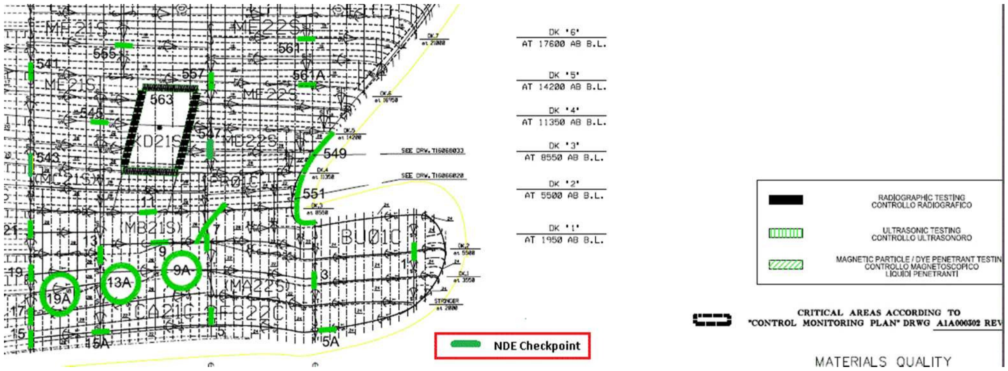

Figure 1 A Typical NDE inspection plan
Figure 1

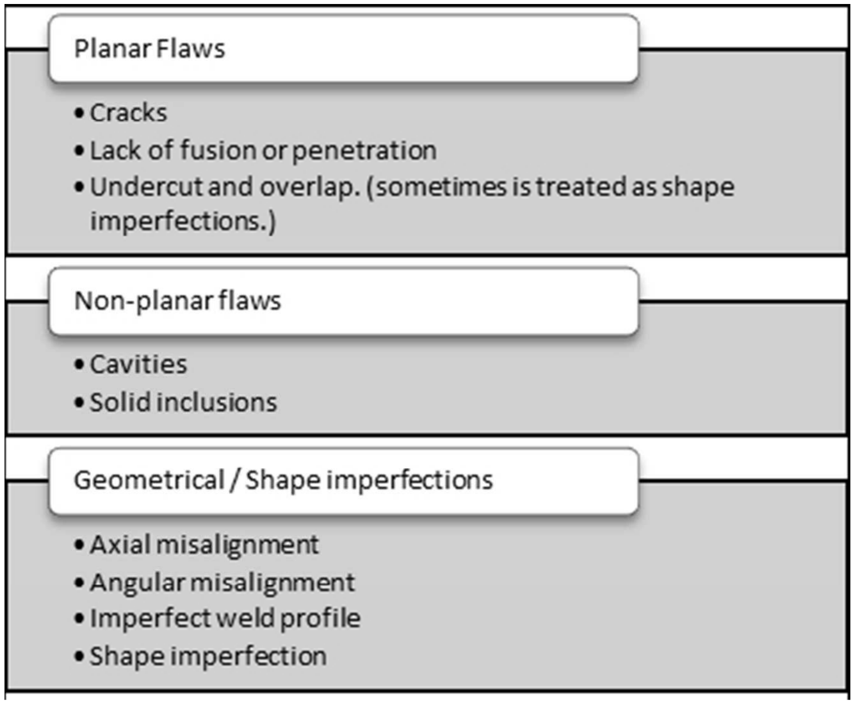

Figure 2 Classification of weld flaws
Figure 2

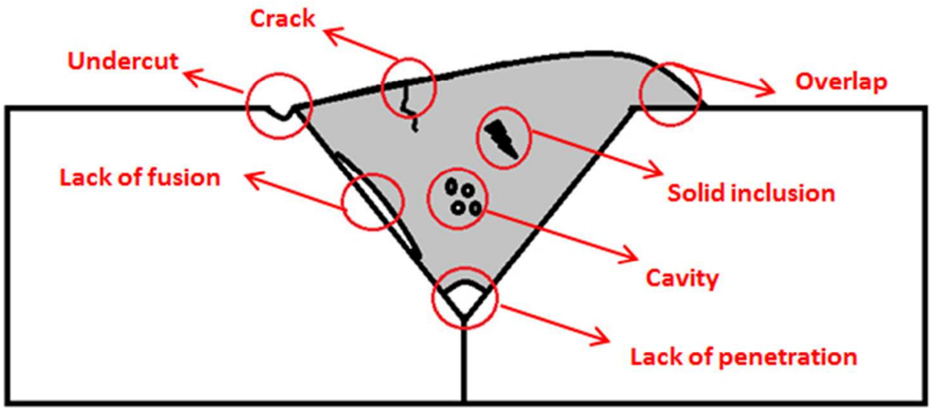

Figure 3 Typical weld defects
Figure 3

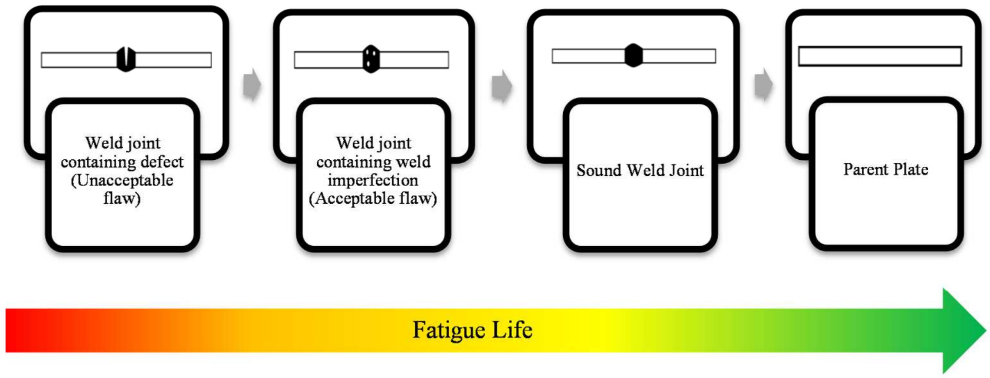

Figure 4 Effect of Imperfections on the fatigue life of welded joints
Figure 4

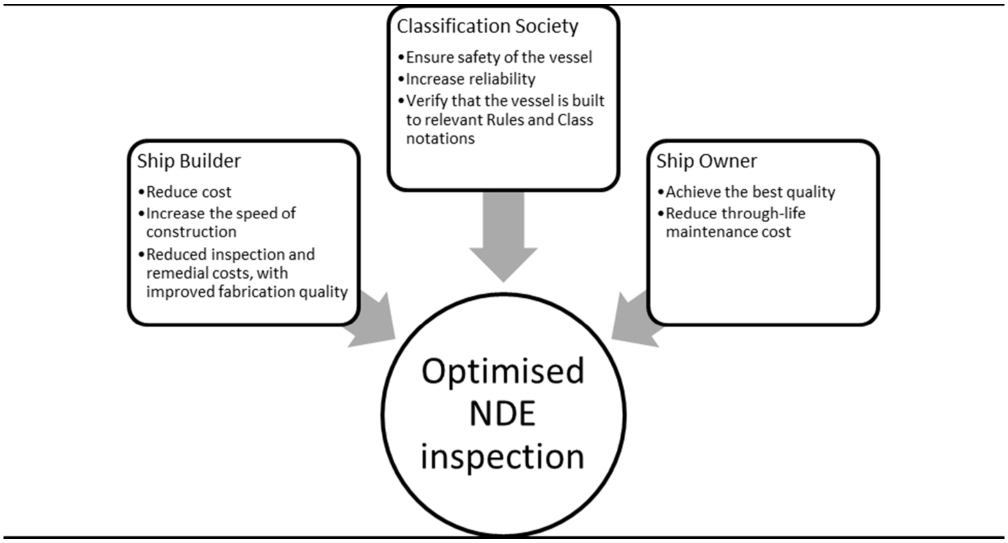

Figure 5 Objectives of shipbuilding key stakeholders
Figure 5

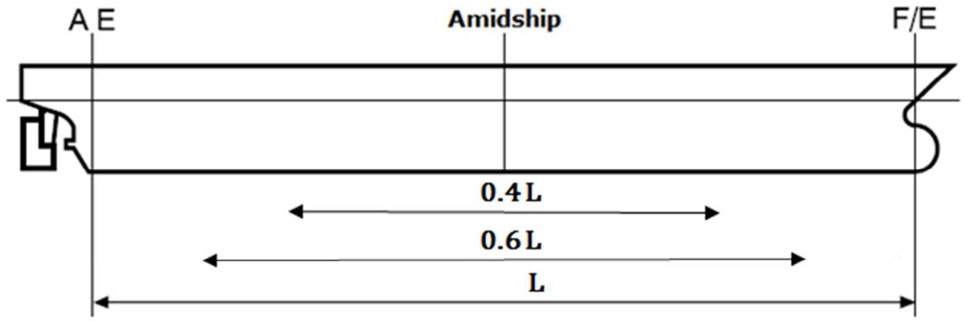

Figure 6 Definition of midship length
Figure 6

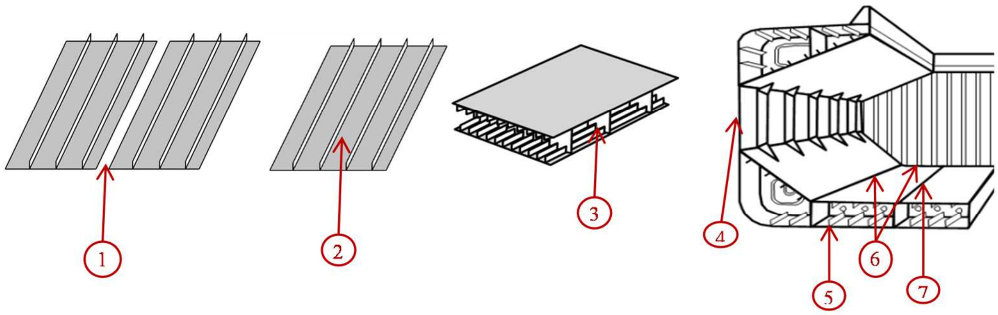

Figure 7 Typical weld types application in shipbuilding
Figure 7

Table 4 Requirements of Classification Societies for additional inspections

Register	Additional NDE if one defect found	Additional NDE if defect rate exceeds a certain value	Remarks
ABS	Additional UT to determine the extent of non-conformity	If high proportion of checkpoints for example 90% 95% are defect free, inspection length can be reduced from 1250mm to 750mm	• Additional inspection is to be, if the pattern of non-conformity suggests the non-conformity exists for an extended distance. • When non-conformity is at the end of a checkpoint, additional Ultrasonic inspection is required to determine the extent of the non-conforming area.
RINA	NA	NA	NA
KC	NA	If survey before repair exceeds 20% of total number of checkpoints, it should be increased to a minimum of 40%.	NA
NK	1. Additional NDE for other two parts within welds lines if the defect is found in plates members and girders 2. In1., non-destructive testing is to be extended to all length of the welded joints 3. Notwithstanding the requirements specified in 2., all length or all number of welded joints may be repaired 4. Faulty welds found in 2., are to be repaired. 5. Notwithstanding 1. to 4., repair process and additional NDE in other welded joints are to be carried out	If faulty welds are more than 10% of number of inspected, requires investigation of cause and improving quality	NA
DNV	For each section of the weld to be repaired two more of the same length shall be tested	N/A	• If systematically repeated defects are revealed, the extent of the testing shall be increased under same conditions and where similar defects may be expected • If non-conforming discontinuities are found to occur regularly, the reason shall be investigated. The Welding Procedure Specification (WPS) shall be reassessed before continuation of welding
LR		If beyond Normal limits necessary corrective actions need to be taken	• When warranted by previous results, the extent should be increased • When continuous or semi continuous defects are found additional length of welds adjacent to and on both sides of the defective length are to be subject to further volumetric examination

Table 1 Summary of Class rules on specifying NDE checkpoints
Tabel 1

Table 2 Typical weld types and process in shipbuilding [18] & [19].

No.	Component	Weld type	Process	Remarks
