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Probability of Failure of Damaged Ship Structures – Phase 2

U. Akpan, B. Yuen, K. Shahin, T. S. Koko and F. Lin
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Contractor's Document Number: Technical Report TR-12-01
Contract Project Manager: T.S. Koko, 902-425-5101
Contract Number: W7707-088100
CSA: Malcolm J. Smith, Group Leader / NPSS, 902-426-3100 ext 383

Defence R&D Canada – Atlantic

Contract Report
DRDC Atlantic CR 2012-010
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Canada

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Contract Report
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Abstract

The Phase II report lays out a methodology for assessing the reliability of ships in a damaged condition and looks into the suitability of available tools. Tools for assessing the extent of damage are discussed and algorithms are proposed for computing and combining short term loads on a damaged ship including stillwater and wave loads. A methodology is presented for analysing the residual strength of a damaged vessel that uses the simplified tool, ULTMAT, and the advanced tool TRIDENT. Formulas which can be used for deterministic structural integrity of a damaged vessel are advanced in the form of interactive equations that define the safe envelop of operation. Additionally, reliability analysis methods are developed that account for uncertainties in the loading, structural strength and models used for assessing a damaged vessel. Further study of the damage arising from ship-to-ship collisions is carried out using LS-DYNA to augment the result from the Phase 1 study.

Résumé

Le rapport relatif aux travaux de la Phase II présente une méthode d'évaluation de la fiabilité des navires endommagés et examine l'applicabilité d'outils disponibles. On y discute des outils qui permettent d'évaluer l'ampleur des dommages subis et on propose des algorithmes ayant la capacité de calculer et de combiner les charges appliquées à court terme sur un navire endommagé, notamment les charges associées à la pression de l'eau calme et à celle des vagues. On y présente aussi une méthode d'analyse de la capacité de résistance résiduelle d'un navire endommagé, basée sur l'emploi de l'outil simplifié ULTMAT et de l'outil perfectionné TRIDENT. Dans le cadre de nos travaux, des formules pouvant servir à effectuer l'analyse déterministe de l'intégrité structurale d'un navire endommagé ont été élaborées sous forme d'équations interactives qui définissent l'enveloppe d'exploitation sûre. De plus, on a mis au point des méthodes d'analyse de fiabilité qui tiennent compte des incertitudes liées au chargement, à la résistance structurale et aux modèles qui sont utilisés pour évaluer l'état d'un navire endommagé. Des travaux additionnels en cours portent sur la détermination des dommages subis lors de la collision de deux navires, à l'aide du logiciel LS-DYNA, afin d'accroître la portée des résultats obtenus lors de l'étude de la Phase 1.

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Executive summary

Probability of Failure of Damaged Ship Structures – Phase 2

U. Akpan; B. Yuen, K. Shahin, T. S. Koko, F. Lin; DRDC Atlantic CR 2012-010; Defence R&D Canada – Atlantic; May 2012.

Introduction: Gross damage, such as that resulting from accidents or combat, affects both the structural and watertight integrity of surface ships. Moreover, a damaged ship may have to operate for a period of time with reduced structural strength and altered loading and stability characteristics, if only to get to a port of safety for repairs. The probability of survival of a damaged ship operating in a seaway is of considerable interest both in the immediate response to a damage incident and in ship design. Many uncertainties arise, both in the extent of gross damage that occurs during accidents or combat, as well as in the resulting strength and loading of a ship in a damaged condition. The present study is phase 2 of a larger study with the goal of demonstrating an assessment method for determining probability of failure in a damaged condition that properly accounts for uncertainties that arise during a damage incident.

Results: The Phase II report lays out a methodology for assessing the reliability of ships in a damaged condition and looks into the suitability of available tools. Tools for assessing the extent of damage are discussed and algorithms are proposed for computing and combining short term loads on a damaged ship including stillwater and wave loads. A methodology is presented for analysing the residual strength of a damaged vessel that uses the simplified tool, ULTMAT, and the advanced tool TRIDENT. Formulas which can be used for deterministic structural integrity of a damaged vessel are advanced in the form of interactive equations that define the safe envelop of operation. Additionally, reliability analysis methods are developed that account for uncertainties in the loading, structural strength and models used for assessing a damaged vessel. Further study of the damage arising from ship-to-ship collisions is carried out using LS-DYNA to augment the result from the Phase 1 study.

Significance: The methodologies that have been developed can be used to investigate the reliability of a damaged vessel. Algorithms developed to estimate extreme values for short term wave load, load combination, interaction equations, limit state functions and probabilistic characteristics of load, strength and model parameters will be used in Phase III work.

Future plans: **A**dditional phases are anticipated where a case study will be conducted that will see the proposed method demonstrated first using an undamaged ship and then with the ship in a damaged condition.

Sommaire

Probability of Failure of Damaged Ship Structures – Phase 2

U. Akpan; B. Yuen, K. Shahin, T. S. Koko, F. Lin; DRDC Atlantic CR 2012-010; R & D pour la défense Canada – Atlantique; mai 2012.

Introduction : Les dommages généraux comme ceux causés par des accidents ou des combats influent sur l'intégrité structurale et l'étanchéité à l'eau des navires de surface. De plus, il est possible qu'un navire endommagé doive fonctionner pendant une période donnée, si ce n'est que pour atteindre un port sûr pour y effectuer des réparations, tout en présentant une résistance structurale réduite ainsi que des caractéristiques de chargement et de stabilité modifiées. Les probabilités de survie d'un navire endommagé circulant dans une voie maritime constituent un sujet de grand intérêt, que ce soit dans le domaine des interventions immédiates après un incident ayant causé des dommages ou en matière de conception de navires. Il existe toujours de nombreuses incertitudes liées à l'ampleur des dommages généraux causés lors d'accidents ou de combats, ainsi qu'à la résistance et au chargement du navire endommagé. La présente étude constitue la Phase 2 d'un projet plus global dont l'objectif est de démontrer la pertinence d'une méthode de détermination des probabilités de défaillance de la structure d'un navire endommagé et sa capacité de tenir adéquatement compte des incertitudes associées à un incident causant des dommages.

Résultats : Le rapport relatif aux travaux de la Phase II présente une méthode d'évaluation de la fiabilité des navires endommagés et examine l'applicabilité d'outils disponibles. On y discute des outils qui permettent d'évaluer l'ampleur des dommages subis et on propose des algorithmes ayant la capacité de calculer et de combiner les charges appliquées à court terme sur un navire endommagé, notamment les charges associées à la pression de l'eau calme et à celle des vagues. On y présente aussi une méthode d'analyse de la capacité de résistance résiduelle d'un navire endommagé, basée sur l'emploi de l'outil simplifié ULTMAT et de l'outil perfectionné TRIDENT. Dans le cadre de nos travaux, des formules pouvant servir à effectuer l'analyse déterministe de l'intégrité structurale d'un navire endommagé ont été élaborées sous forme d'équations interactives qui définissent l'enveloppe d'exploitation sûre. De plus, on a mis au point des méthodes d'analyse de fiabilité qui tiennent compte des incertitudes liées au chargement, à la résistance structurale et aux modèles qui sont utilisés pour évaluer l'état d'un navire endommagé. Des travaux additionnels en cours portent sur la détermination des dommages subis lors de la collision de deux navires, à l'aide du logiciel LS-DYNA, afin d'accroître la portée des résultats obtenus lors de l'étude de la Phase 1.

Portée : Les méthodes élaborées peuvent servir à étudier la fiabilité d'un navire endommagé. Les algorithmes développés dans le cadre de la présente phase seront utilisés lors des travaux de la Phase III, notamment ceux permettant d'estimer les valeurs extrêmes des charges appliquées à court terme par les vagues, des charges combinées, des équations d'interaction, des fonctions d'état limite et des caractéristiques probabilistes de la charge et de la résistance et des paramètres du modèle.

Recherches futures : On prévoit que des phases de travaux additionnelles seront exécutées, lesquelles comporteront notamment une étude de cas permettant de démontrer la validité de la méthode proposée, avec un modèle de navire intact et un second de navire endommagé.

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1 Introduction

1.1 Background

Both naval and commercial vessels may experience various forms of damage in normal service conditions or as a result of accidents. Typical kinds of damage incurred by commercial ships include fatigue cracking, corrosion, as well as indentation and rupture due to collision, grounding or heavy seas. In addition, naval vessels may also suffer combat-related blast, fragmentation, and ballistics damage. Assessing the survivability of ships in a damaged condition continues to be an active area of research that encompasses the loss of structural strength, changes to the loading and dynamic stability, damage control, and crew evacuation.

The proposed project addresses the following question: for a ship operating in a given seaway how does the presence of damage affect the probability of structural failure? Previous work by DRDC (e.g., the Improved Ship Structure Maintenance Management project) has generally been concerned with corrosion and fatigue cracking. The present work is concerned with the effect of gross damage to structure, such as may be caused by collisions, groundings, and explosive effects. Gross damage is more challenging to assess than corrosion or fatigue cracking for two reasons:

- If the damage is at or below the waterline, flooding will occur and the loading on the structure may differ from the intact case

- Gross damage may cause not only a reduction in strength and stiffness, but may bring about modes of failure (e.g., grillage collapse of stiffened panels, shear failure of hull girders) that normally would not occur in intact ships.

The ability to assess the probability of failure with gross damage would allow ship designers to improve damage tolerance of new designs through assessment of likely damage scenarios. It would also give naval architects and engineers a tool to assess the risk of operating ships with damage, and would ultimately provide ship owners with improved availability of their vessels without compromising safety.

This study is the second of a three-phase effort whose purpose is to identify a general methodology for assessing the effects of gross damage on ship structural performance, and apply it to some typical scenarios. The three phases of work are structured as follows:

Task 1: A review of available literature and capabilities of available tools and estimate gross damage to large surface ships (commercial vessel or naval frigate) using simulations of collisions.

Task 2: Identify a general evaluation methodology for assessing probability of structural failure in an intact and damaged condition, based on available modeling and computational tools.

Task 3: Conduct a case study using the identified methodology to determine the probability of failure of a ship in an intact and damaged condition while operating in a seaway.

Task 1 was completed in FY 09/10 (under Task 9 of Contract W7707-088100). A review was performed of studies on damaged ships, including an overview of capabilities and tools for modeling gross damage to large surface ships. An investigation was conducted on modeling the extent of damage in collision scenarios using SIMCOL and LSDYNA modeling tools. SIMCOL is a simplified collision modeling tool that is suitable for computing damage probabilities from a large number of collision scenarios and LSDYNA is a more advanced tool that is appropriate for detailed modeling of damage in collision events. Due to budget limitations, only preliminary analysis with LSDYNA was accomplished in Phase 1.

1.2 Objectives and Scope

The overall objective of the study is to develop methodologies for assessing the probability of failure of damaged ship structures with gross damage. The present study is focused on Task 2 which is titled "Identify a general evaluation methodology for assessing probability of structural failure in an intact and damaged condition, based on available modeling and computational tools."

The scope includes:

(i) Further LSDYNA confirmation of SIMCOL. This involves identification and validation of a rupture failure criterion for the structural finite element meshes to be used in the simulations, and execution of LSDYNA simulations for 5 selected collision damage scenarios of a naval vessel.

(ii) Development of a methodology for modeling the reliability of a damaged ship with gross damage using the results of phase 1 study. The methodology should be applicable to all types of gross damage experienced by a surface ship, including the collision scenarios investigated in Phase 1 and must take into account the following in its evaluation of damage effects:
   - The amount of structural damage and flooding likely to occur during a damage event;
   - Stillwater and wave-induced bending moments and shear forces (horizontal and vertical), as well as wave-induced torsional moment in the damaged condition. Short-term probabilistic assessment methods of wave-induced loads should be considered;
   - The ultimate strength of a ship's hull girder in the damaged condition (including bending, shear and torsional strength and their interaction); and
   - Probabilistic and deterministic assessment of damage extent, and ultimate strength.

At this stage of development, the methodology need not take into account the following effects:

- The dynamic stability of the vessel;
- Effect of progressive flooding, and the coupling of flooding, loading, and structural response effects;
- Component structural strength (transverse bulkheads, etc.) except to the extent that it affects hull girder strength; and
- Crack propagation.

The methodology must be capable of predicting the probability of failure over a short time period (1 to 7 days) for a ship in a damaged condition operating in an open-ocean environment.

A scheme for implementing the methodology is to be provided that includes the following:

- An algorithm clearly outlining the solution methodology, including the input and output requirements of each step.
- Recommendations for tools and methods for each of the steps. As a minimum, the use of the following tools shall be investigated.

Type of Analysis	Software Tool
Damage Extent	SIMCOL, LS-DYNA
Stillwater Load (no flooding)	TRIDENT
Stillwater Load including flooding	TRIDENT
Wave Load	FD-WAVELOAD, TD-WAVELOAD, STRUC, SHIPMO, PRECAL
Ultimate Strength	ULTSAS, ULTMAT, TRIDENT
Reliability Assessment	COMPASS

Potential limitations of the methodology shall be identified, including deficiencies in the capabilities of existing tools, and limiting assumptions of the methodology.

The feasibility of the methods should be demonstrated using a few limited test cases.

1.3 Organization of this Document

Chapter 2 is focused on LSDYNA simulation of a damaged ship. An overall methodology is presented in Chapter 3 for modelling the structural integrity of a damaged ship, including the inputs, outputs and available tools. Methods and tools are discussed in Chapter 4 for estimating the extent of damage. Chapter 5 is focused on loads on a damaged ship over a short time frame, including algorithms for estimating extreme loads, load combinations, suitability of available tools, inputs and outputs.

Chapter 6 examines the algorithms and tools for estimating the residual and ultimate strength of a damaged ship. The suitability and limitations of available tools are identified and strategies are presented for assessing the fidelity of estimates of residual strength with simple tools. Models for estimating deterministic structural integrity of a damaged ship are the subject of Chapter 7 and Chapter 8 deals with issues related to probabilistic assessment of a damaged ship.

A summary is presented in Chapter 9 of the study and recommendations for the next phase and the list of references is provided in Chapter 10.

2 LSDYNA Confirmation of SIMCOL

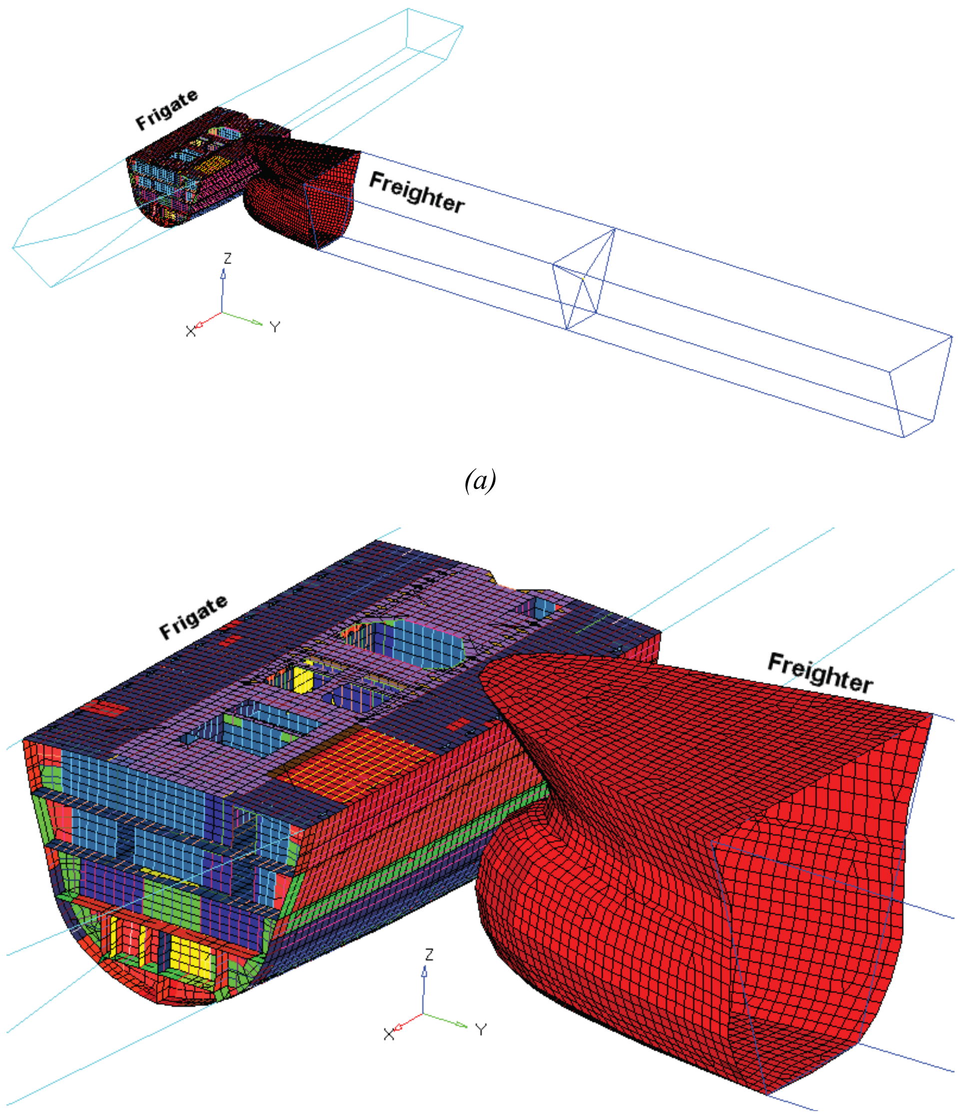
2.1 Finite Element Approach

This chapter describes further finite element analyses by LS-DYNA that were used to confirm the previous LS-DYNA analyses and SIMCOL simulations of the damage caused by a freighter striking a frigate (Akpan et. al., 2010). The finite element modeling and analysis approach adopted in this study was governed by the need to adequately model the complex geometric configuration of the ships, as well as the nonlinear dynamic behaviour of the system due to the collision. The approach consisted of the use of the HyperMesh (2006) and LS-DYNA (2007) finite element software suites. The HyperMesh general-purpose pre- and post-processing program was used for model generation and results processing. On the other hand, the explicit time integration solver in the LS-DYNA suite was used to perform the nonlinear elastic-plastic transient analyses of the ship collision. The software has a wide range of elements, explicit and implicit solvers for performing static and dynamic analysis, and capabilities for handling both material and geometric nonlinearities. Details of the finite element models and analysis results are provided in the following sections

2.2 Finite Element Mesh

Figure 1a shows the overall finite element mesh used to represent the frigate. The mesh was imported from an existing TRIDENT [4] model. Four-node shell elements were used for the sideshell, bulkheads, web frames and stringers. Beam elements were used for all longitudinal and deck stiffeners. The typical element size was 500 mm, however, two mesh refinements were performed as described later in the chapter. In order to simplify the analyses, only the mid-ship was modeled in detail, while the rest of the ship was represented by rigid beams. In addition, a lumped mass, equal to the mass of the rest of the ship, was added to the model at the centre of gravity of the ship.

