shipping |
| MAIB | Maritime Accident Investigation Branch |
| MaRCAT | Marine Root Cause Analysis Technique |
| MLC | Maritime Labour Convention 2006 |
| NASF | Non Accidental Structural Failure |
| NM | Nautical Mile |
| NTSB | National Transport Safety Board |
| OOW | Officer on Watch |
| P&I | Protection and Indemnity |
| SCAT | Systematic Causation Analysis Technique |
| SNAME | Society of Naval Architects and Marine Engineers |
| SOLAS | Safety of Life at Sea |
| STCW | Standards of Training, Certification and Watchkeeping for Seafarers |
| SWH | Significant Wave Height |
| TRACEr | Technique for the Retrospective and predictive Analysis for Cognitive Errors |
| TSBC | Transportation Safety Board of Canada |
| UK | United Kingdom |
| ULCC | Ultra Large Crude Carrier |
| VLCC | Very Large Crude Carrier |

# CHAPTER 1

# INTRODUCTION AND OBJECTIVES

## 1.1 GENERAL

Shipping has been one of the major modes of transportation worldwide for both domestic and international trade because of its large capacity, economy and environment-friendly nature. Although the shipping industry has a fairly good safety record comparable to any other transportation mode, maritime casualty as and when it happens can result in catastrophic consequences such as loss of lives, extensive environmental pollution and loss of property, creating negative publicity and incurring heavy financial loss not only to the ship owner, but to the society and the environment. The frequency of severity of marine casualties may have reduced considerably in recent years, however, statistics indicate that there are still a considerable number of ships involved in casualties leading to ship loss, structural damage, environmental pollution and loss of life. These casualties have occurred despite the initiatives taken at various levels by International Maritime Organization (IMO), classification societies and flag states.

Forensic engineering is defined by Noon (2001) “as the application of engineering principles and methodologies to answer questions of fact” where these “questions of fact” refers to issues with respect to the accident or casualty and various types of failures; and such an explanation matches well with the intent and focus of this study. Although the word ‘Forensics’ implies the legal aspect to the investigations, it is not necessary for all such investigations to be presented in court. It is the scientific and technological methodologies adopted in investigation that makes it suitable for marine casualty investigations. These investigations focus on the processes and conditions behind the casualty and how the same could have resulted in the damage.

‘Marine casualty’ or ‘casualty’ in this study refers to events or sequence of events resulting in “the death of, or serious injury to, a person; the loss of a person from a ship; the loss, presumed loss or abandonment of a ship; material damages to a ship; the stranding or disabling of a ship, or the involvement of a ship in a collision;

material damage to marine infrastructure external of a ship, that could seriously endanger the safety of the ship, another ship or an individual; pollution, or the potential for such pollution to the environment caused by damage to a ship or ships" (MAIB 2015f). The word 'accident' is also interchangeably used for 'marine casualty' or 'casualty' in this thesis at appropriate places and implies the same meaning. Collision, Grounding, Allision and Non Accidental Structural Failure (NASF) are the different types of marine casualties under focus in this thesis. Collision refers to casualties as a result of striking between two or more ships with each other; grounding refers to casualties as a result of the ship touching bottom with the sea bed, shore, coral reefs or ship wrecks, and allision or contact i.e. more commonly referred to, refers to casualties resulting from a ship striking with a fixed object such as pier, navigational buoy, piles, ice, cargo etc. These three represent navigational related casualties in which the human factor issues dominate and hence are the most common casualty types, the consequences of which can at times lead to loss of ships, loss of lives and environmental pollution.

Foundering type casualties involve loss of ship as a result of flooding or breaking into two and sinking. This type of casualty generally happens in open sea and when the ship encounters rough seas or stormy weather. NASF refers to the casualties resulting in damages to the hull structure such as cracks, fractures, deformations etc., and can be as a result of exposure to heavy or rough seas and ship design, construction and maintenance issues.

Marine casualty investigations in the last few decades has seen a greater emphasis on addressing human factor and organizational issues in ship operations and manning leading to human errors and poor performance, as a result of which there is now a greater understanding of the complexities involved in these aspects. Despite the initiative taken at various levels to alleviate the influence of human factor issues leading to diminishing human performance and human errors in operating and manning of ships, marine casualties continue to happen. Human factor issues are still considered one of the primary reasons for many maritime casualties, far exceeding other causes such as technical and mechanical failures, design issues, and environmental conditions. This is despite having identified factors leading to human errors and apparently resolving it through the introduction of advanced navigational equipment i.e. electronic chart, Electronic Chart Display and Information System (ECDIS), Automatic Identification System (AIS), more reliable radars, increased use of traffic separation system and port vessel traffic systems. There appears to be a need to understand the approach taken in analysing the human factor issues identified through the investigation process to bring about changes to prevent their repetition in future. It is envisaged that through this study *best practices* are developed for analysing the identified human factor issues to prevent similar failures in future.

Global warming has resulted in increase in wave heights in certain regions of the oceans and seas world over along with increased frequency of freak or rogue waves and changes in storm tracks. The ship side shell plate is the primary barrier of the ship hull structure that faces the brunt of these higher forces and prevents the ingress of water into the watertight areas. Deflections or deformations of the side shell plate between stiffeners may develop during the construction phase as a result of welding, and during the service life when exposed to wave induced loads. The dented or deflected shape formed as a result of the wave induced loads resembles the sight of a starved horse with its ribs protruding out and such a phenomenon is referred to as Hungry Horse Phenomenon (Kery and Garzke Jr. 2012b) and the deflections formed is referred to as Hungry Horse Deflections (HHD) in this study. HHD influence the ultimate strength values of the side shell plate thus making it more vulnerable to damages in the event of further loading or subsequent casualties. Furthermore, ships operate in highly corrosive environment and corrosion is one of the major concerns affecting the strength of the hull structure, which along with the HHD can further deteriorate the structural integrity of the side shell structure.

Many of the classification rules are based on experience of what was sufficient in the past. Present day ships are far bigger in size and capacity, use different material, are of complex designs and exposed to much harsher environmental conditions and thus many of the earlier requirements may not be sufficient now. In the present scenario, the shipping industry has to be cautious towards casualties as there is no such insignificant leak which is acceptable anymore. In an extreme event such as collision, allision or grounding type casualty as a result of human errors or not, a high level of redundancy will be crucial in limiting the extent of damage to the ship hull and the potential for further unexpected consequences. HHD has been selected as a shortcoming or gap in the classification rules and International Association of Classification Societies (IACS) guidelines on the permissible deflection limits with respect to it has been identified. In the present study, the use of a forensic engineering approach to analyse the criteria i.e. HHD individually and along with corrosion, which impact the strength of the ship structure is discussed. The intent here is to bring about engineering improvements for ships in operation through classification rules and regulatory changes and to provide guidelines which facilitate casualty investigations on this engineering issue.

Welded ship structures experience some degree of damage during its construction and operational life. Material imperfections and selection, improper welding, incorrect fabrication and poor workmanship are the probable causes for damages during construction while fatigue, corrosion and accidents are related to operations. These damages can manifest as cracks in the ship structure either immediately or in due course of time. Considering the complexity and size of modern day ship structures, use of welding as the only joining technique and limited use of non-destructive techniques to assess the quality of the welds, it is possible that not all cracks would be detected and rectified. Under normal operating conditions, these cracks may not pose a direct threat to the ship structural integrity. However, when subjected to a sudden impact force like the one associated with a rogue or freak waves, collision, allision and grounding type marine casualties, these existing cracks could propagate rapidly and lead to ultimate fracture, which in turn could lead to loss of the ship or its cargo.

The focus on crack has been primarily from a fatigue perspective i.e. as the ship gets older, and from a crack propagation perspective. Very little importance is given to crack initiation or formation in the ship hull structure as it appears inevitable given the uncontrolled variables involved in the construction of ships and the operating environment it is exposed to. The much researched crack growth or crack propagation rate phenomenon based on fatigue conditions may not be valid as existing cracks can propagate rapidly thus enhancing the severity of damage to the hull structure in the event of a sudden impact force. Based on this, a need is felt to develop guidelines for the inspection of cracks with respect to the various inducement factors which influence crack initiation corresponding to the operational life of the ship.

The thesis has approached marine casualties from three perspectives viz., human factor issues, engineering issues and inspection issues. The human factor approach is with the intent to prevent the recurrence of marine casualties as a result of human errors and poor performance issues, while the engineering issue and inspection issue approach is to mitigate the extent of damage sustained to the ship hull structure in the event of a marine casualty and to facilitate in marine casualty investigations.

As a basis for the formulation of the present study it is necessary to distinguish between a 'new ship', an 'existing ship' and an 'existing ship with initial damages'. A 'new ship' refers to one which is constructed, launched and just delivered for operations while an 'existing ship' refers to one which is operating and subject to the various mandatory inspections and survey regimes of the classification societies and flag states. Damage sustained to existing ship as a result of being in operation is categorized into deformations, material wastage i.e. corrosion, and fracture, and such ships are referred to as 'existing ship with initial damages' in this study. HHD is one such type of deformations caused by wave induced loads acting on the individual plate panel between the transverse and longitudinal stiffeners of the ship side shell structure.

## 1.2 SCOPE AND OBJECTIVES

Marine casualty investigation has to be given a comprehensive framework which encompasses human factor issues, engineering issues and inspection issues. The various aspects of this framework have been addressed in this thesis.

Based on the above, the objectives are framed as below:

i. To develop *best practices* aimed at resolving the identified human factor issues leading to marine casualties based on the geographical area of the casualty.

ii. To identify criteria for assessment and to develop guidelines for selection and analysis of marine casualties for forensic engineering based investigations.

iii. To develop crack assessment criteria for the ship hull structure based on ship operational life to facilitate inspection and survey.

### 1.3 Outline of the Present Thesis

In all the three objectives addressed in this thesis, the purpose of adopting a forensic engineering based investigation approach has been to prevent the future occurrence of similar failures by identifying or uncovering the product and/or procedural shortcomings and translate these findings into improvements in ship design, construction, survey or operational systems. Thus forensic engineering lends its name to the title of this thesis.

Chapter 1 provides a general introduction of the research topic. Chapter 2 discusses human factor issues in marine casualties and develops *best practices* to analyse and resolve these issues. Chapter 3 deals with engineering based casualty investigations approach i.e. forensic engineering. Chapter 4 develops an crack assessment criteria to facilitate inspection of the hull structure corresponding to the operational life of the ship. Summary and conclusions are provided in Chapter 5. The literature review relevant for each topic discussed in this thesis is included in the respective chapters. Performing or conducting a Finite Element Analysis (FEA) is outside the scope of the present study since FEA has been suggested only as a tool for forensic engineering investigations.

# CHAPTER 2

# *BEST PRACTICES* FOR ANALYSIS OF HUMAN FACTOR ISSUES IN MARINE CASUALTIES

## 2.1 GENERAL

Marine casualty investigations in the last few decades have seen a greater emphasis on human factor and organizational issues in ship operations and manning that result in casualties. Identifying the human factor issues and addressing them through the use of advanced navigational equipment, introduction of regulations aimed at crew training, crew comfort, working etc., are some of the proactive steps taken up by IMO toward preventing the recurrence of such casualties in the future. However, marine casualties continue to happen for much of the same reasons as earlier identified.

In this chapter, the focus is on the human factor issues leading to the marine casualty with the intent to prevent its recurrence as a result of human errors and diminishing performance issues. A novel approach for dealing with human factor issues based on the geographical area of casualty is discussed. The area based issues and the navigation and infrastructure issues in the area of casualty form the basis for analysing and resolving the identified human factor issues. In this study, the geographical area of the casualty is identified based on the Marsden squares grid system. The Marsden squares or Marsden square mapping is “a system that divides the Mercator chart of the world into squares of 10° latitude by 10° longitude” and where “each square is numbered and subdivided into 100 one-degree squares numbered from 00 to 99” (AMS 2012).

For the purpose of this study, ‘open sea’ refers to international waters which are more than 12 nautical miles (NM) off the coast where the ship has full operational speed, ‘limited waters’ represents areas such as channels, straits, coastal waters, harbour, etc. within the 12 NM distance, and ‘terminal area’ refers to the area covering the approach to the terminal or port, anchorage and the areas within the terminal or port (Pagiaziti *et al*. 2015).

## 2.2 STATE OF ART

### 2.2.1 Human Factor Issues in Marine Casualty

Rothblum (2000) was one of the first to introduce the concept of ‘human error’ in marine activities and had highlighted the need to prevent it from happening in the first place by identifying the factors influencing it such as technology, work environment and organizational factors. The background for her study was the casualty statistics that attributed 75-96% of marine casualties to human errors despite improvements in ship design, stability, production process and navigational equipment. She illustrated the profound need to address human factor issues citing examples involving collision of the ships MV *Santa Cruz II* with US Coast Guard ship *Cuyahoga* on a calm clear night eventhough both the ships crew cited each other visually and on radar. A similar case was the grounding of the *Torrey Canyon* during daylight and in calm clear weather. The former casualty resulted in loss of lives while the latter resulted in a major oil spill. In both these cases human errors were the immediate causes for the casualty. Her study highlighted fatigue, inadequate communications, inadequate general technical knowledge, poor design automation, inadequate knowledge of own ship systems, poor maintenance of ships, etc., as some of the human factors issues influencing poor human performance and errors in the maritime industry.

The need to evolve from an approach which focused on technical improvements in ship design and equipment to one which focuses on the role of human factors in maritime safety led to the formulation of guidelines on how to investigate human factor issues in marine casualties and incidents by IMO (IMO 2000). The guideline offered details of the areas of human factor i.e. people factors, organization factors, working and living conditions, external influences and environment etc., which should be inquired during investigations involving marine casualties and incidents and the investigation process aligned to meet such need. A detailed list of human elements leading to diminished performance has been identified and explained in this guideline.

Grech *et al*. (2002) brought to focus issues concerning lack of situational awareness leading to human errors and poor performance. They concluded that more than 75% of the casualties of ships worldwide were attributed to human and organization errors based on the IMO data of 1994. In addition to identifying lack of situational awareness issues, their study stressed the need to uncover the causal factors from the casualty investigation and cautioned against the rampant absorption of advanced technology in an ad-hoc manner. They proposed the implementation and integration of technology should be done with due diligence, because the consequence of increased technology levels is the loss of situational awareness which can significantly affect crew performance in abnormal and critical situations which are time dependent i.e. collision and allision casualties.

Cahill (2002) has documented many of the collision casualties in the 1960's to 1980's and concluded that they were as a result of risk taking behaviour or risk tolerance of Officer On Watch (OOW), lack of situational awareness, restricted visibility, actions during fine crossing, overtaking etc.

Baker and Seah (2004) have analysed the marine casualty reports published by a number of casualty investigation agencies and concluded that around 80-85% of the casualties were as a result of human errors and it presents a significant threat to maritime safety. Furthermore, 50% of the marine casualties are found to be initiated by human error while another 30% of it due to failure of humans to avoid the casualty. Their studies also reported on the various human factor issues leading to human errors.

McCafferty and Baker (2006) have reported of lack of competence, knowledge and ability, fatigue, workload, manning, complacency and risk tolerance as human factor issues which result in casualties or near misses. They have also attributed 80-85% of the marine casualties as a result of human errors, of which more than 50% were initiated by human error and more than 30% associated with human error. Further they have reported of 70% of the casualties in this 80-85% to be associated with situational awareness issues.

Studies by Baker *et al.* (2002) and Card *et al.* (2005) have reported of a high incidence of human errors during operations as reason for marine casualties and conclude that it presents a significant threat to maritime safety.

Reduced failure of technology as a result of improved ship design and navigational aids are found to be the reasons for bringing to focus human errors in maritime casualties according to Hetherington *et al*. (2006). Their study also attributed human errors in ship operations to be as a result of over-reliance on a single technology; design issues i.e. too much automation; personnel issues i.e. fatigue, stress, health; non-technical issues; situational awareness issues; language and cultural diversity issues; communication issues and teamwork. Their study also highlights organizational issues such as lack of safety training, bridge resource management, poor safety climate and safety culture etc. as factors contributing to errors.

The demanding work environment on-board ships when compared to land based installations poses additional stress on human nature and behaviour accounting for their unpredictable and inconsistent actions which may lead to casualties according to Louie and Doolen (2007). They attribute 50-96% of the marine casualties to human errors. Their study investigated the influence of fatigue in crew members with respect to sleep, work and regulations, and found inconsistent sleep times and lack of sleep as a leading cause of fatigue. It also highlighted the OOW perception of not receiving adequate rest based on the current regulations.

Emond (2012) has reported operator inattention to be as a result of obstruction to visibility, general conspicuity (day and night), fatigue and endurance, while operator inexperience is attributed to the use of advanced technology and to over reliance upon a given technology. The safe passage between two ships approaching each other is eloquently summarized by him into 5 steps, which the operators on both the ships are expected to follow. Each of these proposed steps involves a discrete amount of time and starts with detection of the vessel, determining the distance between each other, the speed, the route and expected path, and ascertaining the risk of collision. The above three steps are categorized to fall under human factor issues which involve perception of threat i.e. collision. Step 4 involves determining the appropriate action to be taken in case the threat to collision is perceived and step 5 involves executing the decisions to avoid the collision in a timely manner. The last two steps involve human factor issues from reaction point of view i.e. once the threat to collision is perceived and how the operator reacts to the situation. According to him, failure to comply with any of the 5 steps can result in the collision from taking place. He also highlights human errors in ship operations arising as a result of operator inattention, operator inexperience, excessive speed, improper lookout and under the influence of alcohol and drugs, as factors contributing to a marine casualty.

AGCS (2012) have reported some of the emerging challenges that face the shipping industry in terms of ship size, training and labour, crewing levels, language barrier, new sea routes i.e. the Arctic and polar region, and poor enforcement and coordination.

The average number of collisions have been steadily increasing during the period from 2000-2010 and all this despite the introduction of advanced technology for navigation, increased use of traffic separation systems and port vessel traffic systems (The Standard, 2012). Their study found human element to be the culprit in majority of the marine casualties and reported of improper exchange of watch, improper inferences and improper watchkeeping as leading causes to marine casualties. The report also stressed the need for restricting the usage of mobile phones on the bridge.

Chauvin *et al.* (2013) have referred to the existence of formal and informal rules as one of the possible causes for collision casualties. Informal rules refer to the rules shared between certain types of ships in specific waterways. When people who do not know each other communicate, these informal rules can be a reason for uncertainties and misunderstandings leading to marine casualties. Their study also highlights situations involving collision type casualties taking place despite the officers of both the vessels perceiving the collision threat and in some cases even agreeing to the course of action to be taken, but failing to do so. Casualty statistics presented in their study based on investigations involving 39 ships concluded that decision errors accounted for 82% cases of the casualties while perceptual error accounted for 15%.

Wang *et al.* (2013) have reported human error as a dominant factor contributing to casualties in restricted waters i.e. inland waterways.  Hollaway *et al.* (2016) have reported human error as the root cause of major well known casualties and note that human errors are inevitable no matter how well the crew are trained and supervised.

Several major accidents attributed to mariners fatigue have been reported by Strauch (2015) and they include the grounding of the tankers *Exxon Valdez* and *Royal Majesty* in 1989, the passenger ship *Star Princess* in 1995 and the collision involving the tankship *Eagle Otome* in 2011. He has presented a detailed report on the sleep pattern of the pilot and how a lack of it resulted in fatigue thereby degrading his cognitive performance leading him to delay giving orders to turn the ship at a turnabout and his subsequent alternative actions which eventually led to the collision of the *Eagle Otome*. He has also highlighted how the sleep patterns and mariners fatigue is influenced by the stressful, noisy and dynamic working environment that they are exposed to and where disruptions to rest periods are not uncommon.

Clayton (2015) has reported of a 20 year old Protection and Indemnity (P&I) study of United Kingdom (UK) which cites deck officers and pilot errors responsible for more than 80% of collision casualties at sea and highlight a similar finding in an American Bureau of Shipping (ABS) study in 2003. Human erroneous actions were found to be responsible for 62% and 67% of the marine casualties investigated by European Maritime Safety Agency (EMSA) during the period 2011-2015 and 2011-2014 respectively (EMSA 2015a; 2016a). Eliopoulou *et al*. (2016) have attributed around 80% of the marine casualties to human factor issues.

### 2.2.2 List of Recent Marine Casualties due to Human Factor Issues

- Collision casualty between chemical tanker *MV Orakai* and beam trawler *FV Margriet* in the North Sea on 21st December 2014 due to ineffective lookout by the OOW on *MV Margriet* (MAIB 2015b).

- Grounding of ro-ro passenger ferry *Commodore Clipper* in the approaches of St Peter Port, Guernsey on 14th July 2014 due to insufficient passage planning of voyage and ineffective utilization of vessels ECDIS and information systems by the crew (MAIB 2015d).

- Sinking of general cargo ship *Flinterstar* due to collision with Liquefied Gas tanker *Al Oraiq* on 06th October 2015 in restricted water with pilots on-board both vessels (EMSA 2015b).

- Collision of bulk carriers *Shibumi* and *Sam Wolf* in Singapore Straits on 23rd December 2015 due to ineffective radio watch and communication between both vessels (EMSA 2016b).

- Collision between bulk carrier *Maraki* and vehicle carrier *Ivory Arrow* on 5th December 2015 in a crossing between Dover Strait and West Hinder due to sudden course changes by both ships i.e. Risk taking behaviour (EMSA 2016c).

- Collision between container ship *Kota Duta* and cargo ship *Tanya Karpinskaya* in the Port of Niigata Higashi Ku, Niigata city on 07th February 2012 due to situational awareness issues and task omission issues (JTSB 2015a).

- Collision of container ship *Flevodijk* with the sea wall on the northern side of the Akashi Kaikyo bridge on 19th August 2011. JTSB investigations revealed collision casualty as a result of the OOW falling asleep when on duty (JTSB 2015b).

- Collision between container ship *Yong Cai* and fishing vessel *Shinyomaru* off the north-northeast coast of Rokkosaki in Suzu city on 15th April 2012 because of situational awareness issues and task omission (JTSB 2015c).

- Collision between cargo ship *Daroja* and oil bunker barge *Erin Wood* near Peterhead, Scotland on 29th August 2015. Investigation report highlight OOW's on both vessels not keeping a proper lookout and unaware of the risk of collision (MAIB 2016).

- Collision of container ship *Ever Smart* with oil tanker *Alexandra 1* near the entrance to approach channel in Jebel Ali, UAE on 11th February 2015. Improper lookout and task omissions contributed to this casualty as per the investigation report (MAIB 2015c).

- Grounding casualty involving *MV Antari* in 2008 as a result of OOW sleeping off when going across a busy seaway in Larne, Northern Ireland. Fatigue was identified as one of the human factor issue for this casualty (Halfide 2016).

- Grounding of general cargo vessel *Lysblink Seaways* into the rugged coastline near Mingary pier on 17th February 2015. Investigations revealed that the OOW had become inattentive due to the effects of alcohol consumption (Spark 2016 and MAIB 2015e).

- Collision between pure car carrier *City of Rotterdam* and ro-ro ferry *Primula Seaways* on the River Humber on 3rd December 2015. Investigations revealed the pilot's actions contributed to the casualty and was as a result of 'relative motion illusion' (MAIB 2017).

- Collision between Car carrier *Grande Anversa* and general cargo ship *Sider Capri* travelling in opposite directions in the Dandanelles Strait, Turkey on 27th Nov 2016, resulting in moderate damages to both the vessels. This casualty took place despite a traffic separation system in place (IHS 2017).


**Fig. 2.1: LNG Carrier *Al Khattiya* after Collision with Tanker *Jag Laadki* off Fujairah Offshore Anchorage in the United Arab Emirates in Feb 2017** (*Source:* https://www.marineinsight.com/wp-content/ uploads/ 2017/03/Al-Khattiya.png accessed on 21 June 2017)

- Collision of oil tanker *Jag Laadki* with anchored Liquefied Natural Gas (LNG) carriers *Al Khattiya* and later with *Iglc Anka* at the Fujairah Offshore Anchorage. United Arab Emirates, on 23rd February 2017. Initial investigations revealed that the Master of the *Jag Laadki* had poor knowledge in manoeuvring ships and ignored the "International Rule of Routes", which ultimately led to the collision (Schuler 2017).

### 2.2.3 Marine Casualty Statistics Based on Casualty Type, Ship Type and Geographic Location.

Marine casualties have been typically classified into collision, allision, grounding, fire and explosion, loss of control, foundering, capsizing, hull failure and damage to ship or equipment by EMSA (2016a). Similarly, Maritime Accident Investigation Branch (MAIB) have considered collision, grounding, allision, damage to ship or equipment, fire/explosion, foundering and loss of control as the casualty types based on which casualty statistics have been presented in their reports (MAIB 2015a). Similar classifications of casualty types have also been presented by Transport Safety Board of Canada (TSBC), Marine Department, The Government of the Hong Kong Special Admin. Dept (HK) and Japan Transport Safety Board (JTSB) with some inclusions and deletions in TSBC (2015), HK (2015) and JTSB (2016).

Weng and Yang (2015) have additionally categorized marine casualties based on adverse weather condition, fatal accident and accident time i.e. night time. Papanikolaou *et al.* (2005), Eliopoulou and Papanikolaou (2007) and Primorac and Parunov (2016) categorize marine casualties into six categories which include collision, allision, grounding, fire, explosion and NASF.

Photographs of ships involved in collision, grounding and allision casualties are shown in fig. 2.2 to fig. 2.5.

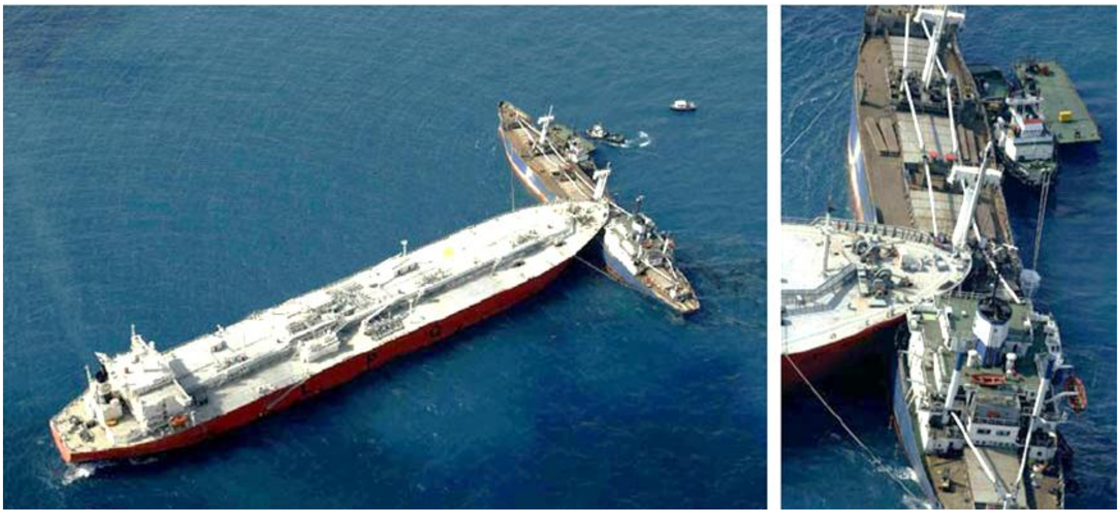

**Fig 2.2: Collision of *Gas Roman* with *Springok* near Singapore Coast in 2003**
(*Source*:https://www.researchgate.net/publication/273317821_Ship_collision_A_brief_survey accessed on 21 September 2017)

**Fig 2.3: Photo of *USS Fitzgerald* after Collision with Philippine-Registered Container Ship *ACX Crystal* Southwest of Yokusuka, Japan in 2017.**
(*Source:* http://globalnation.inquirer.net/158046/7-reported-missing-us-navy-destroyer-collides-ph-flagged-ship accessed on 21 September 2017)


**Fig 2.4: Grounding of Container ship *MSC Malaysia*** (*Source:* http://gcaptain.com/disaster-at-sea-photos-of-maritime-destruction/ accessed on 21 September 2017)

**Fig. 2.5: Allision Casualty of Containership *Xin Fei Zhou* with the Wall of a New Dock Agua Clara on the Atlantic Side of the Panama Canal** (*Source:* https://www.fleetmon.com/media/maritimenews/xinfei.jpg accessed on 10 December 2017)

The casualty types involving AFRAMAX tankers during the period of 1978 to early 2004 have been analysed by Papanikolaou *et al*. (2005) with respect to Loss of Watertight Integrity (LOWI), weather impact, casualty severity, casualty location, pollution and vessel activity at the time of casualty. Collision, grounding and allision accounted for the highest casualty rates at 233 (29%), 194 (25%) and 126 (16%) of the total 792 accidents analysed. NASF casualty rates were 121 (15%), amongst which 36 (29.8%) resulted in LOWI. The LOWI due to collision, allision and grounding type casualties were 39 (16.7%), 36 (18.6%) and 30 (23.8%) respectively. In their study, NASF accounted for the highest severity of casualty when it comes to LOWI with 2.5% of total loss and 18.6% *serious* casualties and this was found higher when compared to collision type casualty. They have also reported that majority of the NASF casualties were reported in open sea, collision and grounding in coastal waters and allision in port area, and most of these causalities including grounding happened when the ship was sailing.

The casualty data for large oil tankers (AFRMAX, SUEZMAX and Very Large Crude Carrier (VLCC)/ Ultra Large Crude Carrier (ULCC)) above 80,000 deadweight (DWT) based on casualties reported for the period 1978-2003 have been analysed by Eliopoulou and Papanikolaou (2007). They have arranged the data to report on casualties based on tanker size, age, severity of casualty, oil spillage and geographical area of casualty. For the 789 cases involving AFRAMAX tankers, 232 collisions, 125 allisions, 194 grounding and 120 NASF casualty types were reported. SUEZMAX tankers recorded 135 collisions, 55 allisions, 70 grounding and 105 NASF casualties of the total 439 reported. VLCC and ULCC reported 150 collisions, 60 allision, 71 grounding and 16 NASF casualties of the total 567 cases. In their study, the geographical area of spills worldwide based on Marsden square grid has been adopted and shows the most severely affected areas to be the Caribbean Sea, Bay of Biscay, St. Helena Island and Cape Town and are represented by Marsden square grid number 43, 145, 371 and 442 respectively. The most number of casualties reported were in the Gulf of Oman, Straits of Malacca - Singapore Strait and Gulf of Mexico and are represented by Marsden square grid number 103, 113 and 82 respectively.

Papanikolaou and Eliopoulou (2008) have investigated data on marine casualties involving tankers of 60,000 DWT and above for the period 1990 -2007. Collision, grounding and allision type casualties accounted for nearly 553 casualties (68%) of the total 814 considered. NASF accounted for 148 casualties of which 6 resulted in total loss and another 46 were categorized as *serious* in casualty severity. Their study showed that NASF casualty type happens mainly when the ship is en-route or in open sea and experiences severe storm/ rough seas (52 such cases reported). They also report of NASF casualty type in younger tankers (except VLCC and ULCC) in the 0-10 years category and attribute it to poor design and construction.

Yip *et al.* (2011) and IMO (2012b) have highlighted some of the major casualties involving tankers, such as grounding of tanker *Exxon Valdez* in Prince William sound, Alaska in 1989 which resulted in spillage of approx. 37,000 tons of oil, collision between tanker *Hebei Spirit* with a barge in 2007 resulting in spillage of 10,500 tonnes of oil, and collision between the tanker *Eagle Otome* with a barge near Port Author, Texas, leaking approx.1700 tonnes of oil.

The collision of the VLCC *Atlantic Empress* with the super tanker *Aegean Captain* in 1979 in the Caribbean Sea which resulted in one of the biggest oil spills has been reported by Youseff *et al.* (2014). They have also reported on numerous other oil tanker casualties during the period 1997-2012 which resulted in more than 700 tonnes of oil spill. Amongst these, grounding related marine casualties accounted for 33% followed by collision at 29%.

AGCS (2012) have reported that 62% of the total losses of ship types during the period 2000- 2010 involved cargo ships with grounding type casualty accounting for 18% followed by collision at 12% and allision at 2.1%.

Statistics of casualties based on Geographical Information System (GIS) data for the period 2006 -2011 has been reported in IMO (2012a). A high of 55% of the casualties in 2007 involved cargo ships in which General cargo ships alone accounted for 21%, followed by bulk carriers at 13% and container ships at 12%.

The Standard (2012) have reported on the financial implications of marine casualties as a result of collision, allision and grounding casualty types investigated during the 10 year period (2002-2012). Their report found 50% of the 85 claims totalling $1 million in the past five years were directly related to navigational issues out of which 42% were as a result of collision, 32% for repair of items damaged due to allision and 15% due to ship grounding. It has also been reported that the average number of collision has been steadily increasing during the period 2000-2010 and all this despite the introduction of advanced technology for navigation, additional navigation equipment, better radars, increased use of traffic separation systems and port vessel traffic systems.

Butt *et al.* (2013) have reported that 63% of the total losses of vessels during the period of 1997-2011 involved cargo ships, in which 42% alone were General cargo ships. Foundering casualty type accounted for 1032 losses, followed by grounding at 298, collision at 44 and allision at 42. Almost 71% of the casualties in European waters are related to collision and grounding casualties as reported by Chauvin *et al.* (2013).

Pagiaziti *et al*. (2015) have analysed the data collected on collision, grounding and allision casualties involving passenger ships and container ships for the period 1990-2012. The passenger ships included in their analysis included cruise liners, pure passenger, ro-pax and ropax- rail. The 430 casualties identified and included in their analysis showed 71% of the casualties due to collision, allision and grounding type casualties involving ro-pax ships, followed by cruise liners at 23%. Another important statistics offered in their study was that more than half of the casualties took place in terminal areas (54%) followed by limited water (41%). Within the terminal area and limited waters all the casualty types had almost an equal contribution in numbers. For containerships, 866 casualties identified during the period from 1990-2012 were analysed in which collision casualties accounted for 54% followed by grounding at 30%. Similar to the results for passenger ships, the majority of the casualties took place in limited waters and terminal areas.

The study by Ugurlu *et al.* (2015) have focussed on marine casualties involving tankers during the period 1998-2010 with the intent to identify the reasons for such casualties. The assessment factors considered in their study were casualty type, casualty frequency, ship damage, navigational sea area type and accident impact on environment. Of the total 379 casualties included in their study, 289 casualties occurred in coastal waters i.e. channels, berth, port area, coastal water, and 90 in open sea. Based on ship tonnage they have reported that 42% of the casualties involved small oil tankers. From a voyage perspective, tankers engaged in short sea shipping journeys were more prone to having a casualty. It is also noted from their study that 52% of the collision and 55% of the grounding type casualties involved small and handy size tankers i.e. DWT between 10000 to 49,999. Their study tried to establish a relationship between oil tanker casualties to the ship tonnage and navigation sea area type. Similar to the analysis performed by Pagiaziti *et al*. (2015), Ugurlu *et al.* (2015) analyse the concentration of the tanker casualties based on the geographical area of operation. Their analysis revealed high risk areas for oil tankers to be coastal areas, and especially, channels like Singapore strait and Oresund.

The statistical accident data originating from various sources have been reviewed and categorized based on ship type, accident type, influence of regulations, ship design, ship age, adverse weather conditions and geographical area of casualty by Primorac and Parunov (2016). They have reported that foundering type casualties during the period from 1990 to 2013 accounted for between 40-50% of the total losses by casualty category and general cargo ships accounted for 40-50% of the total losses based on ship types. The geographical area mapping presented in their study was based on the SIS zone topological system in which the earth is divided into 31 zones. The highest frequency of casualties were reported for zone 12 which represented South China, Indo China, Indonesia and Philippines, followed by Zone 4 representing East Mediterranean and Black Sea and Zone 13 representing Japan, Korea and North China.

Casualty statistics for different ship types for the period 2000-2012 based on the casualty category and total losses of ship have been presented by Eliopoulou *et al*. (2016). General cargo ships accounted for 3228 *serious* casualties followed by bulk carriers at 1609 and container ships at 1090 during the said period. General cargo ships, bulk carriers, car carriers and ro-ro ships in all age groups (0-20 years) exhibited a relatively high frequency of casualties and this was found to increase substantially when these ship types cross the 20 years age group. Their study also showed a comparatively high number of casualties due to hull and machinery damage for most types of cargo ships.

The Bulk Carrier Casualty Report for the period 2005-2015 cited in King (2016) indicate a total of 71 bulk carriers of 10000 DWT and above being lost, in which 26 numbers were as a result of grounding casualty and 8 due to collision related casualties.

In JTSB (2016), statistics of marine casualties in Japanese territorial waters and involving ships under its registry has been published for the period 2011-2015. Their statistics indicates cargo ships accounting for 20-25% of the total ships involved in marine casualties for the period 2010 – 2015. This percentage would be significantly higher if fishing vessels and other non-commercial vessels are excluded from the presented statistics. Furthermore their report also indicate that collision, allision and grounding type casualties put together account for over 75% of the total casualty type during the same period.

Marine casualty statistics reported in EMSA (2015a) indicate nearly 3143 (50%) cargo ships being involved in a ‘casualty with a ship’ during the period 2011-2014 of which 1013 alone were reported in 2014. During the same period of 2011-2014, damage to ships as a result of casualty was the highest for cargo ships (1005 or 48%) amongst ship types, of which 470 alone were reported in 2014.

In EMSA (2016a), a consolidated report of marine casualties for the period 2011-2015 is presented in which a total of 8533 casualties with a ship is reported, of these more than 50% (4368) of the casualties are as a result of collision (1352), allision (1590) and grounding (1426). Cargo ships accounted for the highest number of casualties (4181) or highest percentage (49%) amongst the ship types involved in marine casualty during this period. Casualty statistics based on the type of cargo ships involved in marine casualties in this report indicated General cargo vessels accounting for 33% of the casualties, followed by container ships at 17% and bulk carriers at 15%. Their report have also attempted to provide information on the location of the ship at the time of marine casualty and the nature of voyage involved, based on which it is noted that majority of the casualties involving cargo ships took place during transit and when anchored or alongside.

Marine casualty statistics presented in TSBC (2015) for the year 2015 indicated 58 (28%) casualties due to grounding and 55 (26%) due to collision. Cargo ships accounted for second highest casualty percentage after fishing vessels. In their report they divide the Canadian coastline into four zones i.e. Pacific region, Central region, Atlantic region and Foreign waters, for listing the casualties based on the geographical location of occurrence.