1	Panel plate to panel plate	Horizontal Butt (Seam)	One-sided SAW	Automatic
2	Longitudinal member to panel plate	Fillet	FCAW	Automatic
3	Double bottom inside	Fillet	FCAW	Semi-automatic
4	Side shell(Section weld)	Transverse Butt (Butt)	FCAW	Semi-automatic
			EGW	Automatic
5	Longitudinal member to Longitudinal member	Transverse Butt (Butt)	One-sided FCAW	Semi-automatic
6	Tank top plate to Hopper tank plate and bulkhead	Fillet	FCAW	Semi-automatic
7	Tank top plate to tank top plate	Horizontal Butt (Seam)	One-sided SAW	Automatic
			One-sided GMAW	Automatic GMAW

Table 2 Typical weld types and process in shipbuilding [18] & [19].
Table 2

Table 3 Requirements of Classification Societies for Automatic welding and NDE method

Class	Automatic welding	NDE method
ABS	Can reduce frequency of inspection if Quality-Assurance techniques indicate consistent satisfactory quality, but doesn't specify the amount the reduction	• MPI and DPI defined by manufacturer and approved by surveyors • Volumetric examination check points defined as described • No preference between UT and RT ; left to surveyors decision based on shipyards capabilities
RINA	NA	• MPI and DPI to complement VT • RT is preferred over UT
KC	• All start/stop points automatic welding processes to be examined using RT or UT except for internal members where the extent of testing should be agreed. • Allows reduction of checkpoints if automatic welding has been carried out and the results of the survey verify that the quality of welding procedure is consistent satisfactory quality • If a weld that needs to be repaired is found in an automatically welded joint whose inspections have been reduced, additional radiographs negating the reduction are required until an appropriate period has elapsed and the quality is verified to be stable and satisfactory	• MPI is preferred over DPI • Extent of MP is not defined • RT is preferred over UT • For thicknesses above 30 mm UT is to be used
NK	1. If defects are found in automatic welding, additional NDE testing is to be extended to all lengths automatically welded joints 2. In 1. , the faulty welds to be repaired 3. Notwithstanding the requirements specified in 2., all lengths or all welded joints may be repaired 4. Faulty welds found in preceding 2. are to be repaired. 5. Notwithstanding preceding 1 to 4, repair process and additional NDE in other welded joints are to be carried out according to the surveyors' direction	• RT is preferred over UT
DNV	NA	• 2% of MPI or DPI in general areas • 5% of MPI or DPI for locations within 0.4L amidship • 20% of MPI or DPI in critical locations
LR	NA	• Radiography for plates below 8 mm • UT for the examination of full penetration tee, butt or cruciform welds or joints of similar configuration • Advanced ultrasonic techniques, such as PAUT, may be used as a volumetric testing in lieu of radiography or manual ultrasonic testing • Particular attention needs to be given to defect rates of butt welds in longitudinals. If defects are found in more than 10% of these welds additional inspection needs to be performed.