Figure 1b also shows the overall finite element mesh of the freighter. The freighter was modeled as a 10,000 Mt freighter with a length of 150 m, a width of 20 m, a depth of 15 m and a draft of 7.5 m. The freighter was modeled as a rigid body (Servis and Samuelides,1999; Ozguc et al. 2005) The bow of the ship was modeled using 4-node shell elements, with a typical element size of 750 mm. Similar to the frigate model, the rest of the ship was represented by rigid beams. In addition, a lumped mass, equal to the mass of the rest of the ship, was added to the model at the centre of gravity of the ship.



(a)

(b)

Figure 1: FE mesh of a frigate and a freighter: (a) overall; (b) close-up.

2.3 Material Properties

The finite element model of the frigate was constructed using 350WT steel based on the material properties from the tension tests performed by DRDC Atlantic. The material properties used for the steel in the present analyses are shown in Table 1. The material was modeled with LS-DYNA Material Type 3 (*MAT_PLASTIC_KINEMATIC). On the other hand, the freighter and the rigid beams were modeled as rigid bodies, using Material Type 20 (*MAT_RIGID).

Table 1: Material properties of 350WT steel used in the FE models.

Property	**Value**	
	Present Work	**Previous Work (Akpan et al., 2010)**
Mass Density (kg/m^3)	7,850	7,850
Young's Modulus (MPa)	207,000	207,000
Poisson's Ratio	0.3	0.3
Yield Stress (MPa)	380	350
Tangent Modulus (MPa)	780	2,070
Failure Strain (mm/mm)	0.283*, 0.305**, 0.322***	0.2 Ozguc et al. (2005)

*Original mesh

**First refined mesh

***Second refined mesh

The failure strain used in the ship collision analysis is dependent on the element size in order to simulate the same amount of damage in models with different element sizes. In other words, different failure strains are needed for different element sizes in order to simulate the high strain gradient at the damage site. Therefore, a parametric study was performed to determine the appropriate failure strain to be used in the ship collision models.

The FE models used in the parametric study consisted of a quarter model of a rigid body colliding with a 350WT steel plate, as shown in Figure 2. The steel plate was 3 mm thick and had fixed edges. A series of models were analysed, with decreasing element sizes in the steel plate. The rigid body was given the same reference initial velocity towards the plate in all the models. The aim was to determine the maximum failure strain in each model that would still allow the rigid body to go through the plate, i.e., causing the same amount of damage in the plate, as shown in Figure 3. Using the tension test results as the reference, which had a gage length of 50 mm, thickness of 3 mm and failure strain 0.3, the reference initial velocity of the rigid body was determined using a model with the element size of the gage length. The failure strains determined in the parametric study are plotted in Figure 4. In general, the failure strain required increased as the element size decreased. It is anticipated that it can be extended to an element size of 500 mm. However, this was not done in the current study. The maximum plate element size used in the parametric study was 200 mm, which was equal to the half-width of the rigid body. In order to extend the study to an element size of 500 mm, the half-width of the rigid body would have to be increased to 500 mm, in order to cause the same amount of damage in the series of models, which means the whole series of models have to be reanalyzed using the larger rigid body.

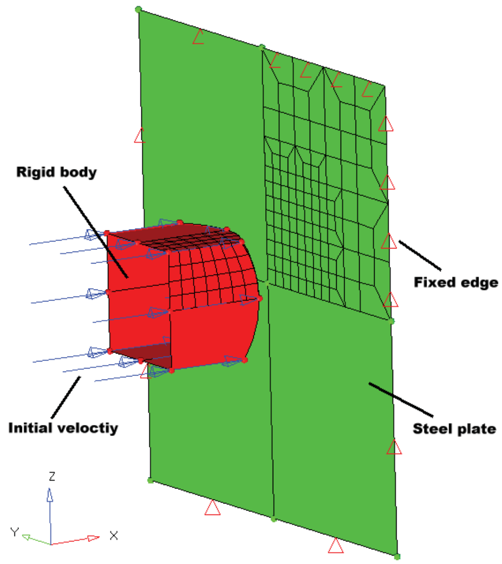


Figure 2: FE mesh used in the parametric study of the failure strain.

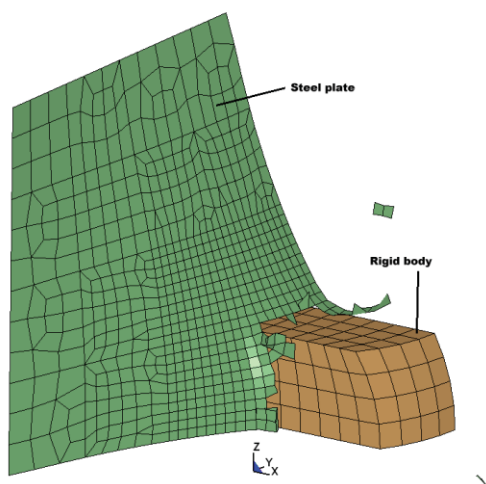


Figure 3: Damage to the steel plate in a typical model in the parametric study of the failure strain.

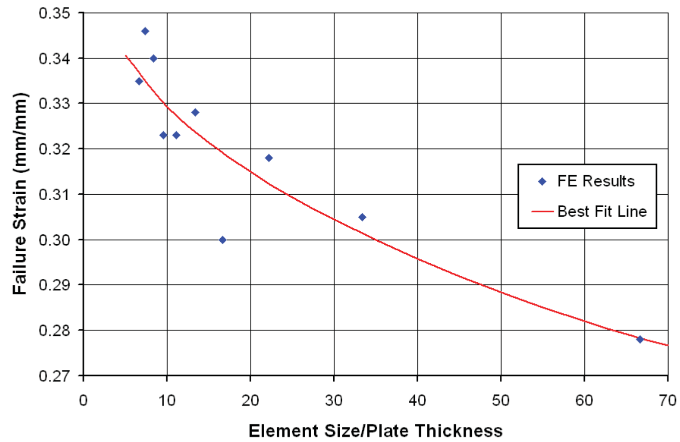


Figure 4: Results of the parametric study of the failure strain.

2.4 Boundary Conditions

Figure 5 shows the boundary conditions applied to the ship models. Since the ships are floating, the displacement at bottom of the ships was constrained in the vertical (z) direction to represent the buoyancy force. Water resistance and added mass were not included in the analysis. In addition, the freighter (the striking ship) was given an initial velocity in the striking direction, while the struck ship was initially at rest.

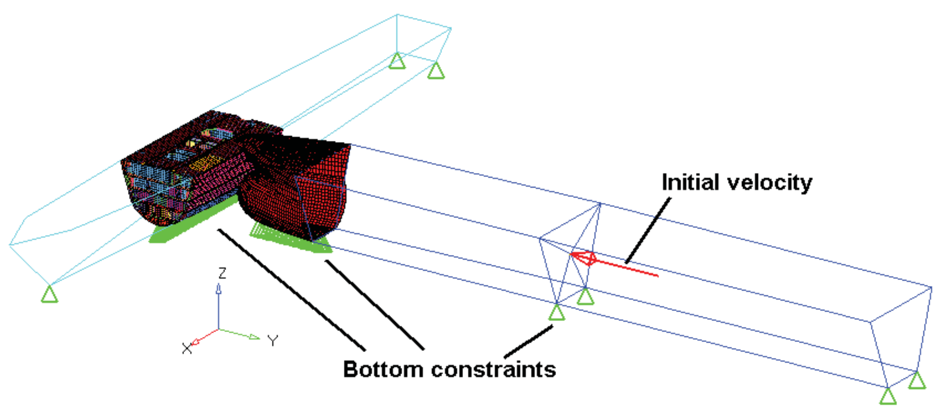


Figure 5: Boundary conditions applied to the ship FE models.

Contact between the ships was defined by the LS-DYNA keyword *CONTACT_ ERODING_SURFACE_TO_SURFACE, which models the fracture of the steel. Once an element reaches the failure strain (see Table 1), the shear stiffness value of the failed element is eliminated. The failed element does not vanish, its mass is always present, but its structural stiffness is set to zero. In addition, eroded nodes are removed from the calculation after surrounding elements fail and a crack opens up.

2.5 Collision Scenarios

Nonlinear elastic-plastic transient analyses were performed to simulate the striking of the frigate by the freighter. The collision scenarios simulated in this study are summarized in Table 2. The ships were assumed to be floating at their respective drafts (6.2 m for the frigate and 7.5 m for the freighter). The strike location considered was at 2.7 m forward of centre of gravity. In addition, three strike angles (50°, 70° and 90°) were considered. A striking velocity of 8 kn was considered for the strike angles of 50° and 70°, while three striking velocities (4 kn, 8 kn and 12 kn) were considered for 90°. In addition, two further analyses (2r1 and 2r2) were performed for Case 2 by refining the frigate mesh around the area of collision. Each mesh refinement consisted of halving the element size of the previous mesh. The mesh refinement for Case 2r2 is shown in Figure 6.

Table 2: Summary of simulated ship collision scenarios.

Collision Case	**Struck Velocity (kn)**	**Striking Velocity (kn)**	**Strike Location (m)**	**Strike Angle (°)**
1	0	4	2.7	90
2	0	8	2.7	90
2r1	0	8	2.7	90
2r2	0	8	2.7	90
3	0	12	2.7	90
4	0	8	2.7	70
5	0	8	2.7	50

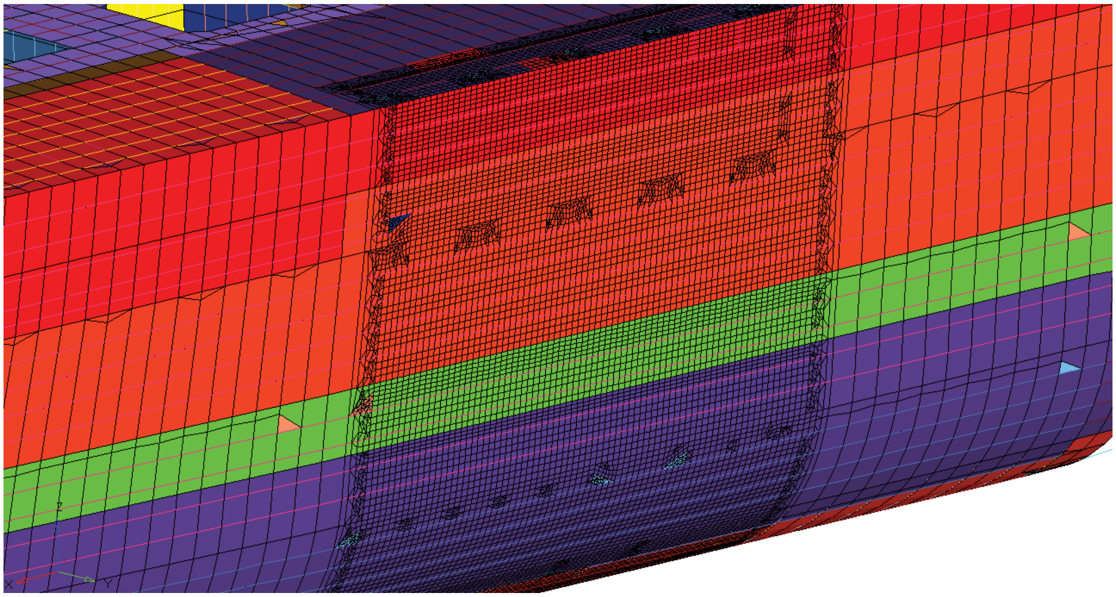
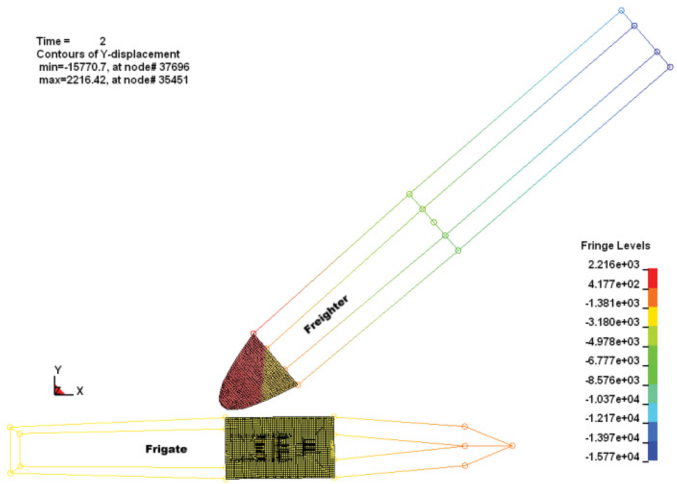


Figure 6: Second mesh refinement of Case 2 (Case 2r2).

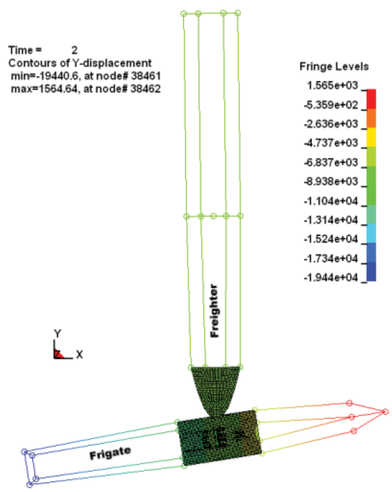
2.6 Results and Discussions

In all the collision scenarios, the initially at-rest frigate began to displace after contact with the freighter. It continued to gather speed and damage to the hull continued to accumulate as the collision progressed through this stage. Eventually, the velocity of the frigate at the point of impact reached the velocity of the freighter but the collision ceased to cause more damage. In fact, for strike angles of 50° and 70°, the frigate was pushed away from the freighter during the simulations, as shown in Figure 7(a). On the other hand, for the 90° strike angle, the two ships were still in contact at the end of the simulations, as shown in Figure 7(b), but no further damage occurred.

It should be noted that the hull was not punctured in any of the collision cases. Instead, the hull was dented to varying degrees, causing failures to the internal structures behind the dent. Typical damages to the hull are shown in Figure 8 to Figure 10. The maximum penetration and length of the damage (dent) for each case is summarized in Table 3. These are compared to the results obtained from the previous finite element analyses and SIMCOL (Akpan et al., 2010). It can be seen that without mesh refinement, the present finite element analyses produced similar results to the previous analyses. However, the mesh refinement of Case 2 resulted in greater damage penetration but not length (Case 2r1 and Case 2r2). Nonetheless, the finite element analyses predicted significantly less maximum penetration than SIMCOL in all cases, even with mesh refinement. It is possible that further mesh refinement could result in greater predicted penetration in the finite element analysis, but it appears unlikely that it could get close to the SIMCOL results. On the other hand, the damage lengths were comparable for 90° strike angle. Nonetheless, both finite element analyses and SIMCOL predicted that increasing the striking velocity would increase both the maximum penetration and the damage length. In addition, both predicted that decreasing the strike angle would decrease the maximum penetration. However, while SIMCOL predicted that decreasing the strike angle would increase the damage length; this was not seen in the finite element analyses.



(a)



(b)

Figure 7: Top view of the ships at 2.0 s: (a) 50° strike angle; (b) 90° strike angle.