A very high percentage of collision type casualties have been reported in the Hong Kong territorial waters for the period of 2011 to 2015 in HK (2011-2015). A high of 204 (58%) collision casualties of the total 351 casualties were recorded in 2011 and a low of 156 (43%) of the total 358 casualties in 2014. Collision, grounding and allision put together consistently averaged more than 65% of the total casualty types during the period 2011-2015..

### 2.2.4 Marine Casualty Classification Based on Casualty Severity

IMO (1997) has classified marine casualties into three categories depending on severity as an attempt to introduce a common approach to casualty investigations and the reporting of such casualties. These classification categories are *very serious casualty*, *serious casualty* and *marine incident*. According to IMO, a v*ery serious casualty* "means a casualty to a ship which involves the total loss of the ship, loss of life or severe pollution". A s*erious casualty* is defined as "a casualty which does not qualify as a *very serious casualty* and which involves; a fire, explosion, grounding, contact, heavy weather damage, ice damage, hull cracking or suspected hull defect, etc., resulting in; structural damage rendering the ship unseaworthy, such as penetration of the hull underwater, immobilization of main engines, extensive accommodation damage etc.; or pollution (regardless of quantity); and/or a breakdown necessitating towage or shore assistance". A *marine incident* "means an occurrence or event being caused by, or in connection with, the operations of a ship by which the ship or any person is imperilled, or as a result of which serious damage to the ship or structure or the environment might be caused".

Marine casualties have been classified into four categories in MSC-MEPC (2008) for the purpose of collecting information and reporting to IMO. The categories identified are *very serious casualties*, *serious casualties*, *less serious casualties* and *marine incidents.* The prescribed format for reporting of casualties of *very serious* and *serious* severity required by IMO and to be complied by the administration or member states is also included in this document. The possibility of including casualties of *lesser severity* which offer useful lessons that can be learnt by performing a full investigation has also been encouraged here. In this IMO document, v*ery serious casualties* are defined as "casualties to ships which involve total loss of the ship, loss of life, or severe pollution", while s*erious casualties* are "casualties to ships which do not qualify as *very serious casualties* and which involve a fire, explosion, collision, grounding, contact, heavy weather damage, ice damage, hull cracking, or suspected hull defect, etc., resulting in: immobilization of main engines, extensive accommodation damage, severe structural damage, such as penetration of the hull under water, etc., rendering the ship unfit to proceed, or pollution (regardless of quantity); and/or a breakdown necessitating towage or shore assistance". An additional classification included is the *less serious casualties* and are defined as "casualties to ship which do not qualify as *very serious* casualties or *serious* casualties".

MAIB has classified marine casualties into four categories viz. *very serious marine casualties*, *serious marine casualties*, *less serious marine casualty* and *marine incident. Very serious marine casualties* is defined by MAIB (2015f) as "Marine Casualty which involves total loss of the ship, loss of life, or severe pollution", while *serious marine casualties* are defined as "an event that results in one of: immobilization of main engines, extensive accommodation damage, severe structural damage, such as penetration of the hull under water, etc., rendering the ship unfit to proceed; pollution; a breakdown necessitating towage or shore assistance". They have further gone on to define a *less serious marine casualty* as "any marine casualty that does not qualify as a *very serious marine casualties* or *serious marine casualties*" and a *marine incident* as "an event or sequence of events other than those listed above which has occurred directly in connection with the operations of a ship that endangered, or if not corrected would endanger the safety of the ship, its occupants or any person or the environment".

The Global Integrated Shipping Information System (GISIS) casualty module maintains information related to marine casualties and incidents submitted to IMO by the respective flag states and administrations in compliance with IMO (2008) requirements. For the purpose of collecting information for populating the GISIS casualty module, IMO has classified marine casualties into four categories namely *very serious casualties*, *serious casualties*, *less serious casualties* and *marine incidents* (GISIS 2017a) and define *very serious casualties as* "casualties to ships which involve total loss of the ship, loss of life, or severe pollution", whereas s*erious casualties* are "casualties to ships which do not qualify as *very serious casualties* and which involve a fire, explosion, collision, grounding, contact, heavy weather damage, ice damage, hull cracking, or suspected hull defect, etc., resulting in immobilization of main engines, extensive accommodation damage, severe structural damage, such as penetration of the hull under water, etc., rendering the ship unfit to proceed, or pollution (regardless of quantity); and/or a breakdown necessitating towage or shore assistance". The *less serious casualties* are defined as "casualties to ship which do not qualify as *very serious casualties* or *serious casualties*" and have been clubbed together with *marine incidents* for the purpose of recording useful information.

EMSA (2015a) has classified marine casualties into four categories viz. *very serious casualties*, *serious casualties*, *less serious casualties* and *marine incidents*. EMSA (2015a) defines *very serious casualties* as "marine casualties involving the total loss of the ship or a death or severe damage to the environment" and s*erious casualties* as "marine casualties to ships which do not qualify as *very serious casualties* and which involve for example a fire, collision, grounding, heavy weather damage, suspected hull defect, etc., resulting in the ship being unfit to proceed, pollution or a breakdown necessitating towage or shore assistance". *Less serious casualties* are defined as "marine casualties that don't qualify as *very serious* or *serious* casualties". *Marine incidents* are defined as "events, or sequence of events, other than marine casualties, which have occurred directly in connection with the operations of a ship that endangered, or, if not corrected, would endanger the safety of the ship, its occupants or any person or the environment".

The evolution of the classification of marine casualties based on severity and a comparison of the definitions for *very serious*, *serious*, *less serious* and *marine incidents* by various investigation agencies and IMO has been highlighted here. A subtle difference in noted in the definitions for *very serious, serious* and *less serious casualties* and *marine incidents* by the investigation agencies and IMO and for the purpose of this study, the definitions proposed in EMSA (2015a) are adopted for its simplicity and ease of understanding.

### 2.2.5 Marine Casualty Data Statistics

A very informative, elaborate and exhaustive report on marine casualties in the European Union has been presented on an annual basis in EMSA (2014; 2015a; 2016a). Their reports cover marine casualties based on its severity, ship types, casualty types, voyage details, concentration of marine casualty based on location, contributing factors, voyage segment etc. The data presented provides detailed information used for ascertaining the vulnerable or high risk casualty categories.

In TSBC (2015), details of marine casualties occurring in the Canadian territorial waters and involving ships under their registry are presented for the year 2015. Their report includes statistical data on marine casualties based on casualty type, ship type and the geographical location of the casualty.

HK have published reports of marine casualties occurring in and outside the territorial waters of Hong Kong on an annual basis and the contents of which is confined to the number of casualties based on casualty type in and outside its territorial waters (HK 2011-2015).

Marine casualties and incidents in the UK territorial waters and involving UK registered vessels elsewhere have been reported in MAIB (2013a; 2014a; 2015a). The marine casualty statistics presented here provides information on casualty based on severity, ship types versus casualty type, overview of the casualty investigation reports with recommendations made etc.

JTSB (2016) has reported on marine casualties and incidents in its territorial waters and involving ships under its registry. Their report encompasses casualty statistics based on the type of ship involved in the casualty and the casualty type. Additional information such as data regarding specific geographical location of the casualty with respect to casualty type, casualty severity, etc., has not been reported here.

### 2.2.6 Marine Casualty Investigation and Data Analysis Methods

#### *2.2.6.1 General*

The Marine Root Cause Analysis Technique (MaRCAT) marine incident investigation process in ABS (2005) has been developed with the purpose of conducting casualty investigations of any magnitude and tailored to meet the requirements of the marine industry. Using the MaRCAT approach allows for the investigator to conduct a root cause analysis and provides a systematic approach to identifying, documenting and trending of the causes of the casualty. It allows for customization based on the clients own management system, for investigations involving a single person of short duration to one which is multidisciplinary and involves considerable time and resources. The MaRCAT process also uses various approaches such as Failure Mode Effect Analysis (FEMA), change analysis, influence diagrams and Fault Tree Analysis (FTA) to bridge information gaps arising during the analysis. Although the investigation process in MaRCAT appears to be written in a manner more aligned to identifying human factors issues, it can also be extended to perform a more detailed investigation once the root cause is redefined in a more technical sense. An interesting observation made in this guide is on when to proceed or initiate a marine casualty investigation. Focus is on those significant few casualties which account for majority of losses and which may probably prevent occurrence of the insignificant casualties.

Similar to the MaRCAT process followed by ABS for marine casualty investigations, Det Norske Veritas (DNV) has developed the Systematic Causation Analysis Technique (SCAT) to perform the root cause analysis (Thompson 2012). This approach involves collection of evidence including the findings from the failure analysis, interviewing key personnel and using the evidence to develop a timeline of the events i.e. lack of inspection, lack of control of operating parameters etc., leading to failure. This is followed by an analysis phase which involves identifying the barriers which prevent the event from happening in the first place and these could be communication procedures, personnel training, pressure and temperature control etc. Failure of the barrier (or all barriers assigned to a particular event) leads to the event from taking place and thus helps identify the root cause of the failure.

Katsakiori *et al*. (2009) have reported and discussed the various casualty investigation methods selected based on the criteria that they are widely used; recently developed; have evolved over time and are described in the literature. Management Oversight and Risk Tree (MORT), FTA, Multilinear Event Sequencing (MES), SCAT, Causal Tree Method (CTM), Casualty Evolution and Barrier function (AEB), Integrated Safety Investigation Methodology (ISIM) etc. are some of the casualty investigation methods detailed in this article. They conclude that casualty causation models have evolved over time from addressing a singular event to identifying multiple causes involving the organization and management, and their interactions with the working activities. The models look at the casualty as a whole rather than addressing it as a sequence of events. Their study also highlights the relationship between the casualty causation models and casualty investigation methods and how they are mutually dependent and why a combination of model-method pairs will be more useful and reliable for the investigation and analysis of the casualty.

EMSA (2015a) have illustrated the use of European Marine Casualty Information Platform (EMCIP) model for casualty investigation, a similar adaptation of which is found in IMO (2014). The investigation process follows identifying the consequences i.e. damaged ship, and working its way backwards to identify the casualty events leading to damage i.e. collision, grounding etc., followed by the accidental event i.e. human error, and the contributing factors at various levels.

The Cognitive Reliability Error Analysis Method (CREAM) method has been used by Akhtar and Utne (2015) to convert the casualty investigation and integrate it to identify common parameters which can highlight new relationships or hypothesis. Their study focussed on fatigue and fatigue factors which affect the crew and collected information on collision, allision and grounding casualties from MAIB and Casualty Investigation Board Norway. Their study using the CREAM taxonomy revealed ‘communication failure’ and ‘irregular working hours’ as the two main contributing factors to collision casualties while ‘observation missed’ and ‘communication failure’ contributed to grounding casualties.

A more simplified approach based on assessment of individual marine casualty investigation reports has been demonstrated by Baker and Seah (2004). In their study they have referred to the various marine casualty reports investigated by Australian Transport Safety Board (ATSB), MAIB and TSBC and summarized the common human factor issues based on the frequency of their occurrence.

In a similar manner, Kum and Sahin (2015) have identified the root causes for 65 reported marine casualties, which include human errors, equipment failure, personnel untrained to use equipment etc., in the Arctic region over a span of 18 years.

Chauvin *et al.* (2013) have demonstrated the use of Human Factor Analysis and Classification System (HFACS) tool for the analysis of collision type marine casualties involving human and organizational factors to identify a pattern of contributory factors. The frequency of occurrence of each human and organization factor identified responsible for the casualty is noted from the individual investigation reports of MAIB and TSBC.

Graziano *et al*. (2016) have developed a new method combining the Casualty Analysis Methodology for Maritime Operations (CASMET) with Technique for the Retrospective and predictive Analysis for Cognitive Errors (TRACEr) to analyse and code grounding and collision casualties. The aim of their study was to identify the main task errors, technical equipment and cognitive domains involved in the casualties. Their results indicated that 96.5% of the task errors were performed in the bridge and a majority of the failures were navigation related (28.7%). Their analysis was based on the investigations of 32 grounding and 32 collision type casualties. This study was not specific to one casualty but took the information from a number of casualties to derive conclusions which could lead to regulatory, safety and operational improvements.

#### ***2.2.6.2 IMO Code for the Investigation of Marine Casualties and Incidents (Resolutions. A849 (20)) and Amendments in Resolution A.884(21).***

The purpose of *Code for the Investigation of Marine Casualties and Incidents Resolution A849 (20)* (IMO 1997) has been to provide a common approach for the investigation of marine casualties and incidents towards identifying the contributing factors leading to such casualties and preventing the future occurrence through incorporation of appropriate remedial measures. This IMO document provides detailed information on the investigative process, the responsibility of investigating marine casualties and the responsibilities of the lead investigating states, the contents of the investigation report, etc. A list of information which need to be gathered particularly for collision, grounding and foundering type of casualties for more detailed investigation are provided.

IMO (2000) amended the *Code for the Investigation of Marine Casualties and Incidents Res. A849 (20)* and focused on the systematic investigation of human factors in marine casualties on the premise that despite application of technical innovations in ship design, construction and operations, a significant number of marine casualties continued to occur. In this IMO document the necessity for a human centric approach in marine casualty investigations was highlighted, as a need was felt to address the human operator in the chain of activities. A need to recognize and fully address human factor issues in maritime industry was essential to bring about a reduction in the frequency of marine casualties. A systematic investigative procedure is outlined here for marine casualty investigations and it is also integrated and adapted to various human factor frameworks i.e. SHEL model, Casualty Causation Model and Taxonomy of Error model. Most importantly the investigation guidelines in IMO (2000) aimed to promote a common approach to casualty investigations without determining any blame or liability. Both IMO (1997) and IMO (2000) were subsequently revoked by the adoption of IMO (2008).

#### *2.2.6.3 Casualty Investigation Code (Resolution MSC. 255(84))*

The adoption of the *Casualty Investigation Code* (IMO 2008) had envisaged the application of a consistent methodology and approach to marine casualty investigations by States and for providing reports to IMO which could be used to assist in addressing safety issues. This Code incorporates and builds on the best practices that were established in IMO (1997) and IMO (2000). The mandatory section in this Code covers the requirements for investigating *very serious* marine casualties and administrative requirements such as which party (flag state or coastal state) is responsible for conducting investigations, powers of an investigation, co-operation, parallel investigations, evidence collection, investigation reports etc. The recommended practices in IMO (2008) provides for additional information which may be needed based on the mandatory requirements and on other issues affecting the casualty investigation.

#### *2.2.6.4 Guidelines to Assist Investigators in the Implementation of the Casualty Investigation Code (IMO Resolution A. 1075(28))*

The intent of this IMO guideline (IMO 2014) has been to prevent the occurrence of similar casualties and incidents from happening again and this would be achieved through a systematic investigation of marine casualties. It is also envisaged to provide a common approach for flag states and administrations to adopt when conducting investigations involving marine casualties and incidents in accordance with the Casualty Investigation Code. The human, organizational, environmental, technical and external factors involved or typically associated with the marine industry are highlighted here. The guidelines also provide qualification of the investigator performing the marine casualty investigation together with a detailed procedure on conducting the investigations. The investigative steps outlined here starts with collection of evidence followed by inspection of the casualty site i.e. ship involved, location etc.; gathering or recording of physical evidence; interviewing and collecting witness information; reviewing of documents; procedures and records i.e. classification, maintenance records, crew records etc.; conducting specialized studies i.e. depending on the nature of investigation; reconstruction of the casualty and analysis; reconstruction of the casualty events and their linked conditions and safety analysis. The investigation ends with reporting of the findings into the GISIS casualty module, preparation and submission of a full investigation report, consultation, publication and follow up of any recommendations made. In the appendix of this document are listed the areas of inquiry for investigation of human and organizational factors.

### *2.2.6.5 Casualty-Related Matters - Reports on Marine Casualties and Incidents – MSC-MEPC.3/Circ.3*

In this IMO document (MSC-MEPC 2008), the information required to be collected and submitted within the specified time frame to IMO by the administration or member states to populate the GISIS casualty module is detailed. Table 2.1 lists the various data required to be submitted based on the casualty severity and specify the timeline for such submissions to be made.

**Table 2.1: Marine Casualty Information to be Submitted as per Casualty Severity** (*Source:* MSC-MEPC, 2008)

| ***Information to be sent in accordance with the type of casualty*** | ***Very Serious casualties*** | ***Serious Casualties*** | ***Less Serious Casualties*** | ***Marine Incidents*** |
|---|---|---|---|---|
| Annex 1 of the attached reporting format | To be provided within 6 months after the casualty in all cases | To be provided within 6 months after the casualty in all cases | May be provided if there are important lessons to be learned | May be provided if there are important lessons to be learned |
| Annexes 2 and 3 of the attached reported format, as well as other relevant annexes | To be provided at the end of the investigation in all cases | To be provided at the end of the investigation in all cases | May be provided if there are important lessons to be learned | May be provided if there are important lessons to be learned |
| Full investigation report | To be provided at the end of the investigation in all cases | May be provided if there are important lessons to be learned | May be provided if there are important lessons to be learned | May be provided if there are important lessons to be learned |

In MSC-MEPC (2008) there are various annexures covering requirements that need to be populated and submitted depending on the nature of casualty. The focus is on *very serious* and *serious* marine casualties with provision to include the *less serious* and *marine incidents* should they provide useful learning lessons. Annex 1 pertains to ship identification and particulars; Annex 2 includes the primary data of the casualty; while Annex 3 covers the supplementary data for *very serious* and *serious casualties*. In addition to these three primary data records, there are seven more annexures which need to be submitted depending upon the nature of the casualty involved. For example, collision, allision and stranding casualty types require Annexure 5 to be completed and submitted as it pertains to details on the damage sustained. Similarly, a fire casualty type requires Annexure 6 to be recorded and submitted.

Annex 1 and 2 are very detailed and cover aspects related to the ship in particular i.e. type, construction and design; voyage details; casualty location; type of casualty; casualty consequences both to the facility, crew and passengers; the environment conditions at the time of the casualty; etc. Attempts are also made to identify the primary causes of the initial event that may range from human errors, structural failure, technical failure of equipment, the operating environment and to any unknown causes leading to the casualty. Annex 3 requires including the principal findings of the investigation, the actions taken and identifying any findings which affect international regulations.

### 2.2.7 Inference

Human factor issues leading to poor performance and human errors are evidently the dominant cause for the high number of casualties in the maritime transportation sector. The attempts made in the last few decades to resolve and completely eliminate these factors have not been entirely successful, not only due to the very unpredictable nature of humans and their tendency of making mistakes either intentionally or unintentionally but probably also because of the way marine casualties have been analysed. The use of advanced technologies i.e. AIS, Automatic Radar Plotting Aid (ARPA), ECDIS etc. and enforcement of regulations i.e. International Safety Management (ISM) Code, Maritime Labour Convention 2006 (MLC) and Standards of Training, Certification and Watchkeeping for Seafarers (STCW) Code etc., which were aimed at reducing the probability of casualties from taking place have also not entirely prevented its recurrence due to earlier identified issues. A review of the various studies which attribute human factor issues responsible for the marine casualty will show six major issues which contribute to human errors or poor human performance. These factors have been identified and are tabulated in table 2.2. In addition to these factors, Baker and

McCafferty (2005), Hetherington *et al*. (2006), Louie and Doolen (2007), IMO (2000), AGCS (2012) and Emond (2012) have further categorized these major issues in subparts and in some cases identified additional human factor issues, thereby highlighting the complexity involved when dealing with this issue.

**Table 2.2: Major Human Factor Issues Contributing to Human Error and Poor Performance**

(Legend : "√" – Applicable, "x" – Not Applicable)

| **Reference →<br>Human Factor Issues ↓** | **Emond (2012)** | **Chauvin *et al.* (2013)** | **Baker and Seah (2004)** | **Card *et al.* (2005)** | **Hetherington *et al.* (2006)** | **EMSA (2015a)** | **Grech *et al.* (2002)** | **Rothblum (2000)** |
|---|---|---|---|---|---|---|---|---|
| 1. Situational Awareness issues | √ | √ | √ | √ | √ | √ | √ | x |
| 2. Improper Lookout/ Task Omission issues | √ | √ | √ | √ | x | √ | x | x |
| 3. Risk tolerance issues | x | √ | √ | √ | x | x | x | x |
| 4. Substance abuse issues | √ | x | x | x | x | x | x | x |
| 5. Over reliance on Technology or Untrained to use | √ | √ | √ | √ | √ | √ | √ | √ |
| 6. Manning & Human Fatigue issues) | √ | √ | √ | x | √ | x | x | √ |

Cargo ships form the bulk of the world shipping fleet and the statistics presented in this chapter reveals a high incidence of these ships being involved in collision, allision and grounding, which represent navigation related casualties (EMSA 2015a). There appears to be a definite lack of uniform guidelines for presenting casualty statistics involving the number of ships, types of ships, casualty type, casualty severity type etc. as well as comparing these data against each other. It has been noted that different investigation agencies and administrations adopt different criteria for representing the findings of the casualty investigation reports, in line with their priorities. In table 2.3, a comparison of the content of the casualty data statistics presented in EMSA (2016a), JTSB (2016), MAIB (2015a), TSBC (2015) and HK (2015) were made and it highlights the inconsistency and lack of uniformity of casualty data presented.

**Table 2.3: Comparison of Marine Casualty Data Statistics**

| S.No | Details of Casualty Data | EMSA | TSBC | HK | JTSB | MAIB |
|---|---|---|---|---|---|---|
| 1 | Data on severity of casualty with a Ship | √ | x | x | x | √ |
| 2 | Data on casualties occurring in the territorial waters and outside | x | x | √ | x | x |
| 3 | Data on casualties by Ship type i.e. Passenger ship, Cargo ship, Service ship etc. | √ | √ | x | √ | √ |
| 4 | Data on casualties by sub-division of Ship type i.e. Oil Tanker, Bulk carrier etc. | √ | x | x | = | = |
| 5 | Comparison of casualty type with Ship type. i.e. number of collision casualties involving cargo ships etc. | x | x | x | x | √ |
| 6 | Data based on distribution by casualty types i.e. Collision, Grounding etc. | √ | √ | √ | √ | √ |
| 7 | Data based on distribution of casualty type with casualty severity | √ | x | x | x | x |
| 8 | Data on factors contributing to casualties i.e. Human error, Machinery failure etc. | √ | x | x | x | x |
| 9 | Data sub-categorizing the factors contributing to casualties i.e. In Human errors -lack of situational awareness, task omission etc.) | √ | x | x | x | x |
| 10 | Consequences to Persons during casualty | √ | √ | √ | x | √ |
| 11 | Data on consequences to Persons based on Ship type and casualty type | √ | x | x | x | x |
| 12 | Geographical location of Ship during casualty | √ | √ | x | x | x |
| 13 | Data on distribution of casualties based on specific location of casualties i.e. International waters, coastal area etc., and Cargo ships | √ | x | x | x | x |
| 14 | Data on casualties based on voyage type i.e. Long Voyage, short voyage | √ | x | x | x | x |
| 15 | Data based on distribution of casualty type with casualty location | √ | √ | x | x | x |
| 16 | Casualty Investigation reports | √ | NF | NF | √ | √ |
| *Legend :* "√" –Yes; "x"- No; "=" – Partial fulfilment; "NF" – Not found | | | | | | |

A need is felt to not only have uniformity and consistency in reporting of the marine casualty statistics but also to broaden the scope of casualty data presented to involve the geographical area of the casualty along with further sub-classifications, similar to what has been considered by Pagiaziti *et al.* 2015 and Ugurlu *et al*. 2015. This would facilitate focussed analysis and future research aimed at not only addressing the human factor issues from a general perspective but also together with other influencing factors i.e. prevailing weather condition, time of casualty, etc.

The classification of marine casualties based on the severity into *very serious*, *serious*, *less serious* and *marine incidents* offers a useful selection procedure for investigations to be carried out and the level of detailing required. While *very serious* severity casualties has been the focus for detailed investigations, *serious* and *less serious* casualties of learning potential are also considered. In table 2.4, a comparison is made on casualty severity based on the statistics provided in EMSA (2014; 2015a) for the year 2013 and 2014, and in MAIB (2013a; 2014a; 2015a) for the year 2013 to 2015. Casualty data based on severity was not found available for the year 2015 from EMSA and hence the same is indicated as 'Not Available' (NA) in table 2.4. The casualty data reported in table 2.4 highlights a very high percentage of *less serious* severity casualties due to various casualty types i.e. collision, allision, grounding etc., and this should be a matter of grave concern as despite the emphasis on addressing human factor issues in marine transportation and incorporation of advanced navigation technologies, casualties continue to occur.

**Table 2.4: Comparison of Marine Casualty Numbers Based on Casualty Severity.**

| Year & Agency → | 2013 | | | | 2014 | | | | 2015 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EMSA | | MAIB | | EMSA | | MAIB | | EMSA | | MAIB | |
| Severity ↓ | No | % | No | % | No | % | No | % | No | % | No | % |
| Very Serious | 81 | 4 | 21 | 3.5 | 99 | 4 | 23 | 4 | NA | - | 24 | 5 |
| Serious | 468 | 21 | 82 | 14 | 765 | 30 | 71 | 13 | NA | - | 48 | 10 |
| Less Serious | 2001 | 78 | 488 | 82.5 | 1718 | 66 | 462 | 83 | NA | - | 411 | 85 |
| Total | 2550 | 100 | 591 | 100 | 2582 | 100 | 556 | 100 | - | - | 483 | 100 |

There are some studies reported which have attempted to analyse marine casualties with respect to the geographical area of casualty. Studies by Ugurlu *et al.* (2015) have tried to establish a relationship for oil tanker casualties based on ship tonnage and the navigational sea area type and report of smaller tankers undertaking short voyages i.e. frequent call at ports, in coastal areas and channels having a higher chance of getting involved in a casualty. Butt *et al.* (2013) have also established a similar relationship for general cargo vessels involved in tramp trade and assigned to substandard flag states and operating in Southeast Asia. The concentration of marine casualties in certain regions of the world has also been reported by Eliopoulou and Papanikolaou (2007) and Primorac and Parunov (2016). However none of these studies attempts to establish a link between the human factor issues and the marine casualties pertaining to a specific geographical area of casualty. The area based issues in a particular geographical area of marine casualty which could influence the human behaviour resulting in them making errors or leading to their poor performance has not been specifically identified and addressed. Similarly, the influence of navigation and infrastructure issues i.e. heavy traffic, inadequate warnings, unrestricted encroachments into seaway, inadequate navigational warnings, out dated or inaccurate navigation charts, etc. in a particular geographical area of casualty on the human factor issues appears also not accounted for.

These shortcomings provides opportunities for accounting the influence the area based issues and the navigation and infrastructure issues could have on the human factor issues, leading to their poor performance and errors.

In summary, the last two to three decades have seen a major focus in appreciating, understanding and attempting to resolve human factor issues in ship manning and operations leading to marine casualties. This has primarily led to the adoption of advanced technologies and improved regulations aimed at addressing human factor issues and in preventing their occurrence in future. Despite all this, marine casualties continue to happen even now and the casualty investigations performed in accordance with IMO guidelines and otherwise reveal one or more of the major human factor issues listed in Table 2.2 being involved. A brief summary of some of the recent collision, allision and grounding casualties involving cargo ships presented in section 2.2.2 bears testimony of the unpredictable nature of human actions and behaviour and of the complexity involved in dealing with human factor issues. Marine casualty statistics appears to identify and analyse human factor issues from a worldwide or larger geographical area and in some cases together with influencing factors such as ship type, voyage details etc. Furthermore a lack of emphasis to understanding how the area based issues and navigation and infrastructure issues in a particular area of casualty can influence human factor issues are noted.

In this regards, a need is felt to systematically address the human factor issues in ship operations and manning by considering the specific geographical area based issues where the marine casualty occurs together with other influencing factors i.e. ship type, voyage type etc. This has been addressed using the *best practices* approach proposed in this study and which is discussed in the subsequent sections of this chapter.

## 2.3 MARINE CASUALTY ANALYSIS BASED ON GEOGRAPHIC AREA OF CASUALTY AND CASUALTY TYPE

Collision, grounding and allision casualty type are generally associated with navigation related issues where the human factor issues have a major contribution in the casualty taking place. A consolidation of the marine casualty data for collision, grounding and allision type casualties reported by MAIB, JTSB and HK for the period 2011- 2015 are performed in this study for comparison purpose. The casualty data from MAIB (2011; 2012; 2013a; 2014a; 2015a), HK (2011-2015) and JTSB (2016) has been considered. The casualty data reported by EMSA and TSBC were also referred to for this study. However the casualty statistics of MAIB, JTSB and HK has been selected because of the similarity of their reporting style and content which facilitates uniform representation of data for this analysis. The territorial waters of the UK, Japan and Hong Kong all represent shipping routes with fairly high volume of cargo movement (Equasis 2015) and area of high casualties.

The assumptions made in this analysis is that the casualty data presented in MAIB (2011; 2012; 2013a; 2014a; 2015a) and JTSB (2016) represent the casualties involved in the territorial waters of the respective countries, as their published reports do not submit information segregating the casualties from within and outside its territorial waters. Furthermore, this assumption is not expected to drastically influence the findings made in this analysis as the purpose here is to propose a relationship between the marine casualty type and the geographical area based issues. Influence of other factors such as weather condition, specific ship type, voyage details, operating period (day or night), visibility etc., at the time of the casualty are also ignored from this analysis since the casualty statistics presented by MAIB, JTSB and HK do not differentiate the casualty data based on these criteria.

In fig. 2.6, a consolidation of the percentage of collision casualties reported for all ship types is illustrated.

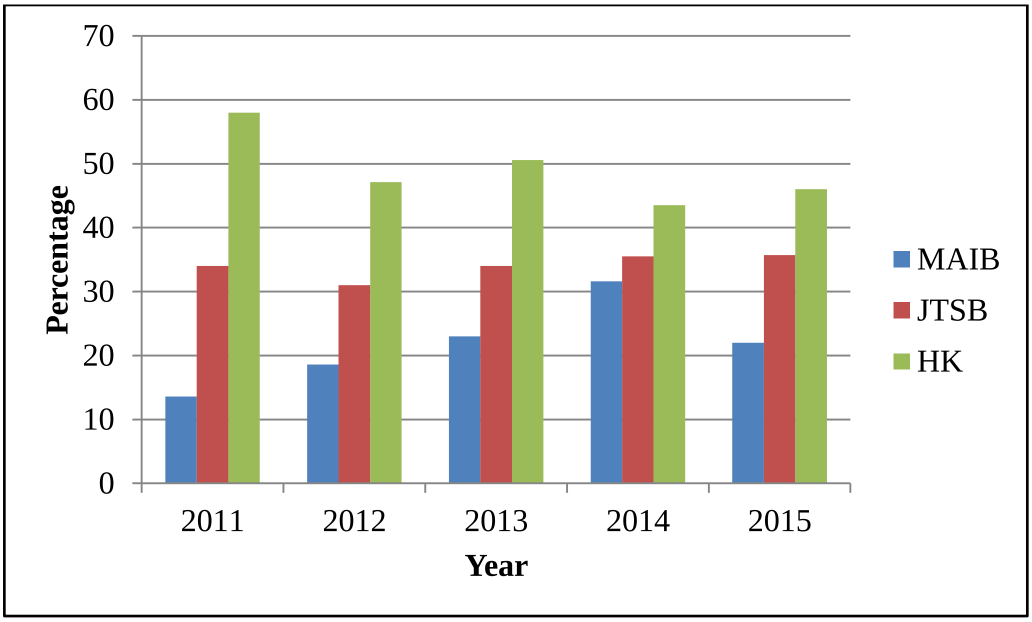


**Fig. 2.6: Percentage of Collision Casualties Involving All Ship Types for the Period 2011-2015**

Around 40-60% of collision casualties involving all ship types happen in the Hong Kong territorial waters and it is the worst case when compared to those reported by JTSB and MAIB. The high percentage of casualties involving collision could be attributed to the heavily congested waters and high traffic volume in this area as Hong Kong is one of major business centres in South Asia. Furthermore there is also a likelihood of high number of general cargo vessels of an elderly age profile flagged with substandard registries and used for tramp trade operating in this region (Butt *et al.* 2013).

In fig. 2.7, a consolidation of the percentage of allision casualties for all ship types reported by HK, JTSB and MAIB for the period 2011-2015 is presented. Although the percentage of occurrence of allision casualties are less when compared to collision casualties, a high of around 28% is reported by MAIB and this represents the territorial waters of the UK.

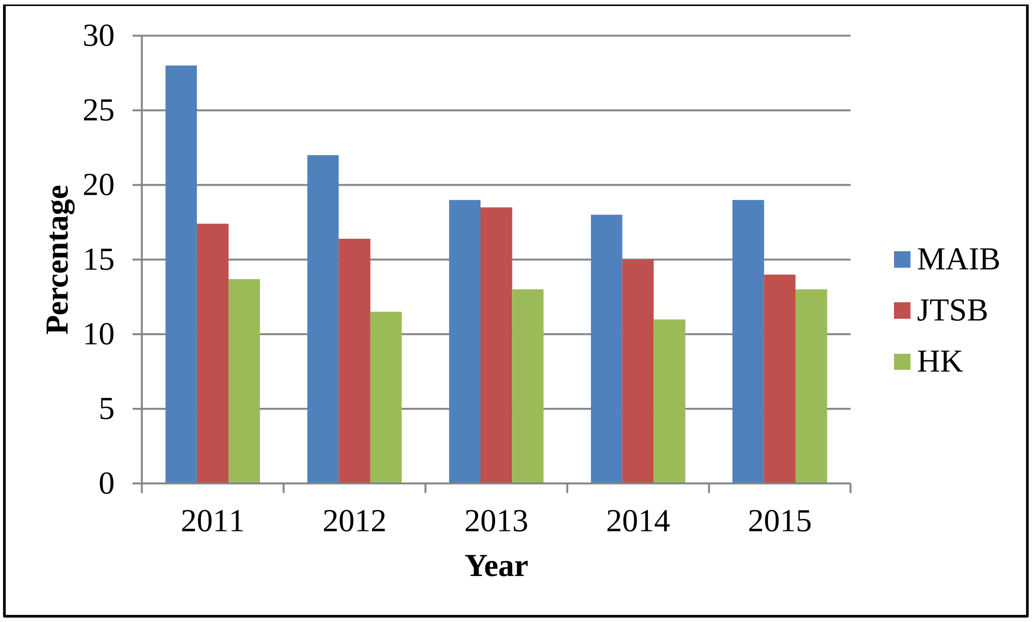


**Fig. 2.7: Percentage of Allision Casualties Involving All Ship Types for the Period 2011-2015**.

The allision casualty statistics of MAIB also shows higher percentages (18-28%) for all the years considered in this analysis, when compared with those reported by JTSB and HK. There was no specific literature found addressing such high percentage of allision casualty in these waters and the author presumes the rough seas associated with the North Sea and North Atlantic Ocean and presence of many offshore structures and platforms in these waters as the contributing factors for this casualty type.

The consolidation of percentage of grounding casualties for all ship types reported by HK, JTSB and MAIB is presented in fig. 2.8. It is noted that the percentage of occurrence of grounding casualties reported by JTSB is higher than allision casualties and less than collision casualties. Grounding casualties reported by JTSB is the highest amongst the three and range between 27-33%. One of the probable reasons for such a high number of grounding casualties could be because Japan is surrounded by the "Ring of Fire", which is a zone of frequent volcanic eruptions and earthquakes. Kery (2012b) has reported that a single event is enough to raise or lower the seabed considerably in this zone and passages assumed to be deep enough for navigation may not be safe anymore.

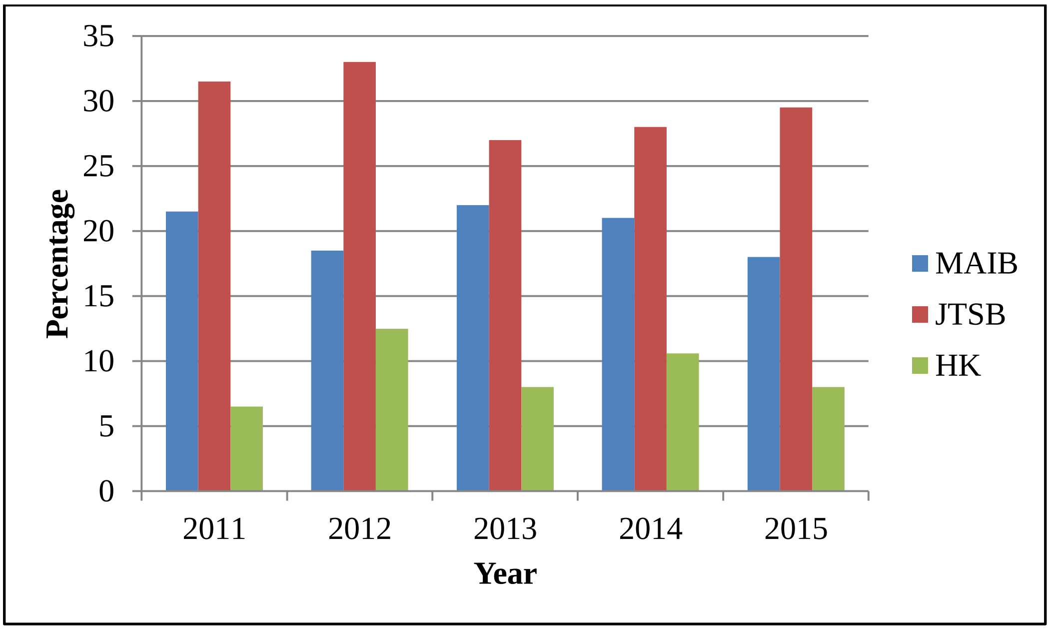


**Fig. 2.8: Percentage of Grounding Casualties Involving All Ship Types for the Period 2011-2015.**

In fig. 2.9 the geographical area covered by the "Ring of Fire" is shown.


**Fig. 2.9: Ring of Fire** (Source: https://sites.google.com/site/volcanoes and theringoffireurja/ accessed on 21 June 2017**)**

The Pacific region of Canada also falls in this “Ring of Fire” zone and TSBC (2015) also reports of a majority of the grounding casualties (53%) in this region.

