

Lin Hong

# **Simplified Analysis and Design of Ships subjected to Collision and Grounding**

Thesis for the degree of doctor philosophiae

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Norwegian University of  
Science and Technology  
Faculty of Engineering Science and Technology  
Department of Marine Technology



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# Abstract

Ship collision and grounding represent significant potential incidents which may result in very unfavorable consequences to both human life and environment. For the purpose of mitigating or preventing the collision or grounding event from developing into consequences disproportional to the original cause, continuous effort is being made by the research community to improve the analysis methods. The continuous concern is exemplified by the successive series of *International Conference on Collision and Grounding of Ships* (ICCGS), initiated in 1996 in *San Francisco* and carried over once every three years since 2001.

The present thesis focuses on the internal mechanics of ships subjected to collision and grounding accidents. Simplified methods for structural analysis are developed as well as their application to accident resistant design.

It is stated in the Foreword of the Proceedings of the first ICCGS, “*Improved techniques for structural analysis will have a profound impact on the design of the ships of the future, enhancing both safety and environmental performance.*” A significant part of the thesis is dedicated to the development of simplified analytical methods for structural analysis of ships during collision and grounding. In many cases, it is essential that the structural performance of ships during accidents can be evaluated quickly, e.g. in a decision support system for ships in emergency situations or in a rational design procedure, where the ship performance in a large number of accident scenarios needs to be assessed. Compared to empirical methods, experimental methods and non-linear finite element methods (NLFEM), simplified methods based on plastic mechanism analysis is considered the most suitable and advanced method for such analysis.

The behavior of web girders during collision and grounding is investigated comprehensively. Depending on the loading scenarios, two types of deformation modes are identified, namely *local denting* and *sliding deformation*. An improved model for local denting is proposed, taking into account important deformation features that have not been considered before. The first plastic mechanism for longitudinal girders during continuous sliding process is developed. The sliding deformation mode is especially geared to analysis of ship grounding over blunt seabed obstructions with large contact surfaces. It is also relevant for side stringers during sliding collision.

It is recognized that the shape and size of the striking object are of crucial importance with respect to the structural damage. As for ship grounding, three major types of underwater obstructions have been defined according to the characteristics of damage occurred during grounding, namely “rock”, “reef” and “shoal”. Most existing studies of ship grounding to date are concerned with “rock” type, sharp obstruction. An application of the proposed simplified method is presented in relation to double bottom grounding over blunt obstructions with large contact surface such as “shoal”. Good correlation between the simplified analysis and numerical simulation is obtained.

Though the response of plates under patch load was initially investigated for ships navigating in ice conditions, it is also of interest for ship collision or stranding analysis due to the fact that the damage is generally local. The resistance of patch loaded plates is derived by extending the classical “roof-top” yield line model. Subsequently, a new yield line pattern, “double-diamond”, is proposed. It gives better prediction in the plastic bending phase. More importantly, the present formulation includes the resistance due to membrane effect when significant permanent deformation is developed. This is especially useful for plate design or damage estimation for plates when abnormal/rare actions such as collisions are considered.

Numerous structural concepts have been proposed for improving the crashworthiness, notably in the past two decades. However, they seem to have a long way to go before being fully accepted. This necessitates studies on ways to improve the structural resistance under the present design regime. Applying the formulation developed for plates under partial lateral loads, a direct and simple design procedure is established for strengthening the side hull against large impact loads. By considering the ductility limit of the material consistently, a simple expression relating the stiffener spacing directly to the allowable permanent deformation has been derived. Eventually, the required plate thickness is simply connected to the material yield strength and the stiffener spacing. The design procedure follows the principles of the accidental limit state criterion and the strength design principles adopted by the NORSOK standard for design of offshore steel structures. The attractiveness of the design approach is that it is based on closed-form solutions for plating and stiffeners in addition to representing the collision force as a design load in a relatively simplified manner. The procedure is demonstrated and verified by the design of a ship-shaped FPSO tank side structure subjected to collision from a 7,500 tons displacement supply vessel.

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December 6, 2008  
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# LIST OF APPENDED PAPERS

## [Article I]

Hong L., Amdahl J. Plastic design of laterally patch loaded plates for ships. *Marine Structures*, 2007, 20(3): 124-142.

## [Article II]

Hong L., Amdahl J. Crushing resistance of web girders in ship collision and grounding. *Marine Structures*, 2008, 21(4): 374-401.

## [Article III]

Hong L., Amdahl J. Plastic mechanism analysis of the resistance of ship longitudinal girders in grounding and collision. *Journal of Ships and Offshore Structures*, 2008, 3(3): 159-171.

## [Article IV]

Hong L., Amdahl J. Rapid assessment of ship grounding over large contact surfaces. Submitted to *Journal of Ships and Offshore Structures*, 2008.

## [Article V]

Hong L., Amdahl J., Wang G. A direct design procedure for FPSO side structures against large impact loads. Submitted to *Journal of Offshore Mechanics and Arctic Engineering*, 2008.

## [Article VI]

Hong L., Amdahl J. Comparative study on plastic formulations of ship shell plating under patch loading. In: proceedings of 27<sup>th</sup> International Conference on Offshore Mechanics and Arctic Engineering (OMAE), June 15-20, 2008, Estoril, Portugal.



# Contents

<b>Chapter 1 Introduction .....</b>	<b>1</b>
1.1 Background and Motivation .....	1
1.2 Objectives and Scope of Work .....	9
1.3 Thesis Organization .....	10
<b>Chapter 2 An Overview of the Mechanics in Ship Collision and Grounding .....</b>	<b>12</b>
2.1 Introduction .....	12
2.2 Methodologies for Internal Mechanics .....	13
2.3 Basic Theory of Simplified Analytical Methods .....	17
2.4 Existing Plastic Methods in Ship Collision and Grounding .....	20
2.4.1 Plastic methods in ship collision .....	21
2.4.2 Plastic methods in ship grounding .....	25
<b>Chapter 3 Simplified Methods for Web Girders in Ship Collision and Grounding and their Application .....</b>	<b>29</b>
3.1 Introduction .....	29
3.2 Simplified method for local denting of web girder [Article II] .....	31
3.3 Simplified method for horizontal sliding of web girder [Article III] .....	36
3.4 Strength assessment of a ship bottom structure [Article IV] .....	41

<b>Chapter 4 Simplified Methods for Ship Plating under Patch Loading .....</b>	<b>48</b>
4.1 Introduction .....	48
4.2 Plastic analysis for plates under patch loading [Article I, VI].....	51
4.3 A comparative study .....	54
<b>Chapter 5 A Direct Design Approach for Ship Side Structures against Collision .....</b>	<b>56</b>
5.1 Introduction .....	56
5.2 Direct Design Approach .....	60
5.3 Application Example .....	63
<b>Chapter 6 Conclusions and Recommendations for Further Work.....</b>	<b>67</b>
6.1 Conclusions .....	67
6.2 Recommendations for Further Work .....	69
<b>Bibliography.....</b>	<b>72</b>
<b>Appended Papers.....</b>	<b>85</b>

# Chapter 1

## Introduction

### 1.1 Background and Motivation

Whenever and wherever there is shipping, there exist risks of accidents such as collision and grounding. Subsequently, such accidents at sea may result in potential economic loss, environmental pollution and fatalities.