Table 3 Requirements of Classification Societies for Automatic welding and NDE method
Table 3

Table 4 Requirements of Classification Societies for additional inspections

Register	Additional NDE if one defect found	Additional NDE if defect rate exceeds a certain value	Remarks
ABS	Additional UT to determine the extent of non-conformity	If high proportion of checkpoints for example 90% 95% are defect free, inspection length can be reduced from 1250mm to 750mm	• Additional inspection is to be, if the pattern of non-conformity suggests the non-conformity exists for an extended distance. • When non-conformity is at the end of a checkpoint, additional Ultrasonic inspection is required to determine the extent of the non-conforming area.
RINA	NA	NA	NA
KC	NA	If survey before repair exceeds 20% of total number of checkpoints, it should be increased to a minimum of 40%.	NA
NK	1. Additional NDE for other two parts within welds lines if the defect is found in plates members and girders 2. In1., non-destructive testing is to be extended to all length of the welded joints 3. Notwithstanding the requirements specified in 2., all length or all number of welded joints may be repaired 4. Faulty welds found in 2., are to be repaired. 5. Notwithstanding 1. to 4., repair process and additional NDE in other welded joints are to be carried out	If faulty welds are more than 10% of number of inspected, requires investigation of cause and improving quality	NA
DNV	For each section of the weld to be repaired two more of the same length shall be tested	N/A	• If systematically repeated defects are revealed, the extent of the testing shall be increased under same conditions and where similar defects may be expected • If non-conforming discontinuities are found to occur regularly, the reason shall be investigated. The Welding Procedure Specification (WPS) shall be reassessed before continuation of welding
LR		If beyond Normal limits necessary corrective actions need to be taken	• When warranted by previous results, the extent should be increased • When continuous or semi continuous defects are found additional length of welds adjacent to and on both sides of the defective length are to be subject to further volumetric examination

Table 4 Requirements of Classification Societies for additional inspections
Table 4

A REVIEW OF NDE METHODS FOR NEW-BUILT SHIPS UNDERGOING CLASS INSPECTION

Peyman Amirafshari[1, 2], Nigel Barltrop[2], Ujjwal Bharadwaj[3], Martyn Wright[4], Selda Oterkus[3]

National Structural Integrity Research Centre (NSIRC)[1]; University of Strathclyde[2]; TWI Ltd[3];

Lloyd's Register EMEA[4]

Abstract

Classification societies require ship manufacturers to perform non-destructive examination of ship weldments in order to ensure the welding quality of new-built ships. Ships can contain hundreds of kilometres of weld lines and 100% inspection of all welded connections is not feasible. Hence, a limited number of weldments are specified by rules of Classification Societies to be inspected for this purpose. There is a variation between the rules and guidelines used by different Classification Societies in terms of both philosophy and implementation which results in significant discrepancy in the prescribed checkpoints numbers and their locations. In this paper, relevant sections of the rules of mainstream IACS (International Association of Classification Societies) members are studied and potential ways of improving them are discussed. The authors have endeavoured to make this study as comprehensive as possible. However, given the challenges of covering every single aspect and variable related to non-destructive examination (NDE) in the Classification Societies' rules and guidelines reviewed here, the authors can only attempt to cover the key features.

1 Introduction

Ship structures are joined with hundreds of kilometres of weld lines. The presence of weld in a structure potentially reduces the structure's fatigue life by means of introducing a discontinuity into the completed weld/parent material joint, and introducing residual stress; this could be further amplified by presences of defects inherent to the welding process. Rules, standards and guidelines may require manufacturers to carry out certain procedures for enhancing weld's reliability, such as weld toe grinding to enhance weld profile geometry (and hence fatigue improvement), heat treatment to improve welded joint's toughness and non-destructive examination (NDE) to detect weld defects. Performing NDE for finished welds is the best way to find possible defects, and, relevant rules require manufacturers to do so. However, only a sample of welds is subject to thorough NDE as it is unfeasible to carry out the same extent of detailed inspection on all ship weldments.

Since welds are designed assuming a good execution, the rules set flaw size acceptance criteria up to a point, which aims to verify the good workmanship/quality levels. Ship structures contain a large number of welded joints and apart from visual inspection it is not feasible to perform 100% NDE. Hence, Classification Societies tend to use a partial inspection regime by specifying a number of checkpoints for examination of welds instead of 100% inspection. Figure 1 shows a part of a typical NDE inspection scheme of a ship with checkpoints highlighted in green colour. This is with a view to assessing the general quality of welding as well as ensuring that the critical structural elements are defect-free. This is aimed to be achieved through recommending tables, formulas, and clauses defining minimum number or length of inspection in various parts of the ship.

Prescribed tables and equations have evolved over time based on engineering judgement and historical experiences of cracks found during service, and do not necessarily incorporate structural analysis of ships.

Each Classification society practices its own set of rules developed on the basis of its own experience As a result, significant differences exist between final inspection plans from different Classification Societies, both in terms of their locations and extent.

This paper starts with a summary of the types of defects that can be found by appropriate NDE regimes and the perspectives of different stakeholders on the NDE inspection regime for new-built ships. It is important to understand the viewpoint of key parties involved as it has a bearing on the NDE regime and ultimately the quality of new- built ships. The next section describes key aspects of NDE inspection as encapsulated in various Classification Societies' standards or guidelines. Typically used NDE techniques and how their optimal selection depends to a large extent on the welding process being used are then described. This is followed by describing acceptance criteria used by various classification societies and the action required should defects be found. The final section of this paper identifies potential improvements over the current approaches and introduces risk-based approaches that are increasingly being used in other industry sectors and are finding acceptance in the shipping sector.

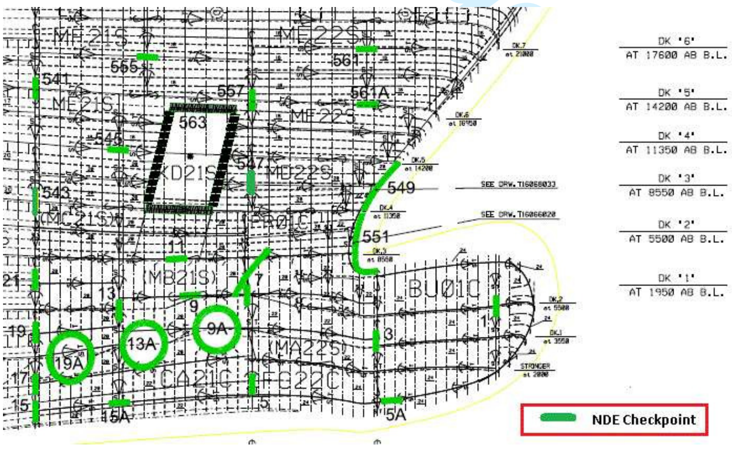

Figure 1 A Typical NDE inspection plan

1.1 Weld imperfections and structural integrity

There is increasing evidence that weld imperfections reduce the fatigue life of welded joints [1][2][3].Figure 2 lists various weld imperfections and Figure 3 illustrates planar and nonplanar imperfections (flaws). As reported by Tobbe [4], even defect sizes as small as 0.5 mm wide and 6 mm long decrease fatigue life below the average life of a sound weld. Figure 4 shows how weld imperfection and weld defects reduce fatigue life of the joint compared with sound weld and parent material. Standards such as ISO 6520 [5]and AWS D3.5 [6] provide a comprehensive guide to the classification of weld imperfections and are widely adopted by marine industry. They can be classified into three broad categories: 1.Planar flaws, 2.Non-planar flaws, and 3.Geometrical imperfections see Figure 2. Non-planar flaws reduce the fatigue life of welded joints, but will be less damaging if good workmanship levels is ensured[7]' [8].

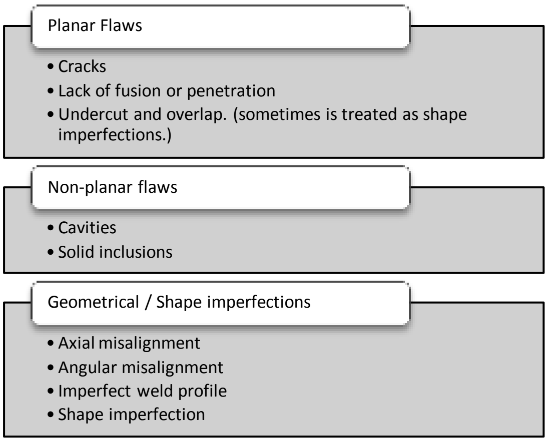

Figure 2 Classification of weld flaws

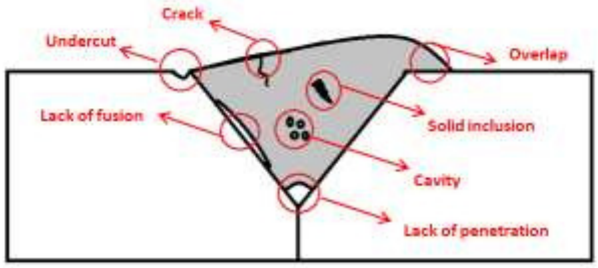

Figure 3 Typical weld defects

In this study, geometrical /shape imperfections are excluded since only planer and non-planar flaws are examined against tolerances using NDE, and the aim of this research is to review such NDE inspection regimes of ships during their construction. Not all flaws in welded connections are regarded as defects. Generally, any deviation from perfect weld is called an imperfection, and an unacceptable imperfection is referred to as a defect [5]. Acceptance criteria are based on good workmanship, and design standards are developed in such a way that if they are met the welded joint is deemed to have satisfied reliability requirements during its service life.