The consolidation of the data based on casualty types reported by JTSB, HK and MAIB in fig 2.6, fig 2.7 and fig 2.8 indicate a predominance of a particular casualty type to a specific geographical area of operation. The analysis presented indicate collision casualties ranking high in Hong Kong territorial waters, grounding casualties in Japanese territorial waters and allision/ contact casualties in UK territorial waters. Similar to this approach, casualties involving oil tankers with respect to worldwide area of casualty has been analysed by Ugurlu *et al.* (2015) while Pagiaziti *et al.* (2015) has compared the casualty statistics between the casualty type with the area of casualty i.e. open sea, limited waters and terminal area, for container ships and passenger ships. Primorac and Parunov (2016) have identified the geographical areas based on the SIS zones topological system which are considered most accidentally risky areas while Papanikolaou *et al.* (2005) have compared the casualty data based on casualty type and location of casualty i.e. open sea, coastal waters, anchorage etc., for AFRAMAX tankers. None of these studies extend beyond to analyse the area specific issues or the human factor issues or the navigation and infrastructure issues, relevant to the area of casualty. The relationship between the marine casualty type and the geographical area of the casualty derived in this analysis provides opportunities for research focussed on resolving the relevant human factor issues pertaining to the particular casualty type in a particular area of casualty. It also provide opportunities for identifying the area based issues and the navigation and infrastructure issues which could influence the human factor issues leading to these casualties.

## 2.4 *BEST PRACTICES* FOR RESOLVING IDENTIFIED HUMAN FACTOR ISSUES

In this thesis, a relationship is proposed between the human factor issues, area based issues (of casualty) and the navigation and infrastructure issues pertaining to a geographical area of marine casualty. This relationship is proposed on the premise that navigation and infrastructure issues and area based issues in a particular geographical area of casualty can influence the human factor issues leading to human errors and diminishing performance. On a similar account, some of the area based issues could also be influenced by the navigation and infrastructure issues and viz- versa, in the particular area of casualty. Thus a concentration of high number of casualties in a particular geographical area as a result of human errors could be related to the specifics of the geographical area which contribute or influence the human behaviour and actions.

The analysis of the issues based on the proposed inter-relationship is intended to resolve the identified human factor issues, by ascertaining and addressing the area based and /or navigation and infrastructure issues, and this forms the *best practices* espoused in this study. This inter-relationship is illustrated in fig. 2.10 and a pictorial representation of the various human factor issues, area based issues and the navigation and infrastructure issues are presented. Relationships are depicted by arrows extending to and from each of these issues. The human factor issues affecting the OOW leading to their poor performance and errors include the physiological, psychological, physical, equipment related, company related and environment related factors leading to violations, slips, lapses and mistakes and these are elaborately listed in IMO (2000). Inadequate sleep, family issues, fatigue, emotions, distractions as a result of using mobile phones, under the influence of alcohol, lack of training to use sophisticated navigation equipment, lack of situational awareness, administrative work while on duty, time pressure, adherence to rules are pictorially represented under human factor issues. The area related issues pertain to the issues in a particular area where the number of marine casualties is recorded to be high. A pictorial representation of rough seas, rocky bottom or coral reefs, ship wrecks, frequent storms, heavy traffic area, heavy fishing activity, weather condition, daytime and night time operations and presence of fixed structures i.e. platforms, jack ups etc. is made to depict these issues. Additional issues which may be relevant but not depicted here are language barriers, informal rules of navigation and ice conditions. The navigation and infrastructure issues pertaining to a specific area of casualty and which are pictorially represented include traffic separation issues, inaccurate charts and/or unavailability of navigation charts, inadequate navigational aids, speed restrictions, accident area warning, pilotage issues, lack of rules or policies restricting encroachment into channel by fishing community or use of waterway during bad weather, penal action, inadequate tug boat operations, pilotage issues, etc.

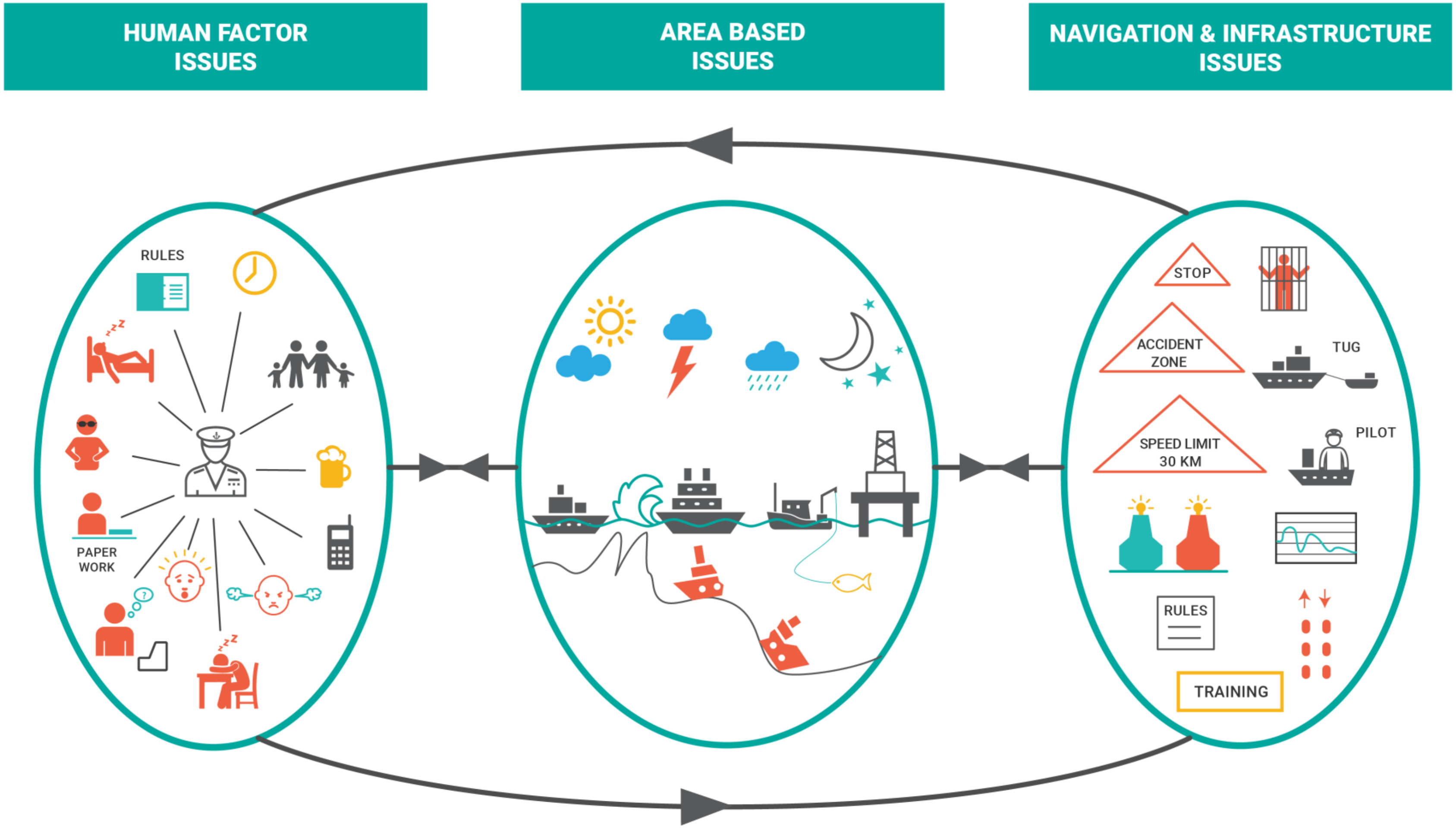


**Fig. 2.10: Inter-Relationship Between Human Factor Issues, the Area Based Issues and the Navigation and Infrastructural Issues in the Area of Casualty**

The relationship amongst these factors proposed in this thesis provides opportunities for correlating the casualty types to the geographical area of operation to narrow down the relevant human factor issues pertaining to the particular casualty type. It will also aid in ascertaining and addressing the navigational and infrastructural shortcomings i.e. lack of traffic separation system, old navigational charts, pilotage issues, lack of navigational buoys etc., created as a result of the area based issues, which when addressed can mitigate or lessen the risk of casualties from taking place as it would alleviate some or all of the reasons leading to human errors. Unlike the earlier analysis in section 2.3 which covered all ship types, the *best practices* approach in this study aims to resolve the dominant human factor issues leading to the casualty in the particular geographical area by considering the particular ship type, the specific voyage details and the specific area of casualty.

The approach proposed here can also be extended to ascertain and resolve the human factor issues based on environmental issues i.e. weather conditions, sea state, daytime and night time operations etc., and is presently not within the scope of this study.

## 2.5 Shortcomings in Marine Casualty Data Statistics and Proposed Additional Criteria for Assessment of Casualties Based on the *Best Practices*

Unlike marine casualty investigations and reporting which have specific and uniform guidelines applicable to all the states based on IMO (2008) and MSC-MEPC (2008), there appears to be a lack of uniformity or lack of consistency in the reporting content of the casualty data statistics amongst the various investigation agencies of member states. The casualty data presented are probably tailored to suit the individual state requirements as it is noted that different investigation agencies/ member states adopt different criteria for assessment and reporting of the findings made from the casualty investigation reports. In table 2.3, a comparison of the criteria based on which the data on marine casualties is compiled and reported by the investigation agencies of member states has been presented. A cursory glance at the contents in table 2.3 would clearly indicate the wide variations as well as inadequacy of the data presented, which could otherwise be useful for analysis purposes and research activities aimed at resolving the identified human factor issues.

The consolidation of the human factor issues related to casualties based on a larger geographic area (i.e. the territorial waters of the country or worldwide area) and involving all ship types appears not really useful in ascertaining the influencing human factor issues as these statistics only restricts in providing a general overview of the various human factor issues involved in marine casualties. The efficacy of such an analysis is also evident from the continued occurrence of marine casualties taking place (see Section 2.2.2) for the very same human factor issues that were identified years ago and apparently assumed to be addressed through the incorporation of advanced navigational technology, regulations pertaining to crew comfort, minimum crew manning levels and so on.

This study recommends adoption of a uniform and consistent approach for casualty statistics reporting by all the investigation agencies and member states, and as a minimum the details presented in table 2.3 of this thesis can be used as a guideline for the information to be compiled and published. In view of the *best practices* approach proposed in this thesis, additional criteria identified based on which the marine casualty is to be evaluated is as follows:

- Marine casualty distribution based on cargo ship type, geographical area of casualty (Marsden squares number) and voyage details.
- Classification of the geographical area of marine casualty within the same Marsden square grid into open sea, limited waters, terminal area with further sub-classification based on the longitude and latitude depending on the concentration of casualties. The distribution of marine casualties in these areas is then to be related to the frequency of occurrence, ship types, casualty type and voyage details.

For the purpose of including these additional criteria for evaluation of marine casualties in accordance with the *best practices*, a template is proposed in this study to facilitate data inclusion and is illustrated in table 2.5. The developed template is unique from the following perspective:

i. The template facilitates easy correlation of the geographical area where the marine casualty takes place to the specific cargo ship type involved in the casualty, the casualty type and the nature of voyage undertaken by the ship.

ii. The geographical area of operation where the casualty takes place is identified based on the Marsden squares grid system. The Marsden squares grid system has been adopted by Eliopoulu and Papanikolaou (2007) for identifying the geographical location of the casualty and appears to be more focused when compared to the SIS zone topological system in which the Earth is divided into 31 zones (Primorac and Parunov 2016). Within the selected Marsden square grid, the proposed template facilitates classification of the geographical area into open sea, limited waters i.e. coastal area, channels etc., and terminal or port areas.

iii. A sub-classification of the geographical area of marine casualty is introduced in the template based on the longitude and latitude of the location (within the same Marsden squares grid and classification area) where there is a high concentration of casualties reported. The sub-classification for limited waters is identified as Geographic location #1, Geographic location #2, etc. while the sub-classification for terminal or port area is identified as Location #1, Location #2, etc. in the template.

iv. The template facilitates inclusion of casualty statistics based on the nature of voyage undertaken for different cargo ship types involved in a particular marine casualty. In this study, a comparison between ships engaged in short voyages and long voyages is found to be of interest as they present varying human factor issues leading to poor performance and human errors.

**Table 2.5: Proposed Template for Data Input on Marine Casualties Based on Geographical Area of Casualty**

*Legend:* SV – Short Voyage ; LV – Long Voyage

| Geographical Area based on Marsden Squares Grid Number | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S.No →<br>↓** | **(1)** | **(2)** | **(3)** | **(4)** | **(5)** | **(6)** | **(7)** | **(8)** | **(9)** | **(10)** | **(11)** | **(12)** | **(13)** |
| 1 | Casualty type, Ship type, Voyage and Analysis →<br>Location ↓ | Collision | | | | | | | | | | | |
| | | Gen. Cargo | | Bulk carrier | | Tankers (oil & product) | | Container Ships | | Ro-Ro | | Others | |
| | | SV | LV | SV | LV | SV | LV | SV | LV | SV | LV | SV | LV |
| 2 | Open sea | | | | | | | | | | | | |
| 3 | Limited waters | | | | | | | | | | | | |
| 4 | Geographic location #1 | | | | | | | | | | | | |
| 5 | Geographic location #2 | | | | | | | | | | | | |
| 6 | Geographic location # etc. | | | | | | | | | | | | |
| 7 | Terminal/Port Location | | | | | | | | | | | | |
| 8 | Location # 1 | | | | | | | | | | | | |
| 9 | Location # 2 | | | | | | | | | | | | |
| 10 | Location # etc. | | | | | | | | | | | | |

In table 2.5, the top row is dedicated to listing the geographical area of casualty based on the Marsden squares grid system. The columns 2-13 are for listing the information on the different casualty types, the different cargo ship type and voyage type and the corresponding casualty numbers. The rows 2-10 cover the different areas within the selected Marsden squares grid number and are divided into open sea, limited waters and terminal area. Additional subdivisions of these areas are provisioned for based on the latitude and longitude of the area where a high concentration of marine casualties are noted.

## 2.6 ANALYSIS OF MARINE CASUALTY DATA BASED ON THE *BEST PRACTICES*

For the purpose of analysis of the marine casualty data based on the relationship proposed between the human factor issues, area based issues and navigation and infrastructure issues in this thesis, the template in table 2.5 is further expanded to include the analysis phase based on the *best practices*. Table 2.6 is proposed specific to collision type of marine casualties involving cargo ships of different types. Similarly the templates for allision and grounding type marine casualties are also proposed and are included in Appendix A1 and A2 of this thesis.

In table 2.6, columns 14, 15, 16 and 17 are the additions made to the template proposed in table 2.5 and represent the sections for the ‘identified human factor issues’; the ‘area based issues’; the ‘navigation and infrastructure issues’ and the ‘recommendations’ respectively. The combined data input and analysis template proposed in this thesis is illustrated in table 2.6 and provides a single platform to holistically view the problem and perform varying analysis based on the nature of problem to be addressed i.e. focussed or general analysis.

**Table 2.6: Proposed *Best Practices* Template for Combined Casualty Data Input and Analysis for Collision Casualties**

Legend : SV – Short Voyage ; LV – Long Voyage

| | Geographical Areas Based on Marsden Square Number | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S.No** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** |
| 1 | Casualty type, Ship type, Voyage and Analysis → | Collision | | | | | | | | | | | | Analysis | | | |
| | | Gen. Cargo | | Bulk carrier | | Tankers (oil & product) | | Container Ships | | Ro-Ro | | Others | | Identified human factor issues | Area specific issues | Navigation and Infrastructure Issues | Recommen-dations |
| | Location ↓ | SV | LV | SV | LV | SV | LV | SV | LV | SV | LV | SV | LV | | | | |
| 2 | Open sea | | | | | | | | | | | | | | | | |
| 3 | Limited waters | | | | | | | | | | | | | | | | |
| 4 | Geographic location #1 | | | | | | | | | | | | | | | | |
| 5 | Geographic location #2 | | | | | | | | | | | | | | | | |
| 6 | Geographic location etc. | | | | | | | | | | | | | | | | |
| 7 | Terminal/ Port Location | | | | | | | | | | | | | | | | |
| 8 | Location # 1 | | | | | | | | | | | | | | | | |
| 9 | Location # 2 | | | | | | | | | | | | | | | | |
| 10 | Location # etc. | | | | | | | | | | | | | | | | |

The analysis section provided in table 2.6 provisions for listing the identified human factor issues (in column 14) specific to a geographical area of casualty for a particular ship type involved in a particular voyage i.e. focussed analysis, or for all the marine casualties in the specific geographical area. The human factor issues involved could vary depending on the ship type and voyage details. As an example, fatigue as a human factor issue due to inadequate rest periods for a general cargo ship involved in frequent calling at ports and engaged in short voyages may not be applicable for the crew of a VLCC engaged in long voyages. The analysis section in the template also provisions for identifying and listing the area specific issues (column 15) and identifying the navigation and infrastructure issues (column 16) in the specified geographical area of marine casualty. Recommendations made as a result of the findings from the analysis of the three issues are the mitigating measures to be adopted and occupy column 17 in the template

## 2.7 CASE STUDY FOR ILLUSTRATING THE USE OF THE PROPOSED TEMPLATE AND ANALYSIS AS PER THE *BEST PRACTICES* APPROACH

The use of the *best practice*s approach is illustrated with a hypothetical case study. The geographical area under consideration is the Hainan Strait or Qiongzhou Strait (see fig. 2.11), which is one of the major shipping routes and this area is numbered as 97 and 98 in the Marsden squares grid. This strait is a body of water that separates the Leizhou Peninsula in southern China with Hainan Island, and connects the Gulf of Tonkin to the South China Sea. For the purpose of this case study the analysis of casualties in Marsden square grid 98 is considered and the proposed template in table 2.6 is populated with arbitrary casualty numbers for the different ship types, locations and voyage segments. The hypothetical casualty statistics presented in table 2.7 indicates a high frequency of collision casualties in the limited water (geographic location #1) of the Hainan strait involving oil tankers engaged in long voyages. Based on this input data, the first phase of the analysis involves identifying the dominant human factor issues pertaining to the 31 casualties considered.


**Fig. 2.11: Map of Hainan Strait**

(*Source:*https://ars.els-cdn.com/content/image/1-s2.0-S0278434314002659-gr1.jpg accessed on 28 September 2017)

For the purpose of this study it is assumed that the psychological (panic and emotional) and physiological (fatigue) issues are the predominant human factor issues common to the 31 casualties reported. IMO (2000) defines 'Emotional' issues as a "state of agitation or disturbance which can affect an individual's normal ability to perform required tasks", 'Panic' as "a sudden overpowering fear that reduces the ability to perform required tasks" while '*Fatigue'* is "a reduction in the physical and mental capability which impairs the ability to react, make decisions etc., and is attributed to physical, mental or emotional exertion".

**Table 2.7: Hypothetical Casualty Statistics for Collision Type Casualties in Hainan Strait**

Legend : SV – Short Voyage ; LV – Long Voyage

| Marsden Square Number - 98 | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S.No** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** |
| 1 | Casualty type, Ship type, Voyage and Analysis → Location ↓ | Collision | | | | | | | | | | | | Analysis | | | |
| | | Gen. Cargo | | Bulk carrier | | Tankers (oil & product) | | Container Ships | | Ro-Ro | | Others | | Identified human factor issues | Area specific issues | Navigation & Infrastructure Issues | Recommen-dations |
| | | SV | LV | SV | LV | SV | LV | SV | LV | SV | LV | SV | LV | | | | |
| 2 | Open sea | | | | | | | | | | | | | | | | |
| 3 | Limited waters | | | | | | | | | | | | | | | | |
| 4 | Geographic location #1 | 12 | 1 | 18 | 15 | 1 | 31 | | | | | 2 | 1 | | | | |
| 5 | Geographic location #2 | 2 | | | 2 | | 2 | | | | | 1 | 1 | | | | |
| 6 | Geographic location # 3 | 3 | 1 | | 2 | 1 | 1 | | | | | 1 | | | | | |
| 7 | Terminal Location | | | | | | | | | | | | | | | | |
| 8 | Location #1 | | | | | | | | | | | | | | | | |
| 9 | Location #2 | | | | | | | | | | | | | | | | |
| 10 | Location #3 | | | | | | | | | | | | | | | | |

The second phase of the analysis involves identifying the area based issues in this particular geographic location #1 which affect or contribute to the earlier identified human factor issues. For the purpose of this study it is assumed to be unregulated encroachment of fish farming nets and buoys into the seaway, heavy traffic of fishing vessels and heavy traffic of commercial ship in the opposite direction. Ships engaged in voyages in this strait have to frequently alter course to avoid fish farming nets and buoys and the fishing vessels, and such sudden and frequent alterations in course brings them in direct risk of collision with the traffic in opposite direction or with the fishing vessels cutting across, and at times leads to collision. This area is also prone to reduced visibility due to fog which worsens navigation situation in these waters. The OOW of the oil tanker is under constant stress and has to be extremely vigilant at all times.

The third phase of analysis involves identifying the navigation and infrastructure issues in this location #1 which could influence the earlier identified human factor issues and area based issues. In this case they are identified to be a lack of vessel traffic separation system, lack of regulations restricting the encroachment of fish farms into the seaway and not following international guidelines when markings and buoys are provided.

The analysis findings are summarized in table 2.8 and a relationship can now be established between the human factor issues, area based issues and navigation and infrastructure issues, based on the specific ship type, voyage type and geographical area of casualty.

**Table 2.8: Listing of Analysis Findings**

| Identified Human Factor Issues | Area based Issues | Navigation and Infrastructure Issues |
|---|---|---|
| Emotional | Fish farms Nets and Markings | No Traffic separation system |
| Panic | Heavy Fishing vessel traffic | No restriction on fish farm limits |
| Fatigue | Traffic in opposite direct | No requirement of fish farm markings and lights |
| | Fog resulting in limited visibility | |
| | Frequent manoeuvring and course change | |

Based on the findings from the analysis, it is noted that the area specific issues can be resolved with improvements addressing the navigation and infrastructure issues. As an example, regulating the encroachment of fish farms into the seaway, implementing a traffic separation system and following international standards for the luminescence of the fishing markers/ buoys will help to resolve the area based issues. These area based improvements will correspondingly reduce or eliminate the emotional, panic and fatigue issues experienced by the OOW of the oil tanker. The OOW would be able to maintain a steady course without frequent manoeuvring as the encroachment of fish farms have been regulated away from the seaway and during restricted visibility conditions he is able to identify the fishing marker buoys well in advance due to adequate lighting intensity.

A more focussed approach to resolving human factor can thus be made based on the *best practices* approach proposed in this thesis.

It is also pertinent to note that the proposed template in table 2.6 facilitates analysis not only specific to the ship type and voyage details i.e. as illustrated in this case study, but can also be extended to analyse all the casualties in the particular geographic location and also the casualties based on the voyage details irrespective of ship type. It is noted from table 2.7 that in addition to the oil tankers, a substantial number of bulk carriers engaged in both short and long voyages, as well as general cargo ships involved in short voyages were involved in casualties in this specific location. The *best pra*ctices developed in this study can facilitate analysis from a broader perspective which includes all the ship types together or for specific voyage types.

## 2.8 PROCEDURE FOR MARINE CASUALTY DATA COLLECTION, ANALYSIS AND REPORTING BASED ON THE *BEST PRACTICES*

In this section, a procedure is proposed for collection of marine casualty data to populate the template in table 2.6; for the subsequent analysis; for reporting of recommendations; monitoring implementation; and finally publishing the findings. This procedure is illustrated in fig. 2.12 together with guidance on the activities involved. In IMO (2008), the flag state of the ship involved in the casualty is primarily responsible for conducting the investigations of *very serious* severity casualties and of casualties of less severity if they are considered likely to provide useful information to prevent their future occurrence.

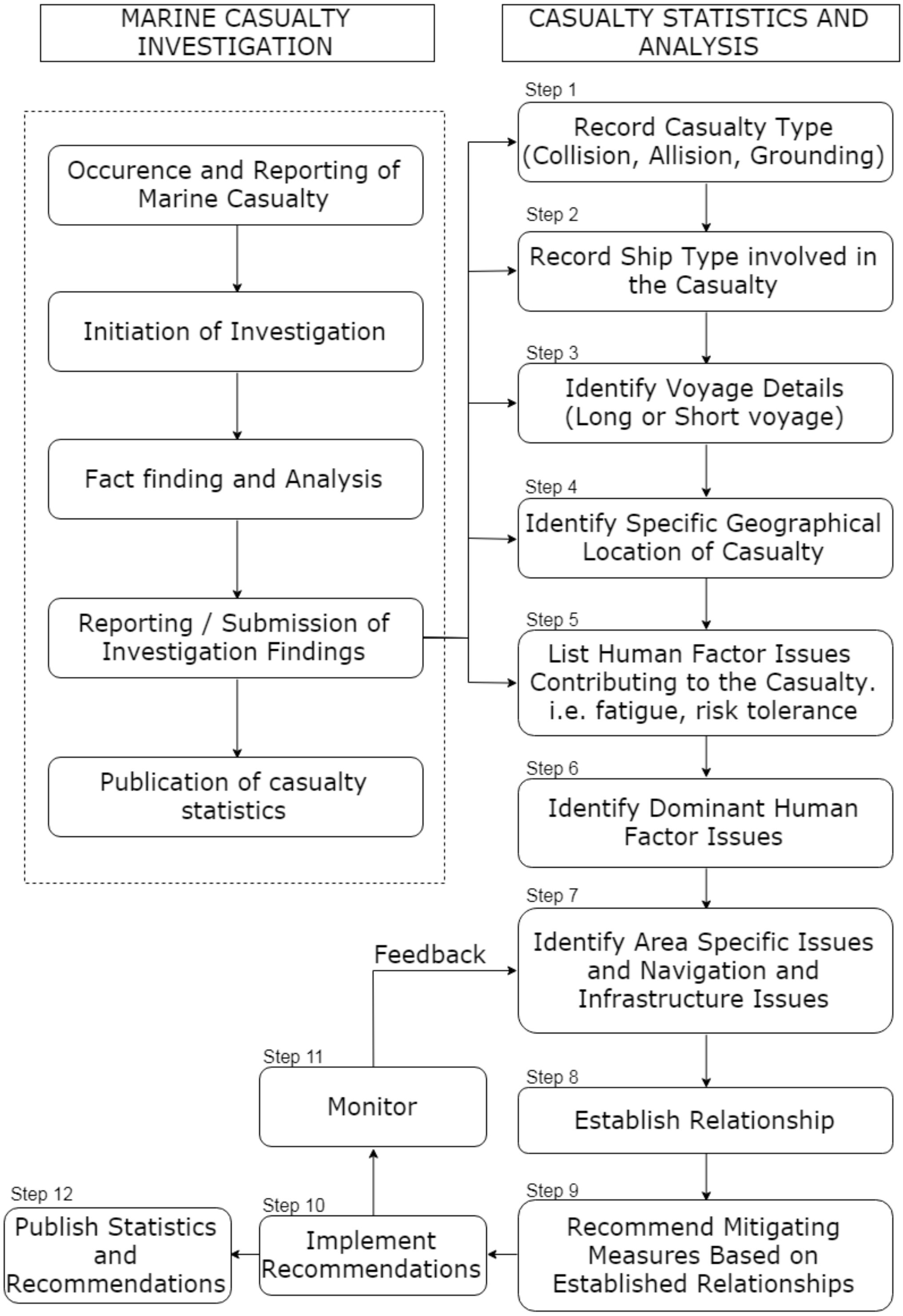


**Fig. 2.12: Procedure for Marine Casualty Data Input and Analysis based on the *Best Practices***

However since the focus of this study is from the geographical area of marine casualty, the recommendation in this study is to have analysis i.e. data collection, analysis, reporting etc., as per the *best practices* formulated here, performed by the coastal state or state under whose territorial area the casualty has taken place. In the event the marine casualty takes place in open sea, the coastal State whose environment is affected by the casualty is then responsible to conduct the analysis as per the *best practices* formulated in this thesis.

The activities involved in each step are as follows:

*Step 1 to Step 5:* The marine casualty investigation reports prepared in accordance to the requirements in MSC-MEPC (2008) and IMO (2014) provide the input information with respect to the casualty type, the cargo ship type, voyage details, geographical location of casualty including its classification and sub-classification, and the human factor issues pertaining to the casualty. The duly filled in Annex 1 and Annex 2 in MSC-MEPC (2008) covering the incident summary is also another useful source for obtaining the input information and are available from the IMO GISIS casualty module. MSC-MEPC (2008) requires the full investigation reports mandatorily for all *very serious* casualties and Annex 1 and Annex 2 for all *very serious* and *serious* severity casualties. Annex 1 in MSC-MEPC (2008) details the ship particulars including ship type, voyage details and casualty type while Annex 2 details the location of the casualty specific to the latitude and longitude and also whether in open sea, limited waters and port/ terminal area. It also provisions for identifying the human factor issues contributing to the casualty (as applicable). Annexure 3 (if submitted) in MSC-MEPC (2008) summarizes the principal findings of the casualty investigation and could provide additional information on the human factor issues leading to the marine casualty.

This thesis recommends submission of the marine casualty reports as per Annex 1 and Annex 2 of MSC-MEPC (2008) for all *less serious* severity casualties involved in collision, allision and grounding casualty types as well, although not mandated. The basis of this recommendation stems from the very high percentage (66-85%) of *less serious* severity casualties, when compared to the *very serious* and *serious* severity as reported in EMSA (2014), EMSA (2015a) and MAIB (2013a, 2014a, 2015a). Inclusion of the casualty data especially involving human factor issues from such a large database would be very beneficial in extracting the best possible results towards resolving the identified human factor issues, as is the intent of the *best practices* in this study.

*Step 6 :* The activity in this step involves identifying the dominant human factor issues leading to the casualties based on the ship type, voyage details and geographical area of casualty. A simple approach similar to the one followed by Baker and Seah (2004), Chauvin *et al.* (2013) and Kum and Sahin (2015) or the more sophisticated approach used by Akhtar and Utne (2015) and Graziano *et al*. (2016) may be adopted to identify the dominant human factor issues based on the desired classification. The selection of the appropriate method would depend on the number of casualties investigated and the number of variables against which the analysis is to be performed.

*Step 7:* The area specific issues influencing or contributing to the identified human factor issues are to be identified and documented here. Some of the influential issues could be heavy traffic, fishing activity, rocky bottom or coral reefs, rough seas, reduced visibility, area of high storm activity, high current, narrow channel, etc., all of which would vary from location to location. This step also includes identifying the deficiencies related to navigation and infrastructure in the concerned geographical area of casualty. Navigational issues relate to vessel traffic separation system, use of specific navigational equipment, crew training, navigational aids, navigational charts etc. while infrastructure issues relate to pilotage services, bigger and tug boats, policies specific to the area, port traffic control etc.

The outcome of the analysis performed in *step 6* and *step 7* is illustrated in table 2.8 of this thesis for the hypothetical case study example and assists to establish an inter-relationship between the various issues involved which could influence the human factor issues leading to marine casualties.

*Step 8*: This step involves identifying the specific navigation or infrastructure issue or issues which when addressed can resolve or mitigate the area based issues and correspondingly the human factor issue contributing to the casualty. Also there may be instances where addressing a specific navigation or infrastructure issue could directly influence or resolve the human factor issue contributing to the casualty. A relationship is then established between the human factor issues, the area based issues and the navigation and infrastructure issues.

*Step 9*: Recommendations are made based on the relationship established in step 8. These recommendations could be procedural changes or operational improvements i.e. implementing vessel traffic separation system, inclusion or updating warnings in navigation charts, restricting encroachment into seaway etc., or making infrastructural improvements i.e. navigational buoys etc.

*Step 10*: This step involves implementation of the recommendations made in step 9.

*Step 11*: The implemented recommendations are monitored for effectiveness through a feedback mechanism from the ship crew and also through analysis of recent casualties (if any) in the same geographical area after the implementation of the recommendations made, and ascertaining whether the earlier identified common human factor issues are still dominant and contributing to diminished performance and human errors.

*Step 12:* Involves publication of the input data, analysis findings and the recommendations made by the coastal state to IMO, by IMO or any other agency.

In this chapter, an inter-relationship between human factor issues, area based issues and navigation and infrastructure issues has been established and *best practices* to analyse and resolve the human factor issues has been developed. The *best practices* approach facilitates a better understanding of the human factor issues with respect to the external environment to which the crew members are exposed to and operate in. Instead of addressing human factor issues leading to human errors and poor performance issues from a worldwide or larger geographical area perspective, the best practices approach facilitates a more focussed analysis based on a smaller geographical area under consideration together with the inherent issues in this area. The use of the *best practices* approach has been illustrated with a hypothetical case study involving an oil tanker passing through the Hainan Strait. In this case, relationships are established between the human factor issues, area based issues and the navigation and infrastructure issues. These are then analysed to alleviate the identified human factor issues responsible for past marine casualties in this area. To facilitate the use of the *best practices* approach developed in this study, templates have been developed to input the required marine casualty data. A detailed procedure is also developed which identifies the input source for casualty data and progresses systematically through the analysis of this data for arriving at the recommendations or mitigating measures to prevent the future occurrence of marine casualties for the identified human factor issues. Inconsistency or non-uniformity in marine casualty data presented by the investigation agencies is highlighted and recommendations made for a more uniform representation of this data.

The developed *best practices* are expected to provide a focussed approach to understanding and resolving human factors issues in marine transportation. It is also expected to facilitate knowledge sharing between IMO and the coastal states on the effectiveness of navigation and infrastructure changes made to address the specific area based issues, and further how these changes facilitated in resolving the identified human factor issues.

After having addressed one of the dominant issues leading to marine casualties i.e. human factor issues, through a forensic engineering investigation approach, the focus of this thesis now shifts to engineering issues which affect the ship hull strength. A forensic engineering investigation procedure is developed to address this issue in the next chapter of this thesis.

# CHAPTER 3

# AN ENGINEERING APPROACH ON MARINE CASUALTY INVESTIGATIONS

## 3.1 GENERAL

The focus in this chapter of the thesis is on highlighting and addressing engineering issues in marine casualties using a forensic engineering investigation approach. This investigation approach is proposed to bring about improvements in the classification rules and regulations affecting the design, construction and inspection of ships with the intent to mitigate the extent of damage sustained to the hull structure in the event of a collision or allision casualty. It is also expected to facilitate in actual casualty investigations for specific engineering issues which could influence the structural integrity of the ship in the event of a marine casualty.

The shipping industry needs to be cautious about global warming issues not only from an emissions perspective but also because it will aggravate other environmental factors such as wind speeds and wave heights. Increase in storm activities in terms of its intensity, duration, change in storm tracks and increased frequency of rogue or freak waves have been reported in certain ocean regions and have been a matter of interest in the last few years in academia and in the maritime industry. Although rogue waves are not directly related to climate change it is more of a secondary effect resulting from the primary effect of climate changes i.e. increase in storm activity in terms of its intensity, duration and wind factor, and storm track changes (Bitner-Gregersen *et al.* 2014).

The global fleet has more than doubled in the last few decades and with the decline in volume of trade as a result of recession due to drop in crude oil prices, it is very likely that many of the ships are going to be ill-maintained in an attempt to save costs by the ship owner. In such circumstances even a small scale casualty involving such ill-maintained ships in an ecologically sensitive area can have catastrophic consequences.

Ships operate in a highly corrosive environment and are subject to adverse weather conditions during its operations. As the ship ages, the structural members are influenced by the operating conditions and the original strength of the ship structure is gradually lost. The integrity of the side shell structure is critical to the safety of the ship as not only does it contribute to the shear strength of the hull girder but also forms the outermost boundary of the ship preventing ingress of sea water when the hull is subject to waves and dynamic loading during heavy weather.

Given these issues, there appears to be a need to focus on technical aspects pertaining to the design, construction and maintenance of ships. One such engineering issue identified in this study which affects the strength of ships in the context of marine casualties is HHD, individually and along with corrosion. A forensic engineering investigation approach is formulated towards an analysis of this issue in this study.

## 3.2 LITERATURE REVIEW

### 3.2.1 Environmental Impact

Soares *et al.* (2003) have reported on extreme wave heights close to 20 m and above recorded on 1st Jan 1995, and 10 m and above recorded on 27th November 1997 in the North Sea region. Extreme waves have known to cause severe marine casualties, notably, the loss of bulk carrier *Derbyshire* that was presumably overcome by large waves during typhoon Orchid, and of *MSC Napoli* which developed cracks in the side shell structure near the engine room area as a result of being pounded by 9 m high waves in 2007 (Kery 2012b).

Gulev and Grigorieva (2004) have used the global visual wave data taken from International Comprehensive Ocean-Atmosphere Data Set (ICOADS) along the major ship routes to demonstrate that there is a positive increase in Significant Wave Height (SWH) over the North Pacific (based on 100 year period) and North Atlantic area (based on 50 year period).

Studies on the North Atlantic Ocean wave climate by Wang *et al.* (2004) have projected an increase in both the mean wave height and SWH during the winter and fall season in the Northeast Atlantic Sea in the 21$^{st}$ century. The Generalized Extreme

Value (GEV) analysis performed by them indicate that global warming effects may lead to changes in the size and frequency of extreme wave height events and both the marine and offshore industry should take these aspects into consideration during the design, planning and operations phase.

Khon *et al.* (2014) have reported about the general increasing trend of wave heights in regions over the Arctic Ocean over the last few decades and of the lack of information on earlier wave heights since this area was usually ice covered and the waves were not visible. Global warming has resulted in a substantial retreat of this ice. On a positive note this newly open sea provides a new trading route and opportunities for oil and gas exploration but it also comes with certain unpredictability of the risk involved due to waves and storms in these areas. Though designed to much stringent requirements, ships navigating in these areas still remain at peril because of the unknowns.

Based on the General Circulation Model (GCM) and Global Wave model computation, Mori *et al.* (2010) have projected changes in the future ocean wave from the present. They have concluded that wave heights will increase in the Antarctic Ocean and at both middle latitudes with a decrease in the Equator region. Further, extreme waves due to tropical cyclones are only going to increase in the future. Their findings indicate that there is a clear latitude dependence on average wave height in future and that the future daily wave climate will have a lower mean in the middle latitudes and a higher mean wave height in the higher latitudes and Equator region.

Based on their study on the impact of climate change on extreme wave conditions in the North Sea, Grabemann and Weisse (2008) have concluded that towards the end of the 21st century wave heights may increase by 0.25 – 0.35 m in large parts of the southern and eastern North Sea with an increase in frequency of severe sea states.

Young *et al.* (2011) have investigated the global changes in oceanic wind speed and wave height over a 23 year period from the database of Satellite Altimeter measurements. Their study reported that globally, the increase in wind speed is more significant than wave height for the period under consideration and the increase of extreme events is going to be a lot more when compared to the mean condition. In these extreme conditions there is a strong possibility of increase in wave heights at high latitudes.