Accidents do occur. In recent decades, significant effort has been put into understanding the response of ships, preventing and mitigating the consequences of ships subjected to collision and grounding. This is due to the continuous increasing public concern especially over several catastrophic accidents worldwide. The most famous and severe maritime disaster in human history may be the sinking of *Titanic*, a passenger liner, in 1912. The sinking resulted in 1,517 people perished. It was speculated that the collision with the iceberg initiated the hull to buckle and eventually collapsed. The grounding accident of *Exxon Valdez* in *Alaska* 1989 has been considered one of the most devastating man-made environmental disasters ever to occur at sea. The accident resulted in the pouring of approximately 40,000 tons of oil into a pristine wilderness area, which is now still suffering from adverse effects of the pollution. A single hull tanker, *Sea Empress*, driven by the current, ran aground at southwest *Wales* in 1996 with 73,000 tons of oil spill. About 200 kilometers of coastline was covered with crude oil which caused substantial environmental and aesthetic damage. In 2002, oil tanker “*Prestige*” split in two halves during a storm off *Galicia, Northwest Spain*, see Figure 1-1(b). In total, about 20 million gallons of oil were estimated to be spilt into the sea. *Selendang Ayu*, a cargo ship, ran aground and broke into two off *Unalaska Island* in 2004, see Figure 1-1(c). It created the worst *Alaskan* oil spill since *Exxon Valdez*.

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It is noticed though the accident of “*Prestige*” is not conneted to either collision or grounding, the consequence may have been significantly reduced if decisions such as grounding in a controlled manner (Amdahl and Hellan 2004, Alsos and Amdahl 2005) was made instead of towing it to the open sea. According to the report from *IOPCF* (International Oil Pollution Compensation Fund), collision and grounding are responsible for about 50 percent of all major oil spills in its member states from 1970 to 2005, see Figure 1-2. Studies on significant oil spill accidents can be found in, for example, NOAA (1992), Pu (2005).



(a) “Exxon Valdez” during cleanup.



(b) Oil tanker “Prestige” split and sank.



(c) “Selendang Ayu” broke into two and drifted off Unalaska Island (Courtesy of U.S. Coast Guard).

Figure 1-1: Examples of ship accidents occurred at sea.

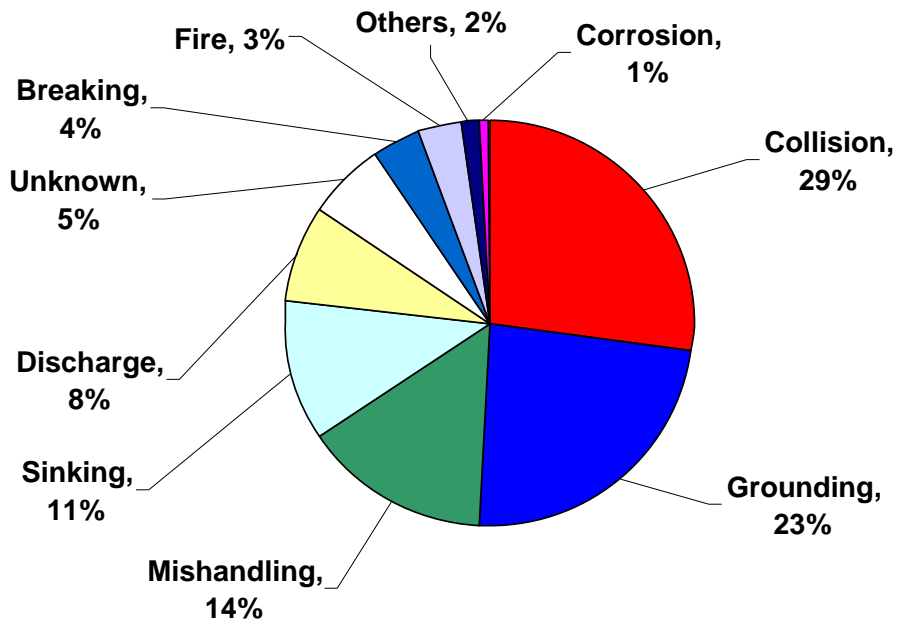


Figure 1-2: Cause of major oil spills from tankers compensated by IOPCF (data from the report of International Oil Pollution Compensation Fund, 2005).

These disasters precipitated the discussions and research on measures to prevent accidental oil spills. Generally, the improvement of marine safety and enforcement of new regulations

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for marine structures were triggered by the disasters. The *Titanic* disaster led to the convening of the first *SOLAS* (International Convention for the Safety of Life at Sea) in 1914. In response to the grounding accident of *Exxon Valdez*, *OPA 90* (Oil Pollution Act, 1990) was commenced where a double hull is made mandatory for tankers shipping in *U.S.* waters after 2015. Similarly, *IMO* (International Maritime Organization) also requires double hull for tankers, but its interim guidelines accept alternative designs if it can be proved to have a level of safety equivalent to a standard double hull tanker. There is a clear indication from *IMO* that more rational safety regulations for individual ships are demanded instead of the generalized prescriptive regulations by use of formal safety assessment. Such formal safety assessment or rational design procedure aims at positively prevent or mitigate the disastrous consequence such as oil spill.

Indeed, design methods on a rational base have been pursued by naval architects at all times as it was stated in the book (Wah 1960), *A Guide for the Analysis of Ship Structures*, - “*It has been the dream of every ship designer to rise above the conventional empirical methods of structural design and create a ship structural design based on rational methods.*”

Amdahl et al (1995) proposed a potential rational design procedure for collision and grounding, as illustrated in Figure 1-3 for design against grounding. Input parameters describing the accident scenarios should be properly and adequately specified. It is then essential to be able to check the structural performance during and after grounding. The consequence of ship accident, for example, in terms of oil spill, has been studied by, for example, DNV (1990), Karafiath and Bell (1993), Michel et al (1997), Samuelides (1999), Tavakoli et al (2008). Sufficient residual hull girder strength is vital to avoid subsequent catastrophic consequences after the ship has been damaged. Ships in damaged conditions have been investigated by, for example, Paik and Lee (1995), Zhang et al (1996), Paik et al (1998), Wang et al (2000, 2002), Fang and Das (2005), Khan and Das (2007). As a last step, it is judged whether the acceptance criterion has been satisfied. The acceptance criterion could be in either deterministic or probabilistic manner. The design procedure for collision is constructed in a similar format.

If such a rational design procedure should be used, especially in the preliminary design stage, it is of paramount importance that the structural damage or strength of various designs can be checked and compared quickly for a large number of potential accidental scenarios. In this context, calculation tools with high efficiency and reasonable accuracy are required. Generally, experiments, finite element methods and simplified methods may be considered. Full- and large-scale physical experiments on ship structures are usually too expensive and risky to be executed. Small-scale tests may be difficult to be interpreted to real scale events due to the intricate scaling laws involved. In the recent decades, large scale numerical analysis of ship collision and grounding, which has been considered as “numerical experiments”, has become practicable because of the rapid development of both the computational capacity and the finite element code itself (Amdahl and Kavlie 1992,

Lenselink et al 1992, Ohtsubo et al 1994, Kuroiwa 1996, Kitamura 1997 and 2002, Kajaste-Rudnitski and Kujala 2001, Amdahl and Johansen 2001, Skallerud and Amdahl 2002, Servis et al 2002, Lehmann and Peschmann 2002, Wisniewski and Kolakowski 2003, Gao 2003, Gu et al 2003, Wu et al 2004, Yamada et al 2005, Zhang and Suzuki 2006, Paik 2006, Zhang and Suzuki 2007, Hong et al 2007, Hong and Amdahl 2007, Tavakoli et al 2007, Zheng et al 2007, Alsos 2008).