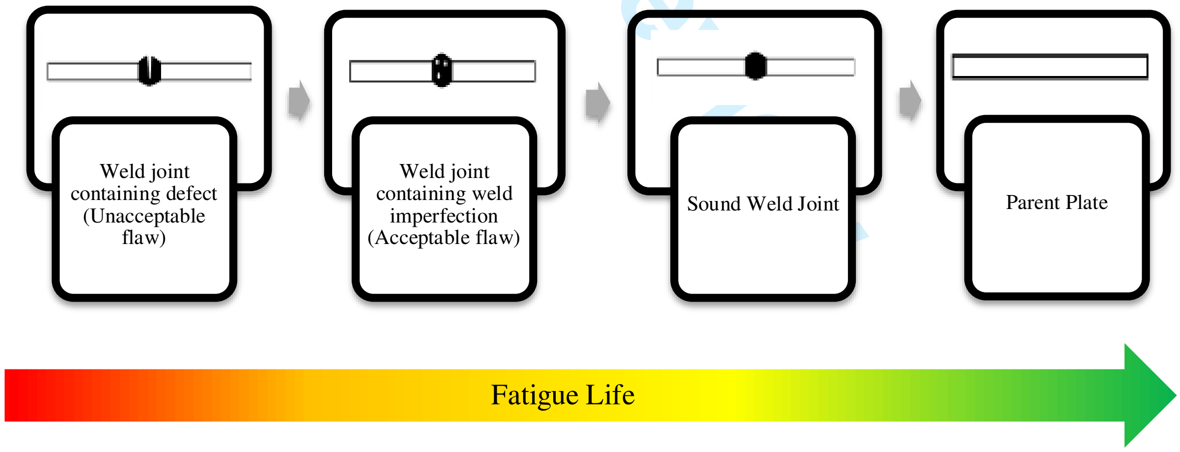

Figure 4 Effect of Imperfections on the fatigue life of welded joints

1.2 Stakeholders' interests

For any inspection regime, it is crucial to define inspection objectives according to the goals of the stakeholders that are involved in the process. There are three key stakeholders involved in ship construction; 1.Ship owner, 2.Manufacturer, 3.Classification society. A Ship owner's desire is to make sure the structure is made as good as possible with minimal maintenance costs. The fewer defects a ship contains before launching, the more reliably it operates, and the long-term maintenance and through-life repair costs are reduced.

Ship manufacturers can reduce construction expenditure by reducing the amount of NDE that needs to be performed, which in turn results in a reduction of remedial actions and faster shipbuilding. Ship owners often have ships being built which are classed under different classification societies, and one concern that may arise is that a classification society with less demand for inspection checkpoints may have an inspection regime that may not be robust enough. Classification societies that permit reduced inspection (other things being equal) argue that their rules are sufficient, and hence there is no need for more extensive inspection.

Manufacturers, on the other hand, would claim that their general workmanship quality is good, and thus, more inspection is considered 'redundant' (or no value added). They feel that some rules are overly conservative and do not take into account the welding quality achieved. This means that they are required to do the same extent of inspection as a manufacturer with a reputation for less emphasis on welding quality. Classification Societies are keen to rationalise their rules and achieve a more robust philosophy for their NDE checkpoint regimes. IACS members in particular strive to establish, review, promote and develop minimum satisfactory technical requirements in relation to design, construction and survey of ships, and other marine units as part of their commitments to IACS directions.

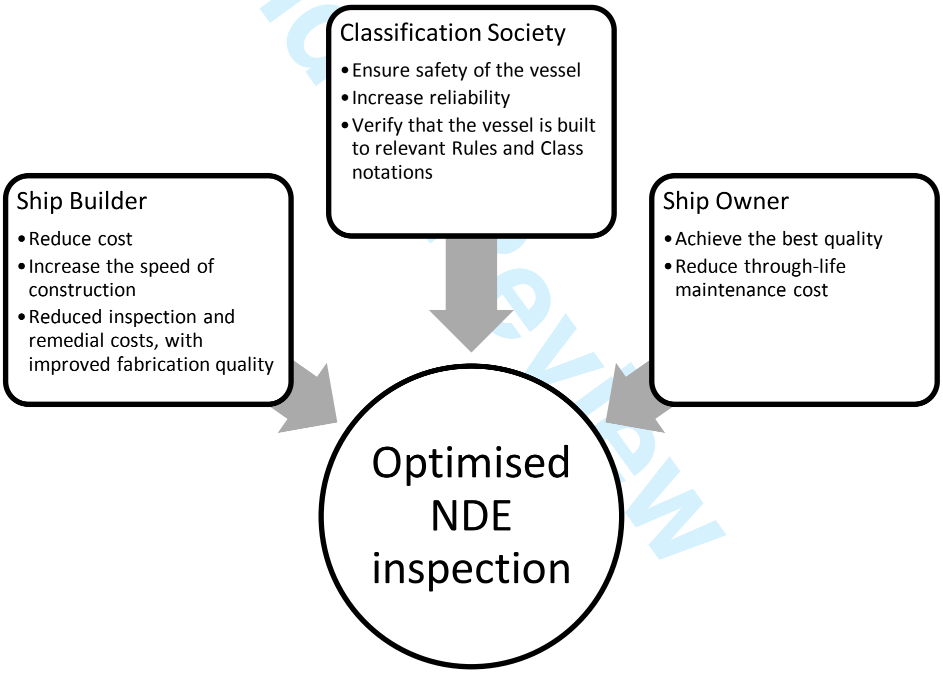

Figure 5 Objectives of shipbuilding key stakeholders

2 Current approaches to NDE inspection

Current approaches of classification societies are centred around two main concepts: one is to assess the general quality of ship by defining the number of checkpoints with recommendation of allocating these checkpoints to more critical members; and, the second is to focus on the relative criticality of areas and specify the extent of inspection accordingly without specifying a set minimum number for whole structure. Table 1 summarises rules of classification societies from these two viewpoints. Most classification societies' approaches have elements from both these concepts. Some approaches may lean more to the first concept and some to the other; some are more prescriptive and some are more principle-based.

2.1 NDE from a Quality-Assurance perspective

The extent of NDE in terms of the minimum number of checkpoints or percentage of welded lines is specified by rules and guidelines. A number of Classification Societies define the number for whole structure using an equation which is function of dimensions of ship or its members Some classification societies employ tables defining the percentage or number of checkpoints for structural members and the rest use a combination of the equation and tables.

ABS

American Bureau of Shipping (ABS) defines minimum number of checkpoints at 0.6L of amidship, required using following equation:

$$N = \frac{L*(B+D)}{46.5} \quad (2.1\text{-}1)$$

Where L= length of the vessel between perpendiculars, in metre (see Figure 6). B= greatest moulded breadth, in metre. D= moulded depth at the side, in metre, measured at L/2. ABS explicitly specifies that spot check of butt joints should be carried out in order to assess the workmanship quality [9].

RINA

Registro Italiano Navale (RINA) mandates equation (2.1 1) for 0.6L amidship areas and instructs additional spot examination for areas outside 0.6L area and sensitive locations [10].

