Crack assessment criteria for ship hull structure based on ship operational life

Ajit Nair, K. Sivaprasad and C.G. Nandakumar
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Ajit Nair1*, K. Sivaprasad1 and C.G. Nandakumar1

Abstract: Steel ship structures are prone to developing cracks as a result of their all welded construction, material imperfections, loading conditions, fatigue and corrosion. Much of the research in this field has been focussed on crack growth or propagation from a fatigue perspective. However cracks can develop as early as during the construction stage itself and not all of them would be detected and rectified. Normally these cracks may not pose a direct threat to the ship structural integrity but when subjected to a sudden impact force typically associated with collision, allision and grounding accidents, these existing cracks could propagate at a faster rate and lead to structural failure and compromise the tank leak integrity. This paper presents criteria for assessment of cracks based on inducement factors which influence crack initiation in the hull structure even during the early stages of operation. Detectable cracks identified during inspection are analysed to determine the inducement factor and the underlying causes for such crack initiation corresponding to the ship operational life. Subsequent repair work performed will not only resolve the identified inducement factor responsible but also ensure that these cracks will not resurface and pose threat to the structural integrity of the ship, even under sudden impact. A relationship is established between these inducement factors and the ship operational life to simplify the inspection and crack assessment process. The circular data visualization technique is adopted to represent this relationship and a procedure is developed to demonstrate the use of the proposed crack assessment criteria.

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PUBLIC INTEREST STATEMENT
Steel ship structures are prone to developing cracks as a result of the way they are built, operated and maintained. Identifying the root cause for crack formation is very complex. Normally these cracks may not pose a threat to the ship structural integrity however when subjected to a sudden impact force typically associated with collision, contact and grounding accidents, these existing cracks could open up at a faster rate and lead to additional structural failure of the ship hull resulting in loss of the ship or its cargo.

In this paper, a procedure is developed to identify the root cause for such crack formation so that when cracks are detected, the repair work resolves the root cause and thereby prevents the crack from resurfacing after sometime. Such a proactive measure would prevent escalation of damage sustained to the ship structure in the event of an accident.
1. Introduction

Accidents at sea in the past few decades have elicited global safety concerns due to the pollution impact they cause to the fragile ecological system, in addition to the loss of life and property. Nowadays, ships and its equipment are built to meet stringent standards of safety and pollution prevention, undergo detailed inspections during construction and while in service, ply on waterways with rules governing its use, and finally are manned by well trained and qualified crew. Despite these measures accidents continue to happen, sometimes with catastrophic consequences. Collision, allision (contact) and grounding accidents figure prominently as the accident type encountered by cargo ships with potentially serious consequences (European Maritime Safety Agency [EMSA], 2015; Japan Transport Safety Board [JTSB], 2016; Marine Accidents Investigation Branch [MAIB], 2015; Youssef, Kim, Paik, Cheng, & Kim, 2014). Almost 40–60% of the accidents involving cargo ships are due to collision, allision and grounding accidents as per accident statistics presented by European Maritime Safety Agency (EMSA, 2015), Marine Accidents Investigation Branch (MAIB, 2015) and Japan Transport Safety Board (JTSB, 2016). The literature is also rich with studies attributing human errors in operating and manning of these ships as one of the primary reasons for such accidents, exceeding other causes such as technical and mechanical failures, design issues, and environmental conditions (Baker, McSweeney, & McCafferty, 2002; Baker & Seah, 2004; Card, Baker, McSweeney, & McCafferty, 2005; Emond, 2012; McCafferty & Baker, 2006). Almost 80–85% of the accidents are as a result of human errors and poor human performance (Baker & Seah, 2004; McCafferty & Baker, 2006).

In the present scenario, the shipping industry has to be cautious towards accidents as there is no such insignificant leak which is acceptable anymore. In an extreme event such as collision, allision or grounding accident 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. One such potential area of concern identified and addressed in this paper is the presence of cracks in the hull structure of all welded steel ships. Presence of these cracks and its behaviour during a sudden impact force i.e. collision, grounding or allision can result in a significant drop in energy absorption by the hull structure resulting in more damage (Abramowicz & Simonsen, 2003).