### DESIGN PROCEDURE FOR SHIPS AGAINST GROUNDING

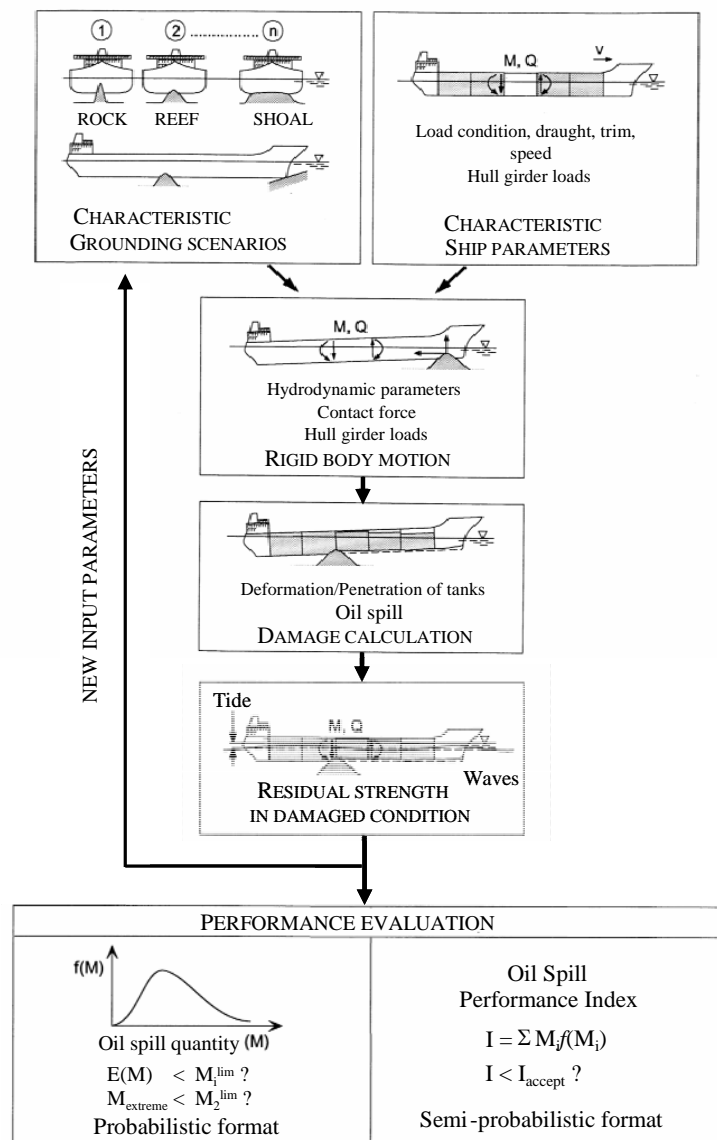


Figure 1-3: Design procedure for ships against grounding (Amdahl et al, 1995).

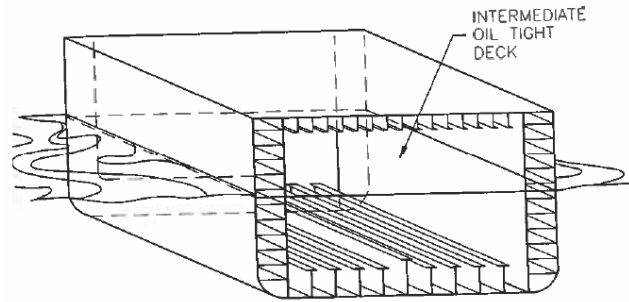
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However, simplified methods, pioneered by Minorsky (1959) for assessment of high-energy ship collisions, remain as advantageous tools regarding both time efficiency and relative prediction accuracy (ISSC, 1997, 2003 and 2006). Further, simplified analytical methods based on plastic mechanism analysis are considered advanced because they can provide significant insight into the deformation processes. The methods become mathematically tractable with reasonable accuracy as long as the mechanism can be constructed simply and as realistic as possible. Therefore, simplified analytical methods are considered the most appropriate means for evaluating the ship structural performance against collision and grounding. Amdahl (1983), Kierkegaard (1993), Wang (1995), Simonsen (1997), Zhang (1999), Wierzbicki et al (1992-2000) have contributed substantially to identification and development of fundamental theoretical models for ship structures subjected to accidental loads.

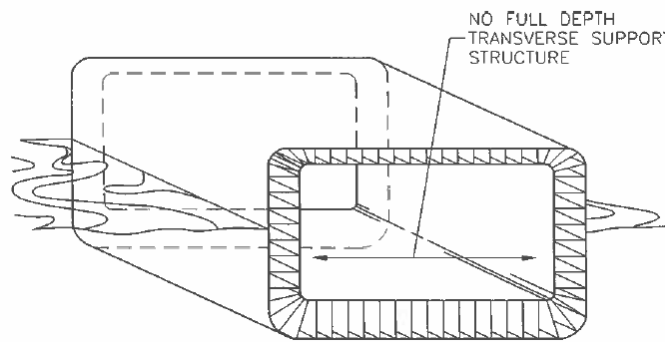
From the design point of view, the introduction of double hull to tanker vessels is believed to be effective in reducing oil spill in the event of collision and grounding (see e.g. Card 1975, DNV 1990, Ito et al 1994, Daidola 1995, Ozguc et al 2005, Zheng et al 2007). In early 1990s, the *NRC* (National Research Council) of *U.S.* has conducted a comprehensive study on design measures to prevent and mitigate oil spill from tankers (NRC, 1991). The design alternatives have been grouped in three categories: adding barriers, oil outflow management and increasing penetration resistance. The advantages and disadvantages of these design concepts have been discussed in detail. In order to further improve the marine safety, continuous attempts are made to propose and apply novel design concepts which are capable of mitigating or preventing potential accidental consequences. Amdahl and Kavlie (1995) proposed a double bottom with varying heights (see Figure 1-4c). The forward cargo tank region, where there is highest damage risk, can be figured with largest height. Kawaichi et al (1995) demonstrated the concept of mid-deck tanker as illustrated in Figure 1-4a. *USDH* (unidirectional stiffened double hull), refer Figure 1-4b, was proposed to provide potential increased resistance against accidental loading (Okamoto et al 1985, Daidola 1995, Kitamura 1997). Steel sandwich panels with X-core (Törnqvist and Simonsen 2004), Y-core (Naar et al 2002, Graaf et al 2004, Hu et al 2005), and other types of cores (Klanac et al 2005) were proved to have larger energy absorption capabilities than the conventional double hull. Jiang and Gu (2004), Yamada (2006), Cho et al (2007) and Endo and Yamada (2008) extended the idea of applying a bulbous buffer bow proposed by Cheung (1969) which deforms easily at the instant of impact. Their studies showed that applying the bulbous buffer bow was an effective way to reduce hazardous consequences in collisions. Tautz (2007) introduced the idea of arranging predetermined breaking points in the double hull so as to increase the penetration depth by separating the inner hull from web frame in collision. Karlsson (2008) presents the concept of a deformable inner barrier, which considerably increases the intrusion depth in case of side collision. These conceptual designs have been more or less proved to be effective regarding collision safety. However, they seem to have a long way to go before being accepted by stakeholders such as



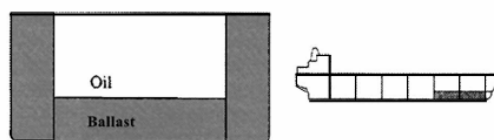
shipowners, classification societies and maritime authorities. This in turn necessitates studies on ways to improve the structure resistance under the present design regime.