KR

Korean Classification society (KR), on the other hand, differentiates between shell plating joints and internal joints of members and employs equation (2.1 1) to estimate the minimum number of checkpoints of welded joints of deck and shell plating in 0.6L amidship areas. This number is reduced to N/10 outside of 0.6L amidship. KR prescribes the required number of checkpoints in table 5 of KR,[11] 2015. Part 2 materials and welding.[10] , 2015. Part 2 materials and welding. [12] depending on whether they are inside or outside 0.6L amidship, and general location of members, in terms of fractions of ship's length L/40, L/8 and L/16 respectively. This results in higher number of checkpoints compared to ABS and RINA as far as minimum number of checkpoints is concerned. KR also recommends additional examinations for the sake of workmanship control for locations such as parts of start, interrupted and end points of automatically welded joints, welded joints hatch corner and other high critical areas [12].

NK

Nippon Kaiji Kyokai (NK) defines the number of checkpoints in terms of division of ship length, individually for each structural member; however as opposed to KR which employs this method only for internal members, NK applies this method to both internal members and shell platings. Depending on the type, the location of the member and whether it is a butt joint or fillet weld, the number of checkpoints differs. Strength deck, side shell plating, bottom shell plating, and hatch side coaming will have 8 to 12 times more checkpoints than other members. Butt joints in 0.6L have three times more checkpoints than those are outside 0.6L area. The number of seam joint checkpoints in plates remains constant across dimensions of the structure [13]. In ship construction, it is very common to call butt welds in longitudinal direction along the length of the ship “seam welds”, and refer to butt welds in transverse direction as “butt welds”.

DNV GL

DNV, on the other hand, doesn’t specify a minimum number of checkpoints and instead requires a minimum percentage of weld seam needed to be examined. Critical areas receive the most attention (20% of the weldment needs inspection) followed by deck/bottom plating within 0.4L amidship (5% of the weldment needs inspection), the lowest amount of examination is prescribed for general areas with (2% of weld seam length) [14].

LR

Similar to DNV, Lloyds Register doesn’t specify a minimum number checkpoints for the whole ship and instead recommends the extent of inspection be defined based on type and location of structural members. Structural members with higher susceptibility to crack initiation receive significantly higher examination extent, either 50% or 100% examinations. More attention is paid to the intersection of butt and seams of fabrication and section welds where 50% examination is required and if these are located at highly stressed area 100% is required. Bilge keel butt welds within 0.4L amidship are also required to be inspected 100% and 33% outside 0.4L amidship. Other items, require less examination (1%-5%)[15].

2.2 NDE from a structural criticality perspective

When a structure is not 100% examined, members that are considered to be more critical receive more attention. Classification societies’ rules and standards more or less reflect this rule in their specifications. As 0.4L to 0.6L amidship area of vessels goes under higher global bending moment, classification societies require more inspection within this area. Additionally, locations that receive higher stress levels are also required to receive more attention. These locations are normally regarded as critical locations. The extent of NDE with regards to critical locations, from different classification societies’ perspective, are reviewed below.

ABS

ABS recommends that when it comes to the selection of checkpoints, more attention should be paid to welds in highly stressed areas, and members that are considered as important structural members by ABS Engineering/Materials/Survey department, but doesn’t specify a quantified measure or specify any particular members [9].

RINA

RINA, on the other hand, lists members and the area that should be examined. Some of these require a specific number of checkpoints to be inspected and some are just indicated that they should be a target for inspection [10].

KR

KR require selection of checkpoints at 0.6L amidship that is 10 times more than outside of this region. When it comes to an internal member, the difference between the number of checkpoints in a member within 0.6L amidship and outside is 2.5 times and 5 times respectively, depending on structural hierarchy and crack susceptibility. For internal members within 0.6L amidship area, weld joints located at the strength deck needs to have twice as many checkpoints as other parts due to their higher contribution to the load resistance [12].

NK

Similar to KR, NK prescribes more inspection checkpoints for butt welds within 0.6L amidship than outside of this zone but the difference is 3 times [13].

DNV GL

DNV divides the ship into three areas: 1. Critical areas: defined as areas in the way of critical load transfer points and large stress concentrations where a failure will endanger the safety of the vessel, 2. Deck/bottom plating within 0.4L amidship, 3. General areas Deck/bottom plating within 0.4 L amidship to be inspected moderately more (5% of their weld seam length) than general areas (2% of their weld seam length).There is a significant rise in percentage of inspection for critical areas to 20%. 20% of weld seam of fillet welds in critical areas are also required to be examined for surface cracks using either MPI (Magnetic Particle Inspection) or DPI (Dye Penetrant Inspection). Examination of fillet welds in general and deck/bottom plating within 0.4L amidship is not required. DNV states that for vessels with no clearly defined strength deck e.g. cruise ships, the decks which contribute most to hull strength should be regarded as strength deck [14].

LR

Lloyds Register, as opposed to DNV, requires 100% inspection of all critical areas as identified through Lloyd's Register's ShipRight SDA (Structural Design Assessment) procedure and ShipRight FDA (Fatigue Design Assessment) procedure [15]. Also, intersections of butts and seams of fabrication and section welds at highly stressed areas, and hatchways coaming to deck at hatchway ends within 0.4L amidships, and bilge keel butt welds within 0.4L amidship are required to be 100% examined. Bilge keel butt welds outside 0.4L are required to be examined 1 in 3 (33%).% of length).

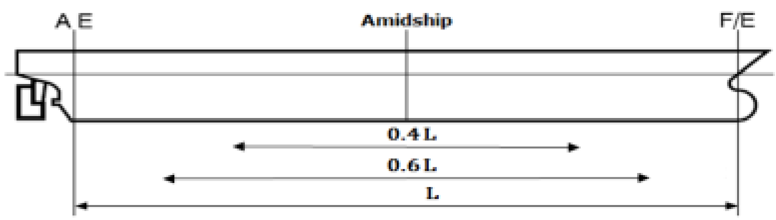

Figure 6 Definition of midship length

Table 1 Summary of Class rules on specifying NDE checkpoints

Class	Sample Type	Extent		Equation	Joint type
		Structural members	Area		
ABS	Number	Hull	0.6L	N	Not Specified
RINA	Number	Hull	0.6L	N	Butt
KR	Number	External members	Within 0.6L	N	Butt
			Outside 0.6L	$N/10$	Butt
	Length	Internal members	Within 0.6L	$1/8\ L, 1/16\ L$	Butt
			Outside 0.6L	$1/40\ L$	Butt
NK	Length	External members	Within 0.6L	$6/10\ L, 2/10\ L$	Butt
			Outside 0.6L	$2/10\ L$	Butt
		Internal members	Within 0.6L	$3/40\ L, 1/40\ L$	Butt
			Outside 0.6L	$1/40\ L$	Butt
DNV	Percentage	Plates	Within 0.4L	5%	Butt/Tee
		General areas	Outside 0.4L	2%	Butt/Tee
		Critical areas	Throughout	20%	Butt/Tee/Fillet
LR	Length	Plates	Throughout	1m in 25m	Butt (Vertical)
				1m in 100m	Seam(Horizontal)
		Structural Items when made with full penetration as follows: 1. Connection of stool and bulkhead to lower stool shelf plating, 2. Vertical corrugations to an inner bottom, 3. Hopper knuckles , and 4. Sheer strake to deck stringer.	Throughout	1m in 20m 1m in 20m	N/A
		Hatchways coaming to deck depending on the location where hatchway ends:	within 0.4L	All	N/A
			outside 0.4L	1 in 2	N/A
			Remainder	1 in 40 m	N/A
	Joint	Longitudinal members	Within 0.4L	1 in 10 welds	Butt(Vertical)
			Outside 0.4L	1 in 20 welds	Butt(Vertical)
		Critical locations	Throughout	All	Not Specified
		Bilge Keel	Within 0.4L	All	Butt(Vertical)
			Outside 0.4L	1 in 3	Butt(Vertical)
		Intersection of butts and seams of fabrications with section welds	Highly stressed	All	Butt/Seams
			remainder	1 in 2	Butt

2.3 Weld type as a factor for the selection of NDE techniques

Welded joints can be made from butt welds or fillet welds. Butt welds can be longitudinally loaded (also known as seam welds in some standards) or transversely loaded, made fully or partially penetrated. Figure 7 and Table 1 illustrate some typical applications of weld type in shipbuilding. Butt weld connections have higher static strength compared to parent materials because the ultimate strength of deposited metal is more than that of the base metal [16].