A crack assessment criteria is presented in this paper which helps to identify the potential sources or inducement factors responsible due to which cracks manifest in the ship hull structure during construction and operation. These inducement factors are categorized based on when they are likely to be the source for crack initiation or formation corresponding to the ship operational life. Possible validation techniques available to confirm the crack assessment to a particular inducement factor based on the inspection findings is also presented. It is the aim of this paper that following the proposed crack assessment criteria presented here will assist to identify the inducement factor and the underlying causes or reasons responsible for crack initiation. Satisfactory resolution of the responsible inducement factor will prevent the resurfacing of crack upon repair work and thus pose minimum threat to the structural integrity of the ship hull structure in the event of it being subjected to sudden impact loads.

The ship operational life is divided into three age groups i.e. 0–5, 6–10 and 11–20 years. For the purpose of this paper, “Inducement factors” are defined as those factors which may directly or indirectly be responsible for crack initiation/formation in the Ship hull structure. Similarly an “Inspector” is defined as a person involved in ship hull inspections and may be a member of the ship crew, ship owner/operator, Class surveyor, forensic investigator and/or any other third party investigation body.
representative who possess the required skill set and knowledge to make informed assessment of the ship hull structure.

2. Literature review

Welded ship structures are susceptible to damage during its construction and operational life. Design inadequacies, material selection, material imperfections, improper welding, incorrect fabrication and poor workmanship are some of the probable causes for damages during construction while fatigue and corrosion are related to operations. These damages primarily manifest as cracks in the ship structure either immediately after fabrication and launching or in due course of time. Crack formation or initiation appears inevitable or unavoidable given the uncontrolled variables involved in the construction of welded ship structures along with other factors, especially the use of high tensile strength steel for ship hull structure (Blagojevic, Domazet, & Zilha, 2002), and finally it’s operation in adverse environment (Stenseng, 1996). Research findings on cracks in the ship hull structure recommend procedures and processes encompassing design, construction and operational issues to prevent it’s occurrence (Beghin, 2006; ISSC, 2009; Stenseng, 1996), however a normal inspection of the ship hull structure would reveal hundreds of cracks (ISSC, 2009; Mahmoud & Dexter, 2005; Mao, 2014), some of which may lead to structural failures (Blagojevic et al., 2002).

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. These deficiencies may eventually lead to rupture or fracture of the structural member over a period of time, if neglected. 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 & Dexter, 2005; Stenseng, 1996).

However it is also widely acknowledged by findings involving large scale experiments and finite element analysis studies simulating ship collision and grounding accidents that existing cracks can propagate during impact loads (Abramowicz & Simonsen, 2003; Simonsen & Törnqvist, 2004). There is a significant drop in energy absorption due to fracture of welds during crushing or collision accidents which can result in more damage to the ship hull (Abramowicz & Simonsen, 2003). Under such 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 at a much faster rate resulting in breakaway of structural members and in turn lead to severity of hull structure damage sustained.

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 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, Gledic, Garbatov, & Soares, 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 (Barsom & Rolfe, 1999). Under such circumstances the focus has always been to determine and control crack growth conditions before final failure.

During ship construction it is rather humanely impossible to detect all significant cracks with the current inspection procedures of the class society and the shipyards. Particular emphasis is given to the cracks detected on major structural members, the ship side and tank top (ASTM F1754-97, 2004; Blagojevic et al., 2002). Use of Non Destructive Examination (NDE) for finding subsurface cracks is also limited as they are expensive and time consuming. Stenseng (1996) classifies a detectable crack to be of length between 25 to 75 mm while ASTM F1754-97 (2004) considers cracks of length
50 mm and more detectable provided conditions such as surface cleanliness, lighting level, inspector stress and viewing distance are satisfactory. On a conservative side, cracks above 50 mm length can generally be considered detectable. Once the undetectable cracks attain a length more than 50 mm to fall within the detectable region, studies indicate a significantly faster propagation rate leading to fractures or failure of the structure involved (Mao, 2014). Hence it is vital that upon crack detection, suitable mitigation measures are taken. A major problem in ship maintenance associated with cracks is attributing or identifying the causes/reasons for crack initiation. There are instances where the earlier repair works done on the detected cracks are ineffectual as these cracks reappear after a period of time. It may be because the correct deficiency was not addressed in the first place.

3. Methodology – Crack assessment criteria for ship hull structure

This paper presents the criteria for assessment of cracks based on inducement factors which influence the initiation of cracks in the hull structure corresponding to the operational life of the ship. The inducement factors along with the attributable causes/reasons considered in this study are detailed in Table 1.