(a) Mid-deck double side tanker (Courtesy of NRC 1991).



(b) Unidirectional stiffened double hull (Courtesy of NRC 1991).



Double bottom only in forward tanks

Double bottom with high and low heights

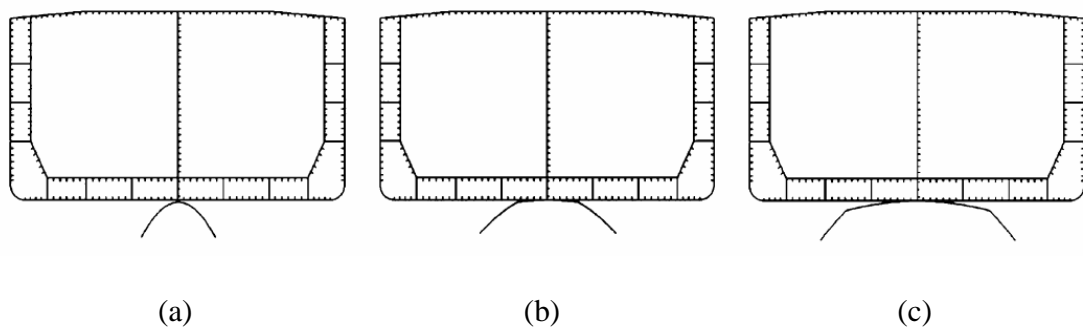
(c) Tanker designs with varying double-bottom heights along ship length (Amdahl and Kavlie 1995)

Figure 1-4: Some design alternatives to prevent or mitigate tanker spills.

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Up to date, based on simplified methods for external and internal mechanics, several tools or software packages have been made available for collision and grounding analysis, for example, *DAMAGE* (**DAM**Age Assessment of **G**rounding **E**vents) (Little et al 1996, Simonsen 1999), *SIMCOL* (**S**implified **C**ollision **M**odel) (Chen 2000, Brown et al 2000), *GRACAT* (**G**rounding and **C**ollision **A**nalysis **T**oolbox) (Friis-Hansen and Simonsen 2002), *MARCOL* (**M**aritime **C**ollision **M**odel of **M**ARIN) (Bogaert and Boon 2007). They can be used in deterministic manner, for analyzing structural response, and, alternatively, in probabilistic manner, for risk analysis. Ultimately, such tools may play a significant role in a rational design framework.

However, taking into consideration the variety of the collision or grounding scenarios, the implementation of such methods is still far from being fully accomplished. For instance, in the case of “*powered grounding*” (Simonsen and Friis-Hansen 2000), the damage characteristics are highly dependent on the topology of the seabed obstacle, not to say the bottom structural arrangement. Alsos and Amdahl (2007) has defined three types of seabed indenter, namely “*rock*”, “*reef*” and “*shoal*”, see Figure 1-5. In addition, grounding may also happen on relatively soft sea bottoms, this has been studied by Ferguson et al (1982), Pedersen (1994), Simonsen and Pedersen (1995), Simonsen and Pedersen (1995), Sterndorff and Pedersen (1996), Feddersen and Lehmann (2007). Generally, different topologies will lead to different deformation or failure modes. Nevertheless, a large body of the existing simplified methods for ship grounding is concerned with sharp seabed obstacles. To a large extent, this is due to the damage inspection in high profile grounding accident exemplified by *Exxon Valdez*. Simplified methods concerned with other types of seabed obstructions other than “*rock*”, for instance obstructions with large contact surface, are rarely seen, although they are considered common (Amdahl et al 1995, Wang et al 2000 and 2002). Theoretical models and calculation approaches are still lacking. A significant part of the present work is dedicated to this.



**Figure 1-5:** *Seabed topology with reference to bottom size: (a) rock; (b) reef; (c) shoal (Alsos and Amdahl, 2007).*

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## 1.2 Objectives and Scope of Work

The present work is carried out as a part of the Strategic University Project – *ScenaRisC&G* (Scenario-based Approach to Risk Analysis of Ship) funded by the Research Council of Norway. Commenced from 2005, the primary aim of this project is to develop rational tools for assessment of risk related to ship grounding and collision when sailing in restricted waterways. In this context, procedures for assessment of consequences in terms of structural damage and the amount of cargo spill once collision or grounding has occurred, or in the event of intentional grounding, are to be developed. Different scenarios should be checked in relation to given acceptance criteria.

Under this circumstance, the objectives of the present work are constituted by the following sub-tasks:

- To gain improved understanding of the internal mechanics of ship structures involved in collision and grounding accidents, notably for ship bottom structures sliding over seabed obstructions with large contact surfaces.
- To identify, develop and verify theoretical failure modes for web girders in ship collision and grounding. The web girders may behave differently in different loading conditions and different seabed topologies. To fully understand the deformation pattern for various conditions is a prerequisite for analyzing ship structural performance in various accident scenarios.
- To develop an integrated calculation tool from simplified methods for individual structural members for assessing the strength of a ship sub-structure such as a double bottom during grounding.
- To investigate the collapse mechanism of ship plating under lateral patch loading, and study the strength reserve when significant permanent deformations have been developed. The design equation converted from the resistance formulation may be used in ice impact design, collision resistance design, slamming impact design and design against other types of impact loads.
- To establish direct design procedures based on simplified methods for ship structures against large impact loads such as collision. The design procedure should be formulated as simple as possible. The strength design principle in NORSOK standard for construction of steel structures and the principle of accidental limit state should be considered.
- To analyze large-scale integrated collision and grounding processes by using non-linear finite element methods, taking into account the mesh size effect, effect of fracture and friction. Reliable numerical simulations can always be used to serve as the tools for verification of simplified methods and design approach.

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## 1.3 Thesis Organization

The chapters of the present thesis are organized as follows:

After a brief introduction in **Chapter 1** concerning background, motivation and objectives of the work, **Chapter 2** gives an overview on the mechanics of ship collision and grounding. Decoupling the problem into external and internal mechanics, the chapter focuses on introducing and comparing various types of methods for analyzing internal mechanics. By comparison with experiments, finite element methods and empirical methods, simplified methods based on plastic mechanism analysis are considered to be the most suitable for quick evaluation of ship structural performance in collision and grounding, especially in an early design stage. After a brief description of the basic theory and concepts for plastic mechanism analysis, a brief review is given of the existing simplified methods for structural analysis of ship collision and grounding.