Vanem *et al.* (2014) have reported that classification rules which are to deal with the environmental loads acting on the ship during its lifecycle are developed based on the historical observations of metocean conditions and argue that such an approach is no more representative of the future conditions given the present climate change perspective. They have investigated the possible impact to ship safety as a result of potential climate change on the ocean waves especially with respect to wave induced bending moment in the North Atlantic Ocean. Based on one of the modelling approach adopted by them in their study, an increase of 1.47 m to 2.08 m (10.2% to 14.4%) in the significant wave height at the end of the century based on the 20 year return levels is expected. Correspondingly this figure is 1.62 to 3.04 m (9.7% to 18.1%) for a 100 year return period. Such an increase can potentially influence the structural loads and safety of the ship, based on current designs. Their study indicates an approximately 10% increase in the wave induced bending moment as a result of increased wave height towards the end of this century. It also highlights additional challenges imposed on the ship hull structure as a result of fatigue damage and slamming impact.

Bitner-Gregersen *et al.* (2014) have reported the dependence of the shipping industry (including classification societies) on the Global Wave statistics (GWS) Atlas data which were published in 1986 and are based on lower wave heights. It is based on this data that ships are still currently designed and appears no longer a representative of the present climatic conditions, given that the world has seen major climatic changes as a result of global warming in the last few decades. They caution against the use of this data anymore since it has not been updated after it was published in 1986. The recording over the last many years has been lost and given the studies that indicate the wave height to be changing since the middle part of the 20th century and early 21st century with increase noted in the North Atlantic and North Pacific Ocean while decreasing in the southerly latitude of Northern Hemisphere. They report that an increase of 0.5m in the SWH in the North Atlantic Ocean will have a large impact on the present tanker designs.

In IACS (2000), the standard wave data for the design of ships carrying goods at sea are published based on the GWS data of 1986.

### 3.2.2 Impact of Ship Age on Marine Casualties

Psaraftis (2006) has contested that ship age should not be a criterion linked to safety as it is also influenced by how well the ship is maintained. It is possible that older and better maintained ships may be safer than younger ill maintained ships and hence no mandatory age limit should be imposed for ship decommissioning. Statistics of marine casualties versus ship age presented in his study indicate a steady increase in casualty frequencies as the ship gets older, with the maximum casualties recorded for the age group between 15-19 years. It also reports of a considerable number of casualties involving younger ships in the age group between 0-4, 5-9 and 10-14 years.

The highest percentage of marine casualties involving Suezmax and VLCC-ULCC is in the age group of 11-15 years, closely followed by these ships in the 16-20 years age group as reported by Eliopoulou and Papanikolaou (2007). Casualties have also been reported for these tankers in the age group of 0-5 and 6-10 years, however not as significant as the earlier two age groups.

Papanikolaou and Eliopoulou (2008) have investigated the impact ship age has on marine casualties based on data involving tankers greater than 60,000 DWT for the period from 1990-2007. Their investigations did not provide a clear indication relating the age of vessel to marine casualties other than the frequency of casualties related to collision, allision and grounding increases when the ship turns 15 years and older. On the contrary, they found that there was a high frequency of collision and grounding type casualties for tankers in the 0-5 years age group, much more than the other age groups.

The statistical analysis of marine casualties involving oil spills in the Mediterranean based on the age of the ship in REMPEC (2011) indicates a majority of the ships (31%) in the age group of 16-25 years to be involved in casualties. This is followed by ships in the 26-35 years and 6-15 years age group accounting for 22% and 18% respectively. During the period 1977 – 2010, the average age of the ship involved in a marine casualty was noted to be 17.7 years. Their study does not fully agree to link the age of the ship to the possibility of occurrence of a casualty as some of the ships involved in major marine casualties were not so old. On the contrary it was found rather important to link the level of maintenance corresponding to the age of the ship.

Their study also reported of similar results for ships involved in marine casualties leading to release of hazardous and noxious substances.

WWF (2013) have reported ships over 10 years old with other risk factors more likely to be involved in a shipping casualty. Butt *et al.* (2013) have analysed data on ship losses based on the average age of the ship for the period 1997 to 2011 and found the average age to be above 20 years and this has been steadily increasing since 1997.

An increasing trend in NASF casualty type has been reported for SUEZMAX and AFRAMAX type oil tankers in the age group 11-15 years by Primorac and Parunov (2016). Insufficient maintenance as the vessel is nearing its economic life of 20 years was one of the reasons attributed to this trend. Their study also reported of younger aged Double hull tankers (0-5 years) during the period 1990-2007 showing remarkable structural failures during rough weather, which clearly were not attributable to maintenance issues.

Frequency of marine casualties with respect to vessels age and cargo ship type is captured by Eliopoulou *et al.* (2016). They report of General cargo ships, bulk carriers and car carriers of all age groups (0-20 years) frequently being involved in casualties. As the age crosses 20 years, bulk carriers and car carriers show an increased frequency for casualties when compared to other ship types. In the age group of 0-5 years, ro-ro ships, general cargo ships and car carriers show significantly high frequency for casualty occurrence and they attribute this to the quality problems associated with building them in cheap yards.

### 3.2.3 Influence of Substandard Ships, Substandard Owners and Irresponsible Flag States

Mandryk (2011) has reported that the East Mediterranean and Black Sea region accounts for higher cases of collision, allision and grounding casualties when compared to Australasia region and has also overtaken the North Europe and Asia region despite having a low level of shipping activity. The number of serious casualties in this region has shown a gradual increase during the period 2006 to 2010 and he attributes this to an increase in the presence of substandard owners, bogus registries and substandard class ships operating in these areas along with an elderly age profile.

Butt *et al*. (2013) have highlighted how some of the flag states adopt a minimum number of international conventions to remain competitive and attractive to ship owners. Such actions of these flag states defeat the very purpose of having enacted various international standards aimed at the safety of the seafarers and the environment.  Their report provides statistics of flag states involved with the highest detention rates for the period 2009-2010 and which also indicates cargo ships to account for the highest detention rates by vessel type for the period 2009-2011. Their report also mentions of older vessels i.e. 20 years and above, being forced to migrate to a different geographical area of operation i.e. Black Sea and Far East Asia, and take up registries with black listed flag states as the IACS members refuse to class these vessels which are assumed to be more vulnerable to casualties. Similar to this, when it comes to classing vessels with substandard flag states, Psaraftis (2006) has highlighted the reluctance of IACS Class societies to class these ships citing retaining their share of business as more important than ensuring maritime safety.

Almost 35% of the total number of ships are associated with flag states that have been black listed in atleast one of the MoU i.e. Paris MoU, Tokyo MoU and US Coast Guard, according to Equasis (2015). Around 29% of the ships in number, above 500 GT are classed by non IACS members or have no record of any class being accorded to them, amongst which cargo ships make the bulk. Furthermore their statistics indicate that older vessels i.e. 25 years and above, are more likely to be non IACS classed.

Clayton (2015) have reported on how Flag states circumvent the minimum manning levels required in accordance with MLC and approve reduced manning levels to remain competitive in market. One of the purposes of MLC was to address fatigue issue of the ship crew and guidelines were formulated in this regard specifically addressing manning and rest periods.

### 3.2.4 Hungry Horse Deflection (HHD)

#### *3.2.4.1 General*

Kery and Garzke Jr. (2012b) have referred to the hungry horse phenomenon as dished in plate deformations on the individual plate panel between transverse and longitudinal stiffeners revealing the backing structure. The deformed structure bears resemblance to the ribs on a starving horse and such deformations or deflections are as a result of wave induced damages on the ship side shell structure encountered during storms and rough weather. Fig. 3.1 and fig. 3.2 are pictures showing HHD on the side shell structure of cargo ships.


**Fig. 3.1: HHD on the Starboard Side Shell Plating**

(*Source*: http://worldmaritimenews.com/archives/135758/baltic-aframax-rates-nosediving/ accessed on 21 September 2017)

**Fig. 3.2: HHD on the Port Side Shell Plating**

(*Source*: http://www.baesystems.com/en-aus/download-en-aus/multimediaimage/webImage/ 20151116083025/1434554672290.jpg accessed on 21 September 2017)

A schematic representation of HHD of plating between the stiffeners is illustrated in fig. 3.3.

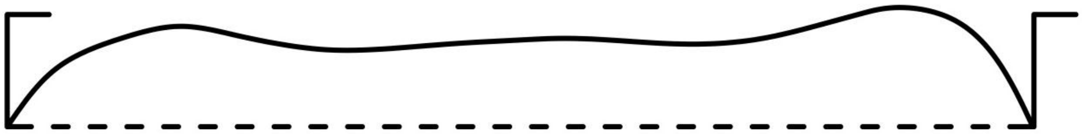

**Fig. 3.3: Schematic Representation of Hungry Horse Shape Deflection**
(Source: Jiang and Soares 2013)

A partial 3-D view of HHD of plating between the stiffeners is shown in fig. 3.4

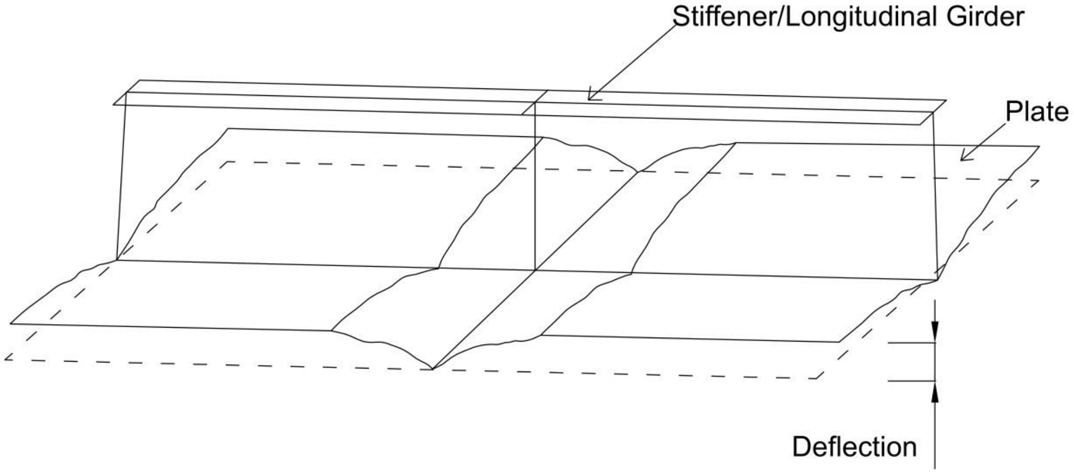


**Fig. 3.4: Partial 3-D View of HHD**

(*Source:* Masaoka and Mansour 2008).

### 3.2.4.2 Survey and Inspection Requirements for HHD

Guidelines on the structural inspections to be carried for 'new ship', 'existing ship' and 'existing ship with initial damages', during construction and repairs are outlined in ASTM (2004). Inspection for fairness of plating between stiffeners is highlighted as one of the checks to be performed. The permissible deflection or deviations acceptable for ships under construction and in service are however not provided.

The unified requirements in IACS (2016b) for hull classification surveys have specified the schedule and scope of the annual, intermediate and special surveys for all self-propelled vessels. The survey requires repairs to be promptly done when damages or wastages are over the allowable limits and in the opinion of the surveyor impairs the structural strength or watertight integrity of the vessel. Such damages or wastages could include buckling, grooving, detachment, corrosion or fracture. Additional survey requirements depending on the ship types are provided under various sections of this document. There is no requirement specified on the permissible deflection limits for the side shell plate between stiffeners in this document.

The recommendations presented in IACS (2016a) for the Surveys, Assessment and Repair of Hull Structure for General dry cargo ships provide procedures for the surveyor of IACS member societies and other regulatory bodies to carry out survey assessment of the hull structure. Ships in service undergo periodical surveys by classification societies and other regulatory bodies to detect possible structural defects and damages and to establish whether the extent of deterioration impairs the safety of the ship. To facilitate such inspections, the damages that can be sustained in different areas of the ship hull structure other than due to a marine casualty are highlighted with no specific requirement on the permissible deflections limits of the side shell plating between stiffeners. Guidance is also provided to the surveyor for inspection and identification of probable causes for damages and on the repair methods available to rectify it.

The deficiencies recognized in IACS (2016a) for the ship hull structure are categorized into three, namely: material wastage, fractures and deformations. All of these are likely to manifest during the normal course of operation of the ship and not necessarily as a result of collision or grounding casualty type. In this guide, material wastage is attributed to corrosion; fracture to stress concentration at weld defects, flaws and fatigue; and deformations to impact loads i.e. bottom slamming or wave impact force, navigation in extreme weather conditions, allision, inadvertent overloading, etc. The areas in the hull structure which need to be inspected for deformations is provided along with the repair work required to restore it to its original shape and position based on the depth and extent of deformation. However no specific information is provided on what depth or extent of deformation is permissible and it is left to the judgement of the attending surveyor to decide whether rectification or replacement is required.

Along very similar lines, IACS has also issued Guidelines for the Surveys, Assessment and Repair of Hull Structure for bulk carriers (IACS 2004), for container ships (IACS 2005) and for Double Hull oil tankers (IACS 2007). In these guidelines as well, the deficiencies recognized are material wastage, fractures and deformations followed by comprehensive written and figurative details of the areas to be inspected and the corresponding repair work to be carried out for different cases. Here also there is specific information provided on what depth or extent of deformation is permissible and it is left to the judgement of the attending surveyor to decide whether rectification or replacement is required.

The Shipbuilding and Repair Quality Standard (IACS 2013) has provided guidance on shipbuilding quality standards for the hull structure for new constructions in part A and for existing ships undergoing repair works in part B. For new constructions, specific requirement is provided for the fairness of plating between the stiffeners and is specified not to exceed 8 mm for the parallel and fore and aft part of the side shell plating. Figure 3.5 represents the requirements in IACS (2013) and deflections of such nature arising in new constructions are as a result of the welding process or fabrication issues. The same requirements are also applied in IACS (2016c) and the classification rules in ABS (2007) and DNV-GL (2017), which refers to IACS (2013) for shipbuilding quality standards of the hull structure for new constructions. For repair works of ships in service, recommendations are made to check the alignment of the side shell plating but without any specific guidelines on the permissible deflection limits.

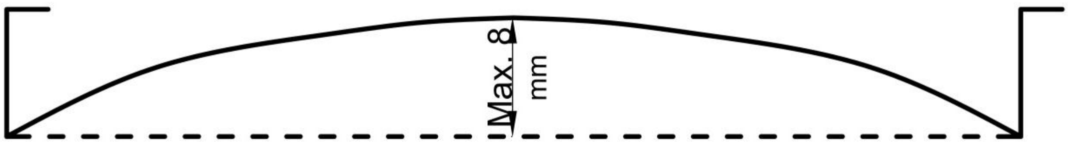


**Fig. 3.5**. **Buckling Shaped Deflection of Plate between Stiffeners**
(*Source*: IACS (2013))

### *3.2.4.3 Influence of Dents and Deformations on the Strength of Rectangular Plates*

Dow and Smith (1984) have investigated the behaviour of rectangular plates having various forms of initial deformations under compressive loads. They have identified fourteen such forms of initial deformations along with analytical formulae to calculate the deflection values. They concluded by highlighting that the amplitude of the initial deformation is the governing factor and less dependent on the shape and position of the deformation along the length of the plate.

Ueda and Yao (1985) have investigated the effect of welding induced initial imperfections on the ultimate strength of rectangular plates in compression and two methods have been proposed i.e. deflection method for thin plates and the curvature method for thick plates to determine it. The amplitude of the welding induced deflections were recorded from 33 plate panels of ship plating for the purpose of their study and the coefficients of the initial imperfections expressed in sine series have been calculated.

The effects of the shape, size and location of dent on the ultimate strength of an already deformed or imperfect steel rectangular plate subject to axial thrust has been investigated by Paik *et al.* (2003). A non-linear FEA is carried out on a rectangular plate subject to axial compressive forces and indented with a spherical and conical shape indenter. The initial imperfection in the steel plate is buckling shaped and as a result of welding operations. The significant findings of this study was that larger is the dent diameter, more is the influence it will have in reducing the ultimate strength, while the shape of the dent does not have much influence on the ultimate strength. Also the location of the dent near the unloaded edges has a more profound effect in ultimate strength reduction when compared to the dent being located at the centre of the plate.

Paik *et al.* (2004a) have investigated the effect of initial deflection shape on the plate collapse behaviour under biaxial compressive loads. Different initial deflection shapes were considered in their investigation, one of which represented the hungry horse shape (fig. 3.3) and is characterised by a steep deflection gradient along the shorter edges when compared to the buckling shape (fig. 3.5). The ultimate strength of the plate with the HHD was found less than the buckling shaped initial deflection and they attributed this to the influence of the particular deflection shape. One major contribution of their study was providing the initial deflection amplitude values for plating between stiffeners when the relevant initial deflection measurements are not available. Corresponding to the shape of the deflections identified in their study, the amplitude values have also been specified.

The influence of asymmetric and symmetric imperfections in adjacent plates on the strength of a single plate using non-linear FEA has been investigated by Luis *et al.* (2008a). In their study, the amplitude of the imperfection is varied and the shape kept constant. Varying of the amplitudes of the imperfections in the adjacent plates provide intermediate strength. Their study concluded that as far as the strength of the plate is concerned, the slenderness ratio is more critical than the shape i.e. symmetrical or asymmetrical, of the imperfections in the adjacent plates. The maximum collapse strength values obtained for symmetrical shaped imperfections may reverse and become minimum collapse strength values as the slenderness ratio is increased. In the case of asymmetrical shaped imperfections, the collapse strength values were low for all cases of slenderness ratios. A comparison of plate models with 3 and 5 plates transversely connected was made to assess the influence on the ultimate strength on a single plate, and the results did not indicate any significant difference.

Jiang and Soares (2013) have compared the effects of the hungry horse shape and buckling shape initial deflection on the ultimate capacity of a pitted corroded rectangular plate subject to biaxial compression using non-linear FEA. In their study, the geometrical attributes of the pit and the slenderness ratio of the plate were modified to ascertain any relationships. The hungry horse shape modelled in their study was based on the amplitude values specified in Paik *et al.* (2004a) and different from the buckling shape typically associated with post welding operations. Their study revealed that the hungry horse shape deflection resulted in lower ultimate strength values when compared to buckling shaped initial deformations, keeping all other influential parameters constant. Their study also highlighted the influence of plate slenderness and pit intensity on the ultimate strength values and concluded that the ultimate strength of both intact and pitted plates was greatly influenced by the initial deflection shape.

A non-linear FEA to predict the behaviour of a rectangular plate with and without local deformations and subject to uniaxial compression has been performed in Saad-Eldeen *et al*. (2015). The initial imperfection was modelled as a half sine wave with its amplitude varying between 1.7 mm to 8.5 mm for varying plate thickness. Their study concluded that increasing the plate thickness reduces the effect local dent depth has on the ultimate displacement and ultimate strength. For thin plates, local dents were found to affect the ultimate strength while global initial imperfections dominated the post collapse behaviour. Increasing the plate thickness reduced the above effects.

Saad-Eldeen *et al.* (2016) have also investigated the ultimate strength, global behaviour and collapse mode of a highly damaged rectangular steel plate with initial imperfections and local permanent indentations. A non-linear FEA is performed to analyse the effect of depth of the local dent of hemisphere, cubic and prismatic shape on plates with different thicknesses. In the case of thin plates, the initial imperfections due to post welding induced dominated the post collapse behaviour and the local dents i.e. as a result of dropped objects etc., affected the ultimate strength values. As the plate thickness is increased the influence of local dent depth on the ultimate strength decreases. Between the three shapes selected for the analysis, the cubic shape presented lower ultimate strength values for all plate thicknesses and dent sizes.

#### *3.2.4.4 Influence of Dents and Deformations on the Strength of Stiffened Panels*

The effect of imperfections caused due to casualty damage i.e. dimple imperfections, on the ability of a globally deformed plate assembly to resist compressive loads using non-linear FEA has been investigated by Luis *et al.* (2008b). Their studies highlight that the effect of the collapse strength is significant based on the amplitude and location of the dimple imperfections. The plate slenderness ratio is also found to be a governing factor which enables the plate assembly to resist the compressive loads. The global deformations were modelled as half sine curve representing a buckled shape deflection.

Sadovsky *et al.* (2005) have investigated the influence of initial deformations obtained from the database of measurements of stiffened panels for ships for evaluating whether the amplitude or energy measure is governing factor for initial deflections of thin rectangular plates subject to longitudinal compression. The initial deformations represent the post welding induced deflections and are of a half sine wave shape. The study concluded that the amplitude to thickness ratio approach yielded a much lower theoretical collapse load when compared to the energy measure system. However they go on add that adopting the amplitude to thickness ratio approach can lead to an overly conservative design.

The advantage of using a numerical analysis approach when compared to the analytical and experimental methods, to calculate the compressive ultimate strength of stiffened panels with initial imperfections has been highlighted by Masaoka and Mansour (2008). Three kinds of initial deflections i.e. stiffener tripping, column buckling and hungry horse have been considered in their analysis. Their investigation using non-linear FEA indicated that the ultimate strength of stiffened plate panels is not influenced by HHD and the results derived are contrary to the findings by Jiang and Soares (2013). This could be because of a low deflection range which does not exceed the plate thickness being considered in the analysis with no mention the shape parameters for the HHD.

Witkowska and Soares (2015) have investigated the ultimate strength and compressive behaviour of locally damaged plate panels with buckling shaped initial deflections or deformations which are post welding induced, using non-linear FEA. The welding induced initial deformations of symmetric and asymmetric shape are also considered. Their analysis concluded that local damage on an already imperfect plate panel reduces the load carrying ability of the panel and, the panel geometry and damage characteristics such as location, size and depth of the dent imperfections influence the magnitude of load carrying ability. Similar to the findings by Luis *et al.* (2008a) this study also reports that the increase in slenderness ratio i.e. above 2, changes the ultimate compressive strength from maximum to minimum values when symmetrical shape imperfections are considered. A comparison of the results based on a single rectangular plate, a single span model and a 3 x 3 span model is also analysed and reported.

Liu *et al.* (2015) have experimentally and numerically investigated the energy absorbing mechanism of an intact and initially damaged stiffened plate specimen that is subsequently quasi-statically punched at the midspan by a rigid wedge shaped indenter. The experimental results are validated by numerical results using a non-linear FEA. Their study highlights that the initial imperfection does not change the global plastic deformation and both the intact and initially deformed specimen experience similar failure modes despite the initial force-displacement behaviour being different.

#### *3.2.4.5 Influence of Dents and Deformations on the Strength of Square Plates*

Raviprakash *et al.* (2011) have investigated the effect of various dent parameters such as dent length, width and depth on the ultimate strength of a square thin plate with longitudinal and transverse dents under uniaxial compression. Their studies indicate that the dent affected region does not contribute to the load carrying capacity of the dented plate, when axially compressed from one side. Their studies concluded that the transverse dents are sensitive to dent length and dent depth, and the load carrying capacity of the dented plate depends on the plate area minus the area of dent affected region.

They have further investigated the effect of dent orientation and the nearness effect of two dents on the ultimate strength of an intact square plate in Raviprakash *et al.* (2012). They conclude that there is no substantial reduction in the ultimate strength between a single dent and two dent cases. Furthermore effect of dent orientation on the ultimate strength is more prominent for transverse dents when compared to longitudinal dents.

In both these studies, a square plate with no initial deformations were considered for analysis of dents on the ultimate strength values.

### 3.2.5 Corrosion

#### *3.2.5.1 General*

Paik and Thayamballi (2007) have referred to the degradation of metals in the marine environment as marine corrosion. It is considered as one of the age related deteriorations which results in the failure of the ship, including its total loss. Corrosion directly impacts the safety and integrity of the structure. Their study broadly discusses the various types of corrosion i.e. general or uniform, pitting, grooving, weld induced etc. that manifest in the hull structure; the corrosion process with and without coating protection; the corrosion rates at various locations; and the inspection methods available to ascertain the material wastage.

Corrosion is defined as the “chemical or electrochemical reaction between a material, usually a metal and its environment that produces a deterioration of material and its properties, usually an oxide is formed” in IACS (2003). General or Overall corrosion is defined in IACS (2003) as one which “appears as non-protective, friable rust of a uniform nature on uncoated surfaces” and subject to corrosive attack each time the rust scale breaks off exposing fresh metal surface. The degree of corrosion is divided into three categories viz. Minor or Insignificant corrosion, Substantial corrosion and Extensive corrosion. It defines Minor corrosion or Insignificant Corrosion as “an extent of corrosion with minor spot rusting and such that an assessment of the corrosion pattern indicates wastage generally not exceeding of 30% of the allowable corrosion limits”; Substantial corrosion as “an extent of corrosion such that assessment of corrosion pattern indicates wastage in excess of 75% of allowable corrosion, but within allowable corrosion limits” and Extensive corrosion as “an extent of corrosion consisting of hard and/or loose scale, including pitting, over 70% or more of the area under consideration, accompanied by evidence of thickness diminution”.

The corrosion mechanism for steel plates is classified as general wastage and localized wastage by Saad-Eldeen *et al.* (2012a). In the case of general wastage there is a decrease in plate thickness which is not necessarily uniform and in the case of localized wastage, the local areas undergo extensive damage and are commonly referred to as pitting corrosion.

Garbatov and Soares (2011) have divided corrosion degradation into three phases, starting with no corrosion as a result of the protective coating, the second phase involves initiation of corrosion as a result of damage or deterioration of the protective coating and results in decrease in thickness of the plate and finally the last phase corresponds to a stop or reduction in the corrosion process when the corrosion rate becomes almost zero.

#### *3.2.5.2 Inspection for Corrosion in Ships in Service*

IACS (2016a) have highlighted material wastage due to corrosion as one of the issues to be inspected during surveys and it identifies the suspect areas where substantial corrosion can take place and is prone to rapid wastage. During inspection when it is found that the side shell structure is significantly weakened by loss of thickness due to corrosion to the permissible minimum thickness, the area is to be cropped and renewed. An option to extend the renewal to the next major survey shall be based on whether there will be sufficient corrosion margin till then based on the present inspection findings.

Similarly, IACS (2004; 2005; 2007) have identified material wastage or corrosion as one of the recognized deficiencies in ships which is to be inspected during the periodical surveys. General corrosion, pitting corrosion and grooving corrosion are the forms of material wastage encountered in ships. The suspect areas where there is a likelihood of substantial corrosion and prone to rapid wastage are identified in these IACS documents for the various regions of the hull structure.

In ABS (2016b), a simple procedure to calculate the material wastage has been developed to determine under which severity category it falls under. Where extensive corrosion is reported during inspections, it has specified the need for the individual plates or structural members to be cropped and renewed and provides the requirements to be complied to for such activity. In the case of substantial corrosion, areas identified to have this may be subject to additional surveys and examination in accordance to the requirements in the rules as well as have the thickness measured during the subsequent periodical surveys.

In part B of IACS (2013), guidance on quality of permanent repairs of the hull structure of ships in service including the typical repair methods are covered. Where renewal of plating is required for areas with excessive corrosion, guidelines for the welding sequence of inserts, material grade, alignment, weld finish, Non-Destructive test requirements are specified here. Similarly the welding requirements for removing pitting corrosion are also specified.

#### *3.2.5.3 Influence of Corrosion on Ship Strength*

The ultimate shear strength of corroded steel plate elements under in-plane shear loads have been investigated by Paik *et al.* (2004b) and found significant reduction in the ultimate strength values for plate elements with general corrosion and pitting corrosion.

Saad-Eldeen *et al.* (2012a) have investigated the effect of corrosion degradation on the ultimate strength of the steel box girders. The study found corrosion to reduce ultimate strength values and influence the mechanical properties of steel in addition to reduction in thickness. A similar finding was reported by them in Saad-Eldeen *et al.* (2012b).

For modelling of general corrosion in the finite element model, two approaches have been followed by Saad-Eldeen *et al.* (2012b). In the first case they have modelled the corrosion degradation as an average thickness reduction on the plate and in the second case the real thickness measurements are input at the nodal locations on the finite element model. Their study revealed no significant difference in the ultimate strength if the corrosion degradation is modelled either ways.

Jiang and Soares (2012a) have investigated the effect of corrosion pits on steel plates under uniaxial compression and reported of volume loss dominating the decrease in the compressive capacity of the pitted steel plates. The plate slenderness ratio was found to govern the collapse modes of the plate. The deterioration in the ultimate compressive strength of the plate was found to be more severe for the case where the distributed pits were on one side of the plate compared to the double sided pits with the same total thickness reduction.

Following their earlier study under uniaxial compression, the effect of pitting corrosion on the ultimate strength of steel plates under biaxial compression has been investigated by Jiang and Soares (2012b). Their study found plate slenderness to have a considerable influence on the biaxial interaction curves, and volume loss and loading ratios to have a significant effect on the remaining strength of the plates.

Saad-Eldeen *et al.* (2013) have investigated on the strength assessment of aged box girders with corrosion deterioration matching 0.2 year, 17.9 years and 23.3 years respectively. Their study revealed a substantial reduction in the ultimate bending moment and the load carrying capacity of the box girders to the extent of 32.8% and 64.6% respectively when compared with the initially corroded plate matching 0.2

years corrosion deterioration. In addition to reduction in thickness, corrosion also influenced the mechanical properties of the material.

Jiang and Soares (2013) have investigated the effect of initial deflections both thin horse shape and buckling shape on the ultimate capacity of plates with pitting corrosion under biaxial compression. Their study found a significant influence of the initial deflections due to thin horse shaped deflections on the ultimate strength of the pitted plates and attribute this to the deflection facilitating the collapse of the plate, which is further exaggerated by the corrosion effect.

### 3.2.6 Forensic Engineering and Marine Casualty Investigations

#### *3.2.6.1 Forensic Engineering - Definition*

The origin of the word Forensic comes from the latin word forensis meaning “in open court, public”. It is defined by the Oxford English Dictionary as “relating to or denoting the application of scientific methods and techniques to the investigation of crime” (OED 2017). The Merriam–Webster dictionary defines Forensics as “belonging to, used in, or suitable to courts of judicature or to public discussion and debate” and also defines it as “relating to or dealing with the application of scientific knowledge to legal problems” (Merriam-Webster 2017).

Noon (2001) has defined forensic engineering as “the application of engineering principles, knowledge, skills, and methodologies to answer questions of fact that may have legal ramifications”. In this definition, “questions of fact” refers to issues with respect to the casualty. The application of scientific and technological methods in the evidence collection and analysis phase is what distinguishes forensic engineering investigations from other investigative methods, which focus on organizational issues, management issues and human errors.

Carper (2001) has cited the definition of Forensic Engineering from Specter (1987) as “the art and science of professional practice of those qualified to serve as engineering experts in matters before courts of law or in arbitration proceedings”, and he defines a forensic engineer as “a professional engineer who deals with the engineering aspects of the legal problem”. During the course of these investigations, product or procedural deficiencies can be found which could extend beyond the investigation scope. One of the highlights of such investigations is the opportunity that the forensic engineer derives in making recommendations based on the findings made.

According to Smith Jr. and Schmidt, Jr. (2012) “Forensic engineering is the use of engineering skills and fundamentals involving matters that are more likely to become the subject of a dispute to be resolved in a court of law or other similar forum. If there is a loss of significant value any subsequent investigation of that loss by an engineer can be considered forensic engineering”.

The role of forensics in engineering is elaborated by Thompson (2012) as “Forensic in engineering primarily deals with the investigation of materials, products, structures or components that fail or do not operate as functionally intended thereby causing personal injuries/ loss of lives, loss of property or damage the environment”. According to him, forensic engineering is performed with the intent to establish the root cause of failure which will lead to improvement in the performance or life of a component and prevent future occurrence of similar failures.

#### *3.2.6.2 Characteristics and Phases of Marine Casualty Investigations*

A very detailed literature on forensic engineering investigations has been documented by Noon (2001) in which such investigations start with the end result of a casualty and evidence is gathered to ‘reverse engineer’ how the failure occurred. He highlights the subtle difference between forensic engineering, failure analysis and root cause analysis and how these words are at times used interchangeably. While failure analysis focuses on the part or component that failed and is concerned with material selection, design issues etc., root cause analysis ascertains the managerial aspects of the failure. He also highlights the multidisciplinary approach to forensic engineering based investigations as various scientific techniques and technologies are used to elucidate a result and findings of one or a set of analysis from one discipline could be the input for another. The investigative process is illustrated as an investigative pyramid where a substantial portion of the pyramid bottom is dedicated to verifiable facts and evidence and is considered the most important step. This is followed by an analysis phase of the evidence collected and with conclusions at the apex of the pyramid.

Noon (2001) also discusses the ‘singularity’ of casualties in investigations based on forensic engineering as the finding and methods developed during the investigation cannot be used over and over again. This impacts the cost of the investigation. He also reports of the possibility of the casualty itself destroying the evidence and the loss of the defective part amongst the casualty debris.

An informative article describing the investigation process, skill set and knowledge required to complete a forensic engineering based investigation is detailed by Smith, Jr. and Schmidt, Jr. (2012). They outline the investigative steps aligned to the engineering requirements and procedures in the event of formal court proceedings. They propose the investigation to follow a logical sequence following scientific methods, and point out that the success of the investigation depends on the “degree to which the party efficiently receives the information it needs and is able to act in its own best interest based on that knowledge”. They provide the technical competencies required of the investigator for investigating different types of marine casualties. The role of the investigator is defined as one seeking to find the root cause of the casualty and who wishes to communicate the findings so that the occurrence of this casualty is not repeated.

ABS (2005) elaborately discusses the various steps involved in a marine casualty investigation. Once the investigation is initiated, the sequential steps include gathering and preserving the data, analysing the collected data, identifying the root causes and developing and reporting recommendations. Upon completion of the investigations it also provisions whether a detailed analysis is to be performed and proposes the ‘learning potential’ as the basis for selection. *Very serious* and *serious* severity casualties happen in small numbers but offer high potential for learning the mistakes made and the use of pareto analysis for this selection purpose has been proposed in this ABS document.

According to Carper (2001), forensic engineering need not always be directly related to legal issues and the principal purpose of it can also be to determine the causation so as to prevent the future occurrence of a casualty for the same reasons. Conducting of a forensic investigation typically fosters a sense of fear in the other party that it is being conducted to proceed for litigation purposes. Sometimes this fear allows for an easy negotiated out of court settlement and hence many cases do not see litigation. Carper provides a detailed list of qualifications of the forensic engineer first amongst which is technical competency i.e. in the relevant specialized engineering discipline. Qualities such as knowledge in legal procedures, detective skills, oral and written communications and high ethical standards are the other required qualifications. He outlines data collection and information dissemination as one of the important steps to the success of the investigation and emphasizes the role of forensic engineer in doing so in an accurate and complete manner.

The subtle difference between forensic and a failure investigation has been highlighted by Thompson (2012) given that both types of investigations retrace the processes and procedures leading to the casualty. According to him, forensics refers to investigations from a legal perspective. If the intent of investigations is to reveal the management actions which contributed to the casualties, a root cause analysis can be performed. He further highlights the process of investigating and collecting data related to the failed component and proper documentation of the collected evidence, records and documents as essential for a forensic engineering type of investigation.

Kery and Garzke Jr. (2012a) argue that the Guidelines for Marine Forensic Investigations developed by Society of Naval Architects and Marine Engineers (SNAME) are aimed to identify remedial measures that mitigate the future occurrence of similar casualties and also assist in litigation purposes. They highlight the shortcomings of the investigative procedure in ABS (2005) and IMO (1997) from a forensic investigation perspective. It finds ABS (2005) document more aligned to finding the root cause of the casualty while IMO (1997) focuses on the legal responsibilities of the member states and who is responsible for the investigations depending on where the casualty occurred etc. However, the checklist of items listed for data gathering in IMO (1997) is comprehensive and very useful according to them from a forensic investigation perspective. The steps involved in conducting the forensic investigations in the SNAME document extend to ship wrecks as well. Hence, in addition to activities such as data gathering, regulatory and classing data, interview of witness, there are also additional steps involving ascertaining the ship cargo, its destination and sailing port to ascertain the use of consumables such as fuel oil and other perishables etc., lifting of parts and handling and preservation of evidence before the actual analysis of the casualty is initiated etc. From a forensic analysis perspective, they highlight the need for the casualty investigator to identify the primary damage and the subsequent secondary damages.

Kery (2012a) has reported of the involvement of various parties and disciplines to illustrate the multidisciplinary aspect of forensic investigations for a casualty where a vessel was lost due to structural failure. The designers and the ship operators will be involved to determine design flaws, insufficient design strength, and/ or unexpected loads. The metallurgist would be concerned with the properties of the material used and its weaknesses. The shipyard will be concerned with any deficiencies in the construction practice which did not realize the required strength.

Strauch (2012) has discussed on the investigation process followed at National Transportation Safety Board (NTSB) for marine casualties. Data collection is the first step and includes recording of the casualty, eye witness account, data from voyage data recorder etc. This is followed by an investigative phase where expertise from operational and engineering specialist is taken to aid in the investigation. Finally the findings are reported with recommendations. The investigative process is demonstrated for the casualty investigation involving the allision of containership *M.V Cosco Busan* with the San Francisco–Oakland-Bay bridge in 2007.

#### *3.2.6.3 Guidelines to Assist Investigators in the Implementation of the Casualty Investigation Code (Resolution A.1075 (28))*

The purpose of the guidelines in IMO (2014) has been to provide practical advice for the systematic investigation of marine casualties and to provide a common approach for flag states and administration to adopt when conducting such investigations involving marine casualties and incidents in accordance with the *Casualty Investigation Code* (IMO 2008).

In this guideline, a general step by step procedure is outlined for the investigator to follow. It starts with the collection of evidence followed by inspection of the casualty site; gathering or recording physical evidence; interviewing and collecting witness information; reviewing documents, procedures and records; conducting specialized studies i.e. depending on the nature of investigation; reconstruction of the casualty and analysis; reconstruction of the casualty events and their linked conditions; and safety analysis. The investigation ends with reporting of the findings in accordance with the reports in IMO (2008). This includes preparation and submission of a full investigation report, consultation, publication and follow up of any recommendations made.

#### *3.2.6.4 Casualty-Related Matters - Reports on Marine Casualties and Incidents (MSC-MEPC.3/Circ.3)*

MSC-MEPC (2008) has provided details of the information required to be collected and submitted within a specified time frame to IMO by the Administration to populate the GISIS casualty module depending upon the type of casualty severity. The document includes ten annexures, which, depending on the type of marine casualty and severity, needs to be populated. Annexure 1 pertains to ship identification and particulars. Annexure 2 includes the primary data while annexure 3 has the supplementary data for *very serious* and *serious* casualties which need to be submitted. In addition to the above primary three data records, additional annexures are required to be submitted depending on the nature of the casualty type, for example collision, allision and stranding casualty type requires Annexure 5 pertaining to details on the damage sustained to also be reported. Similarly a fire casualty type requires Annexure 6 pertaining to the fire casualty to be recorded and submitted.