Some of the inducement factors detailed in Table 1 along with their attributable causes/reasons have been identified by the referenced authors primarily from a fatigue perspective, which generally happens after the ship is put into service and is operational for a considerable period of time. However from this study perspective, the authors of this paper strongly believe that the above mentioned inducement factors can 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. This is further confirmed by statistics presented by Bea, Pollard, Schulte-Strathau, and Baker (1991) which confirm the presence of cracks

| Inducement factor   | Causes/reasons                                                                 | Reference                                                                 |
|---------------------|-------------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Design              | Inadequate strength and support of structural members                         | ISSC (2009), Stambaugh and Wood (1987)                                     |
|                     | Incorrect prediction of loads                                                 | Beghin (2006)                                                              |
|                     | Abrupt dimensional changes, Use of different material type or grade, Use of High tensile steel sections | Blagojevic et al. (2002), Lloyd's Register of Shipping (LR, 2009), ISSC (2009), Beghin (2006) |
|                     | Complex weld geometry, inappropriate weld type and weld size                  | ISSC (2009), Lloyd's Register of Shipping (LR, 2009), Beghin (2006), Fricke and Kahl (2008) |
| Welding process     | Improper weld                                                                 | Beghin (2006), Mann (2011)                                                |
|                     | Presence of weld impurities – slag, porosity, contamination etc.             | Beghin (2006)                                                              |
| Fabrication and workmanship | Geometrical misalignment                                                     | Blagojevic et al. (2002), Beghin (2006), Chakarov, Garbatov, and Soares (2008), Barsom and Rolfe (1999) |
|                     | Presence of notches and structural discontinuities                            | Lloyd’s Register of Shipping (LR, 2009), Stambaugh and Wood (1987)         |
|                     | Block assembly issues and welding sequence                                    | Fu, Laurenço, Duan, and Estefen (2016)                                    |
| Material properties | Use of thick steel sections                                                   | Lloyd’s Register of Shipping (LR, 2009), Mann (2011)                       |
|                     | Non homogenous material composition                                           | Mann (2011)                                                               |
| Temperature         | Prolonged exposure in low temperature areas                                   | ISSC (2009), Stambaugh and Wood (1987)                                    |
|                     | Nature of Cargo                                                               | ISSC (2009)                                                               |
| Accident            | Dent and deformation in structure due to dropped object, contact, slamming, pounding etc. |                                                                 |
| Fatigue             | Corrosion                                                                     | ISSC (2009), Garbatov and Soares (2011), Beghin (2006)                    |
|                     | Welding process                                                               | Beghin (2006), Mann (2011)                                                |
|                     | Fabrication and workmanship                                                   | Beghin (2006), ISSC (2009)                                                |
| Corrosion           |                                                                                | Beghin (2006), Blagojevic et al. (2002), Kwon and Frangopol (2012), Soydam and Frangopol (2013), Garbatov and Soares (2011) |
in newly constructed ships. It is based on these premises that the above inducement factors are included in the proposed assessment criteria even during the early operational life of the ship.

The operational life or age of the ship referred to in this paper represents the period after ship construction. The age groups selected are 0–5, 6–10 and 11–20 years, assuming a ship life of 20 years. The rationality for selecting such an age groupings is firstly for simplifying the inspection process and for assigning the appropriate inducement factor considered to cause crack initiation/formation corresponding to the operational life of the ship, and secondly for aligning it to special periodical surveys conducted every 5 year period by the Classification societies (American Bureau of Shipping [ABS], 2016). Further, underlying causes/reasons of crack initiation attributable to a particular inducement factor form the basis for the crack assessment criteria in this paper.

4. Crack assessment criteria based on ship operational life

4.1. Crack assessment criteria during the period 0–5 years of ship operational life

A newly built ship is expected to be crack free 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/operator surveyor through visual inspection and NDE. 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. A lot 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 NDE of the joint, if required.

During the period 0–5 years of operation, the ship is put to service and operating under various conditions i.e. fully loaded, ballast, loading and unloading cycles etc., 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 the particular voyage (Mansour & 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 may be cracks. Undetectable cracks formed during 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 tel-tale signs of which are difficult to ascertain as such because cracks generally manifest at the weakest link in the structure which could be the weld joint or at notches and flaws in the structural members and can easily be confused for other inducement factors.

In addition to design issues, the welding process related and fabrication and workmanship related inducement factors 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 which are 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 and/or poor workmanship practices can contribute to crack initiation as a result of the high internal stresses generated in the structure due to these factors (Stambaugh & Wood, 1987).