**Chapter 3** deals with the development of simplified analytical methods and their application, with emphasis on the behavior of ship web girders. [Article II], [Article III] and [Article IV] are associated with this chapter. In [Article II], a new folding mechanism for the crushing of web girders under localized in-plane loads is proposed. The local denting failure mode is generally observed during collision and grounding. The proposed model for local denting captures several features of the local crushing process of the girder which have not been accounted for by any of the existing models. In [Article III], a new deformation pattern for longitudinal web girders when sliding over seabed obstructions with large contact surface, namely sliding deformation, is identified. [Article IV] presents the application of the simplified methods from individual structural members to structure assembly such as a ship bottom. A simple calculation tool for ship grounding is developed which is especially relevant for blunt seabed obstructions with large flat contact surface. Bottom resistance in terms of energy dissipation has been verified by NLFEA.

**Chapter 4** presents the plastic mechanism analysis for ship plates under patch loading. In [Article I], the classical “roof-type” collapse mechanism for plates under uniform pressure is extended to plates under patch loading. A new mechanism called “double-diamond” has been proposed in order to improve the resistance prediction in the plastic bending phase. Another but important development is that the strength reserve, due to membrane effect when significant permanent deformation develops, has been derived. Further, in [Article VI], the formulation developed in [Article I] is extended to account for plates under general patch load, i.e. the load on the plate is limited in both directions. Aftermath, a comparative study is performed for the proposed formulation with respect to various existing formulations.

**Chapter 5** is regarded as an application of the simplified methods for patch loaded plates developed in Chapter 4. A simple and direct design procedure for ship side structure against

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collision has been proposed in this chapter. The progressive collision load is found to be similar with ice impact load, and can be simply expressed by a pressure-area relationship. This can be easily implemented into the governing design equation for plating and stiffener. Without changing the main parameters of the side structure, the direct design procedure determines the plating thickness, taking into consideration of the material ductility limit, and the stiffener scantling. It is verified by integrated finite element analysis that the sample FPSO side structure designed according to the proposed procedure will have enough strength to withstand the collision force, while the deformation suffered is moderate. This complies with both strength design principle according to NORSOK standard and the principle of accidental limit state.

**Chapter 6** summarizes the work done and gives some recommendations for future study.

## Chapter 2

# An Overview of the Mechanics in Ship Collision and Grounding

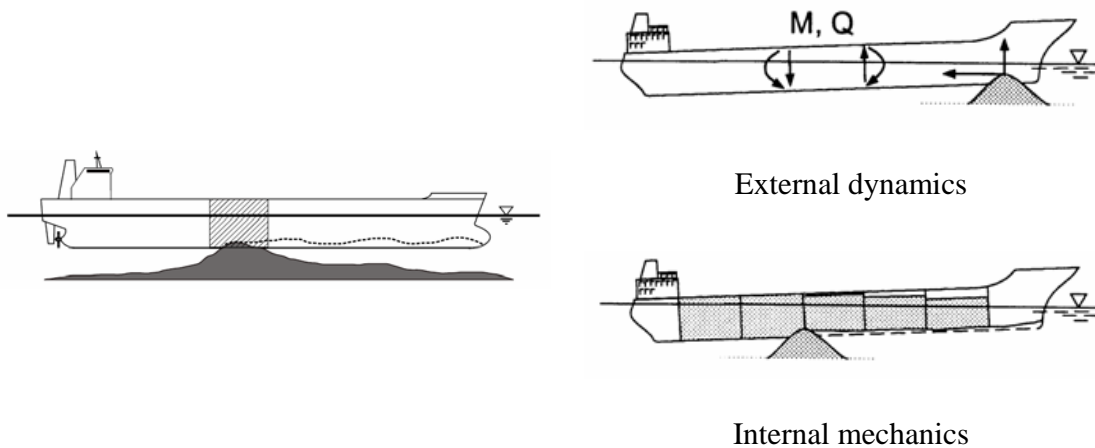
Generally, the mechanics of ship structures during collision and grounding is studied by empirical method, experimental method, finite element method and simplified analytical method. The method based on plastic mechanism analysis is considered highly suitable for fast analysis because of its simplicity and relative accuracy. Basic theory behind simplified analytical method is briefly introduced, followed by an extensive study on the existing simplified methods.

### 2.1 Introduction

Although the problem of ship collision and grounding may be solved in an integrated or coupled way (Brown 2002a), it is common to simplify the analysis by decoupling the process into “*external dynamics*” and “*internal mechanics*” (Petersen 1982, Paik and Pedersen 1995, Simonsen 1997, Yamada and Pedersen 2007), see Figure 2-1. A study by Brown (2002b) has shown that the total energy absorbed by the struck ship is similar by using coupled and decoupled methods.

The external dynamics solves the global rigid body motion problem and hull girder loads, and subsequently estimates the total energy to be dissipated by structural deformation and friction. The external dynamics has been studied by, for example, Petersen (1982) and Pedersen and Zhang (1998) for collision, Asadi (1989), Simonsen and Wierzbicki (1996)

and McCormick and Hudson (2001) for grounding problems. Internal mechanics calculates the structural response given a certain amount of energy to be dissipated. The force-deformation curve is representative for the response of a structural component or assembly.



**Figure 2-1: External dynamics and internal mechanics of ship grounding.**

The present work focuses on the latter problem. Various methods for internal mechanics are briefly introduced herein. After an outline of the basic theory for plastic methods, existing simplified analytical methods for ship collision and grounding are reviewed.

## 2.2 Methodologies for Internal Mechanics

As mentioned in Chapter 1, various methods are available when dealing with the problem of internal mechanics. These methods can be classified into the following four categories:

- Statistical or empirical method;
- Experimental method;
- Nonlinear finite element method;
- Simplified analytical method.

Based on the analysis of 26 actual collision accidents, Minorsky (1959) established a linear relationship between the volume of the destroyed material and the related energy dissipation. Being recognized as a pioneering work, Minorsky's method has been widely used in analyses due to high-energy collision and grounding accidents. It becomes so attractive especially to ship designers because of its simplicity. Minorsky's method was modified by many researchers since then, for example, Woisin (1979). Nevertheless, an inherent problem of statistical or empirical method is that it is always questionable when applying the formula derived from existing ships to future ships with different structural

arrangements. Pedersen and Zhang (2000) made an attempt to improve Minorsky's formula by taking into account the influence from the structural arrangement, material properties and damage patterns.

Experiments are considered the most straightforward method to investigate the impact process and observe the structural behavior. Woisin (1979) reported results of large-scale bow collision tests performed in the 1960's so as to investigate the effect of collision protection type side structure. Amdahl (1983) performed a series of crushing tests for four types of ship bows. Later, model-scale double hull indentation tests were performed by Amdahl and Kavlie (1992), Paik et al (1999), Amdahl and Alsos (2007). ASIS (Association for Structural Improvement of Shipbuilding Industry) in Japan launched a seven year project on "*Protection of Oil Spills from Crude Oil Tankers*" jointly with *Netherlands*. Within this project, large scale collision (Carlebur 1995) and grounding (Vredeveltdt and Wevers 1995) experiments were conducted as well as model scale tests (Kuroiwa et al 1992, Kuroiwa 1993, Ohtsubo et al 1994). Rodd (1996a, 1996b) reported 1:5 scale dynamic grounding experiments carried out at the Carderock Division of Naval Surface Warfare Center, USA. Wevers et al (1999) reported full-scale collision experiment executed in Netherlands to study the crashworthy performance of a conceptual side structure, see Figure 2-2. Experimental results are widely considered as the most convincing means for understanding the local and global structural behavior, verification of numerical simulations and theoretical formulations.