Annexures 1 and 2 are very elaborate and cover aspects related to the ship in particular i.e. type, construction and design; voyage details; casualty location; type of casualty; its consequences both to the facility, crew and passengers; the environment etc. It also attempts to identify the primary causes of the initial event, for instance human errors, structural failure, technical failure of equipment, the operating environment and any unknown causes leading to the casualty.

#### *3.2.6.5 Case Studies of Forensic Engineering Based Casualty Investigations*

Garzke Jr. and Simpson (2012) have discussed the sequence of events leading to the collision of the passenger ship *Andrea Doria* with *Stockholm* in 1956 and the subsequent happenings that finally resulted in the sinking of the *Andrea Doria* with many lives lost. Although *Andrea Doria* was a new vessel complying with the latest Safety of Life at Sea (SOLAS) regulations, the damage sustained as a result of the speed, penetration and post collision motion with *Stockholm* resulted in extensive damage that led to her sinking. Their investigations revealed a number of technical shortcomings in the design of the *Andrea Doria* which contributed/ or escalated the damage sustained due to the collision event.

Gill and Wahner (2012) report on the sinking of the Ro-Ro passenger ferry *Herald of Free Enterprise* in 1987 based on the initial investigations reports published for court inquiry purpose. The events leading to the casualties are reported along with the task omissions by the crew and the design aspect of the ship which resulted in escalation of the flooding in the below deck spaces. The investigation revealed that during the period when the casualty took place, there were no regulations which disallowed the ro-ro vessels from going to sea with open bow doors. However, as the size of the ro-ro vessels became larger and larger, they became more vulnerable because of the large open spaces below freeboard deck could either be flooded as a result of open bow doors or as a result of penetration of the hull in a collision casualty. The regulations failed to identify and address these new threats as the ships being built and operated became larger.

D'Angelo *et al.* (2012) have revisited the earlier investigation findings of NTSB on the sinking of the passenger vessel *Ethan Allen* in October 2005. They highlight various inconsistencies and omissions in the NTSB report based on their own forensic analysis of the casualty and the probable causes. They argued that the initial investigation results were invalid because it failed to consider the vessels' turn on its stability (heeling forces imposed as a result of the turn), incorrect weight estimation and failure to follow industry standard procedures etc.

Christensen *et al.* (2012) have highlighted the lessons learned by the shipping community from the forensic analysis of various casualties after the *Titanic* and how these investigations paved way for regulations and rule changes aimed at the safety and design of ships. Investigation findings of the *Titanic* casualty resulted in design changes such as Margin line as a regulation and raising the main transverse bulkheads to the bulkhead deck, while regulations aimed at safety involved 24 hour radio watch communications, lifeboat capacity for all onboard and Ice patrols. Similarly investigation findings on the collision casualty of *SS Andrea Doria* brought about design requirements for watertight closure mechanism for vent dampers, stop check valves on water systems and limits to accessing the centre of the ship. Meanwhile safety requirements involved communications for passing situations, improved radar training and use of life rafts. They also highlight on some major changes in the way ships are designed and constructed based on investigation findings on the tank design requirements after the sinking of the *Torrey Canyon* in 1967, Stability requirements for Ro-Ro passenger vessels after the sinking of *Herald of Enterprise* in 1987, Double hull requirements after the sinking of *Exxon Valdez* and watertight subdivision for Ro-Ro passenger ferries after the *Estonia* casualty in 1994.

The structural failure and subsequent foundering of the 1977 built general cargo vessel *Swanland* on 27 November 2011 has been investigated in MAIB (2013b). The vessel was carrying limestone as cargo and heading into the rough seas and gale force winds when the structural failure occurred. A detailed investigation included assessment of structural condition based on earlier records, review of recent structural surveys and repairs, and modification work done. This was followed by an analysis to determine the structural failure behaviour, structural loading effects and reduction in structural strength as a result of modifications and repair. The reasons highlighted for the structural failure were improper loading of cargo which resulted in significant stresses in the vessels midship section and exposure to rough seas which further exacerbated the stresses generated due to improper cargo loading. Finally, a lack of maintenance and repair leading to corrosion and wastage significantly weakened the structure further. Other contributing factors identified included management and operational issues, and non-compliance with regulatory requirements.

Papanikolaou *et al.* (2014) have investigated the sinking of the Ro-Ro passenger ferry *Heraklion* on December 8, 1966 in the Aegean Sea resulting in the death of 200 people. Preliminary casualty investigation revealed that the vessel did not have the appropriate safety and class certificates, was improperly loaded with trucks in the transverse direction and was operating in a rough weather conditions at the time of the casualty. A detailed analysis based on engineering concepts performed in their study revealed that the vessel capsized because it had insufficient freeboard that resulted in down flooding of large void spaces below the freeboard deck and due to the effect of multiple free surfaces.

Schauer (2016) has presented the case study of the events leading to the structural failure of the Bulk Carrier *New Carissa* in February 1999 as a result of transverse bending from waves, sea floor scouring and impact loading from bottom pounding. The ship grounded on an undeveloped sandy beach near Coos Bay, Oregon and was fully broached to the incoming seas. The breaking waves that impacted the hull were much higher than normal sea swells and finally the ship broke into two parts. His report highlighted the impact that the incoming waves can have on the ship hull when it is fully broached and drawbacks related to the use of high strength steel with respect to fatigue resistance have been discussed.

The loss of over 300 passengers in the South Korea *Seowl* ferry accident in April 2014 has been systematically analysed by Kee *et al.* (2017) using the Rasmussen Risk Management Framework and the associated Accimap technique. The Accimap analysis performed by them have revealed three physical conditions directly contributing to the capsizing of the ferry and they are poor restoring force, shift of improperly secured cargoes and  a sudden turn of the ship. Additional non-technical factors identified as contributing to the marine casualty using the Accimap technique and which are secondary to the earlier mentioned primary factors, are the technical and operations management, company management issues, and regulatory bodies and government.

### 3.2.7 Critical Review of the Literature

Little is known of the frequency of occurrence of rogue or freak waves or for that matter the magnitude of other ocean waves. Even less is known about the severity of the wave induced forces which the ship experiences in service. In contrast to other transportation means, the shipping industry is exposed to many unpredictable phenomena due to the very unpredictable nature of the seas and ship designer does not have much control over what to predict. The effect of heavy weather on the ship structure can be detrimental to its safety as wave induced loads affect the hull girder bending and shear forces from a global perspective while wave pressure from a local load perspective. Severe local pressure induced by waves can cause local deformation of the ships side shell structure and this deformation or deflection is commonly referred to as HHD.

Environmental issues relating to global warming will have a significant impact on the wave heights. Although research in this field show varying conclusions on the impact global warming will have on wave height increase in certain areas of the oceans worldwide, it is imperative that the shipping community be proactive rather than reactive in addressing issues related to increased wave heights and frequency of rogue waves. This is all the more critical given the fact that ships are still being designed based on the GWS Atlas data which were published way back in 1986 (Bitner-Gregersen *et al.* 2014 and IACS 2000).

Maintenance of ships, poor design and construction issues are noted to be issues which could influence NASF casualties from taking place and also these issues can escalate the damage sustained during a subsequent collision or allision type casualty. Focus on ship age alone can be misleading. Substandard ships, substandard registries and irresponsible flag states could contribute to the risk of a marine casualty taking place involving these ships, even if they constitute a small portion of the world fleet. The influence of environmental issues and of a marine casualty on an ill-maintained or substandard ship having HHD alone or along with corrosion is best expressed in fig. 3.6, the outcome of which could be LOWI, environmental pollution, loss of lives and loss of ship.

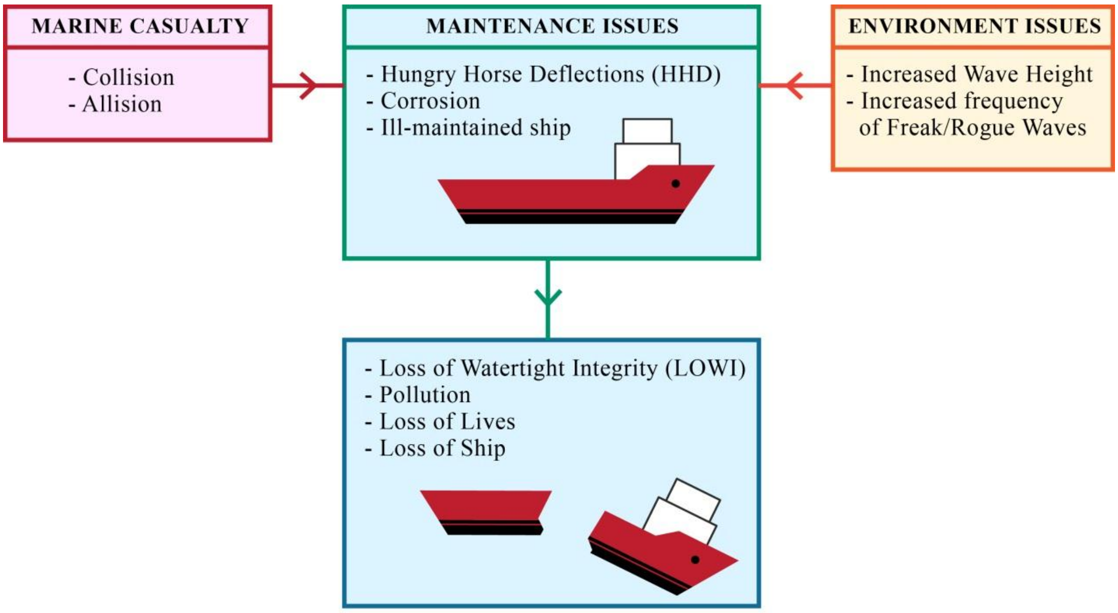


**Fig. 3.6**: **Influence of Environmental Issues and Marine Casualties on an Ill-Maintained/ Substandard Ship.**

Deformations, fracture and material wastage are identified as the critical parameters based on which the survey guidelines are formulated for Dry cargo ships, Double Hull tankers, container ships and bulk carriers. With respect to deformations in the side shell plating between stiffeners i.e. HHD, a definite shortcoming or gap has been identified in the permissible deflection limits between a new construction and an 'existing ship with initial damages'. IACS (2013) specifies the maximum permissible buckling shaped deflection of plating between stiffeners for new building as 8 mm. When the ship is in service it is quite natural for it to be subject to wave induced loads, the impact of which will lead to further deflection of the already deformed or deflected plate and further assume a hungry horse shape pattern. IACS and classification rules neither address the change in shape of the side shell plating between the stiffeners nor does it specify a permissible deflection limit. Rather it is left to the judgement of the attending surveyor to address this issue based on his experience and observations. Such an approach appears to accept a diminished strength of the hull structure especially when various studies reviewed here indicate that hungry horse shape deflection and its amplitude are governing factors with respect to reduced ultimate strength values and collapse mode of plates. Such an initially deformed structure is not expected to resist any external loads arising during a collision or allision casualty thereby impeding the crashworthiness characteristics of the ship. Further, the absence of clear guidelines prompts the ship owners not to accept the new building criteria as a benchmark for replacement.

Forensic engineering based investigations are not new to marine casualty investigations but the few reports available indicate that only sensational marine casualties appear to go in for such detailed investigations. This is because of an exaggerated focus owing to the enormity of the damages, environmental pollution, loss of lives and constant media attention i.e. *Titanic, Costa Concordia, Seowl* ferry etc. Although lessons learned from such casualty investigations resulted in major design and regulatory changes it has not found much wider acceptance. It may be inferred that the ease of performing investigations aligned to human factor and organizational issues from a cost, time and resources perspective is one of the motivating factors for adopting such an approach when compared to a forensic engineering investigation approach. Also, when the preliminary investigation findings reveal outright the involvement of human errors or diminishing performance in the occurrence of the casualty, the focus is more on resolving the primary issues rather than the secondary effects i.e. extent of damage to the ship structure, etc.

It may also be argued that the investigation procedure in IMO (2014) is not prepared from a technical sense and appears more aligned to identifying the human factor and organizational issues leading to marine casualties. This argument has been evidenced from the review of the full investigation reports (listed in table 3.1) available from the IMO GISIS casualty module and flag state investigation reports for collision, grounding and allision type casualties of *very serious*, *serious* and *less serious* severity. In all these reports reviewed in table 3.1 as a part of this study, there is only a brief mention of the damage sustained due to the casualty. The fact that the damaged ship was ill-maintained, was of inferior design or construction etc., is lost due to the investigations' focus on identifying the human factor and operational issues.

**Table 3.1: Review of Full Investigation Reports of Selected Marine Casualties**

| S.No | Casualty severity | Casualty type | Ship name and type involved in the casualty | Casualty date | Source |
|---|---|---|---|---|---|
| 1 | Very Serious | Collision | *City of Rotterdam* (Pure Car carrier) and *Primula Seaways* (Ro-Ro freight ferry) | Feb 2017 | MAIB (2017) |
| 2 | Very Serious | Grounding | *Lysblink Seaways* (General Cargo) | 18 Feb 2015 | MAIB (2015e) |
| 3 | Very Serious | Collision | *MV Orakai* (product Tanker) with *Margriet* (Fishing vessel) | 21 Dec 2014 | MAIB (2015b) |
| 4 | Very Serious | Collision | *Darya Gayatri* (Bulk carrier) with *Paula C* (General Cargo) | 11 Dec 2013 | MAIB (2014b) |
| 5 | Serious | Collision | *British Cygnet* (Oil tanker) with *Vera* (Container ship) | 02 Dec 2006 | IM (2006) |
| 6 | Very Serious | Collision | *Ostende Max* (Bulk carrier) with *Formosaproduct* Brick (Oil Tanker) | 19 Aug 2009 | IM (2009) |
| 7 | Less Serious | Allision | *Navios Northern Star* (bulk Carrier) with Buoy | 14 March 2016 | GISIS (2017b) |
| 8 | Very Serious | Collision | MSC *Alexandra* (Container ship) with *Dream II* (Oil tanker-VLCC) | 3 August 2016 | GISIS (2017c) |
| 9 | Very Serious | Collision | *Consouth* (Cargo ship) with *Pirireis* (Dry cargo) | 29 April 2013 | GISIS (2015) |

It is only in the case of foundering casualties that investigations focus on the structural condition of the ship to ascertain the weakness in the hull structure which led to the escalation of damage and subsequent sinking (MAIB 2013b). The review of the investigation reports listed in table 3.1 also do not give evidence of any specialized studies or engineering analysis being performed for the damaged area to ascertain the reasons for the level of damage sustained to the hull structure as a result of the casualty.

To summarize, the marine casualty investigations performed in accordance to IMO guidelines appear to lack an engineering evaluation of the damage sustained to the hull structure for the *very serious* and *serious* severity casualties involving collision, allision and grounding. It is also noted that there is no emphasis on ascertaining the structural condition of the ship prior to the casualty in these investigations. A definite shortcoming or gap in the classification rules and IACS guidelines on the permissible deflection of the side shell plate between stiffeners for ships in service due to hungry horse phenomenon has been identified in this study. Continuing to ignore this deficiency and leaving it to the judgement of the attending surveyor to decide when the damaged plate is to be replaced appears no longer acceptable. This is in context with studies showing increased SWH; increased frequency of rogue or freak waves in some oceans of the world; ships being designed based on wave data dating to 1986; and reduction in ultimate strength values due to HHD, individually and along with corrosion.

A need is felt to address engineering issues such as HHD identified in this study through marine casualty investigations and for this purpose a forensic engineering investigation approach is espoused. With HHD in focus, the investigation procedure proposed in this study is discussed in the subsequent sections of this chapter.

## 3.3 CRITERIA FOR ASSESSMENT

### 3.3.1 HHD and Corrosion

The effect of heavy weather on the ship structure can be detrimental to its safety as wave induced loads affect the hull girder bending and shear forces from a global perspective while wave pressure from a local load perspective. Severe local pressure induced by waves can cause local deformation of the ships side shell structure and HHD is one such example.

The general tendency of the ship master is to avoid areas of heavy weather and if that is not possible adopt measures such as reduced speed or stop the ship to limit the chance of hull damage as a result of the severe climate (Shu and Moan 2009). Nevertheless wave induced loading represents a very important source of structural loading both from a local and global perspective.

The review of the requirements in the classification rules and IACS guidelines reveal no requirements specifying the permissible limits for HHD and it is often left to the judgement of the attending surveyor to decide appropriately. On the contrary, studies investigating the ultimate strength of rectangular steel plates and stiffened panels with buckling shaped and hungry horse shape deflections indicate a reduction in values when compared to an intact plate. A comparison based on the same criteria between buckling shape and hungry horse shape imperfection reveals the latter having a more profound influence in ultimate strength reduction. The presence of corrosion is seen to further aggravate the reduction in ultimate strength values (Jiang and Soares 2013). In these circumstances, not only are these ships more prone to LOWI and developing cracks and fractures when encountering rough seas, but these deformations also impair the energy absorbing capacity of the side shell structure in the event of the ship being involved in a collision or allision casualty type.

In this context, HHD individually and along with corrosion has been identified as the criteria for assessment in this study based on which guidelines are developed for the selection of casualties for analysis together with an investigation procedure to facilitate its assessment.

### 3.4 *LESS SERIOUS* SEVERITY CASUALTIES

Marine casualties are typically classified based on severity into *very serious*, *serious*, *less serious* and *marine incidents* with the aim to distinguish the extent of damage sustained and for setting a criterion for carrying out casualty investigations in accordance with MSC-MEPC (2008). Furthermore such classifications allow to focus the investigations on certain casualties based on the impact it may have on the learning curve i.e. meaningful conclusions can be derived from the investigation.

A *less serious* severity casualty involving a collision or allision casualty type would be of a less magnitude wherein no major damage is sustained to the ship for it to fall under the more serious categories as per EMSA (2015a). A low intensity collision or slight scrapping between ships, allision with pier, etc., resulting in dent or deformations to the structure and which does not cause any loss of lives, loss of asset and environmental damage, would presumably fall under this *less serious* severity category. Collision and allision type casualties constitute a case where damage is sustained to the ship side shell structure, which is the focus of this chapter of the thesis. Data from Table 2.4 in chapter 2 indicate the occurrence of *less serious* casualties in the range 66% to 85% and is alarmingly very high. Despite the emphasis provided to human factor issues in reducing human errors and poor performance issues in ship operations and manning, if such minor skirmishes and contacts continue in such high percentages, the probability that one of them might turn into a *very serious* casualty and that too in an environmentally sensitive area would be very high.

The performance of a ship in casualty has been a matter of academic focus for the last two to three decades and many studies have been performed to understand and address issues on energy dissipation (Paik and Pedersen 1996), bow structure type (Sun *et al.* 2015; Liu *et al.* 2015; Haris and Amdahl 2012; Hogstrom and Ringsberg 2012), survivability (Schreuder *et al.* 2011; Hogstrom and Ringsberg 2012) and their evaluation approaches. A *very serious* and *serious* severity casualty generally involves substantial damage to the ship hull covering a significant area and forensic engineering based casualty investigation on these casualties may rarely bring about the inherent weakness in the structure prior to damage. This is because the defects if any would be lost as a result of the casualty itself. The cost of modelling and analysis of such an extensive damage would involve lot of resources, expertise, time and cost. Furthermore the assumptions made on influencing parameters such as speed, angle of contact, weather condition, striking vessel bow structure, material behaviour, soundness of weld etc. could distort the results significantly. The question whether these detailed investigations on the *very serious* and *serious* severity casualties will result in meaningful lessons learned may also lead to abandoning the idea of conducting it in the first place. On the other hand, a *less serious* severity casualty involves a lesser area and lesser extent of damage when compared to the more severe cases and the initial defects to the hull structure would not be distorted or lost to the extent as in the severe cases. Moreover, the resources, expertise, time and cost of conducting the investigation would be far less and the results from the analysis could provide meaningful conclusions resulting in rule & regulatory changes affecting the design, construction and survey of ships.

A *less serious* casualty presents a smaller damaged area with or without rupture of side shell plating typically associated with collision and allision casualties. Investigation of the damaged area using the numerical analysis tools (i.e. FEA) would be much faster, easier and efficient to model. It could also be used to determine the forces or loads that could have caused the damage sustained. The reduced time and cost of the analysis when compared to analysis of the more severe casualties and the possibility of performing multiple simulations using such tools could prompt wider acceptance for considering the forensic engineering based investigation approach on marine casualties. The results derived from the analysis can assist in simulating the behaviour of the structure with different types of deformities i.e. HHD, weld induced deflections, cracks and fracture, etc. something that would otherwise be lost or ignored with the damage sustained, in the event of a *serious* or *very serious* casualty.

An additional classification of casualty type called NASF has been introduced by Papanikolaou *et al*. (2005; 2006) and Primorac and Parunov (2016) and it refers to existing deformities in the hull structure such as deformations, crack, fracture, etc. as a result of structural degradation, overstressing due to excessive loading or design and construction issues. Selection of *less serious* severity casualties could also present an opportunity to analyse the existing deformities associated with NASF together with the forces generated during the casualty and allow for extrapolating these results when analysing the more serious cases. It can also assist in explaining the implications the existing deformities have in escalation of the damages sustained in the event of a collision and allision casualty.  Findings from such analysis can help identify gaps and shortcomings in the existing rules and regulations, which have been written based on experience and at times do not even have engineering basis to justify it (Kery and Garzke Jr. 2012a).

## 3.5 FORENSIC ENGINEERING BASED INVESTIGATION PROCEDURE

The steps involved in conducting investigations from a forensic engineering perspective have been documented by Noon (2001) and Smith Jr. and Schmidt Jr. (2012), while the procedure in ABS (2005) and IMO (2014) appear aligned from a general casualty investigation perspective although it provisions for detailed analysis. It is important to note that casualties of the *less serious* severity are not required to be reported or investigated in accordance with MSC-MEPC (2008) unless such investigations can result in any important lessons learned. However the severity of the casualty would not be known till such time the investigator inspects the vessel to ascertain the level of damage sustained. Furthermore, there is no timeline specified for submission of the initial casualty details as per MSC-MEPC (2008) for these *less serious* severity casualties.

In this thesis, the investigative steps outlined in IMO (2014) are adopted for the purpose of keeping the investigation procedures as aligned as possible to the present marine industry practices. To these investigation steps modifications are proposed to maintain the focus on the selected criteria for assessment i.e. HHD individually and along with corrosion, and to narrow down on the marine casualty based on the damage sustained and ease of performing any detailed analysis. To the investigation steps in IMO (2014), modifications are made in the contents to 'Gathering or recording physical evidence' and 'Conducting specialized studies', while 'Selection of Marine Casualty for Investigation' is an addition made to the existing procedure to facilitate appropriate selection of the casualty to be investigated for HHD, which is the focus of this study. These changes are highlighted in italics for cases where modifications are made to the existing procedure and in bold where an addition is made. The changes made are enumerated in detail in the subsequent sections of this chapter.

i. Extent of Investigation

ii. Initial response

iii. Site management
iv. Start-up meeting
v. Collection of evidence
vi. Inspection of casualty site
*vii. Gathering or recording physical evidence*
viii. Witness Information
ix. Reviewing documents, procedures and records
**x. Selection of casualty for investigation**
*xi. Conducting specialized studies*
xii. Reconstruction and Analysis
xiii. Reconstruction of the casualty events and their linked conditions
xiv. Safety Analysis
xv. Reporting

For the sake of brevity, the investigative steps in IMO (2014) in which no major changes are anticipated with respect to the criteria for assessment selected in this study, are not further discussed or explained here in detail. A copy of the IMO document is attached in Appendix 3 of this thesis for any additional information or cross referencing purpose. The onus of conducting the forensic engineering based investigations based on the proposed procedure for the selected criteria for assessment rests with the flag state of the ship involved in the marine casualty. The above recommendation is in line with the requirement in IMO (2008).

### 3.5.1 Gathering or Recording Physical Evidence

In the context of this study where the focus is on HHD, guidelines are proposed on gathering or recording physical evidence specific to this engineering issue. It is pertinent to note that damages sustained during collision and allision casualty could erase the initial deformations or damages (Kery 2012a). The corrosion level of the damaged plate may thin out as a result of stretching of the plate due to the lateral force and, similarly, initial plate deformations may be superimposed with the subsequent indentation as a result of the collision or allision impact. Hence it is necessary to observe and record the structural condition in the near vicinity (both internal and external) of the damaged area.

In the case of corrosion levels, the average wastage levels can be calculated based on the approach followed in ABS (2016b). The arithmetic average of the percentages of the individual plate wastages in the vicinity i.e. top, bottom and both adjacent sides, of the damaged portion can be measured. The sum total of these readings divided by the number of readings taken will provide an average wastage value in percentage, based on which the corresponding thickness reduction from the rule required or as built thickness can be determined.

A similar approach is proposed to be adopted for HHD since wave induced loads act over a fairly large area of the side shell structure and the average depth of indentations in the vicinity of the damaged area can be used as a general representative of the initial deflection of the damaged section before the casualty. Fig. 3.7 shows the section of the side shell structure with the damaged plate panel number 9 as a result of collision or allision casualty. The plate panels 1 to 8 surrounding the damaged panel are assumed to be having initial deformations of the shape represented in fig. 3.3 i.e. HHD.

The terms *a* and *b* in fig. 3.7 refers to the length and width of the individual plate panel between the stiffeners in the forward direction of the ship.

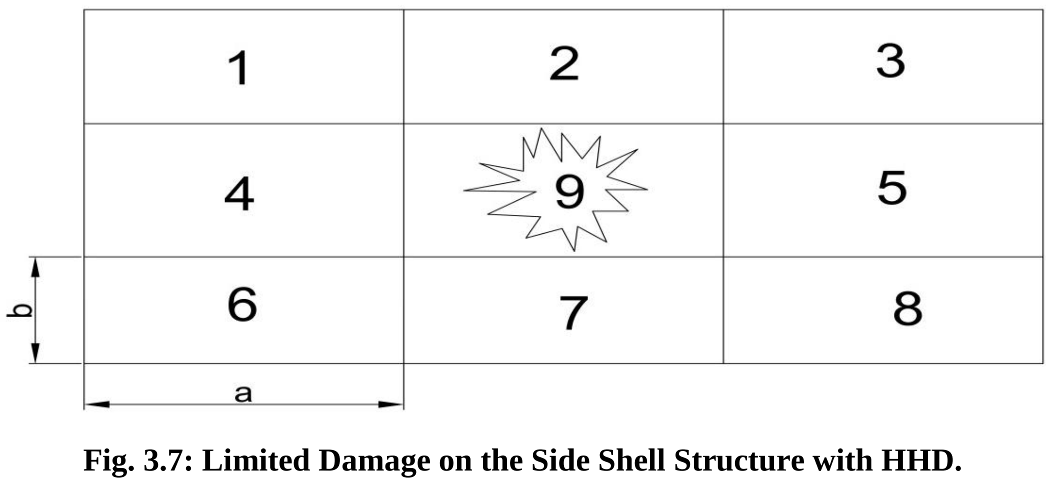


**Fig. 3.7: Limited Damage on the Side Shell Structure with HHD.**

For subsequent engineering analysis, the minimum input data required to be collected at site for the damaged and undamaged portion of the side shell in accordance with fig. 3.7 is identified and a template prepared to input the values. The proposed template is shown in table 3.2 and the input information required to model the panel and to carry out the analysis are provided.

**Table 3.2: Template to Input Data Collected as Evidence for Analysis**

(Legend: ‘x’ – Not Applicable)

| **Panel Number →**<br>**Plate Panel Particulars ↓** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
|---|---|---|---|---|---|---|---|---|---|
| Length of plate (a) | | | | | | | | | |
| Width of plate (b) | | | | | | | | | |
| Original plate thickness ($t_o$) | | | | | | | | | |
| Final plate thickness ($t_f$) | | | | | | | | | |
| Hungry Horse Deflection ($w_e$) | | | | | | | | | x |
| Hungry Horse Deflection for damaged plate ($w_{0avg}$) | x | x | x | x | x | x | x | x | |
| Plate Material | | | | | | | | | |
| Yield strength value | | | | | | | | | |
| Youngs Modulus | | | | | | | | | |
| Frame Space | | | | | | | | | |
| Panel Location (Frame Space) | | | | | | | | | |

In table 3.2, The terms ‘a’ and ‘b’ refer to the length and width of the individual plate panel between the stiffeners; ‘$t_o$’ refers to the original plate thickness and ascertained from the vessels ‘as built’ drawings; ‘$t_f$’ refers to the final plate thickness measured at site. In this study material wastage as a result of general corrosion is considered and a uniform reduction in thickness is assumed. The deepest deflection due to HHD for the undamaged plate panels are measured from site and are represented by ‘$w_e$’ and the average of these deflections is used to represent the deflection ($w_{0avg}$) of the damaged plate panel number 9. Provision to include information on the plate material, its properties and location of damage (i.e. frame space, location from deck or bottom) is also provided for in the proposed template.

The HHD for the damaged plate panel i.e. 9 can be approximated from the arithmetic average of the deepest deflections of the individual plate panels in the vicinity i.e. top, bottom and both adjacent sides, of the damaged portion and is represented by $w_{0\text{avg}}$. The sum total of the deepest deflection values for the undamaged plate panels divided by the number of readings (n) taken will provide an average deflection value ($w_{0\text{avg}}$) which can then be used for the analysis purpose. This calculation is represented in Eq. 3.1.

$$w_{0\text{avg}} = \sum_{i=1}^{n} \frac{w_{ei}}{n} \tag{3.1}$$

Where the extent of damage is more extensive and covers a larger area i.e. more than one plate panel, the numbering system in fig. 3.8 may be used for gathering the input information.

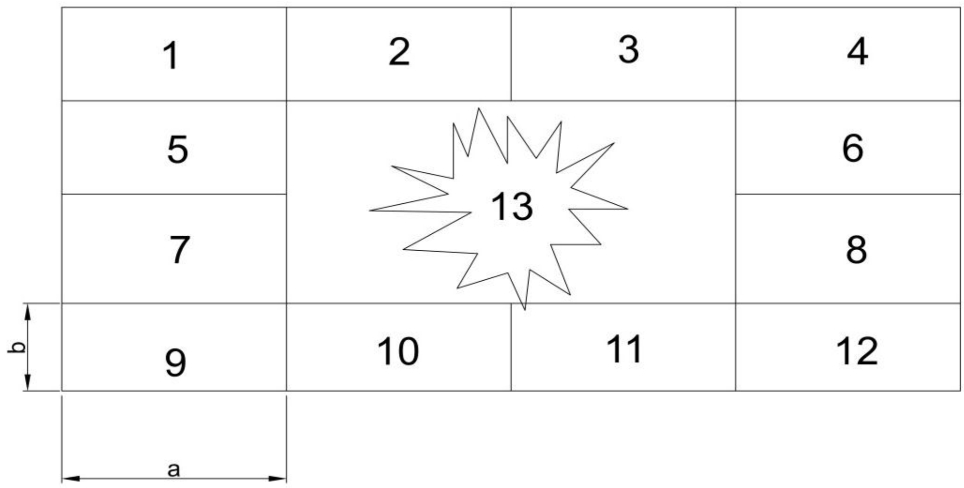


**Fig. 3.8: Extensive Damage on the Side Shell Structure with HHD.**

Here the plate panel number 13 in fig. 3.8 represents an area covering four individual plate panels which are damaged during the marine casualty. The average deflection value ($w_{0avg}$) for these four plate panels can be ascertained by using equation 3.1, modified to accommodate the extra panels (n=12).

It is also recommended to photograph the damaged area and its vicinity. This is relevant in the context that a detailed or specialized analysis may only be performed at a later date and such photographic evidence will be essential for guiding the investigator during the analysis and reconstruction phase of the investigation.

### 3.5.2 Selection of Marine Casualty for Investigation

In the context of this study where the focus is on conducting a forensic engineering investigation for marine casualties where HHD has been noted on the side shell structure which is damaged, it is essential that the appropriate casualties are selected for such investigations. The intent behind this approach is to ensure selection of cases which offer useful lessons when analysed and can be performed in an economical and efficient manner. In this regard, this particular step is proposed to be added into the investigation procedure adopted in IMO (2014) with the purpose to filter out or narrow down the number of casualties to be subject to specialized analysis.

The proposed guideline for selection of marine casualties for investigation and specialized studies based on the context of this thesis is presented in fig. 3.9. The usefulness of investigating marine casualties of the *less serious* severity has been detailed in earlier section 3.4 of this chapter and is selected as one of the factors influencing selection of casualties for more detailed investigations. The identification of the casualty to be of *less serious* severity can be ascertained at the very early stages of the investigation process during the phase 'inspection of the casualty site' and would not necessarily warrant completion of the entire IMO investigative process to ascertain the nature of severity.

HHD manifest on the side shell of the hull structure and from this perspective only collision and allision casualty types are considered relevant for further detailed investigations. Cargo ships not only account for the highest percentage amongst ship types but also accounts for the highest number of casualties, and statistics revealing the same has been covered in section 2.2.3 of chapter 2 in this thesis.

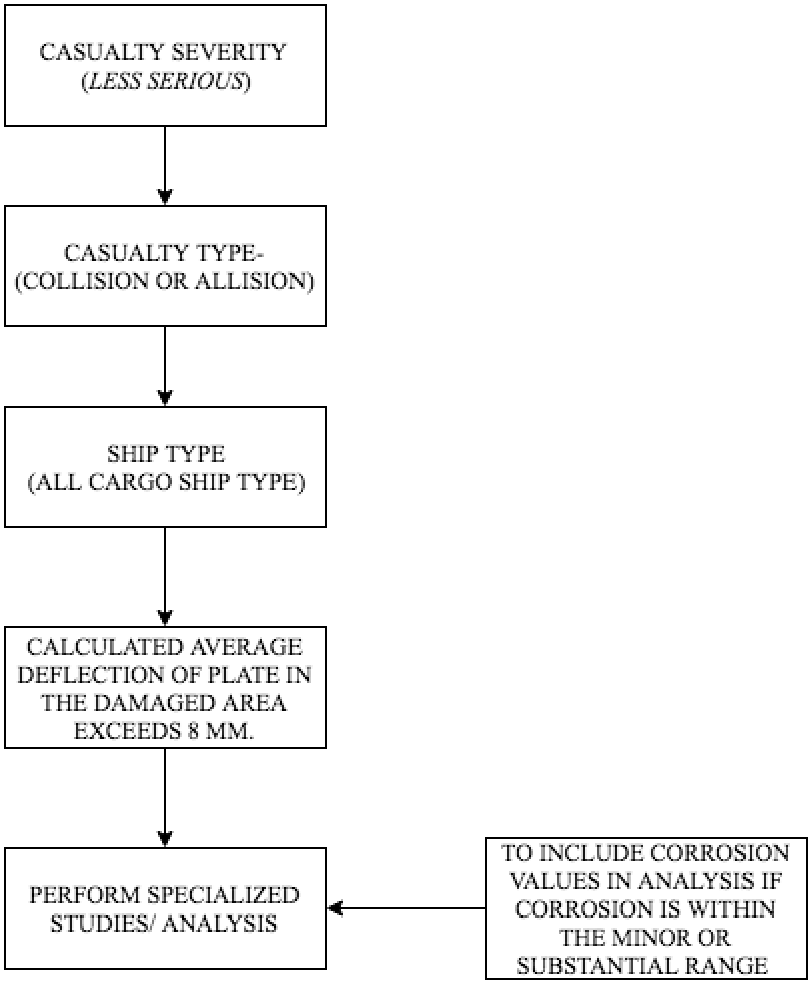


**Fig. 3.9: Guidelines for Selection of Marine Casualty for Investigation and Specialized Studies**

The pollution impact to the environment in the event of a casualty involving cargo ships i.e. oil tanker, product carrier etc. can be catastrophic and is another governing factor for its selection. Hence, engineering based investigation of marine casualties involving cargo ships can offer a better understanding on their design, construction, survey and operational issues to bring about changes and improvements in the rules and regulations pertaining to it.

The selected casualties are then further filtered out based on the initial damages sustained to the ship prior to the collision and allision casualty types. This study focuses on HHD based on the gap identified in the requirement for permissible deflections to the individual plate panel between the transverse and longitudinal stiffeners. Based on the measurement taken under 'Gathering or Recording Physical Evidence' in section 3.5.1, if the calculated average deflection ($w_{oavg}$) of the damaged plate panel exceeds 8 mm i.e. permissible limit for new construction as per IACS (2013), the need for a detailed or specialized analysis is proposed. Alternatively, if $w_{oavg}$ is found to be 8 mm and less, the need to pursue a detailed investigation is done away with.

In this study the influence of corrosion on the ultimate strength of the rectangular plate and stiffened panels has been documented based on various research studies in this field. Similarly the influence of corrosion along with the initial deflections either due to post welding related or wave induced have been documented. IACS and classification rules define the extent of corrosion based on Insignificant corrosion or Minor corrosion, Substantial corrosion and Excessive corrosion. Both Insignificant or Minor corrosion and Substantial corrosion present situation which indicate material wastage but do not require any renewal of the plate as the extent of wastage is within the allowable corrosion limits. The influence of this material wastage i.e. within the allowable limits, together with HHD should also be considered when determining the permissible or allowable deflection limits of the side shell plate between the stiffeners.

### 3.5.3 Conducting Specialized Studies

There are three approaches for performing specialized studies of the ship hull structure; the simple analytical approach, the numerical approach and the experimental approach. Amongst these three, the numerical approach provides a reliable, cost effective and efficient means to predict the deflections, stresses and ultimate strength of unstiffened and stiffened plates and structural components with imperfections. Analytical methods fail due to lack of exact solutions or because of the involvement of a variety of approximations or assumptions while experimental methods due to time and cost implications (Masaoka and Mansour 2008). One of the main challenges when performing experimental tests on stiffened panels to determine the ultimate strength under uniaxial loads or biaxial loads is to ascertain the appropriate boundary conditions as in reality. The stiffener panels are supported by longitudinal girders and transverse frames which are strong members and the actual load sharing mechanism between the stiffeners, plating and supports is not fully known. Although experimental studies provide a better understanding of the deformation process during a collision event, the enormity of representing a real collision problem in a laboratory set up and factoring a large number of parameters associated with the ship during the collision event makes it potentially inaccurate and cost ineffective (Liu *et al.* 2015). Where small scale experiments are performed in lieu of large scale experiments, the costs are still high and the intricate scaling effects involved makes it difficult to interpret the results at real scale conditions (Sun *et al.* 2015).