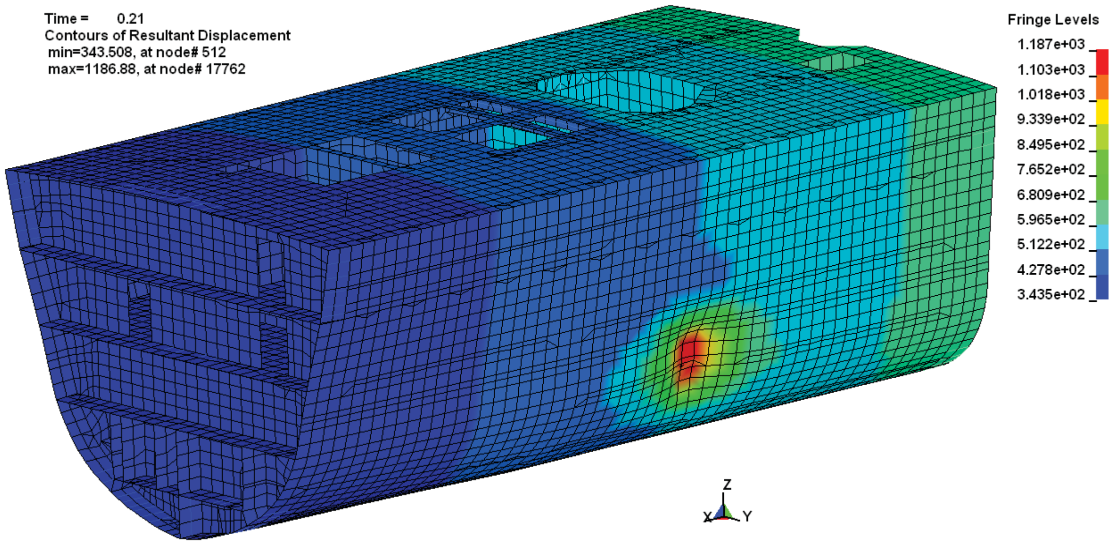


Figure 8: External view of the damage to the frigate hull in collision Case 3.

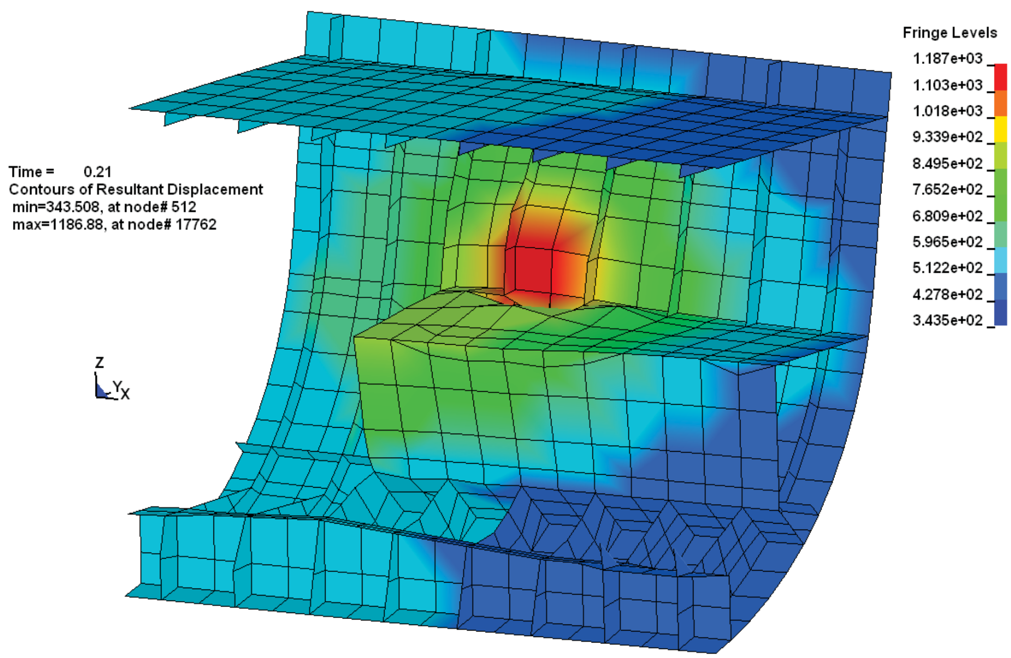


Figure 9: Internal view of the damage to the frigate hull in collision Case 3.

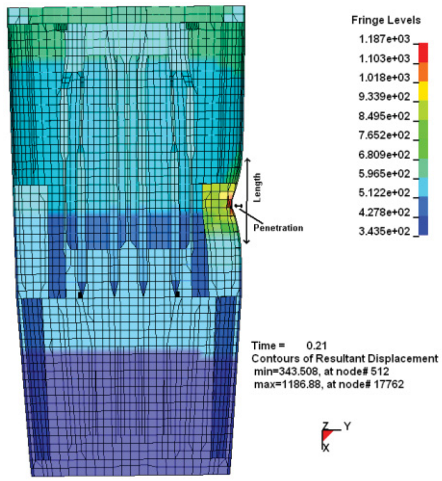


Figure 10: Top view of the damage to the frigate hull in collision Case 3.

Table 3: Summary of collision damages.

	LS-DYNA					
	Present Work		Previous Work (Akpan et al 2010)		SIMCOL	
Collision Case	**Penetration (m)**	**Length (m)**	**Penetration (m)**	**Length (m)**	**Penetration (m)**	**Length (m)**
1	0.183	3.0	0.186	3.0	1.420	3.385
2	0.419	5.5	0.420	5.5	2.841	6.771
2r1	0.480	5.5	N/A	N/A	N/A	N/A
2r2	0.543	5.5	N/A	N/A	N/A	N/A
3	0.644	8.5	0.643	8.5	4.262	10.160
4	0.168	5.5	0.173	5.5	2.437	8.085
5	0.114	3.0	0.115	3.0	0.932	11.513

3 Overall Methodology for Estimating Failure Probability of a Damaged Ship

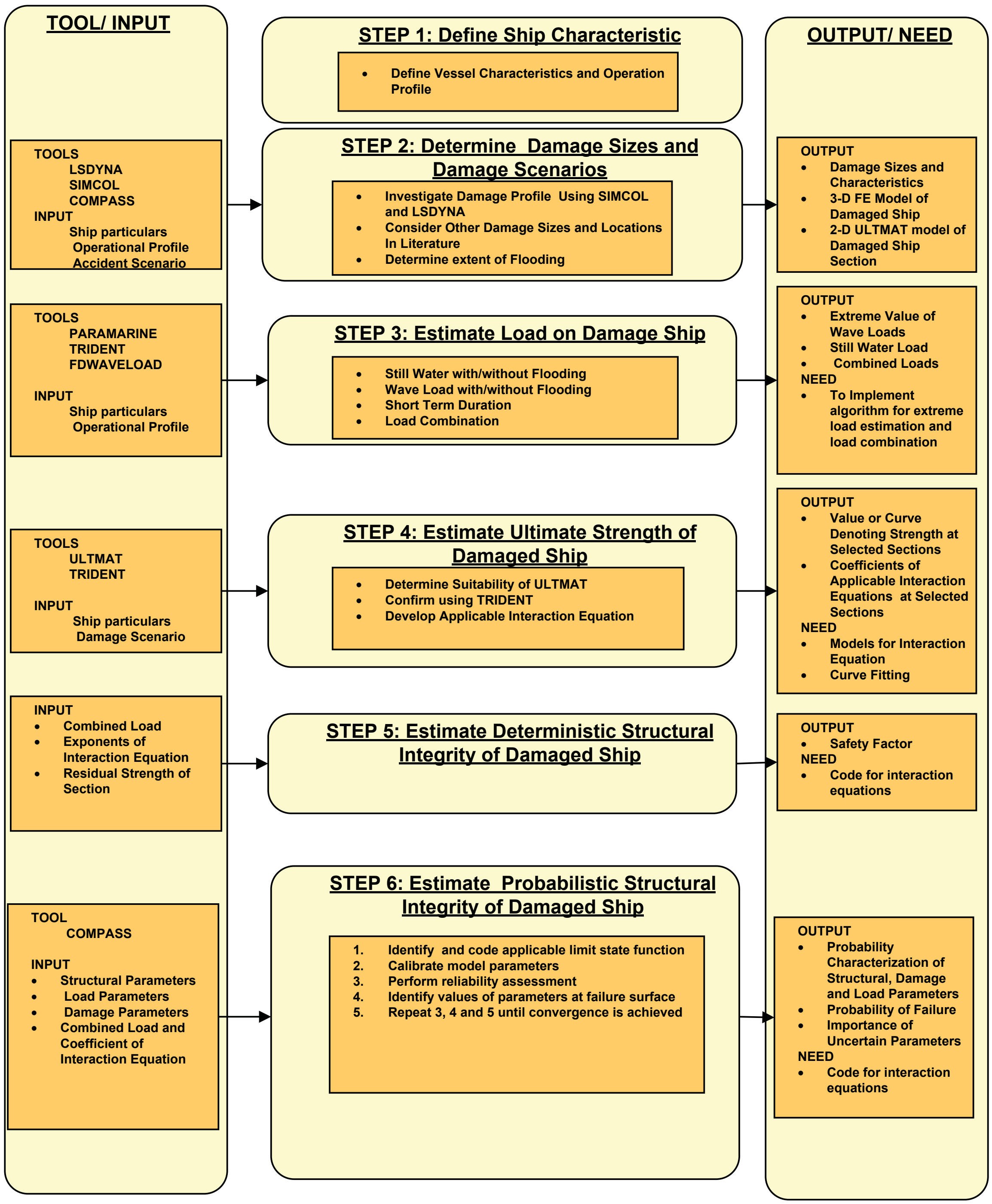


Figure 11: Overall methodology for estimating probability of failure of a damaged ship.

The overall methodology for analysing the probability of failure of a damaged ship is shown in Figure 11. It involves 6 basic steps:

1. Definition of ship characteristics and operational profile. The main particulars of the ship under consideration and operational profile should be defined and used in building the models;
2. Determination of damage size and scenarios and development of suitable 3-D and 2-D model representation of the damaged vessel; Determination of the extent of flooding resulting from damage and change in ship attitude (heel, trim) resulting from flooding;
3. Estimation of loads on the damaged ships;
4. Estimation of the ultimate strengths of the damaged ship sections;
5. Estimation of the deterministic structural integrity of the damaged vessel using appropriate interaction equations; and
6. Estimation of the probabilistic reliability of the damaged vessel.

The tools and input parameters as well as the output and limitations of available tools are summarised in Figure 11 and presented in detail in Chapters 4 to 9. Although the methodology is developed for ship collision damage, it can be applied to other types of damage events as well.

4 Estimation of Damage Sizes and Damage Scenarios

4.1 Introduction

In order to evaluate the structural integrity of a damaged vessel, realistic estimates of damage sizes should be made. The three tools used in the current research for characterizing collision damage sizes are SIMCOL, LSDYNA and COMPASS. The steps that are proposed for estimating realistic damage sizes, scenarios and building a damaged ship model for analysis are:

1. Use literature and experience to suggest realistic stuck and striking vessel particulars, speeds and damage locations;
2. Estimate damage sizes using the simplified tool, SIMCOL, and obtain damage statistics using COMPASS; and
3. Use the advance tool, LSDYNA, to collaborate estimates of damage sizes from the simplified tool.
4. Once the damage sizes are selected, then build 3-D model of the damaged vessel using TRIDENT and obtain 2-D model of damage section for ULTMAT analysis.

Steps 1 to 3 have been performed in Phase 1 of the study while step 4 will be performed in Phase 3 when a case study is executed. A summary is given in this chapter of the steps involved in using SIMCOL and LSDYNA tools and some of the findings from Phase 1 study.

4.2 Steps Involved in using SIMCOL

SIMCOL is a simplified tool that can be used to calculate the length and penetration of damage sizes during a ship collision event. The analysis performed by SIMCOL is two-fold: external ship dynamics, to estimate collision forces and velocities, and internal ship deformations, to calculate the extent of damage in the struck ship.

In the Phase 1 study, SIMCOL results were fed into COMPASS and used to estimate the probability density functions of maximum penetrations and damage lengths in the event of a collision between a commercial vessel and a naval frigate. Three commercial vessels were considered, 100 kDWT Aframax tanker, 30 kDWT dry cargo carrier and 10 kDWT freighter. The particulars of the striking ships and struck ship used are summarised in Table 4 and Table 5 respectively.

SIMCOL has material database for four grades of steel, mild steel, H32, H36 and H40. The frigate used in Phase I study had yield and ultimate stresses of 320 MPa and 450 MPa, respectively, therefore, H32 (Yield Strength 320MPa, Ultimate Strength 450 MPa) was selected from SIMCOL library to represent the frigate.

Table 4: Striking ship particulars.

Striking Ship Particulars	Aframax Tanker	Handymax Dry Cargo Carrier	Handysize Freighter
Length between perpendiculars (m)	238	220	150
Breadth (m)	43	25	20
Depth (m)	21	20	15
Draft (m)	14	10	7.5
Displacement (kg)	100×10^6	30×10^6	10×10^6
Half entrance angle (degrees)	45	50	50

Table 5: Naval frigate input parameters in SIMCOL.

Ship Particulars	Ship type	Single-hull
	Length between perpendiculars (m)	129.0
	Breadth (m)	11.33
	Depth (m)	16.35
	Draft (m)	6.20
	Displacement (kg)	5×10^6
Number of transverse bulkheads		10
Locations of transverse bulkheads, measured from FP (m)		13.3, 26.3, 44.3, 53.3, 70.3, 80.3, 88.3, 97.3, 107.3, 118.3
Number of longitudinal bulkheads		0
Smeared shell thickness (mm)		13.9
Smeared deck thickness (mm)		23.5
Smeared bottom thickness (mm)		43.2
Material grade for shell plating		2

The main outputs from SIMCOL analysis are maximum penetration and damage length. For a given set of struck and striking ships, the maximum penetration and damage length depend on several factors, including the speeds of the two ships, the impact location and the strike angle. The following parameters were used in Phase 1 study:

- Striking ship speed: Weibull (1.0, 4.0).
- Struck ship speed: Weibull (0.75, 3.0).
- Strike angle: Normal (90^o, 25^o).
- Strike location: midship, 40-m fore and aft of midship.

In Phase 1 study, the input to SIMCOL was a set of 60,000 randomly generated realizations of the two ship speeds and impact angle for each strike location. The ship speeds were limited to 24 knots for the frigate, 20 knots for the Aframax tanker and 25 knots for the dry cargo carrier and the freighter. This reflects typical maximum speeds of these types of vessels. Furthermore, the impact angle was limited to the range of applicability of SIMCOL, between HEA+5 and 175-HEA.

Outputs from SIMCOL analyses were used to compute damage statistics for the struck vessel and typical statistics are presented in Table 6, where it is shown that the mean values of maximum penetrations and damage lengths are highest for collision with Aframax, which is the heaviest ship, and lowest for the freighter, which is the lightest ship. Thus the size of the striking ship is a major factor in determining the magnitude of the damage. The mean values of maximum penetrations have largest values when the frigate is struck at the midship section. The probability distribution that best describes maximum penetrations and damage lengths at all locations for all striking ships was shown to be one-sided normal distribution.

Table 6: Damage statistics.

Striking Ship	Location	Parameter	Mean Value	Standard Deviation
Aframax	40 m from midship	Damaged Length (m)	4.9	4.8
		Maximum Penetration (m)	1.4	1.3
	20 m from midship	Damaged Length (m)	6.3	5.6
		Maximum Penetration (m)	1.8	1.6
	Midship	Damaged Length (m)	6.3	5.2
		Maximum Penetration (m)	1.9	1.7
	-20 m from midship	Damaged Length (m)	5.7	4.9
		Maximum Penetration (m)	1.6	1.5
	-40 m from midship	Damaged Length (m)	4.8	4.1
		Maximum Penetration (m)	1.3	1.2
DCC	40 m from midship	Damaged Length (m)	4.9	4.6
		Maximum Penetration (m)	1.2	1.1
	Midship	Damaged Length (m)	6.2	5.0
		Maximum Penetration (m)	1.6	1.5
	-40 m from midship	Damaged Length (m)	4.9	4.2
		Maximum Penetration (m)	1.1	1.1
Freighter	40 m from midship	Damaged Length (m)	4.1	3.9
		Maximum Penetration (m)	1.0	1.0
	Midship	Damaged Length (m)	5.1	4.3
		Maximum Penetration (m)	1.3	1.3
	-40 m from midship	Damaged Length (m)	4.2	3.8
		Maximum Penetration (m)	1.0	1.0

4.3 Steps Involved in using LSDYNA

LS-DYNA has complex non-linear finite element capability that can be used to calculate the extent of damage and penetration during a ship collision event. The steps involved in using LS-DYNA are presented in Chapter 2 and Phase 1 of the current study. They include finite element meshing of the structure, definition of material properties, boundary conditions, collision scenarios and performance of non-linear elastoplastic transient analysis.

Typical collision scenarios that were simulated during Phase 1 study are summarized in Table 7 The ships were assumed to be floating at their respectively draft (6.2 m for the frigate and 7.5 m for the freighter). The strike location considered was at 2.7 m forward of centre of gravity. In addition, three strike angles (50°, 70° and 90°) were considered. A striking velocity of 8 kn was considered for the strike angles of 50° and 70°, while three striking velocities (4 kn, 8 kn and 12 kn) were considered for the 90° strike angle. A summary of typical collision damages is given in Table 8.

Table 7: Summary of simulated ship collision scenarios.

Collision Case	**Struck Velocity (kn)**	**Striking Velocity (kn)**	**Strike Location (m)**	**Strike Angle (°)**
1	0	4	2.7	90
2	0	8	2.7	90
3	0	12	2.7	90
4	0	8	2.7	70
5	0	8	2.7	50

Table 8: Summary of collision damages.