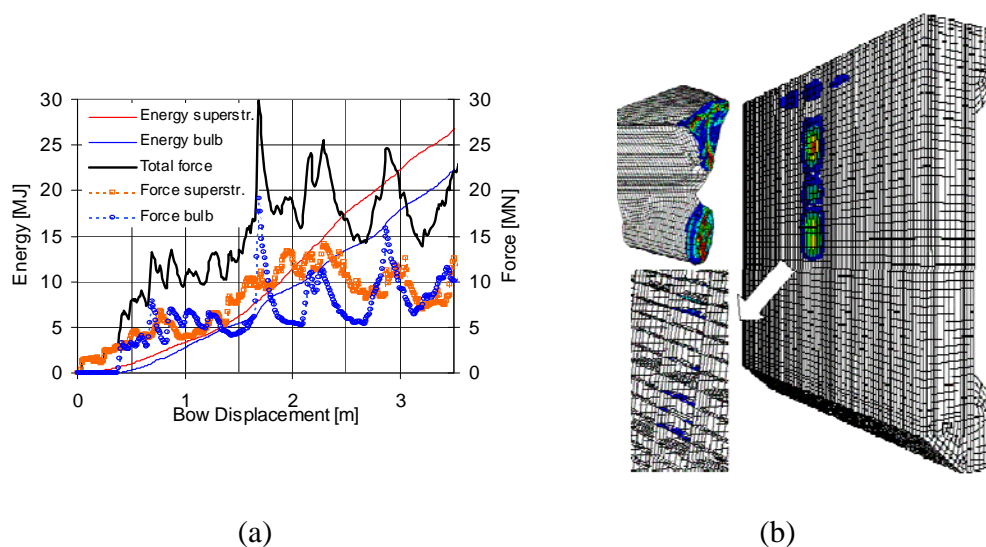


**Figure 2-2: Full-scale collision experiment in the Netherlands (Wevers et al 1999).**

Very often, experiments are carried out to shed light on the internal mechanics of ship collision and grounding. For example, the "*concertina tearing mode*" for plates was found from plate cutting tests where the cutting wedge was blunt (Wierzbicki 1995). Wang et al (2000) identified four primary failure modes involved in ship collision and stranding from the observation of a series of nine tests. However, large-scale physical experiments on ship structures are usually too expensive and risky to be executed. Small-scale tests may be



difficult to be interpreted to real scale events due to the intricate scaling laws involved. Tabri et al (2008) recently examined the feasibility of model-scale collision experiments. The results from model-scale tests may agree with large-scale tests if proper scaling laws have been applied to assure the physical similarity.



**Figure 2-3: A collision analysis between ship bow and FPSO tank side structure by using NLFEA: (a) force and energy dissipation curve; (b) deformation of bow and tank side. (Moan et al 2003).**

*NLFEA* (Nonlinear finite element analysis) is considered the most powerful tool for analyzing structural problems, and is often regarded as “numerical experiments”. Several commercial finite element software programs are available and capable of analyzing impact problems, such as *LS-DYNA*, *MSC/DYTRAN*, *ABAQUS*, *PAMCrash*. Figure 2-3 shows the results of a collision analysis between a ramming ship and an FPSO tank side by using *NLFEA* method (Moan et al 2003). The force and energy dissipation curves are obtained as well as the detailed structural deformation both in bow and side structure. *NLFEA* is considered highly general because no structural responses are required to be known prior to executing the simulation. Numerical simulations often produce satisfactory results as long as the controlling parameters are properly defined. However, a few problems, for example, fracture initiation and propagation in large scale shell structures, typical for ships, still remain unsolved. Fracture initiation and propagation is one of the key issues regarding the strength of the ship structures subjected to collision and grounding (ISSC 2003, ISSC 2006, Törnquist 2003, Törnquist and Simonsen 2004, Alsos et al 2008a, 2008b). On the other hand, concerning the complexity of the problem, *NLFEA* is still expensive due to the considerable time consumption in terms of modeling and computation, especially when a large number of scenarios need to be analyzed. The results of the simulations depend significantly on the skill and knowledge of the user which makes it difficult for application by ship designers. As discussed by Woisin (1999), both physical and numerical

experiments may be mainly served as means for validating simplified analytical methods. Besides, simplified finite element method, especially known as *ISUM* (Idealized Structural Unit Method), has been described in Paik and Thayamaballi (2003, 2007). The method combines the simple model with finite element technique, resulting in a reducing computation time compared to *NLFEM*. Application of *ISUM* for collision and grounding analysis can be found in Paik and Pedersen (1996), Paik et al (1999), Paik and Seo (2007).

Simplified analytical methods based on plastic mechanism analysis were introduced to the naval architecture industry in the 1960s. Alexander (1959) is regarded as the predecessor to apply plastic methods for analysis of thin-walled structures. Simply denoted as plastic method, simplified analytical methods are characterized by capturing the basic structural deformation mechanism with little modeling efforts. In other words, the failure mechanism is considered to be known prior to analysis which implies extensive fundamental research work on the mechanism analysis. This will offer more insight into the structure response. Simplified analytical methods are recognized as the best at balancing modeling difficulty with prediction accuracy (ISSC 1997, 2003 and 2006).

The features of the aforementioned methods are summarized in Table 2-1.

**Table 2-1: Main features of the methods for internal mechanics.**

	Modeling effort	Calculation effort	Result	Accuracy
Statistical/empirical method	very few	very few, hand calculation	energy	reasonable
Simplified analytical method	few	few, hand calculation	energy, load	good
Non-linear finite element method	considerable	considerable, expensive commercial FE software package	energy, load, stress	satisfactory if properly modeled
Experimental method	moderate to extensive*	intensive data collection and processing	energy, load, stress	most convincing

\* The modeling effort for experiments may span significantly according to the experimental scale.

All in all, empirical methods are not robust because they are usually concluded from historical data or extrapolated from experimental results. As compared to other methods, they can hardly provide information on impact loads. Full- or large-scale experiments are not affordable for the ship industry. *NLFEM*, though successfully applied in many situations, are not practical due to the cost constraints and high level of expertise. Concerning the large

amount of potential accident scenarios to be evaluated in a realistic or rational design procedure against collision or grounding, simplified analytical method is considered as the most suitable method for evaluating the ship structural performance for the moment.

However, the limitations of simplified methods should not be disregarded (ISSC 1997). The limitations may typically be specific failure modes, shape of indenter, structural arrangements, welding failure and fracture. If the assumptions made in the theoretical model do not comply with actual structural response, the predicted energy dissipation may become erroneous.

## 2.3 Basic Theory of Simplified Analytical Methods

Simplified analytical methods aim at providing quick estimates with reasonable accuracy. It is typically denoted “*plastic method*”, “*energy method*” or “*kinematic method*”. As described and summarized e.g. by Jones (1972), Jones (1989), the plastic method has been used extensively and also successfully by, e.g. Amdahl (1983), Wierzbicki and Abramowicz (1983), Wierzbicki et al (1992-2000), Kierkegaard (1993), Wang (1995), Simonsen (1997), Wang et al (2000) for investigating the crashworthiness of ship structures. Originating from the “*upper bound theorem*”, the plastic method requires the construction of a kinematically admissible displacement field, and then equating the external and internal energy dissipation rate to find the lowest force. The results always show surprisingly good agreement with experiments. This is mainly due to the fact that a well-defined mechanism model should accommodate the major characteristics of the deformation observed from experiments.