The other three inducement factors considered in this age group are the Temperature related, Material related and Accident related factors. 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 (Barsom & Rolfe, 1999). Although very significant contributions have been made in the field of material science and material selection to prevent such brittle fracture type failures, this 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. Also, using materials with improved charpy values alone does not prevent brittle fractures (Barsom & Rolfe, 1999). Accidents such as allision/contact with pier, berth or other ships and dropped objects during cargo handling can result in dents and deformations in the ship hull structure, 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 result 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 the above inducement factors can contribute individually or combine together under favourable conditions to cause crack initiation and/or 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 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 cascading effect existing between the various inducement factors which may contribute to crack initiation. This paper illustrates two such cases where root cause for crack initiation can be masked by other inducement factors. Figure 1 illustrates an example where the Inspector is likely to notice the geometrical misalignment of the structure where crack initiation is identified and attribute it to fabrication and workmanship related inducement factor, while the root cause was structural damage as a result of an accident. Similarly Figure 2 illustrates a case which involves both design and fabrication related inducement factors. 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. 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 thorough examination of the structure surrounding the crack.

4.2. Crack assessment criteria during the period 6–10 years of ship operational life

The inducement factors considered during the period 0–5 years of the ship operational life are considered relevant and applicable during the period 6–10 years also. Furthermore there is a likelihood of resurfacing of cracks which were earlier detected and rectified because the root cause behind the crack initiation was incorrectly addressed during the earlier inspection and subsequent repair work.
The 6–10 years age classification has been introduced in this paper to accommodate fatigue related inducement factor to this analysis 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 very stringent that their operational life is generally considered half of that of ships operating in world trade area (Det Norske Veritas [DNV], 2010; DNV GL AS [DNV-GL], 2015). In consideration to the above, fatigue is included as a crack inducement factor in this age group.

4.3. Crack assessment criteria during the 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 which can lead to crack initiation during this period. Any of the earlier discussed inducement factors i.e. design, fabrication and workmanship issues and welding process related deficiencies which were unresolved or unidentified in the earlier operational period of 0–5 and 6–10 years, would now be associated and dealt with from a fatigue and corrosion perspective.

Crack initiation due to corrosion is primarily due to 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; the first phase involves no corrosion because of the steel structure being protected by paint or protective coating. Corrosion is only initiated once this protective coating is damaged. Beghin (2006) proposes a rate of corrosion per year for different ship types, for different locations and for different cargo type carried in the cargo tanks. He considers a rate of corrosion of 0.1 mm/year in service for cargo ships and 0.2 mm/year for bulk carriers while an unprotected ballast tank deteriorates at a rate of 0.4 mm/year and coated ballast tank at 0.2 mm/year. The worst case scenario according to Beghin (2006) is for a cargo tank carrying white products where the corrosion rate of 0.35 mm/year at the ship deck and bottom when compared to 0.2 mm/year for black products. 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 rate of corrosion proposed above by Beghin (2006). Based on the rate of corrosion per year 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.

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 (Parunov et al., 2013), improper designs, geometrical misalignments and poor workmanship (Blagojevic et al., 2002) may also contribute (individually or collectively) to fatigue crack formation (Beghin, 2006). The connection of the longitudinal on the side shell to the transverse web frames are most prone to fatigue cracks and that too the majority being below the full load and ballast waterlines. Initiation of such cracks is attributed to the pulsating hydrodynamic pressure on the ship hull due to wave and ship motions (Blagojevic et al., 2002).

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. Lloyds Register
of Shipping, DNV-GL AS, etc., and International Association of Classification Societies have published guidelines on fatigue assessment, which give valuable guidelines on the areas where the structural members are prone to fatigue related failure and the corresponding defect correction procedures to be adopted (Lloyd’s Register of Shipping [LR]’s, 2009). In addition to the assessment criteria proposed here, the inspector should also be guided by such Class documents when evaluating crack initiation due to fatigue related issues.

5. Circular data visualization of age based crack assessment criteria for ship hull structure

The proposed age based crack assessment criterion for the ship hull structure is illustrated using the circular data visualization technique. Corresponding to the ship operational life/age, the relevant inducement factors with it’s underlying causes/reasons, expected inspection findings and validation methods are depicted in the circular data visualization diagram in Figure 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, 6–10 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/reasons 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. These annular rings are sequentially numbered AR-1 to AR-5, starting from the innermost annular ring to the outermost annular ring.