Collision Case	**Finite Element**		**SIMCOL**	
	Penetration (m)	**Length (m)**	**Penetration (m)**	**Length(m)**
1	0.186	3.001	1.420	3.385
2	0.420	5.501	2.841	6.771
3	0.643	8.502	4.262	10.160
4	0.173	5.501	2.437	8.085
5	0.115	3.001	0.932	11.513

4.4 Summary of Damage Sizes and Locations in the Literature

In order to select the damage scenarios for the next phase of the study, damage scenarios and suggestions from the literature should be consulted along with results from simulation. Some of the pertinent literatures that may be of interest were discussed in Phase 1 and are summarized in this section. This includes LR rules for damage of naval vessels summarized inTable 9 and the damage scenarios which were considered by the US Navy in a study that involved naval frigates shown in Figure 12.

Table 9: Extent of damage in navy vessels-LR rule (Lee et al., 2006).

Military Threats	The extent of damage due to military threats defined as the minimum of the shock or blast damage that is likely to result from a specified weapon threat.	
Collision damage to the side shell	Level A	- 5m longitudinally between bulkheads - From the waterline up to the main deck - Inboard for B/5 m
	Level B & C	- 5m longitudinally anywhere including bulkheads -from the bilge keel up to the main deck - Inboard B/5 m
Grounding or raking damage to the bottom structure	Level A	- length of 5m anywhere forward of midships - upwards for 1 m or the underside of the inner bottom, whichever is less - breadth of 5m
	Level B & C	- length of 0.1L anywhere forward of midships - upward for 1 m or the underside of the inner bottom, whichever is less - breadth of 5m

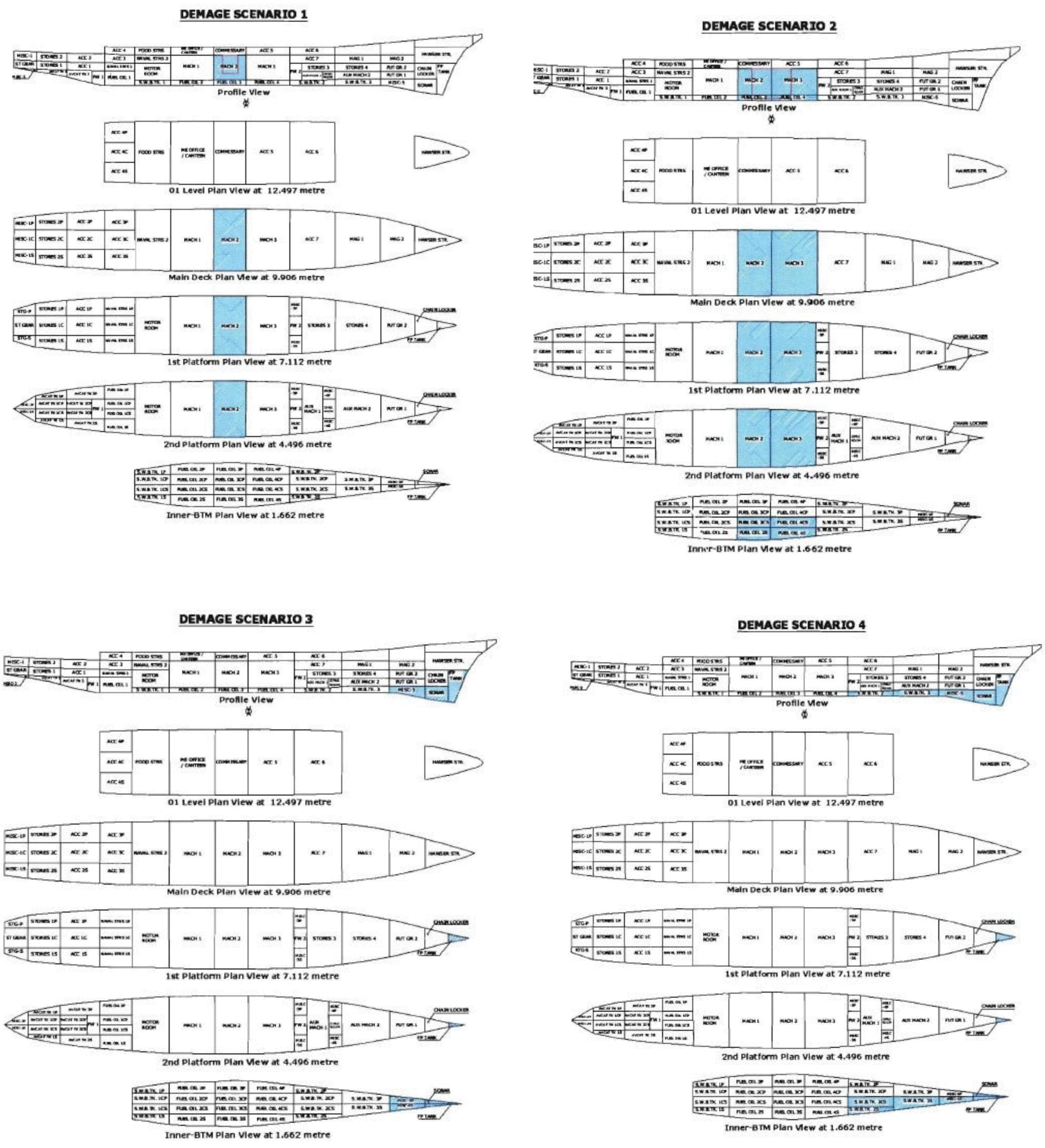


Figure 12: Damage scenarios considered in Lee et al., 2006 and Sun et al., 2008.

5 Estimation of Loads on a Damaged Ship

5.1 Introduction

The main loads on a damaged ship that need to be estimated are stillwater and wave loads. Stillwater loads can be evaluated from proper consideration of the mass distribution over the ship length, the variability in the cargo loading and the buoyancy of the ship. Wave loads result from the interaction of wave forces on the vessel. The added mass approach is one method that can be used for modelling the stillwater load due to flooding of a damaged vessel. In this approach, the seawater which floods into the vessel is assumed to become part of the vessel mass, and to move with the vessel. The added mass approach is only applicable to cases where the ship structure is till buoyant, it does not account for loss of buoyancy. The five steps that are proposed for computing the loads on a damaged vessel are:

1. Estimate the components of stillwater loads with/without flooding using PARAMARINE and TRIDENT;
2. Estimate the components of wave loads with/without flooding using WAVELOAD;
3. Estimate extreme values of the wave loads using relevant short-term time frame that is required for the vessel to travel through one or more sea states as it makes its way to safety;
4. Combine the components of wave loads using the appropriate frequencies and response amplitude operators;
5. Combine the components of the stillwater and the wave loads.

Existing tools can be used for steps 1 and 2. Algorithms and procedures for executing steps 3 to 5 are proposed. The four components of load that are of interest when analysing a damaged vessel, the available tools and algorithm that need to be implemented are summarised in Table 10.

It is noted that the PARAMARINE tool does not have capability for estimating the Stillwater horizontal bending moment and torsional bending moments. This is a gap which may limit the application of the tool is some damage cases.

Table 10: Summary of loads on a damaged ship.

Load	Component	Symbol	Tools and Remarks
Still Water	Vertical Bending Moment	M_{VSW}	Obtained from TRIDENT, PARAMARINE PARAMARINE needed when there is flooding
	Horizontal Bending Moment	M_{HSW}	Obtained from TRIDENT
	Torsional Bending Moment	M_{TSW}	
	Shear Force	F_{SSW}	
Wave Induced	Vertical Bending Moment	M_{VW}	Response Amplitude Operators, RAO, Obtained from WAVELOAD Code for determining extreme value to be implemented in next phase. Algorithm for extreme value discussed in section 5.3
	Horizontal Bending Moment	M_{HW}	
	Torsional Bending Moment	M_{TW}	
	Shear Force	F_{SW}	

Table 11: Steps involved when using TRIDENT to estimate the stillwater bending moments of a damaged ship.

Step	Task
Step 1	**Create FE Mesh** The finite element mesh should include structural (beam, shell, plate, … etc) and fluid elements, as shown in Figure 13.
Step 2	**Specify Mass distribution** The added lumped masses are specified using an ASCII Weight Curve file (*filename.wcf*) which lists the magnitudes and locations of lumped masses along the length of the ship, as shown in Figure 14. Mass is assumed to be uniformly distributed across the width of the ship, varying only in the longitudinal direction.
Step 3	**Perform analysis by using TRIDENT Static Balance Option** The static balance analysis is performed by balancing the buoyancy forces against the ship specified mass (element mass, specified lumped-mass, or both). Figure 15 and Figure 16 show the steps required to perform a static balance analysis.
Step 4	**Output** Review the results of the static balance analysis. Results include: Calculated draft, trim, and heel; Still water bending moment and shear force diagrams; Wave induced (hogging and sagging) bending moment and shear force diagrams; Figure 17 through Figure 20 show typical results from static balance analysis.

5.2 Procedure for Estimating Still Stillwater Load on a Damaged Vessel

Two tools, PARAMARINE and TRIDENT, can be used to estimate vertical stillwater bending moment. TRIDENT can also be employed to estimate horizontal and torsional stillwater bending moment and PARAMARINE does not have the capability to estimate these loads and this is a gap. PARAMARINE, which can handle both flooded and non-flooded damaged vessels, is used by Canadian DND and DRDC. TRIDENT, on the other hand, can only handle non flooded damaged vessel and is readily available to the current project team at Martec as well as DND/DRDC. Since PARAMARINE can handle flooded cases, in an ideal situation it should be possible to use it to estimate parameters that are relevant to a flooded damaged vessel, including weight redistribution, draft, trim and heel angle. These parameters can then be employed in TRIDENT to determine the stillwater bending moments of the flooded damaged vessel. However, the project team does not have any experience with using PARAMARINE in this way and it is therefore uncertain if this can be done with the current version of PARAMARINE. This may be a gap that has to be addressed. The steps involved in using TRIDENT are summarised in Table 11. It is noted that the damage in TRIDENT is modelled by removing sections of the ship structure that are considered damaged, that is, essentially creating a hollow section on the undamaged ship.

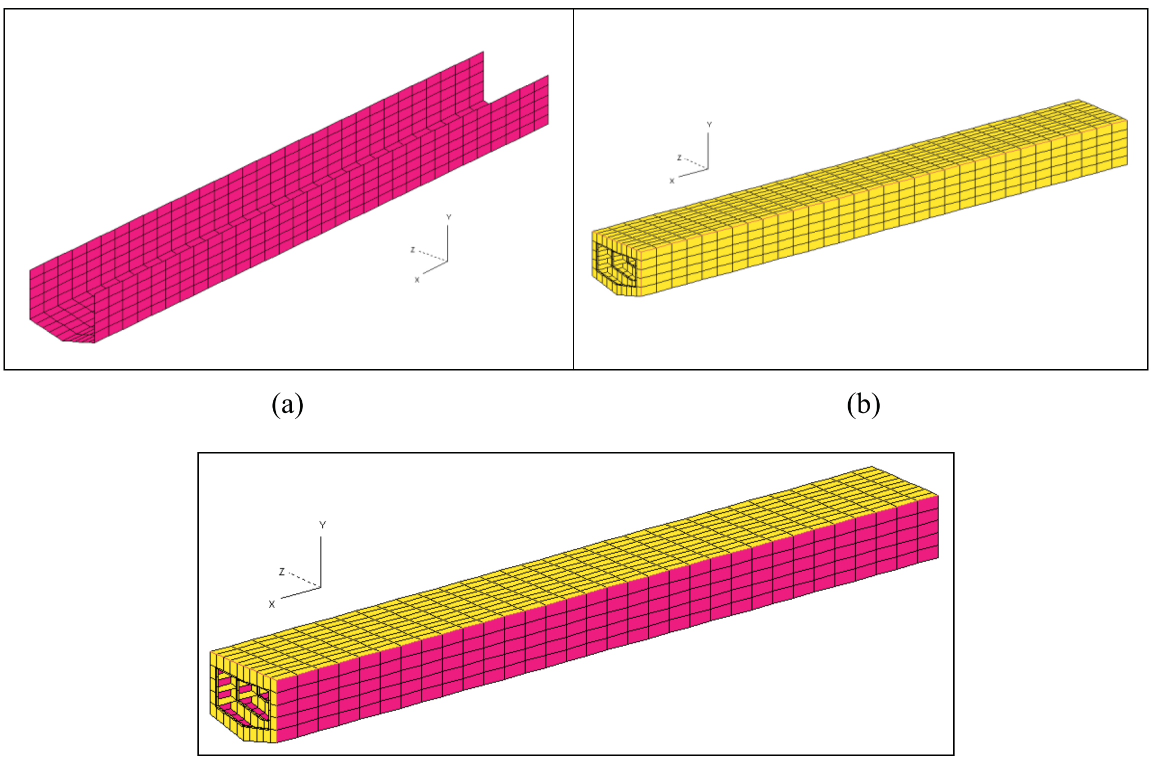


Figure 13: Finite element mesh.

```
MASSDI   3
! BLOCK   AFT X      FWD X      MASS (N*s^2/mm)
1            0        2000       15.0174
2         2000        4000       30.0349
3         4000        6000       30.0349
4         6000        8000       45.0523
5         8000       10000       45.0523
6        10000       12000       60.0698
7        12000       14000       60.0698
8        14000       16000       75.0872
9        16000       18000       60.0698
10       18000       20000       60.0698
11       20000       22000       45.0523
12       22000       24000       45.0523
13       24000       26000       30.0349
14       26000       28000       30.0349
15       28000       30000       15.0174
ENDMAS
```

Figure 14: Format of lumped mass weight curve file.

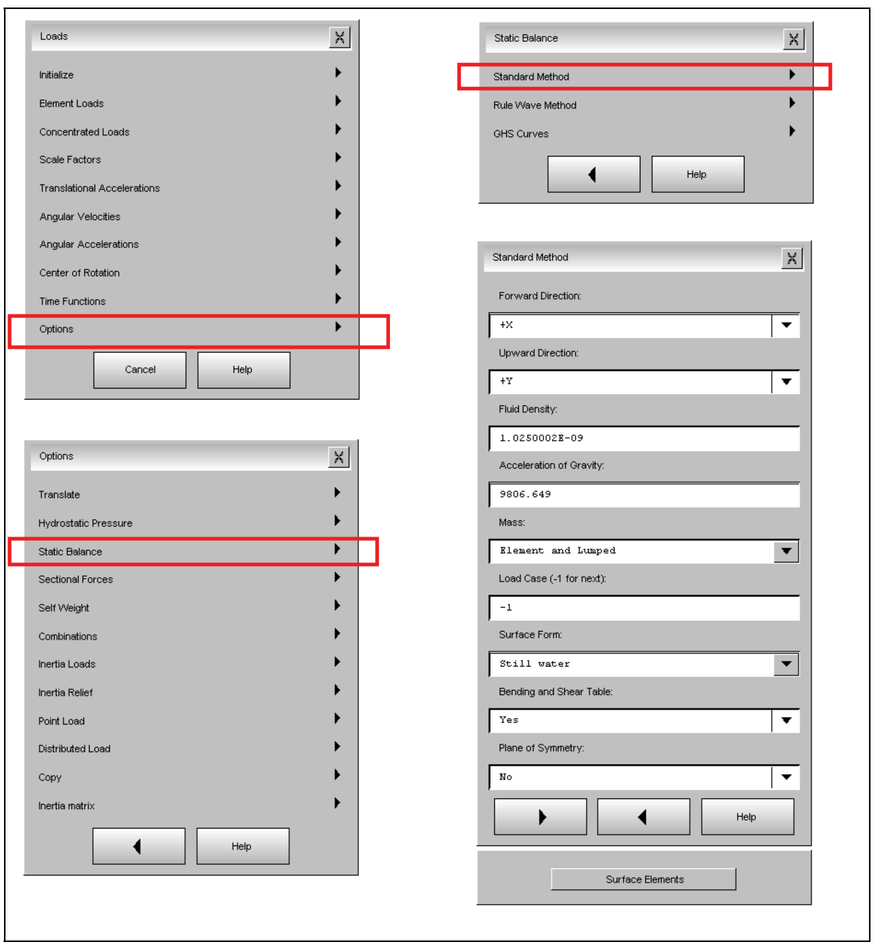


Figure 15: Definition of still water static balance load case.

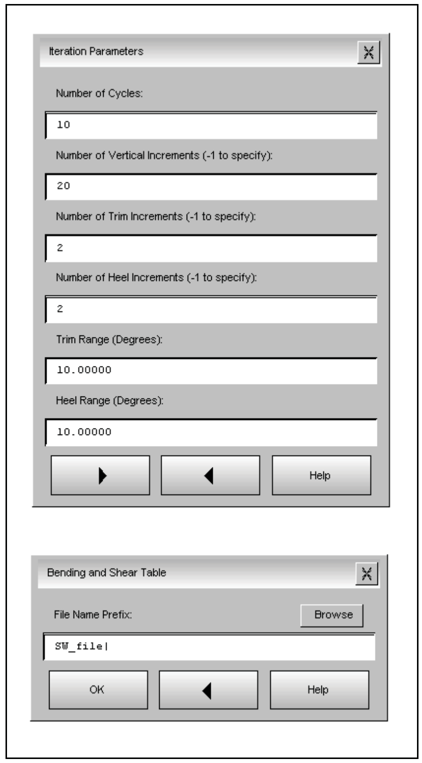


Figure 16: Definition of still water static balance solution parameter.