Amongst the various numerical methods, FEA is preferred as an analysis tool for estimating the “controlled failure, the maximum deformation, or the largest loading which can be sustained by a structure” (Liu *et al.* 2015). Since the FEA seeks solution in a discretized domain, mesh density can be varied at various locations as per the discretion of the analyst. There is sufficient scope for having plate elements of dimensions of a few meters on a side shell as well as plate elements of a few millimetres along a welded joint. Besides, the actual structural behaviour of the component can be traced by using the most appropriate finite element which has the required features like geometry i.e. rectangular or triangular, degrees of freedom and stress strain displacement fields employed for generating property matrices. Since FEA is used in high speed, large storage electronic computing environment, advancements in graphics can effectively be utilized in pre-processing the data i.e. generation of geometric models, and in post processing the output for visualising response or for simulation.

Kitamura (2002) advocates the use of FEA approach for quantitative assessment of the crashworthiness of the structure or for the verification of the simplified analytical methods. In both these cases, FEA approach allows for performing numerical experiments at a reasonable cost when compared to large scale physical experiments where the reliability and accuracy of the data for actual collision or grounding casualties may be hard to assess. Another advantage that FEA provides in this context is the ability to recycle the models many times to assess various permutations and combinations to derive more accurate and acceptable results (Kitamura 2002).

There has been literature available on the ultimate strength analysis of the ship structures with initial imperfections using non-linear FEA by Paik *et al.* (2003; 2004a); Jiang and Soares (2012b; 2013); Witkowska and Soares (2015); Saad-Eldeen *et al.* (2015; 2016). In some cases, the analysis generally incorporates material and geometrical non-linearities. The output from the FEA is a load deflection curve and ultimate strength has been post processed from this. The suggestion in the present study is to conduct the relevant structural analysis such as ultimate strength analysis using non-linear procedures, impact analysis etc., on the ship structure with initial imperfections of the HHD shape. From the load deflection curve available from the incremental and iterative procedure, identify the load or time step corresponding to the measured or observed deflections. The various steps involved in the general procedure for the ultimate strength analysis such as geometric modelling, incorporation of boundary conditions, selection of load steps etc., can be readily used in this process.

FEA can be employed as a part of forensic investigations on marine casualties or for investigations to bring about rule changes or improvements based on marine casualty data, for:

a. Ultimate strength estimation of ‘existing ship with initial damages’ i.e. HHD and corrosion, and ‘existing ship with initial damages’ together with local damage due to collision or allision.

b. Ascertaining the limit state of serviceability to recommend the renewal of side shell plate based on permissible limit of initial imperfections caused due to HHD individually and along with corrosion.

#### 3.5.3.1 Modelling for HHD

Modelling of HHD for FEA is one critical aspect which has been discussed in this section. Predominantly two shapes of initial imperfections or geometrical imperfections are noted for plates viz. the buckling shape and the hungry horse shape. While the buckling shaped deflections are primarily as a result of post welding operations, the hungry horse shape deflections are caused due to wave induced loads on the side shell plate.

Initial deflections on the plate has been measured at various locations in the ship structure and processed to obtain the pattern of models for Hungry horse shape in Ueda and Yao (1985). Initial imperfections are introduced as a mathematical model by means of equations by Paik *et al.* (2004a); Sadovsky *et al.* (2005); Luis *et al.* (2008a, 2008b); Jiang and Soares (2013) and Witkowska and Soares (2015).

In majority of the studies reviewed the initial imperfections are modelled based on the buckling shape (Paik *et al.* 2003; Sadovsky *et al.* 2005; Luis *et al.* 2008a, 2008b; Witkowska and Soares 2015) presumably for its simplicity.

It is only in a select few studies (Paik *et al.*2004a; Jiang and Soares 2013) that the initial imperfections are modelled with a hungry horse shape representing HHD. These studies reveal that the ultimate strength values of the plate (corroded and non-corroded) with HHD under biaxial compressive loads are lower than that with buckling shaped imperfections.

In the present study, the initial imperfections of hungry horse shape are mainly considered for the side shell. Equation 3.2 from Jiang and Soares (2013) has been programmed and values of $B_{0i}$ from Paik *et al.* (2004a) used to generate a hungry horse shape.

$$w = w_0 \sum_{i=1}^{m} B_{0i} \sin\frac{i\pi x}{a} \sin\frac{\pi y}{b} \tag{3.2}$$

In Eq 3.2, *x* is the longitudinal axis, *y* is the transversal axis, *m* is the mode of imperfection in the *x* axis and assumed to be *m*=11 and *n* is the mode of imperfection in the *y* axis and assumed to be 1 and $w_0$ is the amplitude of the imperfection or depth of deflection. The value for $w_0$ to be considered in eq. 3.2 in the case of modelling of the undamaged plate panels is equal to the deepest deflection depth '$w_e$' and when used for modelling the damages plate panels it is equal to '$w_{oavg}$'. The values of '$w_e$' and '$w_{oavg}$' are taken from table 3.2 and which are obtained from the procedure explained in section 3.5.1. The length and width of the plate is represented by *a* and *b*, and $B_{0i}$ represents the amplitude of the hungry horse shaped deflections which is given in table 3.3. The calculated values of *w* are then incorporated in the finite element model by changing the vertical position of element nodes without inducing any additional stresses (Saad-Eldeen *et al.* 2016).

**Table 3.3 Amplitude of Hungry Horse Shaped Initial Deflection**

(Source Paik *et al.* 2004a)

| $B_{0i}$ | Value | $B_{0i}$ | Value | $B_{0i}$ | Value |
|---|---|---|---|---|---|
| $B_{01}$ | 1 | $B_{05}$ | 0.2127 | $B_{09}$ | 0.001 |
| $B_{02}$ | -0.0235 | $B_{06}$ | -0.0371 | $B_{10}$ | -0.009 |
| $B_{03}$ | 0.3837 | $B_{07}$ | 0.0478 | $B_{11}$ | 0.0005 |
| $B_{04}$ | -0.0259 | $B_{08}$ | -0.0201 | | |

As an example, the shape of the HHD for a plate of dimensions $a$ = 3800 mm and $b$ = 870 mm and $w_0$ = 25 mm is illustrated in figure 3.10, by inputting the amplitude values $B_{0i}$ from table 3.3 into the equation 3.2. The length $a$ is plotted along the longitudinal axis $x$ and width $b$ along the transverse axis $y$. The hungry horse shape generated in fig. 3.10 is characterized by a steep deflection gradient along the transverse axis $y$ which is the shorter edge (Paik *et al.* 2004a) and multiple mounts along the longitudinal axis $x$ which is the longer edge to signify the unevenness of the wave impact on the structure.

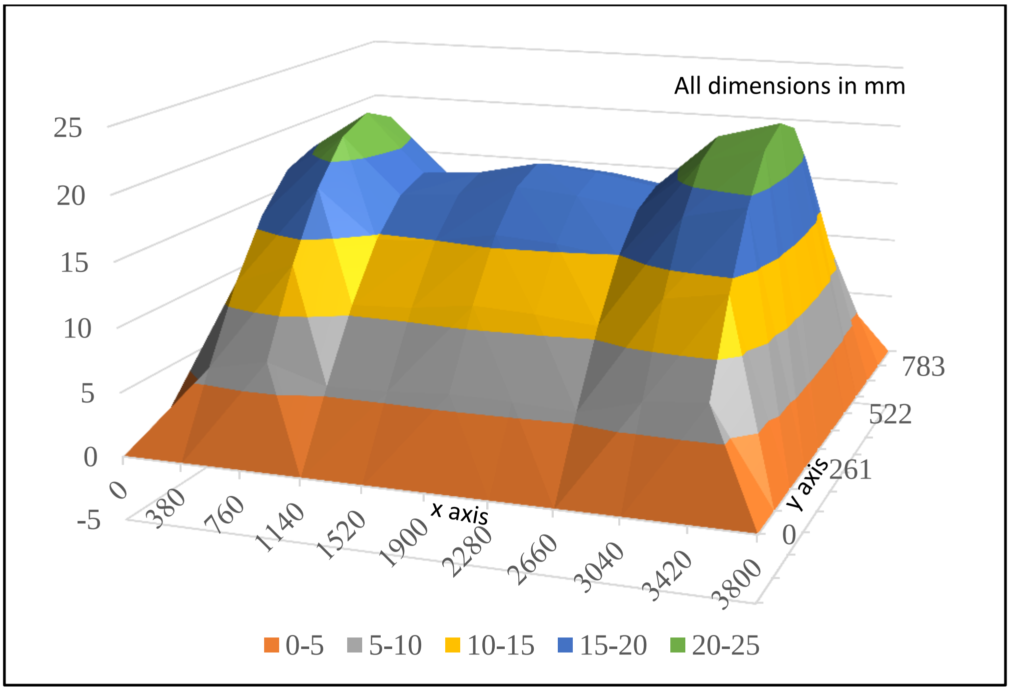


**Fig. 3.10: Shape of HHD for Deflection Value 25 mm**

#### 3.5.3.2 Modelling for Corrosion

The main types of corrosion encountered on ship are the general and pitting corrosion. In general corrosion there is a uniform reduction of plate thickness and the ultimate strength calculations can be carried out by excluding the thickness lost (Jiang and Soares, 2012a). Any of the two approaches followed by Saad-Eldeen *et al.* (2012b) can be adopted for modelling of general corrosion in the finite element model as no significant difference in ultimate strength values have been reported between the two. In the first approach, the corrosion degradation is taken as an average thickness reduction on the plate while in the second approach, the real thickness measurements are input at the nodal locations on the finite element model. Modelling for pitting type corrosion has been extensively documented in the literature by Jiang and Soares (2012a; 2012b; 2013) and is not further elaborated in this study.

In this chapter, a forensic engineering based investigation procedure is developed to investigate specific engineering issues in marine casualties. The investigation procedure developed works around the procedures developed by IMO, to ensure that a common approach is still maintained for conducting investigations by the interested parties. The focus has been on specific engineering issues and in this study HHD, individually and along with corrosion has been identified as the criteria for assessment on which the investigation procedure is developed. Guidelines are developed on ‘gathering or recording physical evidence’ specific to HHD from the marine casualty together with the analysis to be performed to facilitate these investigations. A guideline for selection of marine casualties suitable for forensic engineering investigation from an HHD perspective has also been developed in this study. The intent of these guidelines is to ensure that only those few marine casualties are selected for which the investigation can reveal meaningful results and can assist to bring about rule and regulatory improvements.

The forensic engineering investigation procedure developed in this study for HHD can be readily used by marine casualty investigation agencies to ascertain the level of maintenance of the ship involved in the casualty, for cases which are presented in a court of law.

# CHAPTER 4

# ASSESSMENT CRITERIA FOR INSPECTION OF CRACKS IN SHIP HULL STRUCTURE

## 4.1 INTRODUCTION

During its operational life, ships are subject to ship owner, classification, regulatory and port state inspections on a periodic basis to ascertain the general condition of the vessel. This would include as a minimum, inspecting the structure for material wastage, deformations and fracture. During such inspections, cracks of detectable lengths could also be found and repaired using standard procedures in IACS (2013). A major problem in ship maintenance especially in regards to cracks is identifying the causes for crack initiation as there are instances where the earlier repaired work done on the detected cracks would be ineffectual as these cracks reappear after a period of time.

In this chapter, the focus is on inspection issues pertaining to cracks to mitigate the extent of damage sustained to the hull structure in the event of a marine casualty. Cracks can develop as a result of ship design, construction, operation and maintenance issues, and also due to marine casualties i.e. NASF etc. Cracks formed as a result of any of these issues could further escalate the damage sustained to the ship hull structure under the influence of the sudden impact loads typically associated with collision, allision and grounding casualty types and due to wave induced loads which the ship encounters during heavy weather. Thus cracks warrant due attention within the survey and inspection regime of the ship hull structure.

For the purpose of this study, the ship operational life refers to the period after ship construction and is divided into three age groups i.e. 0-5 years, 6-10 years and 11-20 years. While the focus in this study is on cracks, fracture and crack are treated together here as fracture is as a result of failure of a crack. Inducement factors are defined as those factors which may directly or indirectly be responsible for crack initiation/ formation in the ship hull structure. An “Inspector” is defined as a person involved in ship hull inspections and may be a forensic investigator, member of the ship crew, ship owner representative, class surveyor, and any other third party investigation body representative who possesses the required skill set and knowledge to make informed assessment of the ship hull structure. NASF refers to the scenario "where the hull presents cracks and fractures affecting ship structural integrity and seaworthiness" (Papanikolaou and Eliopoulou 2008) and can potentially lead to LOWI. Such casualties happen mainly when the ship is en route or in open sea and experiences severe storm or rough seas.

## 4.2 BACKGROUND STUDY

### 4.2.1 Impact of Ship Age and Maintenance Issues on NASF Type Casualty

Bea *et al.* (1991) have discussed about fatigue cracks and the way it influences the structural maintenance regime for both new and ships in service, especially tankers. The practical difficulties associated with inspections of all spaces in a tanker make it not possible to detect all significant cracks. These practical difficulties encountered should be translated into the design and construction of new builds. The statistics presented by them report of cracks manifesting in even younger vessels (0-5 years age), where fatigue damage would not have yet set in. The number of cracks detected show a somewhat steady number for the age between 5-13 years and peaks at 15 years of age when the majority of the cracks are detected.

The casualty types involving AFRAMAX tankers during the period of 1978 to early 2004 are analysed by Papanikolaou *et al.* (2005) with respect to LOWI and other issues. Their studies reported 121 (15%) casualties resulting from NASF, amongst which 36 (29.8%) resulted in LOWI. Their study also recorded 39% of the NASF casualties were as a result of environmental issues i.e. rough sea etc.

Papanikolaou *et al.* (2006) have reported on casualties involving AFRAMAX tankers during the period 1978-2003. They report NASF casualty type showing a 'bell shaped' behaviour indicating ships of middle age (11-15 years) being frequently involved in casualties when compared to other ship age groups. NASF casualty type was also reported for ships aged in the 0-5 and 6-10 year age group and an increasing number is noted as the ship ages.

Eliopoulou and Papanikolaou (2007) have reported of Suezmax and VLCC-ULCC of 11-15 years age having the highest percentage of being involved in marine casualties, closely followed by these ship types in the 16-20 years age group. Casualties were also noted for these tankers in the age group of 0-5 and 6-10 years, although not significant when compared to the 11-15 years and 16-20 years age group.

Papanikolaou and Eliopoulou (2008) have investigated casualties involving tankers of 60,000 DWT capacity and above for the period 1990-2007. Amongst the total 814 cases considered, NASF accounted for 148 casualties of which 6 resulted in total loss and another 46 were categorized as *serious* in casualty severity. They also report of NASF casualty type in younger tankers (except VLCC and ULCC) in the 0-10 years category and attribute it to poor design and construction issues.

A general increasing trend in NASF have been noted for large oil tankers 10 years and above and specifically for AFRAMAX and SUEZMAX tankers of the age group 11-15 years by Primorac and Parunov (2016). Insufficient maintenance as the vessel is nearing its economic life of 20 years has been one of the reasons attributed to this trend. Their study also reported of younger aged tankers showing significant structural failure with specific mention of Double hull tankers of 0-5 years age during the period 1990-2007 showing remarkable structural failures during rough weather, which clearly were not attributable to maintenance issues.

### 4.2.2 Influence of Cracks on Ship Structural Strength

Abramowicz and Simonsen (2003) have conducted a series of tests on axially compressed ‘X’ shaped and ‘T’ shaped specimens of steel and aluminium material to investigate the effect of fracture of welds or parent material on the energy absorption of ship structure subassemblies during deep collapse. Their investigations revealed a significant reduction in energy absorption for real life welded ship components which show fracture and this reduction in energy absorption was found substantially high for the ‘X’ shaped specimen of aluminium material

Simonsen and Tornqvist (2004) have presented a combined experimental and numerical procedure for development and validating macroscopic criteria for prediction of fracture propagation in plate structures under plastic conditions. The crack propagation tests involved stretching of steel and aluminium plates of varying thickness with edge cracks and centre cracks to ascertain the crack length increase corresponding to the machine cross-head displacement and to measure load vs the cross-head displacement. The experimental results were then modelled in FEA where the simulated crack growth is forced to correspond with the experimental observations. A crack propagation criteria is proposed in their study and validated by simulating a grounding accident of a double bottom.

Experimental investigation of fatigue crack propagation in welded stiffened panel under various configurations i.e. spacing, geometry, heat input used for welding, was conducted by Mahmoud and Dexter (2005). The experimental results of the different configurations were compared against each other and also against an unstiffened panel. The conclusions drawn highlighted a substantial reduction in crack propagation rate for stiffened panels compared to unstiffened panels and this was attributed to the restraint effect and the compressive residual stress between stiffeners arising from the welding process. Stiffener spacing was also found to influence the crack propagation rate as the magnitude of the compressive residual stress increases as the stiffener interspacing is reduced.

The ultimate strength and collapse response of crack stiffened plates have been investigated using non-linear FEA by Margaritis and Toulios (2012). In their study the cracks were positioned normal to the applied compressive loading and are at the plate-web intersections. Their investigations found crack closure (crack faces coming into contact) as a result of the compressive loading, however crack length can influence the failure mode in the stiffened plate. Also a reduction in the ultimate strength of the stiffened plates with crack damage was noted, significant for higher aspect ratios for the larger crack sizes.

The load carrying capacity of structural members with multiple cracks is investigated by Wang *et al.* (2009) using non-linear FEA. A model with a lead crack and disturbing cracks has been created to analyse the effect the disturbing cracks have on the propagation of the lead cracks. Their study concluded that the position and length of the disturbing crack are not influential on the lead crack as long as they are in the low stress region. Hence multiple cracks in the structure in the vicinity (low stress region) of the lead crack can be ignored from the residual ultimate strength assessment of the structural members.

An experimental study on the collapse mechanism and ultimate strength of crack damaged stiffened plate under axial compressive loads were carried out by Shi *et al.* (2017). Stiffened plates with initial imperfections (of varying depths) and cracks of varying configurations (location, orientation and size) were investigated. To simulate a real crack, they made a pre-cut in the steel plate with an opening thickness of 2 mm and of varying length and orientations, and assumed to extend through the thickness of the plate. The experimental investigation reported that under compressive loading the pre-cut crack does not propagate and the crack gap decreases. The through cut crack in the stiffened plate may result in the loss of cross section which may change the plate slenderness and may significantly influence the failure modes. The crack damage was found to significantly influence the ultimate strength, especially for cracks localized at the centre and edge of the plate in the transverse direction. The initial deformations were also found to significantly influence the ultimate strength values together with cracks.

### 4.2.3 Fatigue Induced Cracks

Crack initiation life has been defined by Stenseng (1996) as “the time it takes for a crack of some length to appear” and from a fatigue assessment perspective this initiation life is a function of the number of cycles at various stress ranges. According to him, the effect of fatigue on the life of a component is divided into three phases, viz., crack initiation, crack propagation and fracture. Once a crack initiates, crack propagation takes place at a stable rate until it reaches a critical length, after which rapid failure or fracture can occur. His study also highlights the sensitivity of the stress values at the crack tip and the need to maintain the loads within permissible limits since the doubling of stresses will lead to an eight time shorter crack initiation period and eight time faster crack propagation rate. He also discusses about the multiple load paths in the ship structure that leads to significant load shedding and prevents the collapse of the hull structure even if a fracture occurs in one component. Such an action in a way prevents catastrophic casualties from taking place. His study also acknowledges that cracks initiation in some parts of the hull structure is inevitable given the complexity of the ship structure and weather conditions it has to encounter through its lifetime.

The influence of construction tolerances and misalignment on the fatigue life of ship structure has been discussed by Blagojevic *et al.* (2002) and they conclude that the extent of misalignment can have drastic effect on the fatigue strength of the ship structure. The effect of corrosion has also been analysed and found quite significant in affecting the operational life of the ship. Their study also compares fatigue damage assessment for the side shell and double bottom structure of an oil tanker using the classification rules of Bureau Veritas (BV), Germanischer Lloyd (GL) and Lloyds Register (LR). The calculated results for fatigue damage exhibit wide variances between the calculations for all of the three classification societies and it calls for uniformity or optimization of the rules. They also highlight the connections between the longitudinal and transverse web frame below the full load and ballast waterlines on the side shell being more prone to developing fatigue related cracks primarily due to the pulsating hydrodynamic pressure acting on the ship hull. Their study cautions on the rampant use of high tensile steel, simplified structural details for higher weight optimization and fabrication procedures from a fatigue perspective.

A detailed study on fatigue design assessment for ships in general and specifically for Double hull oil tankers, bulk carriers and container ships has been presented in LR (2004). The various factors responsible for fatigue cracks have been highlighted in this report and it includes misalignment and poor fit up, welding and material defects, poor manufacturing and fabrication procedures and unfairness of plating.

Fricke and Kahl (2008) have investigated weld root fatigue in fillet welded structures using numerical and experimental techniques. Fillet weld of the non-penetrating or partially penetrating type are commonly used for joining parts in shipbuilding. Under the influence of cyclic loads, fatigue cracks can develop from the sharp corners at the weld root and hence is of much interest. Their investigations consider various connections i.e. cruciform, doubler plate etc., where fillet welds are used and they compare the results obtained based on the various analysis approaches. An important conclusion from their study is that fatigue cracks initiate from the weld root of fillet welds subjected to throat bending.

The influence of various imperfections developed during ship construction and repair on fatigue life as a result of hot spot stress and stress concentration factor in those areas of imperfections has been examined by Chakarov *et al.* (2008). The effect of thickness change misalignment, angular imperfections, permanent distortions etc. on the stress concentration and hot spot stress are discussed individually and in combination. The results of their study conclude that misalignment due to thickness change significantly increases the hot spot stresses with increasing difference of the plate thickness. Similarly when thickness change misalignment is combined with angular imperfections and imperfections due to permanent deformations, the magnitude of change of stress concentration factor depends on the direction of movement and location of the deformation.

ISSC (2009) have discussed the various factors which influence fatigue life such as mean and residual stresses, thickness effect, loading of the structure including load sequences, design, corrosive environment and fabrication. Their study observes that a crack spends 80% of its lifetime as a short crack with a length of less than 1 mm. The study also discusses brittle fracture failure with respect to materials for use in cold climate conditions. The rampant use of fillet welds and partial penetration welding of the ship structure is also discussed with particular emphasis on how the non-fused root faces of such welds can behave like initial cracks.

Beghin (2006) has reported extensively on fatigue of ship structural details and highlights the phases of fatigue in welded structures and sub classifies the fracture phase into 3 categories - brittle fracture, ductile fracture and plastic collapse. He has provided useful guidelines for assessing the rate of corrosion for various ship types when there is no corrosion protection provided and it is reproduced in table 4.1 here. He also highlights that the crack growth period occupies the predominant part of the fatigue life while the crack initiation period is insignificant. The various contributing factors to fatigue cracking are illustrated in his study along with their influence. The main contributing factors identified include general configuration and local geometry of the structure, configuration and geometry of the weld, weld material defects such as undercut, porosity etc., workmanship issues in fabrication, use of high tensile steel, the influence of wave induced loads, etc.

**Table 4.1 Rates of Corrosion for Various Types of Ships**

(*Source* –Beghin 2006)

| Compartment | Type of Cargo | Rate of corrosion (mm/year) |
|---|---|---|
| Ballast tanks | Unprotected | 0.40 |
| | Coated | 0.20 |
| Cargo Tanks | Black products | 0.20 |
| Deck and bottom | White product | 0.35 |
| Cargo Tanks | Black products | 0.10 |
| Elsewhere | White product | 0.15 |
| Bulk carriers | | 0.20 |
| Cargo Ships | | 0.10 |

The fabrication defects which influence fatigue life are presented along with the remedial measures to be adopted. Similar measures to be adopted to improve the fatigue life of welded joints are also elaborated. His study highlights the inconsistencies of fatigue life measurements using the rules of different classification societies and the difference noted being between 1.8 to 20.7 years based on an ISSC study.

Garbatov and Soares (2011) have highlighted the effect corrosion has on the fatigue life of the component. They divide corrosion degradation into three phases. The first phase is described by no corrosion as a result of the protective coating. The second phase involves initiation of corrosion as a result of damage or deterioration of the protective coating and is characterized by a decrease in thickness. Finally, the last phase corresponds with a stop in the corrosion process.

The importance of the governing parameters for crack propagation on corroded deck longitudinal of tankers from a fatigue perspective has been investigated by Parunov *et al.* (2013). Their study highlights the impact welding defects, geometric and material properties and corrosion have on the structural capacity of the welded structure and how it reduces the fatigue strength. Similar to studies by Stenseng (1996), Parunov *et* *al.* (2013) also divide fatigue life into three phases in which crack initiation phase is assumed negligible since it involves a very small part of the total life.

Mao (2014) has reported that cracks can be initiated much earlier than expected because of the wide use of high tensile steel, imperfect fabrication process and uncertainties on ship fatigue design as a result of unknown wave environments encountered in the future. He advocates the need for ship owners and classification societies to manage the risks associated with the presence of cracks to avoid catastrophic consequences. He proposes an approach which efficiently predicts crack propagation and which reliably plans the inspection of cracks and maintenance in ship structure. This approach is supported with an example using the linear elastic fracture mechanics approach to ascertain the number of sea states required for a detectable crack of 10 mm length to propagate from 10 mm to 100 mm and subsequently from 100 mm to 200mm, keeping the ship trading route and her operating conditions the same. The results of the analysis indicate that it takes 1.43 years for the crack to propagate from 10 mm to 100 mm and represents 90% of the total time for the crack to increase from 10-200mm. The crack propagation rate in the 100-200 mm length is very fast and especially even faster after crossing 180 mm length. His study shows that under normal operating conditions, the sea environment i.e. sea states, encountered by the ship is a governing factor for crack propagation rate.

### 4.2.4 Non Fatigue Related Crack Inducement Factors

Barson and Rolfe (1999) have discussed the practical difficulty of fabricating large welded steel structures without introducing some type of defects (i.e. notch, flaw, discontinuity and stress concentration) which eventually lead to fracture over a period of time. In addition to fatigue cracks, cracks that develop as a result of stress concentration due to corrosion are discussed in their study. They also extensively discuss on brittle fracture type failure in structural steel materials. Selecting material with improved notch toughness values cannot alone eliminate brittle fractures as there exist inter relationships among materials, design, fabrication and loading, which can still result in such failures. Although the use of ductile material is more favourable in preventing fractures, they may also not exhibit prior deformation before fracture under some conditions of low temperature and loading. They cite numerous examples involving sudden failure of ships and barges splitting into two to highlight the issues on brittle fracture failures.

Mann (2011) has provided a detailed and informative description of the role of thickness, basic metallurgy, fabrication, welding process, fatigue and material properties in crack initiation. This is one of the few studies to elaborately discuss crack initiation due to factors other than fatigue. Particular emphasis is placed on the welding process since all ships constructed nowadays are fully welded construction. According to him, the welding process itself can simultaneously introduces three risk factors – a crack due to slag inclusions, undercutting, etc., a susceptible microstructure due to heating and cooling and finally a build-up of high tensile stress due to differential cooling post welding. He has also highlighted a few catastrophic structural failures which happened due to cracks and that too without any prior indication of its imminent failure.

Fu *et al.* (2016) have discussed the influence welding sequence has on the induced residual stress and distortion of the plate or assembly resulting in geometrical imperfections. These geometrical imperfections can further lead to mismatch between the structural blocks or block assemblies during construction while the residual stresses can result in reduction of the ultimate strength under compressive loading.

A detailed report on ship fracture mechanism which covers inspection guidelines and identifies the causes leading to fractures has been presented by Stambaugh and Wood (1987). They identify three factors responsible for fractures to take place which are: abnormal forces, presence of flaws and notches, and inadequate material properties at service temperature. Abnormal forces are as a result of environmental forces acting on the ship hull, distribution of loads within the ships, flawed structural design and defects such as misalignment during the manufacturing process. Their study distinguishes between a flaw and a notch and how it can form the origin for a fracture on its own, or together with the influence of abnormal forces and/or fatigue. Lastly, material properties and its influence with temperature are also elaborated. Their report provides guidelines to identify the causes or combination of causes resulting in fractures.

### 4.2.5 Inspection Guidelines for Fracture and Crack

Guidelines for the inspection of the hull structure which includes details of common structural deficiencies and flaws that require attention during the periodic inspection by class societies, flag states and ship owners has been detailed in ASTM (2004). Fractures and cracks figure prominently as one of the critical issues and the document provide details of the critical locations where such deficiencies can manifest. This document puts the onus on the ship owner to be responsible for ensuring that his vessel is properly maintained through an in-house inspection programme (especially with respect to fractures and cracks) rather than an over reliance on periodic surveys by classification societies, port state control and flag state representatives. The inspection guidelines consider fractures of 50 mm size and more to fall within the detectable range provided the surface is sufficiently clean and adequate lighting level is provided.

IACS (2013) has provided the procedure for repair of detected cracks using the welding process.

The IACS unified recommendations specifying the guidelines for the Surveys, Assessment and Repair of Hull Structure for General dry cargo ships (IACS 2016a) has identified fractures as one of the deficiencies to be addressed during surveys and typically found in locations where stress concentration occurs. According to these guidelines, fractures can also manifest at the start or end of a welding run, at intersection of welds, welding at toes of brackets, cut outs, rounding corners at the end of stiffeners etc. It also reports on fatigue fractures and how it can impair the watertight integrity of the hull structure.  The report divides the ship hull structure into many divisions and detailed instructions are provided on where to inspect the hull structure for fractures and what action or remedial measures are to be followed up to rectify it, once detected. The report however does not mention the underlying causes which resulted in the fracture or specifically address the inducement factors responsible for the fracture to develop. The report also makes no reference to cracks.

Similarly the recommendations in IACS (2004) for bulk carriers, IACS (2007) for Double Hull oil tankers and IACS (2005) for container ships identify fractures as one of the damages to be inspected during surveys. These guidelines specify the area of inspection with respect to the uniqueness of the ship structure along with the remedial measures to be adopted for repairs.

LR (2004) has identified the various factors responsible for fatigue cracks in ships, in general and specifically for double hull oil tankers, bulk carriers and container ships. These factors are discussed along with guidance to designers for adopting fatigue life improvements designs. This document provide details of the critical areas in oil tankers, bulk carriers and container ships where fatigue cracks can develop along with the remedial actions to be adopted or performed from a design, construction and repair perspective.

IACS (2000), DNV (2010) and DNV-GL (2015) have all reported of higher sea states and significant wave heights in the North Atlantic region when compared to other worldwide operations.

### 4.2.6 Inference

Within the survey and inspection regime of classification societies and other statutory inspection bodies, cracks i.e. other than fatigue cracks, have received very little attention. Fatigue cracks and fracture appear to be of a major concern to the shipping community primarily because of its potential effects on the hull and tank leak integrity and the influence it has on the structural capacity of the hull. There are very limited studies on factors contributing to crack initiation other than from a fatigue perspective. Studies by Primorac and Parunov (2016), Papanikolaou *et al.* (2005; 2006), Papanikolaou and Eliopoulou (2008), Mao (2014) and Bea *et al.* (1991) indicate cracks developing in the hull structure irrespective of fatigue conditions. Statistics by Papanikolaou *et al.* (2005; 2006) on NASF and Bea *et al.* (1991) show cracks manifesting in ships between the age group of 0-5 years and 6-10 years as well, which indicates that cracks could be initiated at a very early stage of the ship operational life.

There has been a lot of focus on the fatigue life of ship structure components and welded joints, especially from the crack propagation perspective. All these studies assume crack initiation as inevitable given the complexity of the ship structure, inherent problems associated with the welding process i.e. the main joining technique, and the environmental conditions in which ships operate.

Studies by Mao (2014) have reported on crack propagation rate escalating upon reaching a critical limit. Hence it is essential that cracks are identified well before it reaches a threshold limit and compromises the structural integrity and safety of the ship. Fracture represents the failure of cracks in its lifecycle and the survey approach by IACS and classification societies appears to be reactive and not the right approach. This is especially in the present context, where there is much negative publicity about marine casualties given the loss of lives and environmental pollution associated with these incidents.

The inducement factors responsible for crack initiation identified from the various studies reviewed here from a fatigue and non-fatigue perspective are summarized in table 4.2. It is noted that much of the research has been from a fatigue perspective for which the main crack inducement factors have been identified together with the causes for crack initiation for each of these inducement factors. The design related crack inducement factor is influenced by strength issues, incorrect design issues both structurally and welding related, abrupt dimensional changes, material selection, etc. The welding process related crack inducement factor focuses on the process related issues such as improper weld and presence of slag, impurities and foreign particles. Fabrication and workmanship related issues during ship construction could result in geometrical misalignment, notches and structural discontinuities and block assembly issues during welding process, any of which could cause crack initiation. Non homogeneous material composition and use of thick steel sections influence crack initiation under material related crack inducement factor.

**Table 4.2 Crack Inducement Factors with Corresponding Causes**

*Legend:* "√" – Applicable ; "x" – Not Applicable

| Inducement Factor | Causes/ Reasons | Fatigue | Ref. | Non Fatigue | Ref. |
|---|---|---|---|---|---|
| Design | Inadequate strength and support of structural members | √ | ISSC (2009) | √ | Stambaugh and Wood (1987) |
| | Incorrect prediction of loads | √ | Beghin (2006) | √ | Stambaugh and Wood (1987) |
| | Abrupt dimensional changes, Use of different material type or grade, Use of High tensile steel sections | √ | Blagojevic *et al.* (2002); LR (2004); ISSC (2009); Beghin (2006) | x | None |
| | Complex weld geometry, inappropriate weld type and weld size | √ | ISSC (2009); LR (2004); Beghin (2006); Fricke and Kahl (2008) | x | None |
| Welding Process | Improper weld | √ | Beghin (2006); Mann (2011) | √ | Mann (2011) |
| | Presence of weld impurities – slag, porosity, contamination etc., | √ | Beghin (2006) | √ | Mann (2011) |
| Fabrication and Workmanship | Geometrical misalignment | √ | Blagojevic et al. 2002; Beghin 2006; Chakarov et al. 2008; | x | |
| | Presence of notches and structural discontinuities | √ | LR 2004 | √ | Stambaugh and Wood 1987 |
| | Block assembly issues and welding sequence | √ | Fu et al, 2016 | x | |

| Table 4.2 cont. | | | | | |
|---|---|---|---|---|---|
| **Inducement Factor** | **Causes/ Reasons** | **Fatigue** | **Ref.** | **Non Fatigue** | **Ref.** |
| Material Properties | Use of thick steel sections | √ | LR (2004) | √ | Mann (2011) |
| | Non Homogeneous material composition | x | None | √ | Mann (2011) |
| Temperature | Prolonged exposure in low temperature areas | √ | ISSC (2009) | √ | Stambaugh and Wood (1987) |
| | Nature of Cargo | √ | ISSC 2009 | x | None |
| Accident | Dent and deformation in structure due to dropped object, Allision and NASF | x | None | √ | Stambaugh and Wood (1987) |
| Fatigue | Corrosion | √ | ISSC (2009); Garbatov and Soares (2011); Beghin (2006) | x | None |
| | Welding Process | √ | Beghin (2006); Mann (2011) | x | None |
| | Fabrication and workmanship | √ | Beghin (2006); ISSC (2009) | x | None |
| Corrosion | Exposure to Sea water environment | √ | Beghin (2006); Kwon and Frangopol (2012) Garbatov and Soares 2011) | x | None |

Low temperature strongly influences crack initiation especially brittle fracture type failures and for this reason exposure to low temperature areas and carriage of cargo maintained at low temperatures are identified under this category. Accidents resulting in dents and deformations in the hull structure due to marine casualties such as collision, allision, and NASF etc. result in regions of high stress concentration. In these areas of high stress concentration crack initiation can take place. Fatigue related crack inducement factor is highly researched and primarily attributed to corrosion, welding process and fabrication and workmanship issues. Corrosion is also independently considered as a crack inducement factor due to the fact that marine structures are continuously exposed to a saline environment resulting in corrosion related stress concentration in the affected areas due to material wastage. There are some studies which identify the same crack inducement factors together with the corresponding causes and reasons from a non fatigue perspective and they have also been identified and listed in table 4.2.

Cracks can manifest at a very early stage in the operational life of the ship and not necessarily due to fatigue conditions alone. Design, construction, maintenance and operational issues can contribute to crack initiation in the ship hull structure. There appears to be no clear guidelines for inspection of cracks and even more so based on the operational life of the ship. Furthermore, little emphasis is provided to identify the correct inducement factor responsible for the initiation of cracks other than from fatigue conditions, to prevent the recurrence of cracks once repaired. In this study, focus is on crack initiation from a non-fatigue perspective to facilitate inspections for repair and marine casualty investigations. The subsequent sections in this chapter aim to address these issues through the development of an age based crack assessment criteria which facilitate inspection of cracks in the hull structure corresponding to the operational life of the ship.

## 4.3 CRACK ASSESSMENT CRITERIA FOR SHIP HULL STRUCTURE

### 4.3.1 Crack Inducement Factors

Crack formation or initiation appears inevitable or unavoidable given the uncontrolled variables involved in the construction of welded ship structures and the adverse environment in which it operates. These cracks can have a detrimental effect on ship safety as they reduce the local strength of the structure, compromise the tank leak integrity and structural integrity of the hull by increase in global stress. If neglected, these deficiencies may eventually lead to rupture or fracture of the structural member over a period of time. Cracks are also associated with NASF casualty type and studies report of a reasonably high percentage of such casualties involving both younger and older ships (Papanikolaou *et al.* 2005; 2006). Also is the reasonably high percentage of ships lost due to foundering type casualty which is generally associated to LOWI and/or breaking into two in rough weather (Butt *et al.* 2013). Nevertheless not all these cracks are serious, primarily because ships are very redundant and the tolerance is a function of the overall structural redundancy, ductility and fracture toughness of the structural components (Mahmoud and Dexter 2005; Stenseng 1996).

However, it is also widely acknowledged by findings involving large scale experiments and finite element analysis studies that existing cracks can propagate during impact loads i.e stretching (Simonsen and Tornqvist 2004; Abramowicz and Simonsen 2003). There is a significant drop in energy absorption due to fracture of welds during crushing (i.e. collision type casualties) which can result in more damage to the ship hull (Abramowicz and Simonsen 2003). Under these conditions of impact loading, the much researched crack growth or crack propagation rate phenomenon based on fatigue conditions would not be valid and cracks will propagate rapidly resulting in breakaway of structural members and in turn lead to severity of damage sustained to the hull structure.