This paper also presents the procedure to be followed while using the proposed circular data visualization diagram for crack assessment of the ship hull structure. An example of a general cargo ship operating in the world wide trade area and having an operational life in the category 0–5 years is considered. The structural member under inspection is a fillet weld connection between the side shell and the side shell longitudinal and is shown in Figure 4. The annular rings in the proposed age based crack assessment criteria diagram in Figure 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. starting from the innermost ring and moving towards the outermost ring. The step by step procedure listed in Table 2 guides the inspector through the entire investigative process and the use of the age based crack assessment criteria diagram in Figure 3. The inspector upon detecting the crack at the fillet weld connection as shown in Figure 4 would then identify the probable causes/reasons for such crack initiation in the weld joint from the information provided in the crack assessment criteria diagram for the corresponding age of the ship. Detailed observation of the structure in the near vicinity of the reported crack can narrow down the probable causes/reasons from the 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 can then be confirmed using the validation method proposed i.e. in this case NDE.
Figure 3. Age based crack assessment criteria for ship hull structure.
6. Discussion
Crack initiation or formation in the ship hull structure appears inevitable given the uncontrolled variables involved in the construction of ships and the operating environment it is exposed to. It is extremely difficult to detect all significant cracks within the inspection regimes during ship construction and periodical surveys by Classification societies during operation. Collision, grounding and allision accident type present conditions of sudden impact loading where the much researched crack growth...
or crack propagation rate phenomenon based on fatigue conditions may not be valid as existing cracks can propagate at a much faster rate enhancing the severity of damage to the hull structure.

In this paper an attempt has been made to address the escalation of severity of hull damage as a result of cracks by development of the crack assessment criteria which provides guidelines on how to identify the correct inducement factors responsible for the crack initiation once the crack is detected during inspections. Subsequent repair work done will be addressing these identified inducement factor responsible for crack initiation such that these cracks do not resurface and pose a threat to the structural integrity of the ship in the event of accidents involving sudden impact loading.

The age based classification for crack assessment proposed in this paper classifies the relevant or applicable inducement factors corresponding to the operational life of the ship, thereby simplifying the crack assessment process. Such a classification addressing the relationship between the inducement factors to the operational life of the ship has not been attempted earlier and it provides opportunities for future research in this field. Additional inducement factors may be identified and further sub classification of the operational life of the ship may be proposed.

The proposed diagram in Figure 3 representing the age based crack assessment criteria has been developed using the circular data visualization technique. 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/surveys for crack detection in the hull structure. It empowers them 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. This classification provides a single platform wherein the Inspector is able to view and analyse a 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 inspections methods available to validate his findings.

Ship maintenance and repair 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 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 classification is also expected to form a more accurate basis for the Inspector to determine/ascertain the repair work needed well in advance to ensure minimum downtime of the vessel during such maintenance activities in Ship repair yard/dry dock. Appropriate inspection methods which are commonly used by the shipbuilding industry are proposed to validate the onsite findings of the Investigator. These methods range from simple visual indication of the crack to more robust tools such as NDE, structural calculations and finite element analysis, depending on the age of the ship, the location where the crack has been detected and the possible circumstances leading to it.

An attempt is also made in this paper to educate the Inspector of the possible interactions involved between the various crack inducement factors and cascading effect from one inducement factor to another and how they influence crack initiation and crack growth. Such interactions are included to forewarn the Inspector not to be prejudiced to one particular inducement factor alone but rather approach the problem holistically while making crack assessments of ship hull structure.

The proposed age based classification for crack assessment is also expected to be beneficial to Forensic investigators, Insurance surveyors, Class surveyors, Port state control surveyors and other maritime agencies to ascertain the seaworthiness, structural integrity of the ship and the general level of maintenance maintained by the ship owner/operator, to assist in accident investigations, claim settlements, transfer of class, and port state detentions.
7. Conclusion

The crack assessment criterion developed herein identify the various inducement factors along with their underlying causes/reasons contributing to crack initiation in the ship hull structure based on the operational life of the ship and not on fatigue conditions alone. A relationship is established between the various inducement factors and the ship operational life i.e. aging of the ship, with respect to crack initiation/formation.

The understanding of cracks is mainly based on the structural failures observed at site and interpreting the events leading to it is extremely complex physical process. Example of such complexity originating during inspection is highlighted in this study. The age based crack assessment criteria developed and its representation using the circular data visualization diagram in this paper simplifies this complex problem so that corrective actions taken on detected cracks will ensure that they do not resurface and escalate the structural damage to the ship hull in the event of future collision, grounding and allision accidents.

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