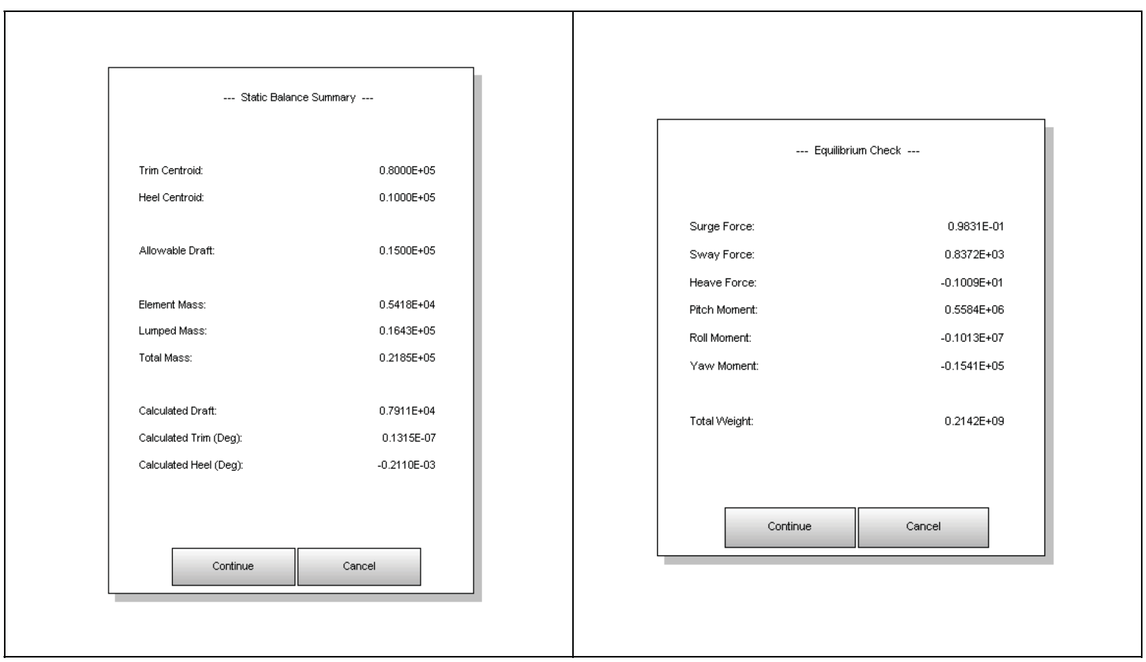


Figure 17: Typical results of still water static balance analysis of undamaged ship.

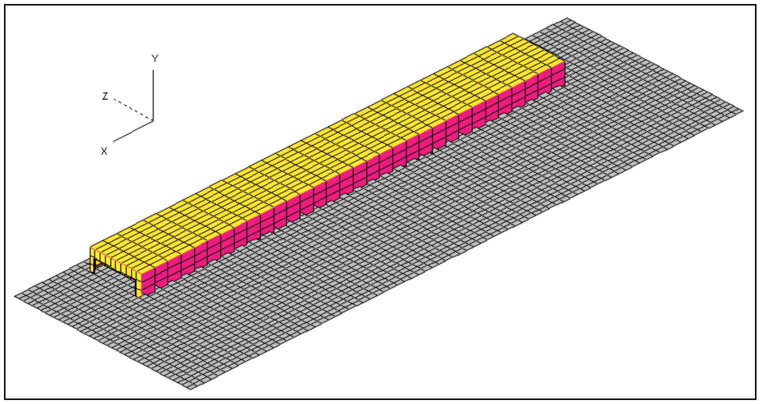
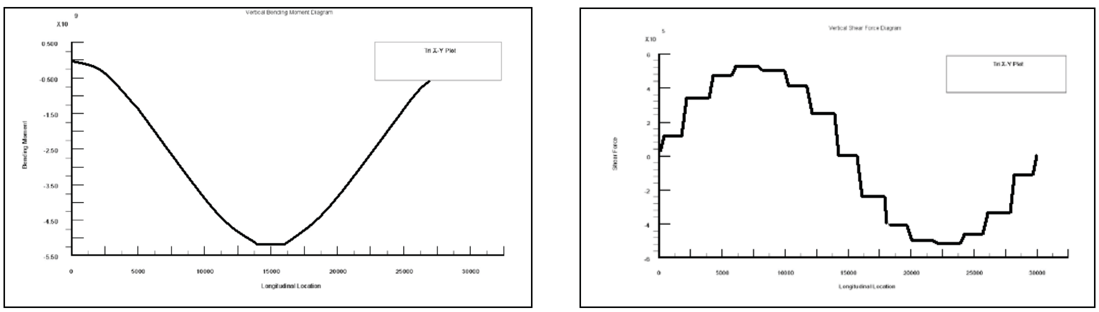


Figure 18: Typical still water static balance results showing surface elements.



(a) (b)

Figure 19: Typical results of static balance analysis, a) still water bending moment diagram; and b) still water shear force diagram.

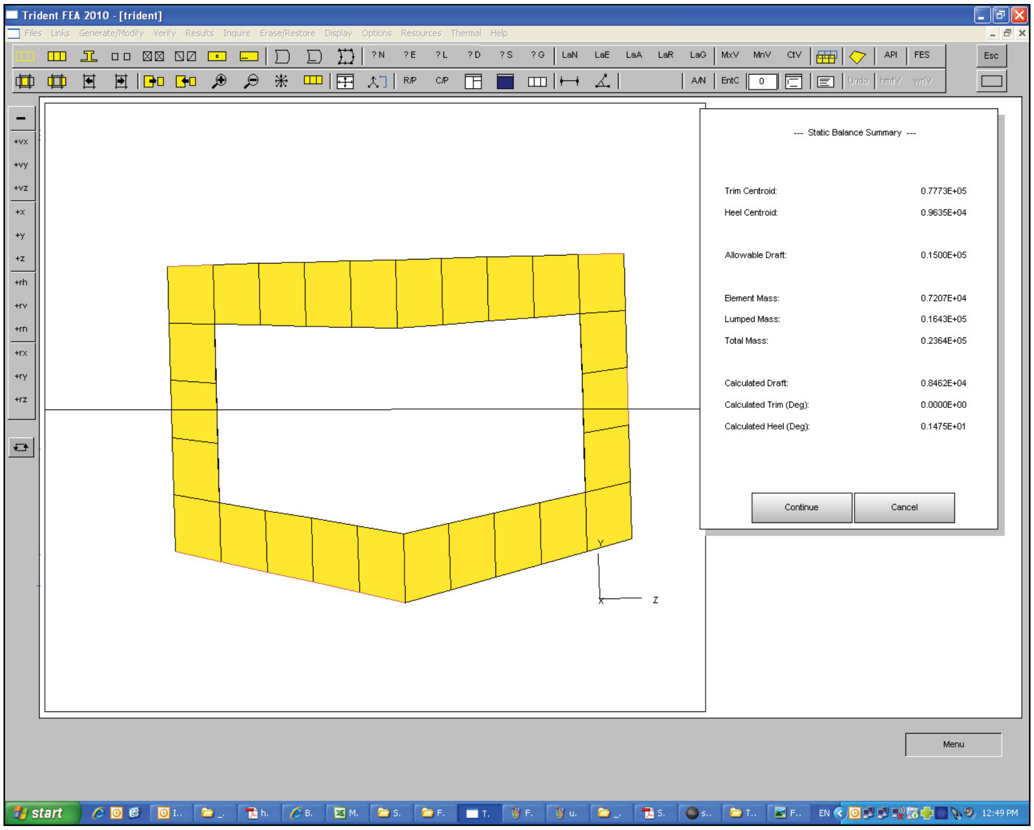


Figure 20: Typical static balance results of a damaged ship showing cross-sectional rotation.

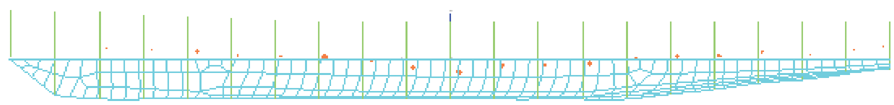
5.3 Procedure for Estimating Extreme Short-Term Waveloads on a Damaged Ship

Before computing the extreme value of short-term wave loads on a damaged vessel the response amplitude operator (RAO), of the wave load on a damaged ship should be determined using WAVELOAD. WAVELOAD is a Martec hydrodynamic software that replaced the old Martec frequency domain hydrodynamic software, FDWAVELOAD. The steps to be taken when using WAVELOAD and methods for determining the extreme values of the load are presented in this section.

5.3.1 Steps in Computing RAO of Waveload Using WAVELOAD

WAVELOAD tool can be used to analyse the wave loads on a damaged ship. Steps in using WAVELOAD are summarised in Table 12.

Table 12: Steps involved in using WAVELOAD for analysis of a damaged ship.

Step	Task
Step 1	**Define Ship Particulars** Hull Type, Length (m), Beam (m), Draft (m), Center of Gravity Radius of Gyration, Heel (deg), Trim (m) Flood volume at its center of gravity (in case of flooding) Shape of the flooded surface
Step 2	**Create Wetted Hullform and surface panel** Provide an accurate description of the wetted surface of the hull
Step 3	**Specify Mass distribution**  Specify an accurate description of mass distribution. It is assumed that the mass is uniformly distributed on each segment. Segments are defined between (x_1 , x_2) pairs specified by the user and they need not necessarily be of equal length. All masses are collected into lumped masses, which are located at the centres of gravity of the mass: lump masses dm(x,y,z), r_{xx}, r_{yy}, $r_{zz,}$ r_{xy}, r_{yz},r_{xz}
Step 4:	**Define Operational Profile** Sea state defined in terms of wave spectral representation of the environment under consideration Hs, Ts, Ship headings Ship speeds Wave frequencies
Step 5	**Perform analysis by running WAVELOAD**
Step 6	**Obtain Response Amplitude Operators of Relevant Output** Vertical Bending Moment My (U, ω, ,θ,X) Horizontal Bending Moment Mx (U, ω, ,θ,X) Torsion Tz (U, ω, ,θ,X), Shear Force (U, ω, ,θ,X)

5.3.2 Algorithms for Determining Extreme Short-term Waveload on a Damaged Ship

The response amplitude operator (RAO) of waveloads computed in the previous section have to be processed in order to determine the maximum or short term extreme value of the load that is applied to the damaged vessel as it transits from the accident location to a nearby safe location. A method for determining the extreme values of these loads is proposed in this section.

An operation profile for the vessel is defined by the loading condition, the vessel's speed and heading and the location typified by the sea state (Tp, Hs). The sea state condition can involve different spectrum such as JONSWAP wave spectrum and Bretschnider wave spectrum. JONSWAP spectrum is defined as follows:

$$S_w = \alpha \frac{H_s^2 \omega_p^4}{\omega^5} \exp\left[-1.25\left(\frac{\omega_p}{\omega}\right)^4\right]\gamma^{\beta}, \qquad \omega_p = \frac{2\pi}{T_p} \tag{1}$$

$$\alpha = 0.0624/[0.23 + 0.0336\gamma - 0.185/(1.9+\gamma)] \;\; \gamma = 3.3$$

$$\beta = \exp[-(\omega - \omega_p)^2/(2\sigma^2\omega_p^2), \qquad \sigma = \begin{cases} 0.07 & \omega \le \omega_p \\ 0.09 & \text{otherwise} \end{cases}$$

and the Bretschnider spectrum is defined by

$$S_w = \frac{5H_s^2\omega_p^4}{16\omega^5}\exp\left[-1.25\left(\frac{\omega_p}{\omega}\right)^4\right] \tag{2}$$

For a selected operational profile, a hydrodynamic analysis from WAVELOAD results in values of encounter frequencies ω_e and RAO of the relevant wave loads such as vertical and horizontal bending moments M_{VRAO} and M_{HRAO} as functions of frequencies. Correlation between the different wave loads can also be computed.

Considering the vertical bending moment, the spectral moment for the vertical bending moment can be computed as

$$m_{Mvn} = \int_0^{\infty} \omega_e^n M_{VRAO}^2 (S_w(\omega, h_s, T_p) d\omega = \int_0^{\infty} \omega_e^n S_{Mv}(\omega) d\omega \tag{3}$$

Specifically the zero, second and fourth moments can be obtained as

$$m_{Mv0} = \int_0^{\infty} S_{Mv}(\omega) d\omega \;\;, \; m_{Mv2} = \int_0^{\infty} \omega_e^2 S_{Mv}(\omega) d\omega, \;\; m_{Mv4} = \int_0^{\infty} \omega_e^4 S_{Mv}(\omega) d\omega \tag{4}$$

Assuming a narrow band process, the response statistics for the vertical bending moments namely, the apparent frequency, ν_{Mv}, the standard deviation, σ_{Mv0} and bandwidth, ε_{Mv} can be obtained using the above expressions as follows.

$$= \sqrt{m_{Mv0}}\,, \qquad \nu_{Mv0} = \frac{1}{2\pi}\sqrt{\frac{m_{Mv2}}{m_{Mv0}}}\,,\; \nu_{Mvp} = \frac{1}{2\pi}\sqrt{\frac{m_{Mv4}}{m_{Mv2}}}\,,\; \alpha_T = \frac{\nu_{Mv0}}{\nu_{Mvp}}\,, \tag{5}$$

$$\varepsilon_T = \sqrt{1-\alpha_T^2}\,,$$

The operational profile in a short term voyage can be described as a Gaussian random process. The probability density function of the maxima vertical bending moment (peak values), M_v, can be represented by a Rayleigh distribution. Integrating the probability density function leads to the cumulative probability distribution of the short-term responses as

$$P(M_V) = \int_0^{\xi} p(\xi)d\xi = 1 - \exp(-\frac{M_v^2}{2\sigma_{Mv0}}) \tag{6}$$

From the above Equation, the short-term probability of exceedance can be established as

$$Q(M_V) = 1 - P(M_V) = \exp(-\frac{M_v^2}{2\sigma_{Mv0}}) \tag{7}$$

Assuming that N is the number of observations or cycles of the random variable over a given period of time, the probable peak value of the vertical bending moment, M_{VEV}, that might be exceeded once out of the N observations can be readily computed by

$$\frac{1}{N} = \exp(-\frac{M_{VEV}^2}{2\sigma_{Mv0}}) \tag{8}$$

This leads to the expression

$$M_{VEV} = \sigma_{MV0}\sqrt{2In(N)} \tag{9}$$

For a given time period, T_s, of a short-term random process, the expected number of positive maxima (peak values) is given by

$$N = 3600T_s\left(\frac{1+\sqrt{1-\varepsilon_{M_V}^2}}{2\sqrt{1-\varepsilon_{M_V}^2}}\right)\nu_{M_V p} \tag{10}$$

Therefore,

$$M_{VWEV} = \sigma_{MV0}\sqrt{2In(3600T_s\left(\frac{1+\sqrt{1-\varepsilon_{M_V}^2}}{2\sqrt{1-\varepsilon_{M_V}^2}}\right)\nu_{M_V p})} \tag{11}$$

Similarly, the probable peak value for the horizontal bending moment can be obtained as

$$M_{HWEV} = \sigma_{MH0}\sqrt{2In(3600T_s\left(\frac{1+\sqrt{1-\varepsilon_{M_H}^2}}{2\sqrt{1-\varepsilon_{M_H}^2}}\right)\nu_{MHp})} \tag{12}$$

And the probable peak value for the torsion bending moment can be obtained as

$$M_{XWEV} = \sigma_{XH0}\sqrt{2In(3600T_s\left(\frac{1+\sqrt{1-\varepsilon_{M_X}^2}}{2\sqrt{1-\varepsilon_{M_X}^2}}\right)v_{MXp})} \quad (13)$$

Equations (11), (12) and (13) can be used to compute short term extreme values for vertical bending moments, horizontal bending moments, and torsional bending moments. It is noted that the magnitude of the extreme values is dependent on the duration on the time frame, T_s. Similar expressions can be developed for the shear force. If the damaged vessel is subjected to more than one short-term sea state the extreme values for all the short term sea states will have to be determined and applied to the vessel. Software for implementing the procedure laid out in the above section will have to be developed during the next phase of the project.

5.4 Algorithm for Combining Components of Short-term Waveloads

Various loads act on a moving damaged vessel including stillwater bending moment, wave induced loads and slamming forces. In this work, only stillwater bending moment and wave induced loads are considered and in the damaged state, it is very important to properly combine all these loads. A typical ship design rule adds together the maximum values of each type of load. This could introduce unnecessary conservatism in the design. Therefore, an alternative strategy that is more realistic is desirable and is proposed in this section. Two types of load combinations are relevant to a damaged vessel:

(i) A load combination that considers different components of wave loads including vertical bending moment, horizontal bending moment, torsion, etc.; and

(ii) A load combination of that involves stillwater bending moment and components of wave loads.

The second type of load combination is straight forward and it involves simply adding the components of still water bending moments to same components of wave induced load. The first type of load combination is more difficult because the components of the wave loads reach maximum values at different frequencies. A procedure is presented for dealing with the first type of load combinations. In general, wave-induced loads have six components that reach maximum values at different times because they have different phase angles. Simply adding the maximum values of the different components will result in a very conservative value. The concept of equivalent wave system has been suggested by Sun et al (2008) and can be used to combine the loads. Components of wave load that should be considered when analyzing a damaged ship are vertical and horizontal bending moments, torsion and vertical shear force. In the following presentation, three wave load components, vertical bending moment M_Y, horizontal bending moment M_Z, and torsion moment M_X are combined using the concept of equivalent wave system. It is noted that the method can be applied to more than 3 load components. Before combining these loads, the RAO and extreme load for the load components should be determined using the strategy discussed in Section 5.3.