A majority of the research on cracks appears to be focused on the crack growth phenomenon rather than on the crack initiation, and with particular emphasis to fatigue conditions.  Probable reasons attributed to this approach based on crack growth are firstly because of the uncontrolled variables involved in the construction of welded ships, wherein introduction of cracks in the structure appears inevitable. Secondly, cracks are not easily detectable and hence go unnoticed during routine inspections especially during the early period of the ship operational life. Thirdly, studies indicate crack initiation period to be less significant when compared to the crack growth period (Beghin 2006; Parunov *et al.* 2013). Once a crack is formed, it spends almost 80% of its lifetime in the region of a short crack (ISSC 2009) before it finally starts to propagate fast leading to failure. Lastly, repair of cracks involves cost and time, and given the ship charter commitments it may not be possible to repair cracks on a priority basis once they are identified. Under such circumstances the focus has always been to determine and control crack growth conditions before final failure.

In this chapter, the criteria for assessment of cracks is based on inducement factors which influence the initiation of cracks in the hull structure. These inducement factors are:

i. Design related
ii. Welding process related
iii. Fabrication and Workmanship issues related
iv. Material related
v. Temperature related
vi. Fatigue related
vii. Corrosion related
viii. Accident related

Many of the these inducement factors along with their attributable causes have been identified earlier from a fatigue perspective, which generally happens after the ship is put into service and is operational for a considerable period of time. Some have also been identified otherwise. However, in this study, the inducement factors identified from both a fatigue and non fatigue perspective are considered to influence crack initiation from a very early stage in the ship operational life, as influence of these inducement factors result in increased stress concentration at the weakest link, thereby creating a source for crack initiation. Such an understanding is agreeable with the reported structural failures involving younger ships in the age group 0-10 years ((Papanikolaou *et al.* 2005; 2006, Mao 2014, Primorac and Parunov 2016) where it is very unlikely for fatigue issues to set in. It is based on these premises that the listed inducement factors are included in the proposed assessment criteria for consideration during the early operational life of the ship.

Additionally, ‘Accident related” inducement factor has been given a broader perspective in this study. In addition to dents and deformations caused by dropped objects on the deck or allision and grounding casualties, slamming and pounding of the hull structure when exposed to rough weather can result in NASF and deformations on the side shell structure i.e. HHD. Dents and deformations as a result of any of these could cause stress concentration in the adjacent load bearing member as a result of the damage sustained. Such areas then become prone to developing cracks at the weakest link.

### 4.3.2 Crack Assessment Criteria Based on Ship Operational Life

The causes/reasons of crack initiation attributable to a particular inducement factor (listed in table 4.2) together with the inducement factor forms the basis for the crack assessment criteria in this thesis. The operational life or age of the ship referred to in this study represents the period after ship construction. The age groups selected are 0-5 years, 6-10 years and 11-20 years, assuming a ship life of 20 years. There are two reasons for selecting these age groupings. Firstly, for simplifying the inspection process and to narrow down to the appropriate inducement factor considered to cause crack initiation corresponding to the operational life of the ship. Secondly, for aligning this grouping to the special periodical surveys conducted every 5 year period by the classification societies (ABS 2016a).

#### *4.3.2.1 Period 0-5 Years of Ship Operational Life*

A newly built ship is expected to be free of cracks and unlikely to be dominated by operational issues such as corrosion or fatigue to cause cracks. Design and construction related issues are most likely to dominate crack initiation in the hull structure during this period. Cracks of undetectable and detectable size should have presumably been identified during the construction stage by the ship builder, the class surveyor and the ship owner representative surveyor through visual inspection and non-destructive tests. However ships are complex and large welded structures and it is difficult to manufacture them without introducing some structural blind spots, some type of flaw, notch, discontinuity and stress concentration. Furthermore, not all the welded connections are subject to such inspections due to cost and time constraints. Much would depend on the experience of the surveyor in detecting such cracks and on the level of quality commitment of the ship constructing yard. The normal procedure followed once cracks are detected during inspection is that they are gouged and re-welded, followed by non-destructive test of the joint, if required (IACS 2013).

During 0-5 years of operation, the ship is put to service and operates under various conditions i.e. fully loaded, ballast, loading and unloading cycles etc., is subject to wave loads and ship motions, and experiences environmental hazards. The ship designer does not have the luxury to accurately predict the response of the ship hull structure as the loads imposed by the sea on the structure is random in nature and operational requirements demand highly variable loads for each voyage and even during a particular voyage (Mansour and Liu 2008). The hull structural members are subject to tension and compression. Imperfections or inadequacies related to ship design and ship construction are likely to dominate and translate into some form of visible deformities, one of which could be cracks. Undetectable cracks formed during the construction period may also grow in size to a detectable length. Design related inducement factors can be one of the dominant reason for crack initiation during this period. The tell-tale signs of which are difficult to ascertain as such because cracks generally manifest at the weakest link in the structure. These weak points could be the weld joint or at notches and flaws in the structural member and can easily be confused for other inducement factors.

In addition to design issues, the inducement factors related to the welding process, fabrication, and workmanship influence crack initiation in the hull structure of all welded ships. The welding process itself can be the root cause for many problems which lead to crack initiation as it simultaneously introduces three risk factors: cracks, a susceptible microstructure as a result of application of heat and subsequent cooling, and finally residual stresses as a result of differential cooling post welding (Mann 2011). Structural discontinuities, geometrical misalignments, block assembly issues during the fabrication process or poor workmanship practices can contribute to crack initiation as a result of the high internal stress generated in the structure due to these factors (Stambaugh and Wood 1987).

The other three inducement factors considered in this age group are related to 'temperature', 'material' and 'accidents'. Prolonged exposure to cold climate along with other contributing factors in the past has resulted in newly built ships and barges cracking into two pieces (Barson and Rolfe 1999). Although very significant contributions have been made in the field of material science and material selection to prevent brittle fracture type failures, ‘temperature’ inducement factor can still be relevant in the present day context because of the shipping industries’ need for year round navigation in ice covered waters i.e. the Arctic Ocean, and prolonged exposure to low air temperature (LR 2004). Also, using materials with improved charpy values alone does not prevent brittle fractures (Barson and Rolfe 1999). Accidents or casualties such as collision, allision with pier or berth and dropped objects during cargo handling can result in dents and deformations in the ship hull structure (Stambaugh and Wood 1987; IACS 2016a), which may increase the stress concentration at the supporting structure i.e. weld joint, thereby creating favourable conditions for crack initiation. The effect of slamming, pounding and green sea forces on the ship hull in adverse environmental conditions can also results in such similar damage. Use of thick steel sections and non-homogeneous material composition are factors considered for ‘material’ related inducement factor. Mann (2011) highlights laminar tearing and weakness at the centre of the section where cut outs are made as causes for crack initiation in thick steel sections from fatigue perspective.

All of these inducement factors can contribute individually or combine together under favourable conditions to cause crack initiation and may also provide ideal conditions to aggravate the crack growth for an already existing crack. Because of these reasons crack assessment is a very complex process as there are frequent instances where once the cracks have been identified and repaired, they may resurface after a certain period of time as the root cause for crack initiation was not addressed appropriately in the very first instance. To avoid such recurrences, the inspector should be aware of the possible interaction and the cascading effect existing between the various inducement factors which may contribute to crack initiation. Two such cases are illustrated here in this thesis where root cause for crack initiation can be masked by other inducement factors thereby providing conditions for its recurrence after repair works have been carried out addressing the wrong inducement factor.

Fig. 4.1 illustrates an example where the ship hull structure is dented or deformed by side contact with cargo loading equipment or allision or slamming and pounding during heavy weather. The loss of structural capacity due to the damage sustained could result in excessive loads being taken by the supporting members leading to its distortion or geometrical misalignment and cracks can manifest at the weakest link in the structure. During routine inspections, the inspector is likely to attribute crack initiation due to geometrical misalignment i.e. fabrication and workmanship issues, of the structure as it would be more easily identifiable, while ignoring the root cause which is the accident related structural damage. It is only when the inspections are carried out soon after the accident or exposure of ship to heavy weather, would the inspector consider crack initiation to accident related inducement factors.

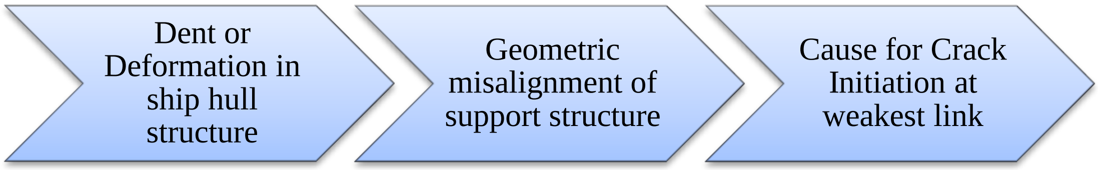


**Fig. 4.1: Interaction Effect of Inducement Factor Contributing to Crack Initiation**

Similarly, fig. 4.2 illustrates an example which involves both design and fabrication related inducement factors. An inadequately designed structural member having a notch formed due to fabrication or workmanship issues, is likely to develop a crack and the weakest link i.e. notch, due to the stress concentration developed in the member.

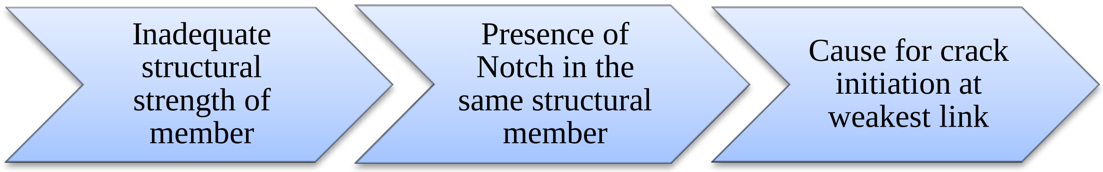


**Fig. 4.2: Cascading Effect of Inducement Factors Contributing to Crack Initiation**

The inspector is likely to be prejudiced to the fabrication related inducement factor upon seeing the crack at the notch on the structural member while the root cause was a design issue. The notch was just the weakest link and after it is repaired, the crack will reappear at the next weakest link. In both these cases the likely recurrence of the crack is high as the root cause for the crack initiation was not correctly identified and resolved. Similar such interactions can exist and a lot would depend on the experience and expertise of the inspector in identifying the responsible inducement factors based on a thorough examination of the structure surrounding the detected crack and of the influence of any other external factors that the ship encountered recently.

#### *4.3.2.2 Period 6-10 Years of Ship Operational Life*

The inducement factors considered during 0-5 years of the ship operational life are considered relevant and applicable for the period 6-10 years as well. In addition there is a likelihood that old cracks may resurface. Such cracks were detected and rectified in the past but resurface because the root cause behind the crack initiation was incorrectly addressed during the earlier inspection.

The 6-10 years age classification has been introduced to accommodate fatigue related inducement factor specifically for ships operating in the North Sea and North Atlantic area. Ships operating in these areas are constantly subject to much harsher environmental conditions when compared to ships operating in the world trade area. The fatigue assessments for ships operating in these seas is so stringent that their operational life is generally considered half of that of ships operating in world trade area (DNV 2010; DNV GL 2015). In consideration of the above, fatigue is included as a crack inducement factor in this age group. The underlying causes for crack initiation identified for this inducement factor are corrosion, welding process related issues and workmanship and fabrication issues, which have been discussed in detail in the next section, which covers the period 11-20 years of the ship operational life.

#### *4.3.2.3 Period 11-20 Years of Ship Operational Life*

During the period 11-20 years in operation, the ship has undergone considerable period in service and deficiencies related to design and construction are presumably identified and resolved. The operational demands and the environmental conditions the ship is subject to in a corrosive medium gives rise to issues related to fatigue and corrosion, the dominant factors for crack initiation during this period. Inadequate maintenance can also be an issue as the ship starts nearing its economic life and the ship owner is unwilling to spend money on repairs, and this can be a reason for crack initiation in the hull structure. The earlier discussed inducement factors i.e. design, fabrication and workmanship issues and welding process related deficiencies which were unresolved due to inadequate maintenance or unidentified during inspections in the earlier operational period of 0-5 years and 6-10 years, would now be associated and dealt with from a fatigue and corrosion perspective. Similarly ‘accident’ related inducement factor has been purposely omitted from the analysis in this age group as fatigue conditions are expected to dominate during this period. However in the event of an accident which is soon followed by an inspection to ascertain the damage sustained, the crack assessment criteria proposed for 0-5 years or 6-10 years under ‘accident’ related inducement factor may be followed for assessment of cracks.

Crack initiation due to corrosion is primarily due to a decrease in thickness of the structural member resulting in increase in stress levels at critical sections (Parunov *et al.* 2013). Garbatov and Soares (2011) divide the corrosion mechanism into three phases and where corrosion is initiated only once the protective coating is damaged. Beghin (2006) has proposed a rate of corrosion per year for different ship types, for different locations and for different cargo type carried in the cargo tanks, when no protection is provided. This is shown in table 4.1 and the worst-case scenario is for a cargo tank carrying white products where the corrosion rate is 0.35 mm/year at the ship deck and bottom. Additionally, classification rules cater for certain corrosion allowances in the design of structural members which is in the region of approx. 20-25% of the member thickness. This corrosion allowance appears to satisfactorily compensate for thickness reduction when considering the worst case of corrosion for an unprotected hull. Based on the rate of corrosion per year in table 4.1 and the corrosion allowances catered for in the design, it is reasonable to consider corrosion as an inducement factor for crack initiation only from the 11th year of ship operational life, provided the ship is rather well maintained.

Ship structures are subject to cyclic stresses due to wave pressure, ship motions and loading conditions during their operation and hence fatigue is an important design criterion while designing and building ships. Fluctuating stresses encountered due to wave induced loads on the ship structure results in fatigue cracking on welded structural details. Underlying factors which were dormant all these years such as welding defects, improper designs, geometrical misalignments and poor workmanship may also contribute i.e. individually or collectively, to fatigue crack formation.

Fatigue induced cracks have been widely researched as it appears to be one of the common and most serious type of structural failure involving ships. The classification societies i.e. LR, DNV-GL, ABS, etc., and IACS have published guidelines on fatigue assessment, which give valuable guidelines on the areas in hull structure where the members are prone to fatigue related failure and the corresponding defect correction procedures to be adopted (LR 2004).

## 4.4 Inspection of Cracks in Ship Hull Structure Based on the Proposed Age Based Crack Assessment Criteria

To facilitate the inspection of the hull structure for cracks based on the proposed age based crack assessment criteria, the circular data visualization technique is adopted to illustrate the relationship between the ship operational life, the relevant inducement factors with its underlying causes i.e. crack assessment criteria, expected inspection findings and validation methods. This relationship together with the expected inspection findings and validation methods proposed are shown in fig. 4.3. The circular data visualization technique is adopted for its simplicity in understanding, compactness of data and handiness especially when inspecting confined spaces generally encountered on board ships.

The diagram is divided into 5 annular rings with additional radial subdivisions. The innermost ring indicates the age based classification of the ship in the category of 0-5 years, 6-10 years and 11-20 years. The second annular ring includes details of the various inducement factors responsible for crack initiation/formation corresponding to the age of the ship. The third annular ring indicates the various underlying causes for crack initiation corresponding to the selected inducement factor. The fourth annular ring provides information on the nature and location of the crack in the structural member or weld joint.  Finally, the outermost ring represents the industry acceptable inspection methods available to validate the findings made by the inspector. The annular rings in the proposed age based crack assessment criteria diagram in fig.4.3 are represented by the legend AR-1 to AR-5, and such means of identification is provided as the inspection procedure is not sequential i.e. not starting from the innermost ring and moving towards the outermost ring. The procedural steps involved in using the age based crack assessment criteria diagram is explained in the following section.

From a forensic investigation approach on marine casualties, the inspector can use the age based crack assessment criteria diagram to carry out damage assessment surveys and ascertain the level of maintenance provided for the hull structure depending on the number of cracks found.

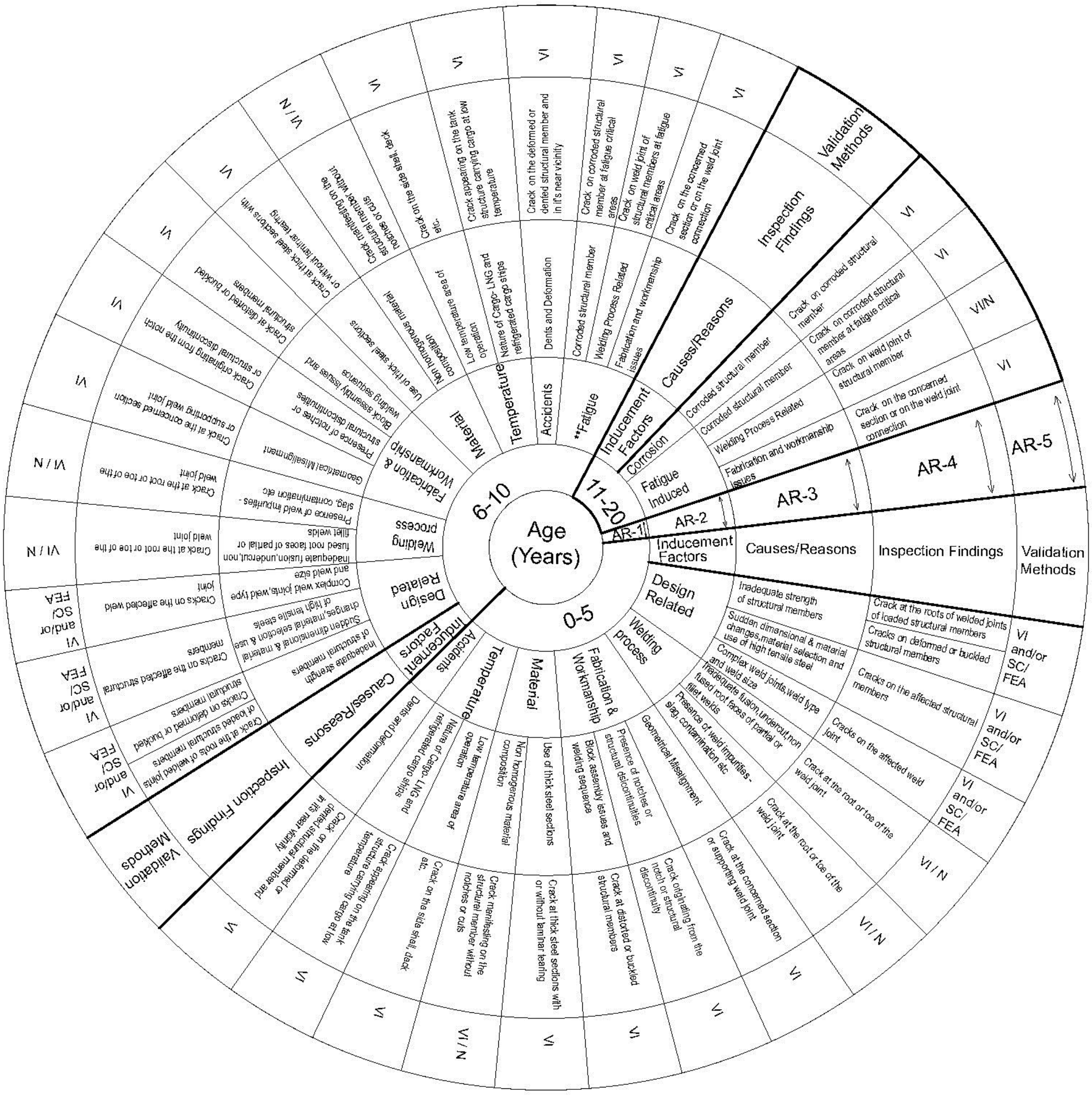

**Fig. 4.3: Age Based Crack Assessment Criteria for Ship Hull Structure**

*Legend :* 'VI' – Visual Indication; 'SC' – Structural Calculations; 'FEA' – Finite Element Analysis; 'N' – Non destructive examination; 'AR' – Annular Ring

Scrutiny of the past inspection records carried out in accordance with the age based crack assessment criteria proposed here could assist to ascertain any prior inherent weakness in the ship structure, which could have contributed to the escalation of the damage sustained. Similarly the classification societies, flag state and port state control could also benefit from theses inspection records during their periodical surveys and damage assessment surveys to identify the weak or crack prone areas which entail detailed surveys.

The simplicity in understanding and use of this diagram provides the ship owner or operator the impetus to use their qualified ship crew to undertake in-house inspection for crack detection in the hull structure. It empowers the qualified ship crew or inspector to make the necessary structural based evaluations on detectable cracks rapidly and with a certain high degree of accuracy, based on the selected age group the ship falls into. It also provides a single platform wherein the inspector is able to view and analyse the detected crack holistically i.e. identify the probable inducement factors responsible for crack initiation based on the nature and location of the crack, the underlying causes/ reasons based on onsite observations and ascertain inspection methods available to validate his findings.

Another advantage of the use of the proposed age based crack assessment criteria is in regards to ship maintenance and repair work. Ship repair and maintenance is a costly and time consuming activity which involves ship inspection, ascertaining the quantum of repair work required, preparing specifications and drawings for the proposed repair and so on. This activity gets all the more complicated and cumbersome as the ship gets older. Equally or more expensive is when the ship is involved in an accident and there is loss of life or environmental pollution as a result of weakened structure. The proposed age based crack assessment criteria is expected to form a more accurate basis for the inspector to determine or ascertain the repair needed well in advance to ensure minimum downtime of the vessel during maintenance activities in ship repair yard or drydock. Appropriate inspections methods which are commonly used by the shipbuilding industry are proposed to validate the onsite findings of the inspector. These methods range from simple visual examination of the crack to the more robust tools such as Non Destructive examination, structural calculations and FEA, depending on the age of the ship, the location where the crack has been detected and the possible circumstances leading to it.

The application of the proposed age based crack assessment criteria diagram in fig. 4.3 is demonstrated with a hypothetical case study together with a procedure providing step by step guidance on the inspection process.

### 4.4.1 Inspection Procedure for Use of the Age Based Crack Assessment Criteria Diagram

The steps involved in the inspection of cracks using the age based crack assessment criteria diagram are as follows:

*Step 1: Refer to Annular Ring AR-1*

Ascertain the age of the ship based on which the appropriate inducement factors and the corresponding causes/ reasons, inspection findings and validation methods are selected for inspection.

*Step2: Refer to Annular Ring AR-4*

Inspect the ship hull structure for cracks and list out the location of the cracks in the structural member based on the findings made.

*Step 3: Refer to Annular Ring AR-3*

Based on the location where the crack is found in the hull structure, identify the possible causes/ reasons for crack initiation. The various possible causes are to be selected which are relevant to the inducement factors based on the selected age group of the ship. In this step, onsite observation of the hull structure in the vicinity of the crack is to be performed to rule out some of the possible causes for crack initiation i.e. design issues, geometrical misalignment, notch, etc. These onsite observations are based on visual examination.

*Step 4: Refer to Annular Ring AR-5*

Identify the appropriate validation technique corresponding to the possible reasons/ causes identified in step 3, to be adopted for the cases which cannot be ascertained by onsite visual examination.

*Step 5: Refer to Annular Ring AR-2*

Based on the findings from the validation tests, ascertain the possible causes/reasons for crack initiation to identify the inducement factor responsible for crack initiation.

The application of the proposed procedure is elaborately detailed in the hypothetical case study, in the following section of this chapter.

## 4.5 HYPOTHETICAL CASE STUDY FOR INSPECTION OF CRACKS USING THE AGE BASED CRACK ASSESSMENT CRITERIA DIAGRAM

The use of the proposed age based crack assessment criteria diagram for inspection of cracks in the ship hull structure is demonstrated with a hypothetical case study. The hypothetical case study involves a General cargo ship operating in the world wide trade area and having an operational life in the category 0-5 years. The structural member under inspection is a fillet weld connection joining the side shell and the side shell longitudinal and is shown in fig. 4.4. Fillet weld of the non-penetrating or partially penetrating type are commonly used connections in shipbuilding (Fricke and Kahl 2008).

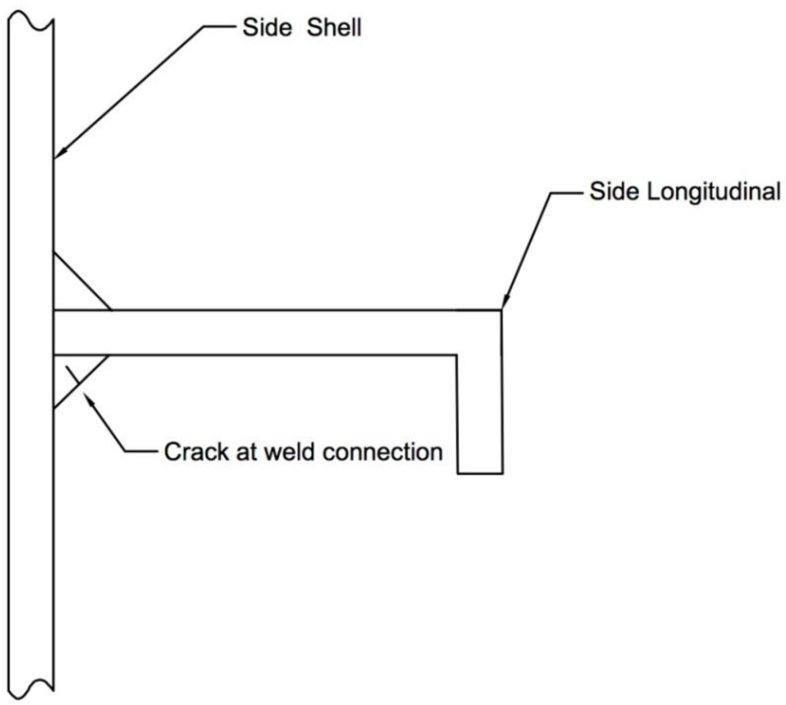


**Fig. 4.4: Crack at Weld Section Between Side Shell and Side Shell Longitudinal**

The inspection procedure for assesment of the crack is detailed in table 4.3.

**Table 4.3: Crack Assessment Using the Age Based Crack Assessment Criteria Diagram for the Hypothetical Case Study**

*Legend :* N – Non Destructive Examination; AR – Annular Ring

| **Step 1** Age of Ship (AR-1) | **Step 2** Inspection Findings (AR-4) | **Step 3** (Causes/ Reasons) (AR-3) | | **Step 4** Validation method (AR-5) | **Step 5** Inducement factor selected (AR-2) | Remarks |
|---|---|---|---|---|---|---|
| | | Possible Causes/Reasons | Onsite observations | | | |
| 0-5 years | Identify crack in the structure inspected i.e. crack at the weld joint connecting side shell and shell longitudinal | Inadequate strength of the structural member | Structural member size similar to other similar connections | | | |
| | | Complex weld joint, weld type and weld size | Fillet weld. Weld type and size similar to other similar connections. No crack initiation noted at other locations. | | | |
| | | Inadequate fusion, undercut, non-fused root faces or partial or fillet welds | To be investigated | N | | |
| | | Presence of weld impurities | To be investigated | N | Welding Process | weld impurities detected during examination |
| | | Geometrical misalignment | None seen | | | |
| | | Dents and deformations | None seen | | | |

The inspector upon detecting the crack at the fillet weld connection shown in fig 4.4 would then identify the probable causes for such crack initiation in the weld joint from the information provided in the age based crack assessment criteria diagram for the corresponding age of the ship. From table 4.3 it can be seen that 6 possible reasons/ causes have been identified involving 4 different inducement factors based on the inspection findings. A detailed observation of the structure in the near vicinity of the reported crack helps to further narrow down the probable causes/ reasons from 6 items involving 4 different inducement factors to the 2 items involving a single inducement factor. The root cause and inducement factor responsible for crack initiation in the concerned weld joint is then confirmed using the validation method proposed i.e. in this case Non-Destructive examination. The inducement factor identified is welding process related as the Non-Destructive examination revealed presence of weld impurities in the weld joint where the crack was located.

In this chapter, crack initiation in the ship hull structure together with the operational life of the ship has been given due importance in the inspection and survey regime. The intent of this approach is not only to mitigate the extent of damage sustained to the structure in the event of a marine casualty but also to prevent the recurrence of cracks, once repaired. The criteria for assessment of cracks corresponding to the operational life of the ship has been developed to facilitate inspection and survey of the ship hull structure in a more timely and organized manner. A state of art age based crack assessment criteria using the circular data visualization technique has also been developed. This visualization shows the relationship between the age of the ship and the crack assessment criteria, together with the inspection activities and validation methods to be followed to ascertain the correct inducement factor and cause for crack initiation. The application of this age based crack assessment criteria is demonstrated with a case study. Cracks manifesting in the ship hull structure at a very early stage of its operational life can now be systematically analysed and resolved by the use of the assessment criteria developed here. The developed age based crack assessment criteria is also expected to facilitate in inspections of marine casualties. The past records maintained on detected cracks in the hull structure based on the age based crack assessment criteria developed in this thesis would provide useful information to the investigators to ascertain any prior inherent weakness in the structure which led to the escalation of damage sustained due to the subsequent casualty.

# CHAPTER 5

# SUMMARY AND CONCLUSION

## 5.1 SUMMARY

Marine casualties continue to happen and at times result in loss of lives, loss of ship and environmental pollution. Cargo ships account for the highest number of casualties based on ship types. Collision, allision and grounding type casualties which are navigation related casualties account for the highest percentage amongst all the casualty types, and are mainly attributed to human errors and diminishing human performance. NASF type marine casualties are also a matter of concern and are associated with poor vessel maintenance, poor design and construction issues.

This thesis has dealt with marine casualties from three perspectives, namely from **human factor issues, engineering issues and inspection issues**. The research efforts initiated with the review of the available literature on all these three aspects. A lack of application of forensic engineering approach to marine casualty investigations has been noticed. A definite need was felt to have a process which can **identify the product and procedural shortcomings** and translate these findings **to improve the design, construction, inspection and operation of ships.** This would potentially prevent the future occurrence of marine casualties or de-escalate the damage sustained in the event of a casualty.

Ships are operated by humans, and one of the dominant reasons for many of the marine casualties investigated has been human errors and diminishing human performance as a result of human factor issues. The forensic engineering investigation approach for analysis of human factor issues in marine casualties has been demonstrated in this thesis. **An inter-relationship between the human factor issues, area based issues and the navigation and infrastructure issues has been established.** Based on this established relationship, ***best practices*** **have been formulated to resolve the identified human factor issues by analysing it together with the area based issues and the navigation and infrastructure issues pertaining to the geographical area of casualty**. **The *best practices* approach**

**developed in this thesis is new, genuine and an original work which has not been attempted earlier.** To facilitate the analysis based on the *best practices*, templates and procedures have also been developed in this study. The use of the *best practices* for resolving the human factor issues is illustrated with a hypothetical case study.

The need for marine casualty investigations from an engineering perspective is espoused citing the lack of engineering content in the casualty investigation reports on marine casualties involving collision and allision of differing levels of severity in accordance with the IMO guidelines. **The criteria for assessment identified in this study is HHD, individually and along with corrosion. A shortcoming or gap in the classification rules and IACS guidelines on the permissible deflection limits with respect to HHD has been identified in this study.** The impact of the present and future climatic changes on the ship side shell structure with HHD is discussed. **A forensic engineering based investigation procedure focussed on the criteria of assessment identified in this study is developed.** This procedure focuses on gathering or recording physical evidence on initial damages or imperfections present before the marine casualty, selection of the appropriate marine casualty for specialized studies and analysis, with respect to the criteria of assessment. **The forensic engineering investigation procedure developed in this study for addressing a specific and relevant engineering issue (HHD individually and along with corrosion) which impact the design, construction and survey of ships is novel, genuine and an original work which has not been attempted earlier.**

Crack initiation or formation in the ship hull structure appears inevitable in present day ships for many reasons discussed in this thesis. **These cracks can develop at a very early stage in the operational life of the ship** and propagate rapidly leading to failure when subject to impact loads typically associated with collision, allision, grounding and NASF. Inspection of cracks poses a challenge as they are not easily detectable. When detected and rectified, cracks may resurface again if the correct crack inducement factor is not identified. To facilitate the systematic inspection of the hull structure for cracks at a very early stage in the operational life of the ship and in marine casualty investigations, an **age based crack assessment criteria is developed in this study**. **A state of art diagram using the circular data visualization**

**technique is developed** to represent the age based crack assessment criteria together with the inspection findings and validation methods available. **The age based crack assessment criteria and the associated diagram developed in this thesis is new, genuine and an original work which has not been attempted earlier.** The use of the state of art age based crack assessment criteria diagram based on the developed procedure is presented with a hypothetical case study.

## 5.2 CONCLUSIONS

The application of a forensic engineering investigation approach addressing human factor issues, engineering issues and inspection issues pertaining to marine casualties is developed and demonstrated in this thesis.

i. *Best practices* are developed in this thesis to resolve the identified human factor issues leading to marine casualties in a geographical area of casualty. An inter-relationship has been established between the human factor issues, area based issues and the navigation and infrastructure issues in this regard. The analysis of marine casualties in a specific geographical area of casualty for human factor issues using the *best practices* approach has been validated with a hypothetical case study and so it can be claimed that the *best practices* developed in this study can be used prevent the recurrence of marine casualties as a result of human errors and poor performance issues.

ii. A forensic engineering investigation approach to resolve engineering issues leading or contributing to marine casualties has been addressed in this thesis using HHD, individually and along with corrosion, as the criteria for assessment. To facilitate the investigations based on the identified criteria of assessment, a forensic engineering based investigation procedure is developed with guidelines for gathering or recording physical evidence, selection and analysis of marine casualties.

iii. The criteria for assessment of cracks in the ship hull structure based on the ship operational life has been developed in this study to facilitate inspections. The developed age based crack assessment criteria for the ship hull structure has been represented using a state of art diagram based on the circular data visualization technique. The use of this crack assessment criteria based on ship operational life has been validated with a hypothetical case study. It can be claimed that this criteria not only facilitates inspection and survey of cracks but also ascertains the root cause and the remedial measures to prevent its recurrence. The developed criteria in this study are expected to facilitate marine casualty inspections, classification surveys, ship owner surveys and port control inspections.

## 5.3 RECOMMENDATIONS

The recommendations made based on the present study are listed below:

a) To encourage a forensic engineering based investigation approach to marine casualties which can bring about improvements in the rules and regulations governing the design, construction, survey and operations of ships, and to make available the investigation findings in the public domain.

b) To adopt the *best practices* developed in this thesis as a tool for analysis of human factor issues leading to marine casualties based on the geographical area of the casualty.

c) To recommend affected coastal states to conduct analysis in accordance with the *best practices* developed in this study for areas within their jurisdiction and where a high concentration of marine casualties is reported. This would facilitate in identifying the area based issues and navigation and infrastructure issues in these areas of marine casualty, which when addressed can prevent the occurrence of casualties in future due to human factor issues.

d) To adopt a uniform and consistent approach to populating marine casualty data based on the various criteria for evaluation identified in this study, amongst all of the coastal states or administration and investigation agencies, and to make such information available in the public domain of the GISIS casualty module.

e) To make compulsory the submission of marine casualty information based on Annex 1 and Annex 2 of MSC-MEPC (2008) for all *less serious* severity casualties involving collision, allision and grounding.

f) To initiate steps to update the standard wave data of 1986 based on the recent wave statistics to ensure that ships are designed and constructed to present environmental trends.

g) To adopt the procedural steps developed in this thesis which facilitates engineering based evaluation of the marine casualty in the *IMO Guidelines to Assist the Investigators in the Implementation of the Casualty Investigation Code*, so as to encourage marine casualty investigations from an engineering perspective.

h) To incorporate the inspection guidelines for HHD in the classification rules and IACS guidelines in accordance with the procedure developed in this thesis and to have the permissible deflection limits for HHD under various levels of corrosion specified.

i) To adopt the use of the age based crack assessment criteria diagram for the ship hull structure developed in this study within the inspection and survey regime of classification societies, ship owners and port state and to make mandatory that such inspection records be maintained throughout the operational life of the ship so as to facilitate investigations involving marine casualties.

j) To adopt the use of the age based crack assessment criteria for the hull structure developed in this study for assessment of the structural damage sustained during marine casualties.

k) To encourage ship owners and operators to conduct in-house inspections of the ship hull structure for cracks in accordance with the age based crack assessment criteria diagram developed in this study.

## 5.4 NOTABLE CONTRIBUTIONS

- A forensic engineering investigation approach encompassing human factor issues, engineering issues and inspection issues related to marine casualties has been demonstrated.

- The influence of area based issues and navigation and infrastructure issues in a specific geographic area of marine casualty on human factor issues leading to human errors and poor performance has been established in this thesis.

- A state of art *best practices* has been developed for resolving the identified human factor issues leading to marine casualties, based on the inter-relationship established between the human factor issues, the area based issues and the navigation and infrastructure issues for a specific geographical area of casualty.

- Templates for populating marine casualty data statistics based on the geographical location of casualty, casualty type, cargo ship type and voyage type, for analysis based on the *best practices* has been developed in this thesis.

- A need for a uniform and consistent approach in presentation of marine casualty information by the administration or member states and investigation agencies is espoused. For achieving this, a set of criteria based on which the casualty data is to be compiled and presented is highlighted in this study.

- A detailed procedure has been developed in this study for performing analysis based on the *best practices* for resolving human factor issues. The procedure covers information right from collection of data on marine casualties to its analysis followed by recommendations made, its implementation, monitoring, feedback and publication of findings. The responsibility of performing these analysis based on the developed *best practices* is also identified and included.

- The implications of increased wave heights and increased frequency of rogue or freak waves as a result of global warming issues is raised. The current use of the standard wave data published in 1986 for design of ships is highlighted.

- HHD has been identified as an engineering issue for which there is a gap or shortcoming specifying the extent of permissible deflections in the classifications rules and IACS guidelines. This individually and along with corrosion has been identified as the criteria for assessment in this study.

- A lack of engineering evaluation in the investigation reports of marine casualties involving collision, allision and grounding of varying severity levels based on IMO guidelines for marine casualty investigations is highlighted. To facilitate such an evaluation, an forensic engineering based investigation approach is advocated and developed here. The procedure developed for investigating the criteria of assessment identified in this study focuses on the investigation steps on 'gathering or recording physical evidence', 'selection of the marine casualty for investigation' and 'conducting specialized studies'.