Butt welds generally possess higher fatigue strength as opposed to connections made with fillet welds. A study by TWI Ltd based on a questionnaire answered by professionals from companies within TWI industrial membership suggests that joint type is the third most important contributing factor in defect repair rate; it has 15% influence on defect repair rate. The same study also suggests that 90% of weld defects are found in fillet welds and 10% in Butt welds [17] .

In this section, the way in which weld type is considered by different classes is reviewed. ABS doesn't specify any special requirement or limits the NDE to particular weld joints [9]. RINA, on the other hand, specifically limits Radiography and Ultrasonic examination to Butt welds, leaving application of MPI and DPI to surveyors' decision to complement visual inspection [10]. KR allows application of VT, MPI, DPI (Visual Testing), MPI, DPI and UT (Ultrasonic Testing) for butt welds, tee joints, corner joints and cruciform joints with both full and partial penetration and RT only for butt welds with full penetration, but specifies the distribution of checkpoints only for butt welds [12]. NK and LR specify distribution of NDE checkpoints for butt welds [13]. DNV requires MPI/DPI of butt T-joints in all areas and fillet welds in critical areas. DNV requires volumetric examination of butt welds and T-joints with full penetration while limiting volumetric examination of T-joints to UT [14]. Lloyds Register emphasises the use of MPI for ends of fillet welds, T-joints or crossings in main structural members at stern frame connections [15].

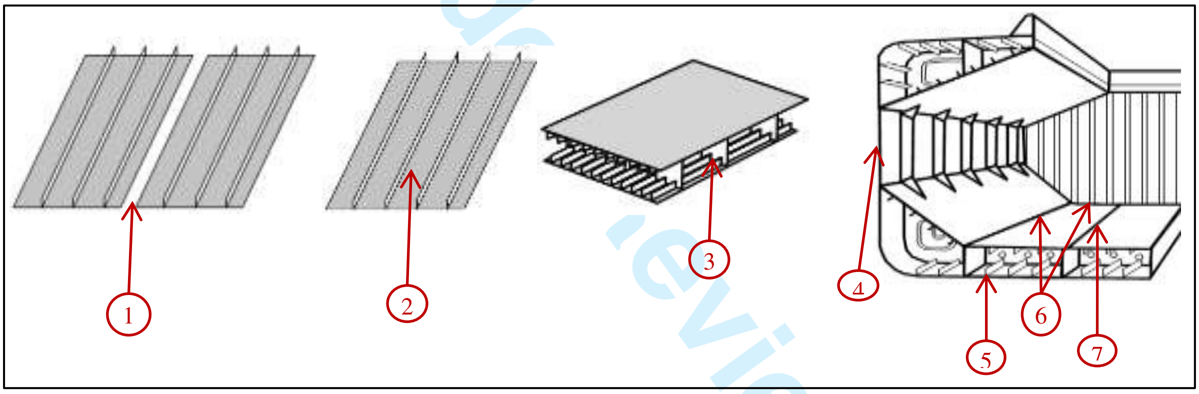

Figure 7 Typical weld types application in shipbuilding [18] & [19].

Table 2 Typical weld types and process in shipbuilding [18] & [19].

No.	Component	Weld type	Process	Remarks
1	Panel plate to panel plate	Horizontal Butt (Seam)	One-sided SAW	Automatic
2	Longitudinal member to panel plate	Fillet	FCAW	Automatic
3	Double bottom inside	Fillet	FCAW	Semi-automatic
4	Side shell(Section weld)	Transverse Butt (Butt)	FCAW	Semi-automatic
			EGW	Automatic
5	Longitudinal member to Longitudinal member	Transverse Butt (Butt)	One-sided FCAW	Semi-automatic
6	Tank top plate to Hopper tank plate and bulkhead	Fillet	FCAW	Semi-automatic
7	Tank top plate to tank top plate	Horizontal Butt (Seam)	One-sided SAW	Automatic
			One-sided GMAW	Automatic GMAW

2.4 NDE techniques

Non-destructive examination methods are employed to detect various weld defects. MPI and DPI are used to detect surface flaws. Radiography and Ultrasonic methods are two volumetric examination methods widely used to detect internal flaws. Other more advanced methods such as Time of Flight Diffraction (TOFD) or Phased Array Ultrasonic Testing (PAUT) can also be used but currently are not very common. All above methods are widely used during the construction of the ship depending on the limitations of the test object. Generally, UT cannot be applied for plate thicknesses below 8 mm, where Radiography must be chosen. Radiography requires access to both sides of the test object and it is not applicable to connections with complex geometries such as T-joints, cruciform joints and fillet welds.

Table 3, below, summarizes the Classification Societies' rules and guidelines specifying application of NDE techniques on finished welds.

2.5 Welding process as a factor in the choice of NDE undertaken

Most commonly used welding processes in the shipbuilding industry are: flux-cored arc welding (FCAWs), submerged arc welding (SAW), double-sided and one-sided, automatic, portable welder, Line welder, semi-Automatic and robotic (see Table 2). FCAWs are most widely used because it offers higher deposition rates over other types of filler metals, thus improving welding efficiency. FCAW also offers high usability in all positions, which is suitable for ship hull construction as hulls comprise large components with flat, vertical, overhead, and curved welding lines [19].

Since hull structures have many confined areas that are difficult to access, one-sided welding by FCAW is common. SAW process is particularly used at for one-sided welding of butt joints of large shell plates [19].

The welding process could also be automated, semi-automated or manual. Automated welding is more reliable but if defective, it is more likely that defects have occurred more extensively. The influence of the welder on the weld parameters is, in most cases, limited to pressing start and stop. The most important variable in automated weld processes is the operator. Hence Classification Societies rules implement special requirements for automated welded connection, particularly at start/stop points (See

Table 3).

The welding process seems to be one of the factors affecting the weld quality. Rules related with the welding requirement are summarised in Table 3.

Table 3 Requirements of Classification Societies for Automatic welding and NDE method

Class	Automatic welding	NDE method
ABS	Can reduce frequency of inspection if Quality-Assurance techniques indicate consistent satisfactory quality, but doesn't specify the amount the reduction	• MPI and DPI defined by manufacturer and approved by surveyors • Volumetric examination check points defined as described • No preference between UT and RT ; left to surveyors decision based on shipyards capabilities
RINA	NA	• MPI and DPI to complement VT • RT is preferred over UT
KC	• All start/stop points automatic welding	• MPI is preferred over DPI

	processes to be examined using RT or UT except for internal members where the extent of testing should be agreed. • Allows reduction of checkpoints if automatic welding has been carried out and the results of the survey verify that the quality of welding procedure is consistent satisfactory quality • If a weld that needs to be repaired is found in an automatically welded joint whose inspections have been reduced, additional radiographs negating the reduction are required until an appropriate period has elapsed and the quality is verified to be stable and satisfactory	• Extent of MP is not defined • RT is preferred over UT • For thicknesses above 30 mm UT is to be used
NK	1. If defects are found in automatic welding, additional NDE testing is to be extended to all lengths automatically welded joints 2. In 1. , the faulty welds to be repaired 3. Notwithstanding the requirements specified in 2., all lengths or all welded joints may be repaired 4. Faulty welds found in preceding 2, are to be repaired. 5. Notwithstanding preceding 1 to 4, repair process and additional NDE in other welded joints are to be carried out according to the surveyors' direction	• RT is preferred over UT
DNV	NA	• 2% of MPI or DPI in general areas • 5% of MPI or DPI for locations within 0.4L amidship • 20% of MPI or DPI in critical locations
LR	NA	• Radiography for plates below 8 mm • UT for the examination of full penetration tee, butt or cruciform welds or joints of similar configuration • Advanced ultrasonic techniques, such as PAUT, may be used as a volumetric testing in lieu of radiography or manual ultrasonic testing • Particular attention needs to be given to defect rates of butt welds in longitudinals. If defects are found in more than 10% of these welds additional inspection needs to be performed.