The theorems of upper- and lower-bound are described concisely as (Sørenseide 1981):

- *Upper-bound theorem (kinematic theorem)*: Of all the kinematically admissible mechanisms, all but the correct mechanism give loads larger than the true collapse load.
- *Lower-bound theorem (static theorem)*: Of all the statically admissible internal force distributions, all but the correct force distribution give loads less than the true collapse load.

Upper- and lower-bound theorems can be applied simultaneously to find the true solution or independently. However, accounting for the complexity of the problem involved in ship collision and grounding, it is considered sufficient to use upper bound theorem, accompanied by means of verification.

Regarding the complexity of the physical problem, some basic assumptions have been introduced into the plastic methods of analysis in order to make the theoretical model as

realistic as possible at one hand, and as mathematically tractable as possible at the other hand. These assumptions are:

- The material is rigid-perfectly plastic, the effect of elasticity is neglected;
- Different energy dissipation mechanisms are decoupled from each other;
- Interaction between different structural elements are neglected, they contribute independently to the total resistance;
- Bending deformation is assumed to be concentrated in plastic hinge lines, and continuous bending is normally neglected;
- The characteristic deformation parameter, such as the crushing distance in the crushing of thin-walled structures, remains constant during the deformation process.

Strictly speaking, the appropriateness of the assumptions has to be justified. For example, there is in fact no clear distinction between different mechanisms within the individual structural member, but it has been shown that such a separation of energy dissipation mechanisms often adequately represents the observed behavior and simplifies the theoretical analysis significantly (Wierzbicki and Abramowicz 1983, Hayduk and Wierzbicki 1984).

Generally, the procedure for developing a simplified calculation method consists of the following steps:

- Identify the basic deformation modes of a structural component by observations of the actual response for a specific action process;
- Develop idealized theoretical models (mechanisms) and derive theoretical formulae which capture the main features of the deformation patterns;
- Compare the theoretical predictions for components or sub-structures with actual incidents or test results to verify the accuracy and effectiveness of the developed simplified formulations.
- Develop simplified calculation tool for a complete structure by assembling the formulations for individual structural components.

Amongst the above procedures, a major challenge is to develop the deformation mechanism from extensive analyses which yields the least upper bound solution. This is usually done on the basis of experimental observations (Wierzbicki 1995, Wang et al 2000, Zhang 1999, Simonsen 1997, Simonsen and Ocakli 1999, Wang and Ohtsubo 1997). Some specific technique may be utilized to help reproducing the deformation mode, e.g. the paper folding method (Jones and Wierzbicki 1983, Hayduk and Wierzbicki 1984, Abramowicz and Simonsen 2003, Hong and Amdahl 2008). Alternatively, the mechanism can also be systematically constructed from a set of basic assumptions in conjunction with the continuity conditions (Wierzbicki and Abramowicz 1983).

Usually, either existing experiments or new experiments are considered inevitable for indentifying deformation modes and verifying simplified methods. However, it is not always feasible to perform experiments considering the complexity of the problems such as expernced during ship collision or grounding. As a numerical alternative, *NLFEA* is considered less costly and less time-consuming than physical experiments. More importantly, it can produce fairly good results provided parameters are defined sufficiently. Therefore, the results of numerical simulations may be used to identify the basic deformation pattern and verify the derived theoretical formulations where experiments are not available.

According to the upper-bound theorem, the work rate of the external loads on the structure can be equated to the internal plastic energy dissipation rate

$$P(\delta)\dot{\delta} = \dot{E}_{\text{int}} \quad , \quad (1)$$

where  $P(\delta)$  is the external load,  $\dot{\delta}$  is the velocity along the loading direction,  $\dot{E}_{\text{int}}$  is the rate of internal energy dissipation.

During the deformation process, the rate of energy dissipation for a general continuous solid body is determined by the volume integral

$$\dot{E}_{\text{int}} = \int_V \sigma_{ij} \dot{\varepsilon}_{ij} dV \quad , \quad (2)$$

where  $\sigma_{ij}$  is the stress tensor and  $\dot{\varepsilon}_{ij}$  is the rate of the strain tensor,  $V$  is the volume of the deformed material.

With a rigid-perfectly plastic material, obeying the von Mises yield criterion, the plane stress yield condition can be written as

$$F_{vm} = \sigma_{xx}^2 - \sigma_{xx}\sigma_{yy} + \sigma_{yy}^2 + 3\sigma_{xy}^2 - \sigma_0^2 = 0 \quad . \quad (3)$$

By assuming rigid-perfectly plastic material and von Mises yield criterion, for a deforming plate, Equation (2) can be separated into two parts representing the rate of bending – and membrane energy dissipation,  $\dot{E}_m$  and  $\dot{E}_b$  respectively,

$$\dot{E}_{\text{int}} = \dot{E}_b + \dot{E}_m \quad , \quad (4)$$

$$\dot{E}_m = \int_V \sigma_0 \dot{\varepsilon}_{eq} dV, \quad (5)$$

$$\dot{E}_b = \sum_{i=1}^n \int_{l_i} M_0 \dot{\beta}_i dl_i. \quad (6)$$

In the above expressions,  $\sigma_0$  is the flow stress, which is a function of strain history and strain rate in real materials. In simplified analysis,  $\sigma_0$  is typically assumed to be constant and taken as the average of the initial yield stress  $\sigma_y$  and ultimate stress  $\sigma_u$ , i.e.  $\sigma_0 = (\sigma_y + \sigma_u)/2$ .  $\dot{\varepsilon}_{eq}$  is the equivalent strain rate,  $\dot{\beta}_i$  and  $l_i$  are the rate of curvature change over  $i$ th plastic yield line and the length of  $i$ th yield hinge line, respectively.  $M_0$  represents the fully plastic bending moment capacity of a plate strip, with unit width and height  $t$ , i.e. plate thickness

$$M_0 = \frac{\sigma_0 t^2}{4}. \quad (7)$$

$\dot{\varepsilon}_{eq}$  is given by

$$\dot{\varepsilon}_{eq} = \frac{2}{\sqrt{3}} \sqrt{\dot{\varepsilon}_{\xi\xi}^2 + \dot{\varepsilon}_{\eta\eta}^2 + \dot{\varepsilon}_{\xi\xi} \dot{\varepsilon}_{\eta\eta} + \dot{\varepsilon}_{\xi\eta}^2}. \quad (8)$$

$\dot{\varepsilon}_{\xi\xi}, \dot{\varepsilon}_{\eta\eta}, \dot{\varepsilon}_{\xi\eta}$  are the strain rate tensor components. Once the mechanism has been identified, the deformation field can be formulated and subsequently the energy dissipation and resistance force, from Eq. (1), can be derived.

In this method, a few free parameters are postulated which have well-defined physical meanings, such as folding wavelength, crushing distance, rolling radius, and so forth. The optimal set of parameters is then determined by means of a postulation of global minimum energy.