- The advantages of selecting *less serious* severity marine casualties involved in collision and allision for a forensic engineering based investigation for specific engineering issues is highlighted.
- Guidelines for selection of appropriate marine casualties for a forensic engineering investigation with particular focus to HHD has been developed in this study. This is to ensure the investigations are economical, timely and provide meaningful results.
- A lack of adequate inspection and survey guidelines in the classification rules, regulations and IACS guidelines for cracks, especially from a non fatigue condition perspective has been highlighted in this study. The study also sheds light on the fact that cracks can manifest in the ship hull structure from a very early stage of the ship operational life.
- The criteria for assessment of cracks in the ship hull structure based on the ship operational life has been developed in this study to facilitate its inspection and survey. Cracks manifesting in the ship hull structure at a very early stage of its operational life can now be systematically analysed and resolved by the use of the assessment criteria developed here.
- A state of art diagram representing the age based crack assessment criteria for the ship hull structure has been developed and its use is demonstrated with a hypothetical case study. A procedure is also developed to provide guidance on the use of the developed age based crack assessment criteria diagram.
- The simplicity with which the age based crack assessment criteria diagram is developed for the inspection of cracks in the hull structure could encourage the

ship owner or operator to use their qualified ship crew to carry out in-house inspections rather than being over reliant on the classification societies for highlighting deficiencies.

- The records generated from inspection for cracks in accordance with the age based crack assessment criteria will provide useful information on the maintenance level of the ship and provide input information to the investigator performing forensic engineering investigations, in the event of the ship being involved in a marine casualty.

- The use of the age based crack assessment criteria can translate into cost savings for the ship owner or operator when the ship goes in for repairs, as he would have an accurate assessment of the repair work needed.

## 5.5 SCOPE OF FUTURE WORK

1. Development of a database of identified human factor issues in marine casualties pertaining to particular geographical area of casualty based on Marsden Squares grid system. This will assist with analysis and resolving the area based issues and navigation and infrastructure issues contributing to human errors and poor performance.

2. The investigate the influence of environmental issues i.e. weather conditions, sea state, day time and night time operations etc. on human factor issues in a specific particular geographical area, and how it can be resolved by addressing the area based issues and the navigation and infrastructure issues.

3. To ascertain the permissible HHD limits at varying corrosion levels and incorporate the requirements in the classification rules and IACS guidelines.

4. Identify any additional criteria which can be evaluated using a forensic engineering approach of *less serious* severity casualties to bring about Rules and Regulatory changes affecting the ship strength with particular focus on NASF casualty type.

5. To maintain a database on the initial imperfections and the damages sustained to the hull structure for *less serious* severity collision and allision casualties involving cargo ships. The information from this database can help develop guidelines for future investigations of more severe nature and of casualties involving NASF.

6. Identify any additional crack inducement factors with their possible causes/ reasons for initiation/ formation in the ship hull structure and to establish the relationship of these factors with the operational life of the ship.

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# APPENDICES

# APPENDIX-1

| Geographical Areas Based on Marsden Square Number | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S.No** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** |
| 1 | Casualty type, Ship type, Voyage and Analysis → Location ↓ | Grounding | | | | | | | | | | | | Analysis | | | |
| | | Gen. Cargo | | Bulk carrier | | Tankers (oil & product) | | Container Ships | | Ro-Ro | | Others | | Identified human factor issues | Area specific issues | Navigation and Infrastructu -re Issues | Recommen-dations |
| | | SV | LV | SV | LV | SV | LV | SV | LV | SV | LV | SV | LV | | | | |
| 2 | Open sea | | | | | | | | | | | | | | | | |
| 3 | Limited waters | | | | | | | | | | | | | | | | |
| 4 | Geographic location #1 | | | | | | | | | | | | | | | | |
| 5 | Geographic location #2 | | | | | | | | | | | | | | | | |
| 6 | Geographic location etc. | | | | | | | | | | | | | | | | |
| 7 | Terminal/ Port Location | | | | | | | | | | | | | | | | |
| 8 | Location # 1 | | | | | | | | | | | | | | | | |
| 9 | Location # 2 | | | | | | | | | | | | | | | | |
| 10 | Location # etc. | | | | | | | | | | | | | | | | |

**Table A.1:** ***Best Practices*** **Template for Combined Casualty Data Input and Analysis for Grounding Casualties**
Legend : SV – Short Voyage ; LV – Long Voyage

# APPENDIX-2

| Geographical Areas Based on Marsden Square Number | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.No | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 1 | Casualty type, Ship type, Voyage and Analysis → Location ↓ | Allision | | | | | | | | | | | | Analysis | | | |
| | | Gen. Cargo | | Bulk carrier | | Tankers (oil & product) | | Container Ships | | Ro-Ro | | Others | | Identified human factor issues | Area specific issues | Navigation and Infrastructure Issues | Recommen-dations |
| | | SV | LV | SV | LV | SV | LV | SV | LV | SV | LV | SV | LV | | | | |
| 2 | Open sea | | | | | | | | | | | | | | | | |
| 3 | Limited waters | | | | | | | | | | | | | | | | |
| 4 | Geographic location #1 | | | | | | | | | | | | | | | | |
| 5 | Geographic location #2 | | | | | | | | | | | | | | | | |
| 6 | Geographic location etc. | | | | | | | | | | | | | | | | |
| 7 | Terminal/ Port Location | | | | | | | | | | | | | | | | |
| 8 | Location # 1 | | | | | | | | | | | | | | | | |
| 9 | Location # 2 | | | | | | | | | | | | | | | | |
| 10 | Location # etc. | | | | | | | | | | | | | | | | |

**Table A.2: *Best Practices* Template for Combined Casualty Data Input and Analysis for Allision Casualties**

Legend : SV – Short Voyage ; LV – Long Voyage

# APPENDIX-3

INTERNATIONAL MARITIME ORGANIZATION

**E**

ASSEMBLY
28th session
Agenda item 10

A 28/Res.1075
24 February 2014
Original: ENGLISH

**Resolution A.1075(28)**

**Adopted on 4 December 2013**
**(Agenda item 10)**

**GUIDELINES TO ASSIST INVESTIGATORS IN THE IMPLEMENTATION OF THE CASUALTY INVESTIGATION CODE (RESOLUTION MSC.255(84))**

THE ASSEMBLY,

RECALLING Article 15(j) of the Convention on the International Maritime Organization concerning the functions of the Assembly in relation to regulations and guidelines concerning maritime safety and the prevention and control of marine pollution from ships,

NOTING WITH CONCERN that, despite the best endeavours of the Organization, casualties and incidents resulting in loss of life, loss of ships and pollution of the marine environment continue to occur,

NOTING ALSO that the safety of seafarers and passengers and the protection of the marine environment can be enhanced by timely and accurate reports identifying the circumstances and causes of marine casualties and incidents,

NOTING ALSO the rights and obligations of coastal and flag States under the provisions of Articles 2 and 94 of the United Nations Convention on the Law of the Sea (UNCLOS),

NOTING FURTHER the responsibilities of flag States under the provisions of the International Convention for the Safety of Life at Sea (SOLAS), 1974 (regulation I/21), the International Convention on Load Lines, 1966 (article 23) and the International Convention for the Prevention of Pollution from Ships (MARPOL) (article 12) to conduct casualty investigations and to supply the Organization with relevant findings,

CONSIDERING that each Administration shall conduct investigations of marine casualties and incidents, in accordance with SOLAS regulation XI-1/6, as supplemented by the provisions of the *Code of the international standards and recommended practices for a safety investigation into a marine casualty or marine incident (Casualty Investigation Code)* adopted by resolution MSC.255(84),

ACKNOWLEDGING that the investigation and proper analysis of marine casualties and incidents can lead to greater awareness of casualty causation and result in remedial measures, including better training, for the purpose of enhancing safety of life at sea and protection of the marine environment, RECOGNIZING the need for *Guidelines to assist investigators in the implementation of the Casualty Investigation Code* (resolution MSC.255(84)) to provide, as far as national laws allow, a common approach for States to adopt in the conduct of marine safety investigations into marine casualties and marine incidents,

RECOGNIZING ALSO the international nature of shipping and the need for cooperation between Governments having a substantial interest in a marine casualty or incident for the purpose of determining the circumstances and causes thereof,

HAVING CONSIDERED the recommendations made by the Marine Environment Protection Committee, at its sixty-fifth session, and the Maritime Safety Committee, at its ninety-second session,

1 ADOPTS the *Guidelines to assist investigators in the implementation of the Casualty Investigation Code* (resolution MSC.255(84)), as set out in the annex to the present resolution;

2 INVITES all Governments concerned to take appropriate measures to give effect to the Guidelines as soon as possible in order to allow effective analysis when conducting a marine safety investigation and taking preventive actions;

3 REVOKES resolutions A.849(20) and A.884(21).

Annex

**GUIDELINES TO ASSIST INVESTIGATORS IN THE IMPLEMENTATION OF THE CASUALTY INVESTIGATION CODE (RESOLUTION MSC.255(84))**

## 1 INTRODUCTION

1.1 The purpose of these Guidelines is to provide practical advice for the systematic investigation of marine casualties and incidents and to allow the development of effective analysis and preventive action. The overall objective is to prevent similar casualties and incidents in the future.

1.2 The ultimate purpose of a marine safety investigation is to advance maritime safety and protection of the marine environment. In the context of these Guidelines, this goal is achieved by identifying safety deficiencies through a systematic safety investigation of marine casualties and incidents, and then recommending or effecting change in the maritime system to correct these deficiencies. It is not the purpose of a safety investigation to determine liability or apportion blame.

1.3 These Guidelines should result in an increased awareness by all involved in the marine industry of the human, organizational, environmental, technical and external factors that may be involved in marine casualties and incidents. This awareness should lead to proactive measures by the maritime community which in turn should result in the saving of lives, ships, cargo and the protection of the marine environment, improvements to the lives of marine personnel, and safer shipping operations.

1.4 These Guidelines apply, as far as national laws allow, to the investigation of marine casualties or incidents in which either one or more States have a substantial interest because the casualty or incident involves a ship under or within their jurisdiction.

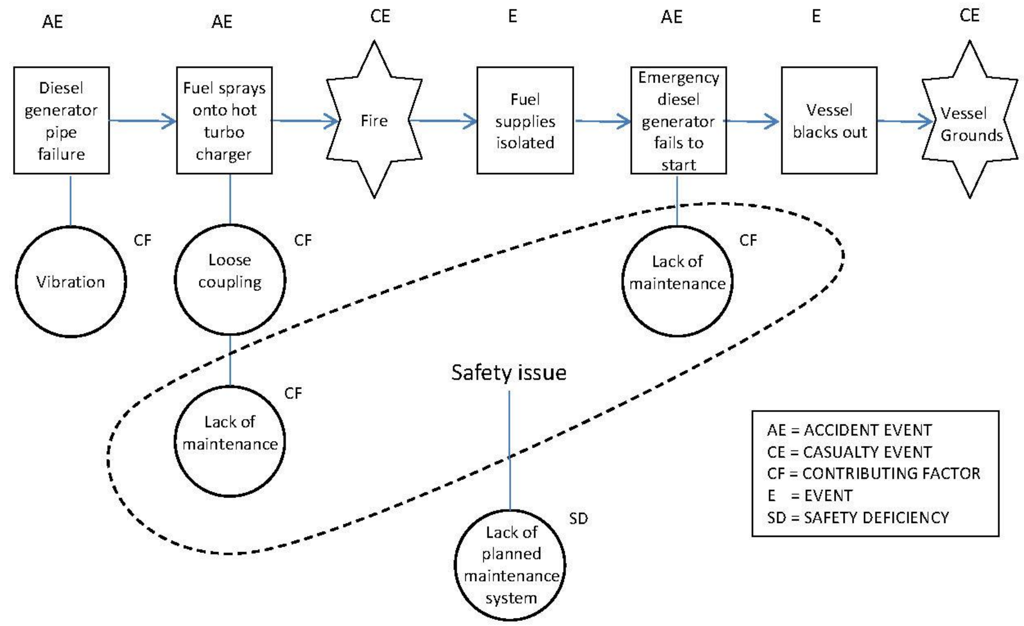
## 2 DEFINITIONS

### 2.1 Table of definitions

See chapter 2 of the Casualty Investigation Code (resolution MSC.255(84)) for terms not defined in these Guidelines.

| | |
|---|---|
| Event | An action, omission or other happening. |
| Casualty event | The marine casualty or marine incident, or one of a number of connected marine casualties and/or marine incidents forming the overall occurrence (e.g. a fire leading to a loss of propulsion leading to a grounding). |
| Accident event | An event that is assessed to be inappropriate and significant in the sequence of events that led to the marine casualty or marine incident (e.g. human erroneous action, equipment failure). |
| Contributing factor | A condition that may have contributed to an accident event or worsened its consequence (e.g. man/machine interaction, inadequate illumination). |
| Safety issue | An issue that encompasses one or more contributing factors and/or other unsafe conditions. |
| Safety deficiency | A safety issue with risks for which existing defences aimed at preventing an accident event, and/or those aimed at eliminating or reducing its consequences, are assessed to be either inadequate or missing. |

2.2 The following diagram illustrates how a sequence of events leading to a casualty occurrence would be classified using the above terms.




## 3 QUALIFICATIONS AND TRAINING OF INVESTIGATORS

3.1 To achieve a systematic and effective safety investigation the appointed investigators need to have expertise in marine casualty investigation and be knowledgeable in matters relating to the marine casualty or incident. Areas of expertise need to include evidence collection techniques, interviewing techniques, analysis techniques and the identification of human and organizational factors in marine casualties and incidents.

3.2 All investigators attending a marine casualty site should have sufficient knowledge in personal safety, taking particular note that the hazards present at a casualty site may well be beyond those encountered in normal ship operations.

3.3 A marine safety investigation Authority should consider developing a formal training programme to ensure that its investigators acquire the necessary knowledge, understanding and proficiency in marine safety investigation.

## 4 NOTIFICATION AND COOPERATION

4.1 Notification of a marine casualty or incident is to be provided to all affected parties as soon as reasonably practicable. Notification includes informing the parties involved in the casualty or incident according to chapter 20 of the Code, as well as any substantially interested State in accordance with chapter 5 of the Code. Notification should preferably be in a format that ensures a prompt acknowledgement from the addressee.

4.2 If the casualty or incident involves substantial interests of more than one State, the States should quickly reach an agreement on cooperation in accordance with chapter 7 of the Code. This agreement may include, but not be limited to:

.1 ensuring that the objectives of each participating State is in accordance with the IMO Casualty Investigation Code;

.2 which State will lead the investigation;

.3 the possibilities to share casualty information and draft safety investigation reports in accordance with chapter 13 of the Code, with regard to national legislation on confidentiality as well as the potential risk of safety investigation findings being used in criminal and civil lawsuits; and

.4 distribution of costs related to the investigation.

4.3 If an agreement in accordance with chapter 7 of the Code cannot be reached, the involved States should seek to share factual information to the greatest extent possible, being guided by the recommended practice in the Code.

## 5 INVESTIGATION

### 5.1 Extent of investigation

5.1.1 Marine casualties and incidents can have many causal factors and the underlying safety issues often exist remote from the casualty site. Proper identification of such issues requires timely and methodical investigation, going far beyond the immediate evidence in search for conditions which may cause future occurrences. Marine casualty or incident safety investigations should therefore be seen as a means of identifying not only the accident events, but also safety deficiencies in the overall management of the operation from policy through to its implementation, as well as in regulation, survey and inspection. For this reason safety investigations should be broad enough to meet these overriding criteria.

5.1.2 The extent of any safety investigation can be divided into five areas:

.1 people;

.2 environment;

.3 equipment;

.4 processes and procedures; and

.5 organization and external influences.

### 5.2 Initial response

An investigation should be carried out as soon as possible after an occurrence so as to limit the loss of perishable evidence including the degradation of witness memory. To be able to start promptly it is essential that the investigating State has a preparedness plan in place which, among other things, will facilitate:

.1 the ready availability of trained investigators;

.2 the availability of specialist help, including experts on human and organizational factors;

.3 ready access to 24-hour contact points for other marine safety investigation Authorities; and

.4 the availability of the necessary predictable resources.

**5.3 Site management**

5.3.1 Site management generally starts even before the investigator deploys to the casualty site. The pre-planning will often need to include:

.1 identification of competencies needed at the casualty site;

.2 identification of hazards and risks that the investigation team may encounter at the casualty site, and the precautions that need to be taken, as well as the personal protective equipment (PPE) that needs to be carried;

.3 identification of particularly vulnerable evidence that needs to be secured as soon as possible including Voyage Data Recorder (VDR) information, documentation of sites that for some reasons cannot be left unchanged until the team arrives, and repatriation of crew members; and

.4 a draft interview schedule that takes into account repatriation of seamen as well as the fact that persons involved can suffer from trauma.

5.3.2 There can be many different stakeholders involved in the aftermath of a marine casualty or incident, each with their own legitimate interests and responsibilities. Coordination at the casualty site is vital to make sure that the evidence collection is successful.

5.3.3 When arriving at the casualty site the hazard and risk assessment should be reviewed to identify any additional risks for the team and to put in place any necessary remedial action before the team starts its work.

**5.4 Start-up meeting**

In safety investigations involving more than one State it is generally wise to set up a meeting with representatives of the other substantially interested State(s) at an early stage. The purpose of the start-up meeting is, among other things, to facilitate:

.1 the sharing of knowledge of what is known about the marine casualty or incident;

.2 the development of an investigation plan;

.3 the delegation of investigation tasks (international coordination); and

.4 the identification of additional help in the form of specialists and/or technical expert examination.

**5.5 Collection of evidence**

5.5.1 During the safety investigation, investigators should aim to gather and record all the evidence and factual data which may be of interest within the scope of the investigation. Physical and documentary evidence and witness statements should be gathered not only at the casualty site, but also from all sources required to fully explain the accident events and their contributing factors (e.g. operation, management, inspection and regulation).

5.5.2 Evidence collection also needs to be broad enough to cover the human, organizational and environmental factors in relation to the casualty or incident. If a human and organizational factor specialist is required, it is essential to include this expert as early as possible in the investigation team.

5.5.3 To facilitate a comprehensive evidence collection it is often wise to:

.1 refer to generic checklists while remaining flexible as evidence once collected will often point to new areas of inquiry; and

.2 use a system to register the evidence collected (evidence log). This is particularly valuable in complex investigations or when more than one State is involved.

5.5.4 It is recommended that the fact-finding stage of the investigation process itself be kept separate from the complete analysis of the collected evidence leading to conclusions and recommendations. Fact finding usually includes, but is not necessarily limited to the areas covered in sections 5.6 to 5.10.

**5.6 Inspection of casualty site**

5.6.1 Inspection and documentation of the casualty site and/or places of interest for the investigation can include inspection of the ship/ships involved, a fairway where the casualty or incident occurred, and underwater survey and filming of the wreckage of a ship.

5.6.2 The collection of evidence that can deteriorate or disappear over time will always be the first priority in evidence collection when the investigator(s) arrives at the casualty site. Photo and/or video documentation of the site in general and in detail, and before any removal of evidence, is generally also a high priority.

5.6.3 Where there is perishable evidence and the investigator(s) may be delayed in arriving at the casualty site, there may be a need to give instructions for the evidence to be preserved.

**5.7 Gathering or recording physical evidence**

5.7.1 Physical evidence can include data from VDR and other electronic devices on board like electronic charting systems, central fire alarm units, as well as nautical charts, weather forecasts obtained on board and logbooks. Physical evidence can also include technical samples of oil, paint or fire residues, and pieces of broken machinery or other broken parts.

5.7.2 It is essential that the person who collects electronic, documentary or material evidence is skilled in applicable techniques for both collection and storage of that type of evidence to prevent contamination, further deterioration or loss.

5.7.3 Some information of great value can also be obtained from external sources such as CCTV, shore radar and radio surveillance systems and Marine Rescue Coordination Centres. Vessel Traffic Services (VTS) centres may also be able to provide valuable information, including recordings of radio traffic and AIS information.

**5.8 Witness information**

5.8.1 Witness interviews should be performed by persons skilled in interviewing techniques to reveal information the witness may be able to provide. The planning of the interview is essential for a successful outcome. Things to be considered include:

.1 time and location;

.2 any need for interpreters;

.3 constitution of the interviewing team and the roles of the team members;

.4 the particular needs of the witness; and

.5 the topic areas to be explored with the witness.

5.8.2 The interviewee should be informed, before the interview starts, about the purpose of the investigation and the conditions under which he/she will be providing information. The witness should generally be interviewed alone, or be accompanied by someone nominated by the witness. The nominated individual should, however, not be allowed to interfere with the interview. The witness should under all circumstances be allowed access to legal advice if he/she wants it (see chapter 12 of the Code).

5.8.3 The interview may be recorded or a written record may be made of the interview. A written record should be discussed with the witness to clarify any anomalies. Witness information should be verified wherever possible. Statements made by different witnesses may conflict and further supporting evidence may be needed.

**5.9 Reviewing of documents, procedures and records**

5.9.1 Documents to be reviewed can include personal and ship-related certificates, reports from the ship's classification society, maintenance records, the Master's standing orders, etc. An assessment may also be made of the company's Safety Management System from its safety policy through to its implementation within the organization.

5.9.2 Government agencies such as customs, quarantine and State Authorities may have useful information relating to crew lists, the general condition of the ship, ship certificates, etc. Coroners and medical records can provide valuable information. Port authorities and independent surveyors can also hold information of use to an investigation. Applicable regulations may also need to be examined.

5.9.3 A good investigation explores the extent of correlation between the documents and reality at all appropriate levels: this will generally require some specialist skills.

**5.10 Conducting specialized studies (as required)**

5.10.1 It can sometimes be necessary to conduct specialized studies to establish how a casualty or incident happened. This can include, for example, metallurgic specialist studies of broken machinery parts, analysis of oil or paint residues, calculation and reconstruction of a ship's stability features, lashing calculations, specialist analysis of weather and sea conditions at the time and place of the casualty or incident, and the use of simulators to reconstruct and analyse a sequence of events.

5.10.2 Where a proposed testing of physical evidence is likely to change its state, other interested parties who may be relying on that evidence should be consulted.

**5.11 Reconstruction and analysis**

5.11.1 There are several different methods of organizing evidence to support reconstruction and analysis in safety investigation, each having its own benefits and drawbacks. To ensure that a casualty or incident is thoroughly examined from a safety point of view, it is essential that the investigation is done with a systemic perspective. A systemic perspective involves going beyond determining "who did what?" and to look for the conditions that influenced different relevant events, even when these conditions are to be found remote from the casualty site. A systemic perspective also puts human factors into context and includes the interactions between man, machine and the organization.

5.11.2 The analysis methods used will help the investigator to think in a structured way but will also have an effect on where the investigator will put his/her focus. Some methods focus on human factors; some support the understanding of the sequence of events; others are more supportive in a complex safety analysis or in understanding technical failures. Analysis methods should therefore rather be seen as tools in a tool box. A good investigation will choose the optimal set of analysis tools to meet the characteristics of that particular casualty or incident. However, the method or the combination of methods used in each investigation should as a minimum requirement support:

.1 reconstruction of the casualty or incident as a sequence of events;

.2 identification of linked accident events and contributing factors at all appropriate levels; and

.3 safety analysis and development of recommendations.

**5.12 Reconstruction of the casualty events and their linked conditions**

5.12.1 The first step in analysis is to review the factual information to clarify what is relevant and what is not, and to ensure the information is as complete as possible or practicable. This stage of the analysis should aim at determining how the marine casualty or incident occurred. The reconstruction is preferably done by using a method that enables a graphical description of the sequence of events. This is beneficial since it allows the investigator to discuss and present the case, and in particular to:

.1 identify gaps in the information;

.2 identify any conflicts in evidence;

.3 provide a graphical description of how different events are related; and

.4 identify contributing factors and their relation to different accident events.

5.12.2 Marine casualty or incident investigation is an iterative process and the reconstruction phase generally identifies a need to make a revision of the evidence collection plan.

**5.13 Safety analysis**

The purpose of a safety analysis is to get a more thorough understanding of the underlying safety issues that can cause or contribute to a casualty or incident. Some investigation analysis methods combine casualty reconstruction and safety analysis into one. Some basic analysis methods can be directly linked to the reconstruction of events, while other safety analysis tools can be derived from different accident causation models and are better used as stand-alone methods. Efficient safety analysis tools:

.1 encourage different perspectives of casualty or incident causation;

.2 support communication and deeper questioning;

.3 enable the identification of safety issues and safety deficiencies, including those remote from the casualty site; and

.4 enhance the development of effective remedial actions at all appropriate levels.

**6 REPORTING**

**6.1 Reporting requirements**

6.1.1 MSC-MEPC.3/Circ.4 requires particular marine casualty data to be entered into the GISIS marine casualties and incidents module, together with the final version of a marine safety investigation report.

**6.2 Final report**

6.2.1 To facilitate the flow of information, the final report of the safety investigation should be well structured and cover what is listed in paragraph 2.12 of the Code. The report should, within its different parts, clearly distinguish between facts and analysis.

6.2.2 Non-judgmental language should be used in the report reflecting the purpose to enhance maritime safety and protection of the maritime environment. Witnesses' names and personal information which may identify them should remain confidential.

6.2.3 In normal investigation practice, gaps in information that cannot be resolved are usually filled by logical extrapolation and reasonable assumptions. Such extrapolation and assumptions should be identified and a statement of the measure of certainty provided. Despite best efforts, analysis may not lead to firm conclusions. In these cases, the more likely hypotheses should be presented.

6.2.4 If safety recommendations are issued these should be addressed to those that are best placed to implement them, such as shipowners, managers, recognized organizations, maritime authorities, vessel traffic services, emergency bodies, and international and regional maritime organizations and institutions. Safety recommendations should always be supported by the facts and analysis of the safety investigation. To gain acceptance, recommendations need to be practical, necessary and likely to be effective.

6.2.5 Where it becomes apparent during an investigation that there is a safety deficiency that presents a serious potential risk to lives, ships or the environment, action should be taken to inform the people or organization responsible for managing the risk. This may take the form of an interim safety recommendation or some other means of correspondence. It is important not to delay action to address such safety risks until the completion of the investigation.

### 6.3 Consultation

6.3.1 In accordance with paragraphs 25.2 and 25.3 of the Code, where it is practicable, the investigator should send a copy of a draft marine safety investigation report for comment to the interested parties as defined in paragraph 2.7 of the Code. This allows a process for correcting matters of fact within a report and the consideration of alternative hypotheses or opinions in relation to the analysis. In addition, it allows responsible parties, e.g. the ship operator, to indicate what safety action may have been taken in relation to a safety issue. Any such action taken should be included in the final report.

6.3.2 The investigator should consider the comments before preparing the final marine safety investigation report, being guided by paragraph 25.3 of the Code.

### 6.4 Publication

6.4.1 The final report should be made available to the public and the shipping industry in accordance with paragraph 14.4 of the Code. The Internet is a valuable tool for making a report available to the public.

6.4.2 A summary of the marine safety investigation report and any safety recommendations, translated into English and/or other major languages, will enable a global public to gain important safety information from the investigation.

### 6.5 Follow-up on safety recommendations

6.5.1 Every recommendation addressed to an individual or specific organization should be followed up within a reasonable period following the release of a final safety investigation report with a view to promoting safety action. It is also good practice to reinforce positive safety action taken to address a recommendation by making it public.

APPENDIX

**AREAS OF HUMAN AND ORGANIZATIONAL FACTORS INQUIRY**

The areas of inquiry set out in this appendix can be used in planning the investigation of human and organizational factors during a maritime safety investigation. Some areas of inquiry overlap or indeed incorporate multiple interactions. The guidance is not meant to be exhaustive, nor is it intended to be a checklist where each point must be investigated every time. Some areas may not be relevant in the investigation of a particular occurrence, while other areas may require deeper investigation. As new human and organizational factors/issues emerge, new areas of inquiry will need to be explored by investigators.

Skilful interviewing can help the investigator to eliminate irrelevant lines of inquiry and focus on areas of greater potential significance. The order and manner in which questions are asked will depend on who is being interviewed and on his or her willingness and ability to recall and describe personal behaviour and personal impressions. Training in cognitive interviewing techniques will assist investigators in eliciting accurate information from interviewees, and is highly recommended. Further, because human interactions, including interviews, can be subject to misunderstanding, it will normally be necessary to verify, cross-check or augment information received from one person by interviewing others on the same subject(s).

While important human and organizational factors/information can be gained through interviewing, investigators must ensure that they also seek additional information through other means. Examination of rosters, procedures, personnel records, safety occurrence reporting records and risk assessment protocols (for example) may provide critical insights into practices, norms and attitudes potentially affecting safety.

**SHIPBOARD ISSUES**

**1 Training and experience**

- Position or rank held.
- Certificate held; length of time the certificate has been held; where trained.
- Experience in the position; both on this ship and over career.
- Length of time on this contract and overall on board the ship.
- Experience on other ships; both with this company and other companies.

**2 Shipboard organizational structure and processes**

- The management/department structure on board the ship.
- The individual's position within the on-board structure; who they work for, who they work with, who they report to and who they assign duties to.
- Normal day-to-day responsibilities, tasks and duties.
- Description of any interaction with personnel ashore.

## 3 Nature of tasks

- Specifics of the task(s) being undertaken at the time of the occurrence, including location.
- Differences between the task at that time and normal operations.
- Description of the social dynamics of the working environment (e.g. alone/pair/team).
- Understanding of the task.
- Familiarity with the task; last time it was performed, etc.
- Available discretion relating to how the task was to be accomplished.
- Training provided for the task; what was the training.
- Procedures, documents and guidance for the task.
- Equipment used for the task; reliability, previous failures, problems and were the crew familiar with it.
- Physical environment; heat, humidity, noise, confined space, exposure to chemicals, etc.
- Workload and/or effort required for the task:
    - To what extent was it within the crew's capability at the time.
    - Were there any tasks that were not done because of the workload.
    - Physical effort involved; pushing, pulling, lifting, etc.
    - Mental effort involved; thinking, deciding, calculating, remembering, looking, searching, etc.
    - Time pressure involved; adequacy of time allocated to the task.
    - Use of scaling questions may assist here (e.g. "on a scale of 1 to 10, where 1 is very easy and 10 is extremely difficult, how (physically) difficult was this task ...").

## 4 Activities prior to occurrence

- Actions and/or activities before coming on watch or reporting for duty.
- Individual's role in the operation being conducted by the ship at the time of the occurrence.
- Individual's location on board at the time of the occurrence.
- What was being observed immediately prior to the occurrence; what was seen, heard, felt, smelled, and thought about.

**5 Work period/rest period/recreation pattern**

- Description of normal duty schedule (e.g. day worker or watchkeeper).
- Description of duty schedule on the day of the occurrence; on the day before and during the week before the occurrence.
- Length of time awake and/or on duty at the time of the occurrence.
- Overtime worked on the day of the occurrence; on the day before and during the week before the occurrence.
- Usual sleep/rest routine (what time asleep and awake).
- Sleep/rest routine in the three days (72 hours minimum) leading up to the occurrence:
  - 72-hour history of time to bed/time to sleep/duty times/nap times.
  - If there is an indication of reduced sleep beyond 72 hours, collect sleep information beyond 72 hours (as a guide, collect information back to two good nights' rest prior to the occurrence).
  - Quality of sleep; disturbances, light sleep, waking, how refreshed when waking.
  - Time of day when sleep is taken (impact on quality).
  - Last extended period of off-duty time.

**6 Living conditions and shipboard environment**

- Description of the adequacy of personal facilities; individual, shared or communal; noisy, cramped, vibrations, temperature, ship's motion, etc.
- Availability and consumption of alcohol and/or non-prescribed medications.

**7 Physical health**

- Symptoms of illness experienced within the 72 hours before the occurrence.
- Medications taken (prescribed, not prescribed).
- Description of the last meal consumed prior to the occurrence; what and when.
- Description of existence and regularity of exercise routine.
- Details of any recent medical examinations, illnesses or injuries.
- Details of any regular or irregular medication, both prescribed and not prescribed.
- Description of quality of vision (e.g. corrective lenses).
- Description of quality of hearing (e.g. hearing aids).
- Name and contact details of personal physician.

## 8 Mental health

- Length of time spent away from family or loved ones.
- Extreme emotions at any time in the days before the occurrence; e.g. feelings of extreme sadness, anger, worry, fear (use scaling questions (1 to 10) to determine level).
- Important and/or difficult personal decisions made recently; e.g. financial or family worries.
- Recent work performance; any concerns from others.
- Stress and/or difficult situations whilst on board and how these were being managed.
- Difficulties with concentration.
- Any mental health issues recently and/or in the past.
- Medications taken (prescribed, not prescribed).

## 9 Working relationships

- Friendships and/or support from other crew members.
- Conflicts and/or clashes with other crew members or supervisors.
- Trust in other crew members.
- Language barriers interfering with work performance.
- Clarity of roles and responsibilities with other crew members.

## 10 Employment conditions

- Contractual arrangements.
- Complaints or industrial action and systems for resolution of these.
- Recent changes to employment conditions.

## 11 Safety policy

- Awareness of the company's safety policy.
- Ship's procedures for dealing with safety issues; methods of reporting and addressing safety concerns.
- Safety training; type, nature and frequency.
- Emergency drills; type, nature and frequency.
- Personal protective equipment (PPE) provided.
- Records and/or knowledge of personal accidents or injuries prior to the occurrence.

**12 Staffing levels**

- Sufficiency of staffing/crewing levels on board.
- Appropriate allocation of crew members to duties.
- Changes to normal staffing/crewing levels.

**13 Standing orders**

- Master's standing orders; for all or part of the crew.
- How are the orders communicated.
- Are the orders in accordance with the company policies.

**14 Level of automation and reliability of equipment**

- Complexity of machinery and automated systems.
- Training provided for systems.
- Competency of crew in using the systems.
- Reliability of systems; any earlier failures.
- Maintenance of systems.
- Are the systems integrated with each other and with the task requirements.

**15 Ship design, motion/cargo characteristics**

- Ship design, motion or cargo characteristics; any features which interfere with human performance (e.g. obstructed watchkeeper vision).

**SHORESIDE MANAGEMENT ISSUES**

**16 Management policies and procedures**

- Existence of and opinion about the effectiveness of the safety management system, including auditing, analysis, reporting and investigation of the occurrence.
- Existence of and opinion about the effectiveness of risk assessment and management policies and procedures relating to ships, personnel and the environment.
- Existence of and opinion about the effectiveness of the role of the Designated Person Ashore (DPA).

**17 Scheduling of work and rest periods**

- The company's work schedule, relief policy and risk management policy on fatigue.
- Adherence to these policies.
- Recent changes to these policies.

**18 Staffing levels**

- The company's policies and practices for determining staffing/crewing levels on board the ship.
- The effectiveness of these policies and practices.

**19 Assignment of duties**

- The company's policies for determining watchkeeping practices and other duties on board the ship.
- The actual watchkeeping practices.

**20 Shore-ship-shore support and communications**

- Means and level of support for the ship's master in conduct of operations.
- The master's reporting requirements.

**21 Voyage planning and port call schedules**

- Policies, procedures and guidelines provided to the master to enable voyage planning.
- Actual practices for voyage planning.

**22 Recreational facilities**

- The company's policies and practices for the provision of welfare and recreational services on board.

**23 Contractual and/or industrial arrangements and agreements**

- Contractual arrangements for all crew members.
- Complaints or industrial action in the last year.

**24 National/international requirements**

- Appropriateness of the applicable international conventions and flag State regulations.
- Effectiveness of the flag State's implementation of the requirements and recommendations of the applicable international conventions.
- Compliance with the requirements and recommendations of the applicable international conventions and flag State regulations.

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# CURRICULUM VITAE

## Personal Information

| | | |
|---|---|---|
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## Educational Qualification

| | | |
|---|---|---|
| *2000 – 2001* | : | MSc "Operations Management and Manufacturing Systems"<br>University of Nottingham, Nottingham, United Kingdom |
| *Result* | | *First Class with Distinction.* |
| *1992 - 1996* | : | Bachelor of Engineering (Mechanical Engineering),<br>University of Mysore, India |
| *Result* | | *First Class with Distinction.* |
| *1991-1992* | : | $12^{th}$ Standard, CBSE Board<br>Kendriya Vidyalaya Andrews Ganj, New Delhi. |
| *Result* | | *First Class* |
| *1989-1990* | : | $10^{th}$ Standard, CBSE Board<br>Kendriya Vidyalaya Andrews Ganj, New Delhi. |
| *Result* | | *First Class* |

## Employment History

| | |
|---|---|
| *Feb 2014 – Feb 2017* | **Indian Maritime University – Cochin Campus**<br>Southend Reclamation Area,<br>NH-47A Matsyapuri P.O, Kochi |
| Designation | Faculty (Contract) |
| *July 2013 – Feb 2014* | **Cochin University of Science and Technology**<br>Department of Ship Technology<br>Kochi - 682022 |
| Designation | Guest Faculty |
| *Sept 2005- March 2013* | **American Bureau of Shipping (ABS) – Pacific Division**<br>438B, Alexandra Road, #06-05/06,<br>Blk B, Alexandra Technopark, Singapore. |
| Designation | Senior Engineering Specialist |

| | |
|---|---|
| *June 2002 – Sept 2005* | **Tero Marine (S) Pte Ltd ,**<br>3 International Business Park,<br>#03-08 Nordic European Center<br>Singapore. |
| Designation | Senior Design Engineer (Piping & Machinery) |
| *Nov 1997 – May 2002* | **National Ship Design and Research Centre**,<br>Gandhigram, Visakhapatnam,<br>Andhra Pradesh, India. |
| Designation | Design Engineer (Piping & Machinery) |
| *Jan 1997 – Nov 1997* | **H.V. Equipments Pvt Ltd,**<br>New Delhi, India. |
| Designation | Project Engineer |

**DECLARATION**

I declare that the entries made in this document are correct and true to the best of my knowledge and nothing has been either concealed or misrepresented by me.

Kochi
/05/2018 Signature

# LIST OF PAPERS SUBMITTED AND PRESENTED ON THE BASIS OF THIS THESIS TOPIC

## 1. Papers Submitted

a. **Ajit Nair, K. Sivaprasad and C.G. Nandakumar.** Crack assessment criteria for ship hull structure based on ship operational life, *Cogent Engineering* (2017), 4: 1345044.

b. **Ajit Nair, Sivaprasad K. and Nandakumar C.G.** Novel Systematic Approach to Assessing Human Factor and Engineering Issues in Marine Accidents, *IOSR Journal of Engineering*, Vol. 08, Issue 3 (March. 2018), V2, PP 61-72, ISSN (e): 2250-3021, ISSN (p): 2278-8719.

c. **Ajit Nair, Sivaprasad K. and Nandakumar C.G.** *Best Practices* for Analysis of Human Factor Issues in Marine Casualties, *Accident Analysis and Prevention* –Communicated.

## 2. Presentation in Conferences

1. **Ajit Nair, K. Sivaprasad and C.G. Nandakumar.** Forensic Investigations : The Way Forward to Marine Accident Investigations, Mastech 2015, Kochi, India