2.6 Additional inspections

Since the inspection is performed partially, it is crucial to interpret the NDE results and to decide if any additional inspection is needed. This is to: 1.Make sure the presence of defects is not systematic and if so, such defects are found and rectified, 2. Ensure welding quality is to good workmanship level. The requirements of Classification Societies for additional inspections are listed in Table 4.

Table 4 Requirements of Classification Societies for additional inspections

Register	Additional NDE if one defect found	Additional NDE if defect rate exceeds a certain value	Remarks
ABS	Additional UT to determine the extent of non-conformity	If high proportion of checkpoints for example 90% 95% are defect free, inspection length can be reduced from 1250mm to 750mm	• Additional inspection is to be, if the pattern of non-conformity suggests the non-conformity exists for an extended distance. • When non-conformity is at the end of a checkpoint, additional Ultrasonic inspection is required to determine the extent of the non-conforming area.
RINA	NA	NA	NA

KC	NA	If survey before repair exceeds 20% of total number of checkpoints, it should be increased to a minimum of 40%.	NA
NK	1. Additional NDE for other two parts within welds lines if the defect is found in plates members and girders 2. In1., non-destructive testing is to be extended to all length of the welded joints 3. Notwithstanding the requirements specified in 2., all length or all number of welded joints may be repaired 4. Faulty welds found in 2., are to be repaired. 5. Notwithstanding 1. to 4., repair process and additional NDE in other welded joints are to be carried out	If faulty welds are more than 10% of number of inspected, requires investigation of cause and improving quality	NA
DNV	For each section of the weld to be repaired two more of the same length shall be tested	N/A	• If systematically repeated defects are revealed, the extent of the testing shall be increased under same conditions and where similar defects may be expected • If non-conforming discontinuities are found to occur regularly, the reason shall be investigated. The Welding Procedure Specification (WPS) shall be reassessed before continuation of welding
LR		If beyond Normal limits necessary corrective actions need to be taken	• When warranted by previous results, the extent should be increased • When continuous or semi continuous defects are found additional length of welds adjacent to and on both sides of the defective length are to be subject to further volumetric examination

2.7 Acceptance criteria

For any weld imperfection there are two approaches for defining acceptance criteria: the first approach is to define acceptance criteria based on good workmanship level and is generally independent of the nature the structure, loading and in-service environment. The second approach is based on Fitness for Service (FFS) which take into accounts stress which the imperfection may experience during service and the environment in which the structure will operate. A review of Classification societies' rules and standards shows that acceptance criteria for weld inspection in shipbuilding industry is based on good workmanship level and not FFS. This is because FFS requires detailed fracture mechanics assessment requiring specific inputs that are not commonly available given the current practice in ship industry. Apart from ABS and DNV, all other Classification Societies apply the same acceptance criteria for all locations and weld types of a vessel. As per ABS, the areas to be inspected are categorised in two classes: Class A and Class B. Inspection of full penetration welds for all surface vessels 150 m (500 ft) and over in the midship 0.6L is to meet the requirements of Class A. Class A may also be specified and applied to surface vessels less than 150 m (500 ft) when special hull material or hull design justifies this severity level. Full penetration welds in way of integral or independent tanks, except membrane tanks, of all vessels intended to carry liquefied natural gas (LNG) or liquefied petroleum gas (LPG) cargo are to meet the requirements of Class A.

Inspection of full penetration welds for surface vessels under 150 m (500 ft), and for welds located outside amidship 0.6L, regardless of the size of the vessels, is to meet the requirements of Class B, provided that Class A has not been specified in accordance with the special conditions noted in the Class A criteria above. Areas that are classified as Class A generally have more stringent acceptance criteria [9]. DNV adopts ISO standards acceptance criteria ISO 23278 [20]for Magnetic particle testing, ISO 23277 [11] for penetrant testing, ISO 10675 for Radiographic testing [21], and ISO 11666 for Ultrasonic testing [22]. Depending on the location of the checkpoint level, 1-3 (in decreasing order of rigour of inspection required), an acceptance criteria is assigned. Generally, areas within 0.4L amidships for container ships have a higher level of acceptance criteria for volumetric inspection [14].

3 Scope for potential improvement

3.1 Limitations of current approaches

1. Current approaches are 'one-size-fits-all' in that they do not depend on the ship type nor allow for a reduction in NDE effort even when there may be clear evidence of good workmanship. In such cases, the question that arises is what rationale should be applied for determining a reduced NDE regime.
2. Current inspection planning methods focus on critical structural members; however, such approaches account only for stress distribution among structural members. An improved method should take into account defect frequency and size distribution as well as member's stress.
3. Current methods do not strictly differentiate between structural members in terms of the consequence of their failure. Hence, for example, failure of a welded connection in the shell plate, which can result in water or cargo leakage, has the same severity as a crack failure in a deck plate of a multi-deck passenger ship.
4. Formation and characteristics of weld defects are a function of welding variables such as welding process, positions, consumables, etc. Apart from checking start-stop of automated welding, prescribed by KR, NK and ABS, current approaches do not fully take into account these variables.
5. Although, the defect rate is recorded by shipyard and surveyors, there is no clear explanation how to interpret this rate: some shipyards adopt a binary method by dividing the number of failed checkpoints by the total number of checkpoints. Other shipyards use a length by length method by dividing the total length of defects found by the total length of measured welds. This results in significant amount of discrepancy between recorded defect rates. It is also not clear how this number represents the welding quality or how it affects the structural integrity of the ship. Should there be a benchmark average defect rate? How should this benchmark be defined? And last but not least, how should this affect the remaining and additional inspections?
6. The number and extent of the inspection checkpoints should include an appropriate sample of all weldments. The sample should correspond to the desired confidence level and take into account weld-related variables, structural criticality, as well as the fabrication stage at which the defect is found. Current rules do not seem to have robust and/ or consistent method to define the number and the location of inspection checkpoints from the sampling perspective.

3.2 Risk-based inspection

Risk-based inspection and maintenance has been used in a variety of industry sectors. There are specific standards for adopting risk-based inspection methods for plant and process equipment [19], [20], [21], and [23], [24], [25], and [26] and there are many software packages supporting operators in implementing such approaches, for example RiskWISE® [27]. In the offshore sector, such approaches have been used particularly for jacket structures, semisubmersibles, and FPSOs integrity management [28], [29]. In the shipping sector, periodic inspections have traditionally being carried out. However, recently there has been increasing interest in risk-based inspections [26], [27] ,[30], [31], and Classification Societies are developing frameworks [23] to enable such approaches to be used, often complementing the traditional time based approach, but sometimes justifying changes to periodic inspections. Recent and ongoing developments in shipbuilding technologies and competitive market demand have pushed shipbuilders to building bigger and more complex ships. It is a challenge for the stakeholders to ensure the safety and reliability of vessels in a cost effective way. Application of established risk-based approaches could allow shipbuilders to implement new complexity and innovations which cannot be justified through current prescriptive rules due to their limitations [32].

Risk-based methods are useful in the assessment of systems with significant uncertainty; particularly in degrading structures. Degrading mechanisms are usually governed by variables which pose a great deal of uncertainty, in these cases the assessors have two options: 1. Deal with the problem by reasonably presuming the worst case scenario and design or inspect the structure accordingly, which is not always feasible. 2. Collect as much information as possible to reduce the uncertainty in order to predict the degradation of the system more accurately, and also to assess the consequence of the degradation. These two steps allow assessors to make a better decision. Risk in this context is the combination of the likelihood of an undesirable event and the consequence of such event. Once the risk that is associated with components or system is estimated, one can take action towards the improvement of that component or system. The improvement can be in design, or optimising inspection maintenance interval or extent. Risk assessment can be Qualitative which normally involves extensive use of engineering judgement, or Quantitative which requires a significant amount of data and numerical estimation of failure probability of the structure. A third approach is semi-quantitative where the attributes are those of both quantitative and qualitative approaches. The choice of the assessment depends on the availability of the data and assessment tools.