When dealing with three load components, there are three possible load combinations and for the purpose of the current discussion will be referred to as load combination 1, load combination 2 and load combination 3. It is advisable that all the load combinations be considered in analysis because it is not possible to know apriori the load combination that will result in the largest load value. Load combination 1 is based on the extreme value of the vertical bending moment, load combination 2 is based on the extreme value of horizontal bending moment and load combination 3 is based on the extreme value of torsion bending moment. The steps that are involved in load combination 1 are outlined in Table 13.

Table 13: Procedure for combining components of wave loads.

Step	Task
Step 1	**Determine the values of the following parameters** $\omega_{y\max}$ - the wave frequency, at which RAO of M_Y is maximum $RAO_{\omega_{y\max}}^{M_y}$ the maximum RAO of M_Y, M_{VWEV} extreme value of M_Y
Step 2	**Calculate the amplitude of the equivalent wave** h_{VWEV} $$h_{VWEV} = \frac{M_{VWEV}}{RAO_{\omega_{y\max}}^{M_y}}$$
Step 3	**Determine RAO values of** M_Z **and** M_X **at** Assume $RAO_{\omega_{y\max}}^{M_Z}$ is RAO value of M_Z at $\omega_{y\max}$ and $RAO_{\omega_{y\max}}^{M_X}$ is RAO value of M_X at $\omega_{y\max}$
Step 4	**Combine the load components using the equation given below** $$L_{C1} = M_{VWEV} + h_{VWEV} \text{ x } RAO_{\omega_{y\max}}^{M_Z} + h_{VWEV} \text{ x } RAO_{\omega_{y\max}}^{M_X}$$ Where L_{C1} is load combination 1. Similar steps can be used to obtain load combination 2 involving the horizontal bending moment as $L_{C2} = M_{HWEV} + h_{HWEV} \text{ x } RAO_{\omega_{Z\max}}^{M_Y} + h_{HWEV} \text{ x } RAO_{\omega_{Z\max}}^{M_X}$ and load combination 3 involving the torsional bending moment as $L_{C3} = M_{XWEV} + h_{XWEV} \text{ x } RAO_{\omega_{X\max}}^{M_Z} + h_{XWEV} \text{ x } RAO_{\omega_{X\max}}^{M_Y}$ where $\omega_{z\max}$ - the wave frequency at which RAO of M_Z is maximum $RAO_{\omega_{z\max}}^{M_Z}$ the maximum RAO of M_{HWEV} extreme value of , $h_{HWEV} = \frac{M_{HWEV}}{RAO_{\omega_{z\max}}^{M_Z}}$ $\omega_{x\max}$ - the wave frequency, at which RAO of M_X is maximum $RAO_{\omega_{x\max}}^{M_X}$ the maximum RAO of M_{XWEV} extreme value of , $h_{XWEV} = \frac{M_{XWEV}}{RAO_{\omega x\max}^{M_X}}$ M_Y is the vertical bending moment M_Z horizontal bending moment M_X torsion moment

5.5 Procedure for Combining Stillwater and Short Term Waveloads

Load components from still water and waveloads should be combined to determine the total load that is applied to a damaged vessel. The resulting combined vertical, horizontal, and torsional bending moments and shear forces will depend on the components of the wave loads that are combined. Typical results of such combinations are shown in Table 14.

Table 14: Typical load combination for short term still water and wave loadings.

Case	Parameter	Symbol
Case 1	Applied Vertical Bending Moment (Load)	$M_{VWEV} + M_{VSW}$
	Applied Horizontal Bending Moment	h_{VWEV} x $RAO^{M_Z}_{\omega_{y\max}} + M_{HSW}$
	Applied Torsion Bending Moment	$M_{TSW} + h_{VWEV}$ x $RAO^{M_X}_{\omega_{y\max}}$
	Applied Shear Force	$F_S = F_{SSW} + F_{SWEV}$
Case 2	Applied Vertical Bending Moment (Load)	h_{HWEV} x $RAO^{M_y}_{\omega_{Y\max}} + M_{VSW}$
	Applied Horizontal Bending Moment	$M_{HWEV} + M_{HSW}$
	Applied Torsion Bending Moment	h_{HPEV} x $RAO^{M_X}_{\omega_{X\max}} + M_{TSW}$
	Applied Shear Force	$F_S = F_{SSW} + F_{SWEV}$
Case 3	Applied Vertical Bending Moment (Load)	$M_{VSW} + h_{XPEV}$ x $RAO^{M_Y}_{\omega_{X\max}}$
	Applied Horizontal Bending Moment	$M_{HSW} + h_{XPEV}$ x $RAO^{M_Z}_{\omega_{X\max}}$
	Applied Torsion Bending Moment	$M_{TSW} + M_{TWEV}$
	Applied Vertical Shear Force	$F_S = F_{SSW} + F_{SWEV}$
Where	Vertical Still Water Bending Moment	M_{VSW}
	Horizontal Still Water Bending Moment	M_{HSW}
	Torsional Still Water Bending Moment	M_{TSW}
	Shear force in Still Water	F_{SSW}
	Extreme Value of Vertical Wave Bending Moment	M_{VWEV}
	Extreme Value of Horizontal Wave bending Moment	M_{HWEV}
	Extreme Value of Torsional Wave bending Moment	M_{TWEV}
	Extreme Value of Vertical Shear force in Wave	F_{SWEV}

5.6 Some Analytic Expressions and Probabilistic Characterization of Loads in the Literature

The next phase of the research work will involve employing the roadmap outlined in Chapter 3 in analysis and the benchmark study may involve using expressions that have been employed in the literature for applied load. Some typical analytical expressions reported in the literature are given in Table 15. It is noted that although the expressions in Table 15 apply to undamaged ship, they have been used in damaged ship studies (Kan and Das (2008), Lee et al. (2006)).

Table 15: Typical analytic expressions used for loads on damaged ships in the literature.

Publication Used	Formula	Remarks
Kan and Das (2008), Lee et al (2006)	$M_{VSW} = \begin{pmatrix} 0.01C_{wv}L^2B(11.97-1.9C_b) \text{ (hogging)} \\ -0.05185C_{wv}L^2B(C_b+0.7) \text{ (sagging)} \end{pmatrix}$ $M_{HW} = \left(0.3+\frac{L}{2000}\right)F_M f_p C_{wv}L^2TC_b$ $M_{VW} = \begin{pmatrix} 110C_{wv}L^2B(C_b+0.7)x10^{-3} \text{ (sagging)} \\ 190C_{wv}L^2BC_b\ x10^{-3} \text{ (hogging)} \end{pmatrix}$ $C_{wv} = \begin{pmatrix} 10.75-((300-L)/100)^{3/2} & 100<L<300(m) \\ 10.75 & 300<L<350(m) \\ 10.75-((L-350)/150)^{3/2} & L>350(m) \end{pmatrix}$ where L,- the rule (length) B- mouded breadth (metre), and C_b block coefficient of the ship C_{wv} -wave coefficient f_p -coefficient corresponding to the probability level (equal to 1 for strength assessment corresponding to probability level of 10^{-8} F_M - distribution factor (taken as 1 midship) T –draught in the considered cross section (m)	IACS minimum hull girder midship oil tankers expressions Unit kNm

There is a great deal of uncertainty associated with the wave and still water loads that are applied to a damaged ship, therefore, load components are usually characterise as random variables with mean values, probability distributions and coefficient of variation or standard deviation. Since the next phase of the study involves reliability-based assessment of damaged ship, a summary of some of the most common probabilistic characteristic of loading components that are presented in the literature is given in Table 16.

Table 16: Summary of some probability characteristics assigned to ship load parameters.

Variable Name	Symbol	Typical Probability Distribution Used	Mean Value	COV	Sources
Vertical Wave Bending Moment	M_{VW}	Fixed Extreme Value Type II			Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008)
Horizontal Wave Bending Moment	M_{HW}	Fixed Extreme Value Type II			Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008))
Torsional Wave Bending Moment	M_{TW}	Fixed Extreme Value Type II			Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008))
Model Uncertainty for Vertical Wave Bending Moment	x_{VW}	Normal	1	0.1 0.15	Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008)
Model Uncertainty for Horizontal Wave bending Moment	x_{HW}	Normal	1	0.1 0.15	Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008)
Model Uncertainty for Torsional Wave bending Moment	x_{TW}	Normal	1	0.1 0.15	Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008)
Vertical Still Water	M_{VSW}	Fixed Normal			Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008)
Horizontal Still Water	M_{HSW}	Fixed Normal			Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008))
Model Uncertainty for Vertical Still Water	x_{VSW}	Normal	1	0.1 0.15	Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008)
Model Uncertainty for Horizontal Still Water	x_{HSW}	Normal	1	0.1 0.15	Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008)

6 Estimation of Ultimate Strength of a Damaged Ship

6.1 Introduction

The response of a damaged ship structure depends on a variety of influencing factors including geometric configuration, material composition and resulting physical properties, production related imperfections such as initial deflections and residual stresses, degradation related to in service issues such as corrosion, ship and environmental load characteristics. This makes the ship structural system a complex problem for analysis and design. The overall ship structure may be considered as a girder to determine the overall loading effects. The most common overall failures of a ship hull girder are normally buckling in compression flange or plastic collapse of the girder flange in tension. Depending on the loading, especially if horizontal moment, torsion loading or shear is considerable, the failure may sometimes initiate in the side shell stiffened panels. The main components of ultimate strength that are of interest are summarised in Table 17. The two primary methods for determination of ultimate strength of a damaged hull girder:

(i) Nonlinear Finite Element Method;

(ii) 2-D Progressive collapse method.

The two main tools available to the project team for computing the ultimate strength of a damaged ship are TRIDENT and ULTMAT. TRIDENT has a nonlinear finite element capability which is accurate but computational expensive while the ULTMAT tool though computationally cheap may not be accurate for some damage scenarios. ULTMAT is a 2-D progressive collapse tool that has load shortening curves embedded in the program. These curves were developed for intact scenarios, therefore, it is essential to verify ULTMAT for individual damage scenario before employing it is assessment.

Table 17: Summary of ultimate strength component on a damaged ship.

Strength	Component	Symbol	Tools and Remarks
Ultimate	Ultimate Sectional Vertical Bending Moment	M_{VU}	ULTMAT and TRIDENT
	Ultimate Horizontal Bending Moment	M_{HU}	
	Ultimate Torsional Bending Moment	M_{TU}	TRIDENT
	Ultimate Shear force	F_{SU}	

The steps proposed for computing the ultimate strength for a selected cross section of a damaged vessel are summarised in Table 18.

Table 18: Step proposed for estimating ultimate strength of a damaged ship.

Step	Description
Step 1	Compute the ultimate strength for the damaged cross section using the simple tool (ULTMAT).
Step 2	Develop interaction equation among the strength components, namely vertical bending moment, horizontal bending moment, torsion and shear stress, using the result from the simple tool, and calibrate the parameters of the interaction equations.
Step 3	Use a coarse model of the damaged vessel to compute the ultimate strength for the damaged cross section with advanced nonlinear finite element tool (TRIDENT).
Step 4	Develop interaction equation among the strength components, namely vertical bending moment, horizontal bending moment, torsion and shear stress, using the result from the coarse advanced nonlinear finite element model, and calibrate the parameters of the interaction equations.
Step 5	Execute a comparative assessment of the interaction equations derived from the simple tool and the advanced tool. If the two results are close or identical use the simple tool for subsequent analysis otherwise use the advanced tool for subsequent analysis.

A more detail presentation of the input and output from the various steps are discussed in the sections that follow.

6.2 Procedure for Computing Ultimate Strength of a damaged Ship Using ULTMAT

ULTMAT is a progressive failure method tool that assumes that the hull girder behaves essentially like a box girder beam, and that plane sections remain plane under bending. It also assumes that structural failure occurs as a result of yielding on the tension side and combined yielding and buckling of the interframe longitudinal structure on the compression side. Interframe collapse means that the transverse frames remain intact, which rules out the possibility of more extensive grillage failures. The assumption of interframe collapse is consistent with modern ship design practices, but it may not hold for ships that have suffered gross damage. As noted by Smith (2008) ultimate strength methods like Progressive Failure must therefore be used with considerable care when assessing damaged vessels. In the current study, depending on the nature of damage the ULTMAT tool can be used to analyse a damaged ship. The types of analysis that can be performed using ULTMAT are:

1. Bi-axial moment-curvature analysis;
2. Hog and sag moment-curvature analysis;
3. Bi-axial static strength analysis;
4. Interaction curve analysis;
5. First-yield bending moment analysis;
6. Plastic bending moment analysis.

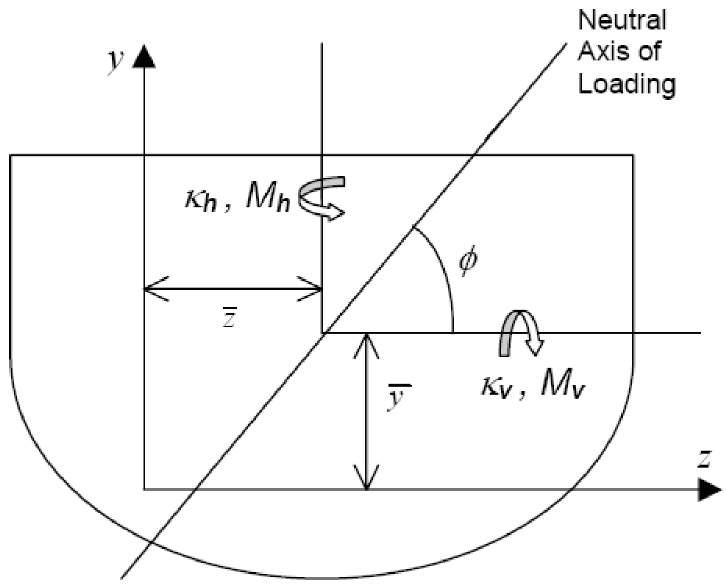


Figure 21: Bi-axial bending of a ship hull girder.

The steps involved in using ULTMAT are summarised in Table 19.

Table 19: Steps involved in using ULTMAT for analysis of a damaged ship.

Step	Task
Step 1	**Define and create the cross section data** The cross section data file defines the longitudinal structure of a ship at a particular cross section. The longitudinal structure between two adjacent frames is input as a collection of small, independently acting units. The three types of structural units that can used to make up the cross section are longitudinal stiffened panels, transversely stiffened panels, and hard corners.
Step 2	**Create material data** The material properties of the structural units must be defined in a separate materials data file for all ULTMAT analyses.
Step 3	**Specify appropriate load shortening curves** Load shortening (L-S) curve should be selected from the databases and files containing additional L-S curves can be created as well.
Step 4	**Perform analysis by running ULTMAT**
Step 5	**Obtain Relevant Output** Interaction curve; Bi-axial moment-curvature result; Hog and sag moment-curvature result; Bi-axial static strength result; First-yield bending moment result; Plastic bending moment result.

The main output from ultimate analysis that is relevant to the current study in the interaction curve involving vertical and horizontal bending moments. Typical vertical and horizontal interaction envelops from ULTMAT are shown in Figure 22 below.

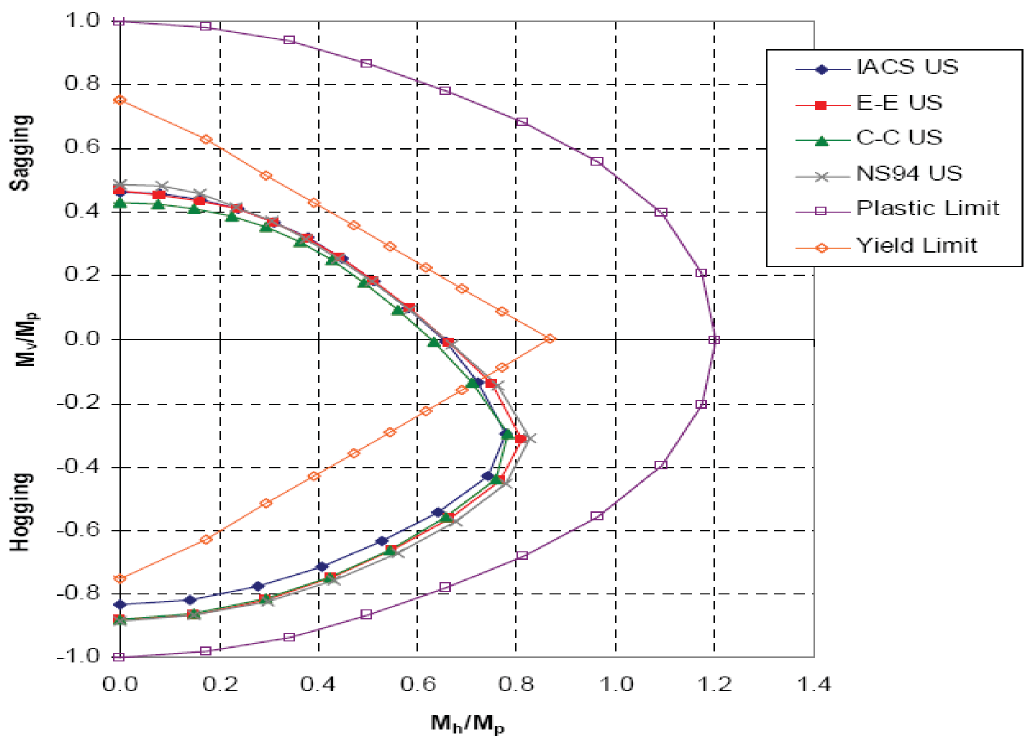


Figure 22: Typical interaction curves for the midship cross section of the HALIFAX class (Smith 2008).