3.3 Risk-based approach in conjunction with sampling theory for Quality-Assurance

Risk-based approaches support decision makers to optimise their inspection by making targeted inspections such that the asset system remains within tolerable levels of risk. In certain cases, time based regimes are informed by risk-based assessments to justify reduced or more inspection (both in terms of inspection frequency and extent).

To address the 'one-size-fits-all' NDE inspection regime, in which regardless of evidence of good workmanship in a particular shipyard, the same rigorous regime is advocated, experience from quality-assurance as used in other industry sectors can be transferred. One could have two levels of inspection with the first level aimed at assessing the quality of workmanship from an appropriate sample (so that desired confidence is achieved) and depending on the result of the first level, determine a more detailed level (with a bigger sample of inspection checkpoints) that is required.

4 Concluding remarks

Ship structures are made of steel members that are joined with welds. Welded connections may contain various imperfection and flaws if welding procedure specification (WPS) parameters are not strictly adhered to. These imperfections are inherent to this joining technology. Design rules and standards are based on the assumption that welds are made to good workmanship level. Any excessive imperfection beyond good workmanship level is considered to be unacceptable and regarded as a defect. Hence, a ship is inspected during construction to make sure it is reasonably defect free. However, since 100% inspection coverage is not feasible, only partial inspection has been required by Classification Societies. Classification Societies have developed rules, standards and guidelines specifying the extent to which inspection should be performed, which intends to:

1. Verify welding execution quality level,
2. Ensure that areas and members with higher susceptibility to defects receive sufficient attention,
3. Find and rectify any excessive variation in defect rates

A review of rules and standards from classification bodies that are members of IACS shows some limitations in current practices. One key limitation is that the rules favour a 'one-size-fits-all' approach. In addition to that, significant discrepancy exists between rules of different classification societies. Inspection regimes need to be adjusted taking cognisance of the perspectives of key stakeholders involved in shipbuilding - specifically, ship owners, manufacturers, and Classification societies. Factors that interest these stakeholders include: assurance of intended safety and structural reliability of the vessel; saving time and the costs associated with NDE and subsequent remedial action; and, incorporating manufacturing quality.

A promising way to achieve targeted and cost-effective inspections is to take a risk-based approach to inspection. The risk-based inspection (RBI) process helps to identify the potential hazard and failure scenarios, their likelihood and their corresponding consequence which in turn enables decision makers to optimise inspection. Current rules, standards and guidelines, in essence, have some level of qualitative risk assessment built into them. However this assessment has evolved over time, and is substantially based on expert opinion and engineering judgement. The authors propose a more systematic and quantitative (analyses – based) approach.

For the purpose of inspection during manufacturing (QC inspection), the risk-based approach needs to be further complemented by statistical methods in order to allow incorporating data and experiences from a manufacturer's quality-assurance program so that the amount of inspection may be adjusted based upon the expected level of quality.

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6 References

[1] F. Mashiri, X.-L. Zhao, and P. Grundy, "Effects of weld profile and undercut on fatigue crack propagation life of thin-walled cruciform joint," Thin-walled structures, vol. 39, no. 3, pp. 261–285, 2001.

[2] H. Remes and W. Fricke, "Influencing factors on fatigue strength of welded thin plates based on structural stress assessment," Welding in the World, vol. 58, no. 6, pp. 915–923, 2014.

[3] A. Deshmukh, G. Venkatachalam, H. Divekar, and M. Saraf, "Effect of Weld Penetration On Fatigue Life," Procedia Engineering, vol. 97, pp. 783–789, 2014.

[4] Y. Tobe and F. Lawrence Jr, "Effect of inadequate joint penetration on fatigue resistance of high-strength structural steel welds," Weld. J.(Miami);(United States), vol. 56, 1977.

[5] B. ISO, "6520-1 (2007)'Welding and allied processes: Classification of geometric imperfections in metallic materials,'" Part 1: Fusion Welding, pp. 6520–1, 2007.

[6] A. C. on W. in M. Construction, D3.5:1993(R2000) GUIDE FOR STEEL HULL WELDING. American Welding Society, 1992.

[7] P. Haagensen and S. Maddox, "Specifications for weld toe improvement by burr grinding, tig dressing and hammer peening for transverse welds," IIW Commission XIII-Working Group, vol. 2, 1995.

[8] D. Béghin, O. F. Hughes, and J. K. Paik, Ship structural analysis and design. Society of Naval Architects and Marine Engineers, 2010.

[9] A. B. of Shipping, Guide for non-destructive inspection of hull welds. 2014.

[10] RINA, Rules for carrying out non-destructive examinations of welding. RINA S.p.A., 2007.

[11] BSI, Non-destructive testing of welds — Penetrant testing — Acceptance levels (ISO 23277:2015). BSI Standards Limited, 2015.

[12] KR, "Part 2 Materials and welding," 2015, pp. 81–94.

[13] NK, "Rules for the survey and construction of steel ships," 2015, pp. 24–31.

[14] DNV.GL, "Rules for classification Ships Part 2 Materials and welding Chapter 4 Fabrication and testing," 2015, pp. 80–85.

[15] L. R. of S. (Firm: 1914-), "Rules and Regulations for the Classification of Ships," Lloyd's Register of Shipping, 2015, pp. 352–354.

[16] Y. Okumoto, Y. Takeda, M. Mano, and T. Okada, Design of ship hull structures: a practical guide for engineers. Springer Science \& Business Media, 2009.

[17] C. F. W. Marcello Consonni, "Repair rates in welded construction - an analysis of industry trends," Welding & Cutting, no. 1, pp. 33–35, 2012.

[18] R. Boekholt, Welding Mechanisation and Automation in Shipbuilding Worldwide: Production Methods and Trends Based on Yard Capacity. Abington Publishing, 1996.

[19] Kobelco, "State-of-the-art automatic arc welding processes meet the latest shipbuilding requirements," Kobelco welding today, vol. 14, 2011.

[20] BSI, Non-destructive testing of welds — Magnetic particle testing — Acceptance levels(ISO 23278:2015). The British Standards Institution, 2015.

[21] BSI, Non-destructive testing of welds — Acceptance levels for radiographic testing Part 1: Steel, nickel, titanium and their alloys. The British Standards Institution, 2013.

[22] BSI, Non-destructive testing of welds — Ultrasonic testing — Acceptance levels (ISO 11666:2010). The British Standards Institution, 2011.

[23] Guidance Notes for Risk Based Inspection of Hull Structures. http://www.lr.org/en/energy/compliance/rules-supporting-software-and-guidance/guidelines/risk-based-inspection-for-hull-structures/: Lloyd's Register Group Limited, 2015.

[24] 206 Risk Based Inspection: A Guide To Effective Use Of The RBI Process. EEMUA, 2006.

[25] API Recommended Practice 580 Risk Based Inspection. USA: API Publications, 2009.

[26] API RP 581 Risk Based Inspection Technology. USA: API, 2008.

[27] "RISKWISE software for Risk Based Inspection (RBI) / Risk Based Maintenance (RBM) software for Oil, Gas & Chemical Plant and Power Plant." [Online]. Available: http://www.twisoftware.com/riskwise. [Accessed: 25–05-2016]

[28] A. Lee, C. Serratella, G. Wang, R. Basu, R. Spong, and others, "Flexible approaches to risk-based inspection of FPSOs," in Offshore Technology Conference, 2006.

[29] DNV, Probabilistic methods for planning of inspection for fatigue cracks in offshore structures. 2015.

[30] U. Bharadwaj and J. Wintle, "Risk-Based Optimization of Inspection Planning in Ships," Journal of Ship Production and Design, vol. 27, no. 3, pp. 111–117, 2011.

[31] N. Barltrop, "Final Report Summary - RISPECT (Risk-Based Expert System for Through–Life Ship Structural Inspection and Maintenance and New-Build Ship Structural Design)," 2014. [Online]. Available:

http://cordis.europa.eu/result/rcn/143029_en.html. [Accessed: 23–05-2016]

[32] A. Papanikolaou, Risk-based ship design: Methods, tools and applications. Springer Science \& Business Media, 2009.