6.3 Develop Interaction Equations among Ultimate Strength Components Using ULTMAT Result

Bi-axial moment-curvature or bi-axial strength analysis, from ULTMAT code when applied over the full range of loading directions, can be used to generate an envelope of ultimate bending moments, known as an interaction curve, defining the safe limit of operation at a given section. In most situations, it is acceptable to use either bi-axial moment-curvature or bi-axial strength analysis to determine the points of an interaction curve; however, some instances arise where moment-curvature analysis gives rise to inaccurate results, as will be explained later. (Smith 2003). A regression analysis technique and an optimization tool will be developed and employed to calibrate the parameters, m and n shown in equation (14), of the interaction equation between the vertical and horizontal bending moment.

$$\left(\frac{y}{M_{VU}}\right)^n + \left(\frac{x}{M_{HU}}\right)^m = 1 \qquad (14)$$

where M_{UH} is the ultimate strength in horizontal bending when ϕ is 90◦, M_{UV} represents the ultimate strength in the vertical bending when is either 0◦ (hogging) or 180◦(sagging) and (x, y) represents the horizontal and vertical ultimate strength, respectively, at a particular . A summary of some typical interaction equation in the literature is shown in Table 20

Table 20: Summary of typical interaction equations for a damaged ship ultimate strength.

Equation	Remarks
$\left(\frac{M_V}{M_{VU}}\right)^n + \left(\frac{M_H}{M_{HU}}\right)^m = 1$	$m = n$, Kan and Das (2008), Gordo and Guede Soares (1996) $m \neq n$, Sun et al. (2008)
$\left(\frac{M_V}{M_{VU}}\right)^n + \left(\frac{M_T}{M_{TU}}\right)^r = 1$ $\left(\frac{M_u}{M_{uU}}\right)^m + \left(\frac{M_T}{M_{TU}}\right)^r = 1$ $\left(\frac{M_V}{M_{VU}\left(1-\left(\frac{M_T}{M_{TU}}\right)^{c3}\right)^{c4}}\right)^{c1} + \left(\frac{M_H}{M_{HU}\left(1-\left(\frac{M_T}{M_{TU}}\right)^{c5}\right)^{c6}}\right)^{c2} = 1$ $\left(\frac{M_V}{M_{VU}}\right)^n + \left(\frac{M_H}{M_{HU}}\right)^m + \left(\frac{M_T}{M_{TU}}\right)^r = 1$	Sun et al. (2008)
$\left(\frac{M_V}{M_{VU}\left(\sqrt[c9]{1-\left(\frac{F_S}{F_{SU}}\right)^{c10}}\right)}\right)^{c7} + \left(\frac{M_H}{M_{HU}\left(\sqrt[c13]{1-\left(\frac{F_S}{F_{SU}}\right)^{c12}}\right)}\right)^{c8} = 1$	Suggested in Sun et al. (2008)
Exponents of interaction equation	*m, n, r, c1, c2,c3,c4,c5, c6,c7,c8, c9,c10, c11,c12,c13*

It is noted that the output from ULTMAT can be used to develop interaction equations that involve vertical and horizontal bending moments, but it cannot be used for cross sections where torsion and shear force play important roles, that is for interaction equations that involve these other damage modes. It is important that the ultimate strength calculations of a damaged ship is verified using TRIDENT.

6.4 Procedure for Computing Ultimate Strength of a Damaged Ship Using TRIDENT

A coarse finite element model of the damaged vessel should be developed using TRIDENT. The steps involved in using TRIDENT are summarised in Table 21. A plot of the interaction curve between the various components of the ultimate strength should be carried out and parameters of the interaction curve should be calibrated for comparison with result from ULTMAT.

Imperfections are very important in ultimate strength analysis of ship structures. In TRIDENT there are two ways to add imperfections to a model. Displacements from a TRIDENT analysis can be superimposed on node coordinates. These imperfections can be in the form of deformations from a stress analysis, a natural frequency analysis or a linear buckling analysis. Deformations can be manipulated prior to imposing them on a model. Different scaling factors can be applied to each component (Δx, Δy, Δz). It is possible to apply the deformations to only a portion of a complete model. Imperfections can also take the form of a 2D Fourier series over a bounded four-sided planar surface. Amplitudes of up to 40 terms in each direction can be specified.

TRIDENT offers numerous ways of specifying damage, that is, loss of structure. The basic approach is to identify all elements in the damaged or undamaged area and then delete the damaged elements from the model. The most efficient way to identify either the damaged or undamaged structure is to use the TRIDENT "Erase/Restore" feature. This offers many ways to selectively identify elements of interest. Elements can be selected by any combination of module number, property number, element type, element number, cursor location, an enclosed volume, and automatically identified internal or external elements.

It is noted that the although TRIDENT has been used to calculate the ultimate load carrying capacity of an intact ship (via a non-linear analysis), it has not been used by either MARTEC or DRDC to calculate the ultimate load capacity of a damaged ship with imperfection even though this capacity exit. Therefore, it is expected that both technical and software challenges will be encountered when TRIDENT is used for ultimate strength of a damaged ship with imperfections and this can be considered a gap in the software and knowledge base.

Table 21: Steps involved in using TRIDENT for ultimate strength analysis of a damaged ship.

Step	Task
Step 1	**Define and create the cross section** **Undamaged Case** Create a finite element model of the longitudinal structure of the ship between two frames at the cross section of interest, as shown in Figure 23. The finite element model shown in Figure 23 includes only half of the cross-section, due to symmetry. Alternatively, the strength of the ship at the cross-section of interest can be determined using a three-hold model, as shown in Figure 24, which takes advantage of the double-symmetry of the structure at this location. **Damaged Case** In the case of a damaged structure, symmetry does not apply and the complete three-hold model is required. Also, a simplified cross-sectional analysis, as shown in Figure 23, is not possible. Figure 25 shows a finite element model of a three-hold model which includes a simulated damage to the side shell structure.
Step 2	**Create material data** The material properties of the structural elements must be defined using non-linear material models in TRIDENT. Also, elements must be assigned a non-linear material/geometric formulation.
Step 3	**Specify appropriate load and boundary conditions** Using TRIDENT, the user can specify a bending moment to be applied at the cross-section of interest. TRIDENT applied this bending moment in the form of concentrated loads, as shown in Figure 26.
Step 4	**Perform analysis by running TRIDENT/VAST**
Step 5	**Obtain Relevant Output** Bi-axial moment-curvature result Hog and sag moment-curvature result Bi-axial static strength result First-yield bending moment result Plastic bending moment result

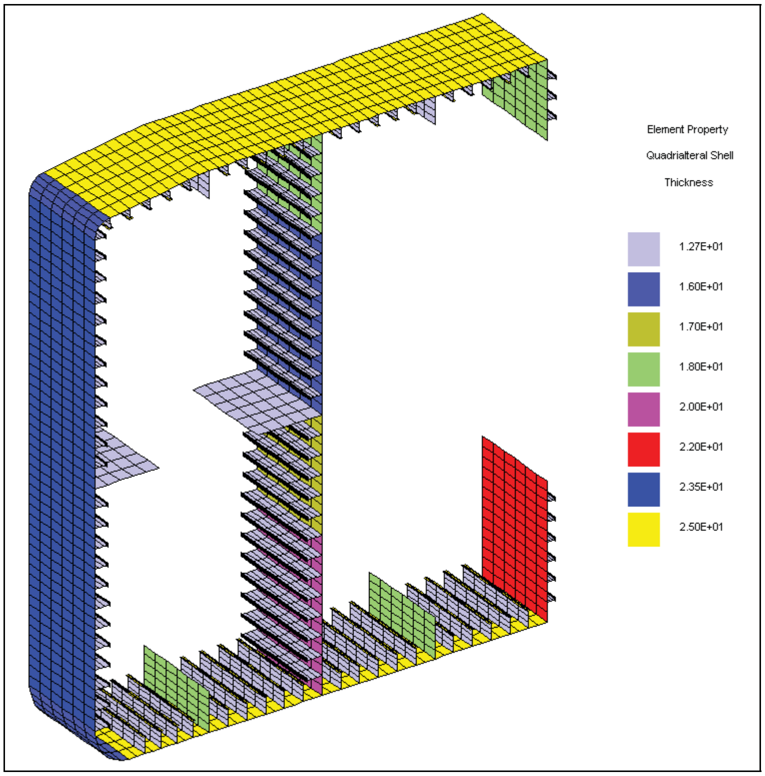


Figure 23: Finite element model of ship cross-section.

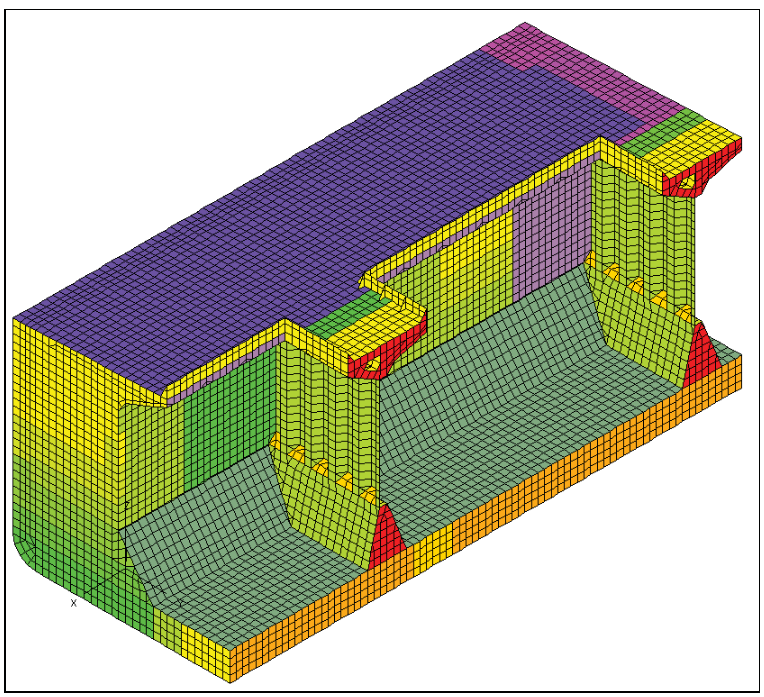
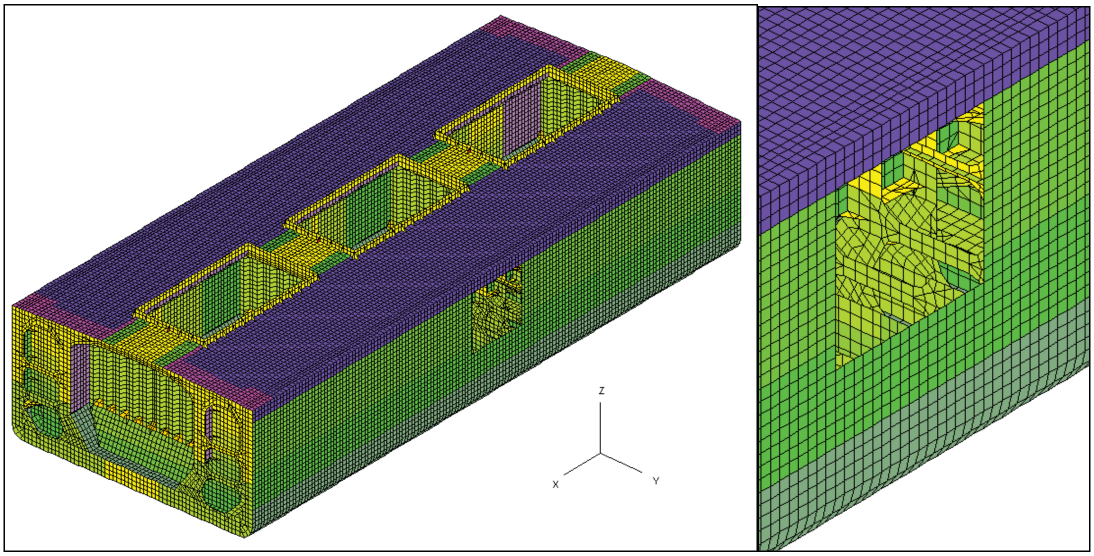


Figure 24: Quarter model of three-hold finite element model.



(a) (b)

Figure 25: Complete three-hold finite element model including simulated damage; a) complete model; b) close-up of damage location.

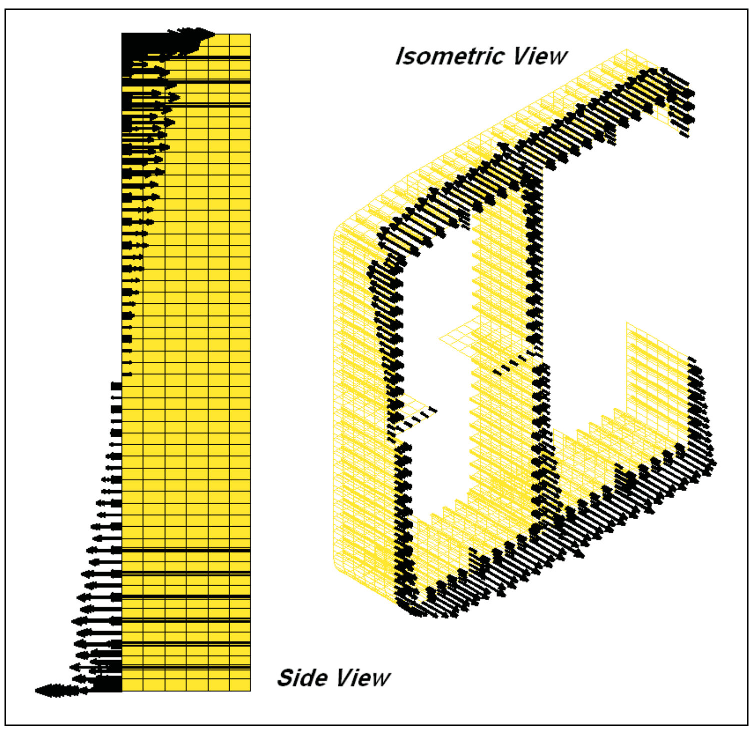


Figure 26: Cross-section bending moment applied using TRIDENT.

6.5 Comparison of Ultimate Strength from ULTMAT and TRIDENT

For damage cases where vertical and horizontal bending moments are the only components that are relevant for structural integrity assessment, a comparison of the result from ULTMAT and TRIDENT should be executed. This can be done by defining an error norm. The procedure will involve developing a coarse model of the damaged section and using TRIDENT to compute the ultimate strength for the damaged cross section. An interaction equation for the damage section is then developed using the TRIDENT result. This is compared with results from ULTMAT and if the coefficients of the interaction equations from the two tools are commensurate then ULTMAT should be used for subsequent analysis. If the coefficient are very different or the nature of the damage from physical observation is such that the simple tool (ULTMAT) is inadequate then the more advanced tool (TRIDENT) should be used.

In cases where the advanced tool is the only tool that is suitable for assessing the ultimate strength of the damaged vessel, a refined finite element model should developed and sensitivity analysis should be performed to investigate sensitivity of coefficient of interaction equation to small changes in damage.

6.6 Some Probabilistic Characterization for Ultimate Strength Parameters in the Literature

There are some uncertainties associated with estimates of residual and ultimate strength of a damaged ship, therefore, ultimate strength components are usually characterised as random variables with mean values, probability distributions and coefficient of variation or standard deviation. Since the next phase of the study involves reliability-based assessment of damaged ship, a summary of some of probabilistic characteristic of ultimate strength components that are presented in the literature is given Table 22.

Table 22: Typical probability distributions assigned to ship ultimate strength parameters.

Variable Name	Symbol	Typical Probability Distribution	Mean Value	COV	Sources
Ultimate Vertical Bending Moment	M_{VU}	Fixed Weibull			Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008)
Ultimate Horizontal Bending Moment	M_{HU}	Fixed Weibull			Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008))
Ultimate Torsional Bending Moment	M_{TU}	Fixed Weibull			Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008))
Model Uncertainty Ultimate Vertical Bending Moment	x_{VU}	Normal	1	0.1	Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008)
Model Uncertainty Ultimate Horizontal Bending Moment	x_{HU}	Normal	1	0.1	Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008)
Model Uncertainty for Horizontal Still Water	x_{TU}	Normal	1	0.1	Jia and Moan (2008, 2009) Sun et al. (2008) Khan and Das (2008)

7 Deterministic Structural Integrity of a Damaged Ship

Once the interaction equation, that is the envelope for the safe operation of a damaged vessel, has been developed, deterministic structural integrity of the vessel can be executed. Consider the typical interaction equation shown below:

$$\left(\frac{M_V}{M_{VU}}\right)^n + \left(\frac{M_H}{M_{HU}}\right)^m + \left(\frac{M_T}{M_{TU}}\right)^r < 1 \qquad \text{safe damaged vessel} \tag{15}$$

$$\left(\frac{M_V}{M_{VU}}\right)^n + \left(\frac{M_H}{M_{HU}}\right)^m + \left(\frac{M_T}{M_{TU}}\right)^r \geq 1 \qquad \text{unsafe damaged vessel}$$

(i) M_V, M_H and M_T are applied vertical, horizontal and torsion loads. In a deterministic structural integrity the value of these loads should be determined using extremal analysis and load combination procedure given in Table 13 and Table 14 All the load cases outlined in Table 14 should be considered for all sea states under consideration.

(ii) M_{VU}, M_{HU} and M_{TU} are residual vertical, horizontal and torsional strength. These are determined using procedure set out in Chapter 6.

(iii) *n, m* and *r* are interaction equations coefficient determined using the procedure in Section 6.3.

The operation of the damaged vessel is considered safe if the interaction equation is less than 1 and unsafe if it is equal to or greater than one, that is, the safety factor is greater than 1.

8 Probabilistic Structural Integrity of a Damaged Ship

8.1 Introduction

Probabilistic structural reliability methods attempt to estimate the probability that a damaged vessel could fail en route to a safe location or harbour. The methods accounts for various types of uncertainties associated with models and parameters that are used in the calculation. These include the natural variations in load and strength components due to the stochastic nature of the ocean environment, variabilities in geometric and material properties of the structure, and inherent uncertainties with the actual engineering calculation process and formulas. Reliability methods are used to express the problem being investigated in the form of a limit state equation, which relates the load and strength variables in such a manner that structural failure occurs when the result of the limit state equation is less than zero. The main steps that are proposed for reliability assessment of a damaged vessel are:

1. Definition of the performance functions and associated random variables;
2. Calibration of performance function parameters as random variables;
3. Computation of the probability of failure; and
4. Assessment of the structural integrity using target reliability levels.

The main tool that will be used for reliability analysis is COMPASS. The steps are discussed in the sections that follow.

8.2 Definition of Limit State Functions for Analysing a Damaged Ship

A limit state function g(X) defines the limit between the safe and failure domains and encapsulates the difference between the structural capacity and applied load:

$$g(\mathrm{X}) = \begin{cases} > 0 & \text{for X in safe set (no hull girder collapse)} \\ = 0 & \text{for X on the limit surface} \\ < 0 & \text{for X in failure set (hull girder collapse)} \end{cases} \tag{16}$$

where X is the vector of random variables involved in describing the uncertainties and variabilities in load parameters, geometric parameters, material properties, damage extent, damage location and its impact on structural and load models. A suitable limit state function that captures the damage scenario should be defined. The limit state function can be defined using simplified or full versions of the interaction equations discussed in the previous chapter. Two typical limit state functions that may be used are given below in equations (17) and (18) are

$$g(X) = k_{VU} M_{VU} - k_{VSW} M_{VSW} - k_{VW} M_{VW} \tag{17}$$

and

$$g(X) = 1 - \left(\frac{k_v M_V}{k_{vu} M_{VU}} \right)^n - \left(\frac{k_v M_H}{k_{HU} M_{HU}} \right)^m - \left(\frac{k_T M_T}{k_{TU} M_{TU}} \right)^r \tag{18}$$

Other limit state functions can be defined using relevant interaction equations. The following comments can be made about the above expressions as they apply to the current project:

1. Mean value, coefficient of variation and probability distribution of the terms (random variables) in the above expression have to be estimated using various tools that are uncoupled from each other, including TRIDENT and FDWAVELOD.
2. The random variables can be placed in three basic groups, random variables that come from uncertainties in loads (Example M_{VW}), random variables that arise from uncertainties in strength or hull girder capacity (M_{VU}), and random variables that arise from uncertainties in modelling (k_V).
3. The tools that are going to be used in estimating the average or mean values of these parameters (ULTMAT, WAVELOAD, TRIDENT) are decoupled, that is separate from each other. An ideal reliability assessment framework requires a coupling of these tools to the reliability assessment tool, COMPASS. This framework is not feasible in the current project, therefore, the limit state functions will have to be developed as analytical expressions and encoded into COMPASS and the random variables will have to be calibrated using COMPASS.

8.3 Calibration of Damaged Ship Parameters as Random Variables

Depending on the limit state model that is adopted for a damaged vessel, the parameters will have to be calibrated, that is specified as a random variables with mean values, probability distributions and standard deviation or coefficient of variation. COMPASS has the capability for calibrating random variables. The following observations should be made when calibrating random variables:

1. Strength or hull girder capacity random variables for example, M_{VU}, is a random function of other random variables namely damage size and location, material properties.
2. Residual strength random variables namely M_{VU}, M_{HU} etc. are correlated and not independent because they depend on the same set of basic random variables. Therefore, correlation between these variables should also be calibrated.
3. Loads random variables for example M_{VW} is a random function of other random variables that define the sea state namely wave height and periods.
4. Load random variables for example M_{VW} and M_{HW} are correlated and not independent because they depend on the same set of basic random variables. Therefore, correlation between these variables should also be calibrated.
5. Model uncertainty random variables require comparison of experimental results against values estimated using numerical models. In the current study experimental analysis is expensive and not planned, so results from literature will have to be used.

In practice it is difficult and expensive to calibrate all the parameters that are involved in reliability assessment of a damaged assessment. Therefore, there is a need to rely on the literature for guidance on applicable probability distributions, mean values and coefficient of variation for some of the parameters. Some of the suggestions from the literature have been discussed in earlier sections of the report.

8.4 Estimation of Failure Probability of a Damaged Ship

Once the limit state function has been defined, the reliability of a damaged vessel can be defined as the likelihood of it functioning according to its designed purpose for a particular time period. The failure probability is one minus the reliability. The reliability of the damaged vessel can be computed using any of the limit state or performance functions $g(X)$ defined in Section 8.2. The failure domain (Ω) is defined by a negative performance function (i.e., $\Omega = [g(X) < 0]$), while its compliment ($\Omega' = [g(X) > 0]$) defines the safe region. The failure probability is computed from

$$P_f = \int_{\Omega} f(X)dX \tag{19}$$

where $f(X)$ denotes the joint probability density function of the basic random variables (X) at time t. As the joint probability density function is generally unknown, evaluation of this convolution integral becomes rather arduous. Several practical approaches have been developed and implemented in COMPASS, including first-order reliability methods (FORM) and Monte Carlo Simulation (MCS). The results of the reliability analysis are probability of failure, importance factors and sensitivity to uncertainties. The steps involved in using COMPASS are shown in Table 23.

Table 23: Steps involved in reliability analysis of damaged ships using COMPASS.

Step	Task
Step 1	**Define and create an Input file that contains** Random Variables (Mean values, standard deviation and probability distribution) Solution Methods Limit state function
Step 2	**Perform analysis by running COMPASS**
Step 3	**Obtain Relevant Output** Reliability index and probability of failure Importance factor/sensitivity factor

8.5 Assessment of Structural Integrity Using Target Reliability

As noted in Phase 1 study, the implied target or suggested target reliability for a selected vessel in an intact condition will have to be derived and used as a benchmark for assessing the structural integrity of a damaged vessel. The values of the target reliability will depend on the uncertainties and probability distributions ascribed to the various random variables. This will be in line with suggestion made in ISSC (2006) where it is suggested that a consistent and state-of-the structural reliability analysis method should be applied in establishing target levels. Therefore, the first step in reliability analysis of a ship with gross damage should be determining the implied reliability of the intact ship.

9 Summary, Conclusions and Recommendations

9.1 Summary and Conclusions

This is Phase II of an overall study to investigate the probability of failure of damaged ship structures. It was focused on developing a methodology for reliability analysis of gross damage to ships and assessing the capabilities of available tools. The overall methodology involves six steps: (i) definition of ship characteristics and operation profile, (ii) determination of damage size and damage scenarios, (iii) estimation of loads on damaged ships, (iv) estimation of the ultimate strength of the damaged ship section, (v) estimation of the deterministic structural integrity of the damaged vessel; and (vi) estimation of the probabilistic reliability of the damaged vessel.

9.1.1 Estimating Extent of Damage

Methods for estimating the extent of damage are encapsulated in three tools that are available for the current project, SIMCOL, LS-DYNA and COMPASS. Steps proposed for estimating realistic damage sizes, scenarios and building a damaged ship model for analysis are: (i) use literature and experience to suggest realistic struck and striking vessel particulars, speeds and damage locations; (ii) estimate damage sizes using the simplified tool, SIMCOL, and obtain damage statistics using COMPASS; (iii) use the advance tool, LSDYNA, to collaborate estimates of damage sizes from the simplified tool and (iv) build 3-D and 2-D models of the damaged vessel using TRIDENT and ULTMAT. SIMCOL is a simplified tool that uses external ship dynamics to estimate collision forces and velocities, and internal ship deformations to calculate the extent of damage in the struck ship. The two main outputs from SIMCOL are the maximum penetration and the damage length. For a given set of struck and striking ships, the extents of penetration and damage are dependent on the speeds of the two ships, the impact location and the strike angle. Its suitability for estimating the extent of damage has been demonstrated in Phase 1. LS-DYNA is an advanced tool that can be used to estimate damage extent as demonstrated in both Phase 1 and the current Phase of the study. The difficulty with using LS-DYNA is in defining the appropriate mesh size and failure criteria. In cases where a large number of damage simulations is executed with SIMCOL, COMPASS can be used to characterise the damage statistics.

9.1.2 Estimating Loads on a Damaged Ship

Loads on damage ships can be broadly classified into three categories: (i) stillwater, (ii) wave and (iii) dynamic –slamming. The current research is focused on stillwater and wave loads. Five steps proposed for computing the loads on a damaged vessel are: (i) estimate the components of stillwater loads with/without flooding using PARAMARINE and TRIDENT, (ii) estimate the components of wave loads with/without flooding using WAVELOAD, (iii) estimate extreme values of the wave loads using a relevant short-term time frame that is required for the vessel to travel through one or more sea states as it makes its way to safety, (iv) combine the components of wave loads using the appropriate frequencies and response amplitude operators, and (v) combine the components of the stillwater and the wave loads. Algorithms have been developed for computing extreme value of waveloads and load combinations. Steps have been presented for using both TRIDENT and WAVELOAD. A summary is given of some common load models and their probabilistic characterization available in the literature.

9.1.3 Estimating Ultimate Strength of a Damaged Ship

Two tools are available for estimating the residual strength of a damaged ship, ULTMAT and TRIDENT. ULTMAT is a simplified progressive failure method tool that assumes that the hull girder behaves essentially like a box girder beam, and that plane sections remain plane under bending. TRIDENT is a nonlinear finite element tool that can be used to estimate the residual strength of a damaged vessel. Because of the high cost of using a finite element tool for ultimate strength estimation, it is suggested that the ultimate strength for the damaged cross section should be computed first with ULTMAT, this should be followed with development of interaction equations among the strength components, namely vertical bending moment, horizontal bending moment, torsion and shear stress, using the result from the simple tool, and calibration of the parameters of the interaction equations. A coarse finite element model of the damaged vessel should then be created and used in TRIDENT to compute residual strength components and interaction equations should be developed among the strength components and calibrated using the finite element results. A comparative assessment of the interaction equations obtained from ULTMAT and TRIDENT should be executed and if the two results are close or identical then the simple tool should be used for subsequent analyses, otherwise the advanced tool should be employed. A summary of various types of interaction equations that can apply to different damage scenarios have also been discussed.

9.1.4 Deterministic Structural Integrity Assessment of a Damaged Ship

Once the appropriate interaction equations for the damage scenarios under consideration has been developed, the safety factor associated with different ship operational scenarios can be determined by computing the load using the strategies outlined in Chapter 5. These loads values can be plucked into the interaction equations to check if it is safe to operate the damaged vessel.

9.1.5 Probabilistic Structural Integrity Assessment of a Damaged Ship

The main tool that is available for estimating the probability of failure of a damaged ship is COMPASS. Four steps proposed for reliability assessment of a damaged vessel are: (i) define of the performance functions and associated random variables; (ii) calibrate the parameters of the performance function as random variables; (iii) compute the probability of failure of the damaged vessel; and (iv) assess the structural integrity of the damaged vessel using selected target reliability levels. There are no limit state functions for damaged vessel in COMPASS, therefore appropriate limit state functions (that is, interaction equations) will have to be selected and encoded into COMPASS. Some of the parameters associated with the selected limit step functions such as residual strength will have to be calibrated as random variables with mean values, coefficient of variations and probability distribution using compass probability characterization features along with the strength estimating tools, TRIDENT/ULTMAT and load estimation tool WAVELOAD. Other parameters such as modelling uncertainties will have to be calibrated using guidance from the literature. Armed with the values of the random variables associated with the selected limit state function, estimates of probability structural integrity and sensitivities to uncertainties can be obtained using COMPASS. Target reliability values should be based on reliability index from an intact vessel and should be used to check if it is safe to operate a damage ship in the presence of uncertainties.

9.2 Gaps in the Analysis Tools, Knowledge-base and Procedures

Several gaps in the analysis tools, knowledge-base and procedures for assessing the probability of failure of a damaged ship have been identified. Some of these gaps will have to be addressed in other to increase the scope of damaged ships that can be addressed in the current study. Some of these gaps can be fixed very easily while others will require modifications to the tools to enhance their abilities for assessing the damage ship problems. A summary of the gaps is presented in Table 24.

9.3 Recommendations

The methodology outline in this study should be implemented and tested by executing the following tasks:

Task 1: Assessing the structural integrity of a selected existing intact ship. This will allow for a hands-on understanding of the capabilities of the tools that have been discussed in this study and estimation of the reliability of an intact design. It will also allow for implementation of algorithms and procedures that have been developed including algorithms for extreme value of loads, load combinations and interaction equations. This assessment will give a benchmark for judging the safety of a damaged ship. The analyses that will be required include the following:

(i) Calculation of still water bending moment and wave-induced bending moments including vertical, horizontal, torsion and shear using TRIDENT, PARAMARINE, and WAVELOAD.

(ii) Estimation of ultimate hull girder strengths for various cross-sections considering the interaction of vertical bending moment, horizontal bending moment and torsion using ULTMAT and TRIDENT.

(iii) Assessment of structural integrity by deterministic and probabilistic approaches considering the uncertainties associated with material properties, geometry and modeling.

Task 2: Define gross damage locations and sizes and study sensitivities of hull girder strength to extent of damage and its location.

Task 3: Assessing the structural integrity of a selected damaged ship using the methodology presented in Figure 11 and discussed in Chapters 5 to 8.

Table 24: Gaps in the analysis tools and procedures.

Tool and Procedures	Gaps
Tools and Procedures for Assessing Extent of Damage	
SIMCOL	Although it can generate a large sample of damage ship sizes, it does not have capability for probabilistic characterization of damage sizes. The COMPASS tool can be used externally for data characterization.
LSDYNA	
Tools and Procedures for Estimating Stillwater Bending Moment	
PARAMARINE	Although it can handle flooding, it is not clear how it can be used to estimate flooding damage related parameters for TRIDENT, such as weight redistribution, draft, trim and heels angles. This will have to be investigated. It does not have capability for computing: Stillwater Horizontal bending moment Stillwater torsional bending moment Stillwater shear force
TRIDENT	Does not have the capability for computing stillwater loading that result from the flooding of the vessel.
Tools and Procedure for Estimating Wave Bending Moment	Although algorithms for estimating extreme values of wave loads have been developed in the current report, they have not been implemented into a software tools that can be readily used. This is a gap that should be addressed during the next phase.
WAVELOAD	WAVELOAD has the capability for handling damaged vessels which has not been tested. There is therefore a knowledge and experience gap. It is anticipated that challenges and modifications may be needed to use the tool on a damaged ship.
Tools and Procedure for load Combination.	Although algorithms for estimating the resultant combined load have been developed in the current report, they have not been implemented in a software tools. Therefore a tool for implementing the load combination will also have to be developed.
Tools for Estimating Ultimate Strength of a Damage Ship	
ULTMAT	Can only handle 2-D cases. Therefore does not have capability for computing Ultimate tensional bending moment; Ultimate shear force. Load shortening curve within ULTMAT are not calibrated for damaged ships.
TRIDENT	Although it has capability for computing ultimate strength capacity of any section, there is no record that that capability has been tested on a damage ship. It is anticipated that unforeseen challenges that may require software modification to TRIDENT will be encountered when it is used on a damaged ship.
Tools and Procedure for Performing Reliability Analysis	
COMPASS	Does not have the limit states for damage ship in its library and does not have a seamless link to tools that estimate ship capacity and loading. These will have to be addressed. Additional challenges are also expected when the tool is tested on limit state functions for damaged ships.

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The Phase II report lays out a methodology for assessing the reliability of ships in a damaged condition and looks into the suitability of available tools. Tools for assessing the extent of damage are discussed and algorithms are proposed for computing and combining short term loads on a damaged ship including stillwater and wave loads. A methodology is presented for analysing the residual strength of a damaged vessel that uses the simplified tool, ULTMAT, and the advanced tool TRIDENT. Formulas which can be used for deterministic structural integrity of a damaged vessel are advanced in the form of interactive equations that define the safe envelop of operation. Additionally, reliability analysis methods are developed that account for uncertainties in the loading, structural strength and models used for assessing a damaged vessel. Further study of the damage arising from ship-to-ship collisions is carried out using LS-DYNA to augment the result from the Phase 1 study.

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