## 2.4 Existing Plastic Methods in Ship Collision and Grounding

Since 1980s, especially during the latest decade, there are numerous works dedicated to the research for ship collision and grounding, for example, Amdahl (1983), Samuelides (1984),

Asadi (1989), Zhu (1990), Ito (1992), Kierkegaard (1993), Wang (1995), Simonsen (1997), Zhang (1999), Peschmann (2000), Lützen (2001), Wang (2001), Törnqvist (2003), Yamada (2006), Zhang (2007), Alsos (2008). Among which, Amdahl (1983), Kierkegaard (1993), Wang (1995), Simonsen (1997), Zhang (1999) have especially focused on identifying, developing fundamental theoretical models in conjunction with ship structures subjected to collisions and grounding. In addition, it is worth mentioning that extensive fundamental research on the mechanics and failure modes involved in tanker grounding accidents has been carried out in “*the Joint MIT-Industry Project on Tanker Safety*”, from 1992 to 2000. This led to the simplified program *DAMAGE*, which can aid the ship designers to improve the crashworthiness characteristics of ship structures.

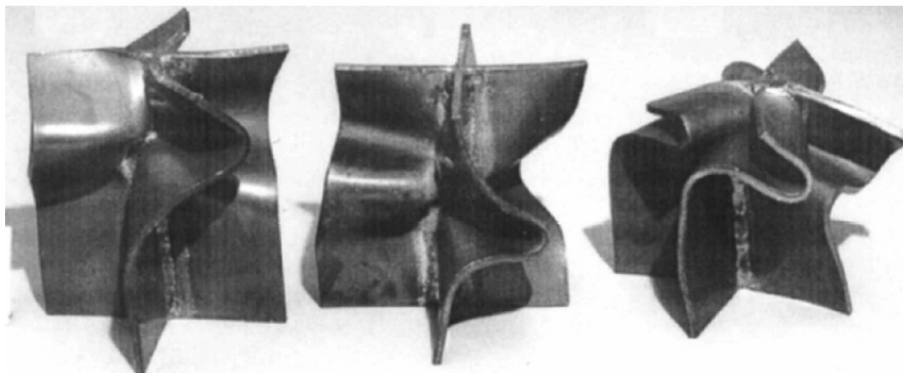
The ship structure is very complex, as is the deformation of the ship structure when subjected to collision or grounding. However, it is common practice to consider the ship structure as an assembly of plated structures. A large part of simplified analytical methods to date for ship collision and grounding are concerned with plated structures.

#### 2.4.1 Plastic methods in ship collision

The typical sub-structures involved in a ship collision accident are conventional or bulbous bow structures, side structures. The major components subjected to collision loads may be shell plating, stringer, bulkhead, main deck, frames. Shell plating is subjected to lateral indentation, the rest structural components are subjected to axial loading which is in the original plane of the plate.

The major structure deformation modes identified in ship collisions are briefly summarized as follows:

- *Axial crushing of L, T, X elements*: In ship bow and side structures, there are numerous intersections formed by stringers, bulkheads, main decks and frames. These intersections can always be discretized into “L, T and X” shaped structural components. Different crushing modes of X-element are observed in Figure 2-4 from axial loading tests.

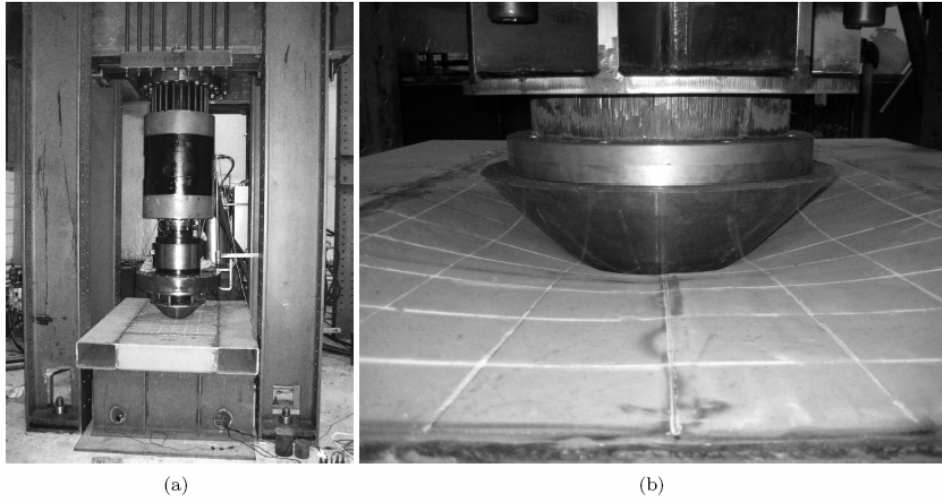


**Figure 2-4: Crushing modes of mild steel cruciforms (Courtesy of the Impact Research Center at the University of Liverpool).**

Wierzbicki and Abramowicz (1983) constructed the basic folding mechanism for thin-walled plated structures. The folding element can serve as special finite element for complex thin-walled structures such as box columns. Amdahl (1983) investigated symmetric and asymmetric collapse modes for cruciforms, and formulated a unified closed form solution for estimating the mean crushing strength of structures composed with “L, T and X” components. Assuming four types of basic mechanisms, simplified formulae for axial crushing of “L, T and X” type elements were developed by Yang and Caldwell (1988). Kierkegaard (1993) concluded that four types of basic folding mechanisms are related to L-elements, namely sliding toroidal surface mechanism, one flange extension mechanism, straight edge mechanism and in-plane deformation mechanism. The crushing mechanism for T and X elements could be a combination of the four basic mechanisms for L element. Adopting Amdahl’s (1983) approach for membrane energy calculation in triangular regions, Paik and Pedersen (1995) predicted the mean crushing strength for an individual plate element. The idea is every complex plated structure can be treated as an assembly of unit plate elements. This is applied to the crushing of stiffened plated structures by Paik et al (1996). Wang (1995) and Zhang (1999) also investigated the crushing behavior of L, T and X elements based on the previous research. Paik and Wierzbicki (1997) and Yamada and Pedersen (2008) performed benchmark studies on axial crushing of plated structures. Abramowicz and Simonsen (2004) found that the fracture may be significant on crushing of L, T and X type structural elements, and proposed to include a fracture parameter into the existing closed form formulations.

- *Lateral indentation of shell plating:* Generally, during ship collision or grounding, a significant amount of energy will be dissipated through plastic deformation of shell plating. Several experiments have been performed to study the behavior of double hull and bottom structures during collision and stranding (Amdahl and Kavlie 1992, Paik et al 1999, Wang et al 2000, Simonsen and Lauridsen 2000, Alsos and Amdahl 2008). The recent panel indentation test at *NTNU* is shown in Figure 2-5. Figure 2-6 depicts the behavior of a bare plate under indentation before and after the initiation of fracture. The definition of a striking object is critical for assessing the strength of a plate. It has been recognized that the impact load from a striking bow or a seabed obstruction can neither be represented as a point load nor a uniformly distributed load (Wang 1995, Wang et al 1998, Wang et al 2000). More realistic models for striking objects has to be employed, e.g. sphere characterized by its radius. As revealed by Wang (1995), spheres with large radius will increase the resistance of the plate. After being punctured, the shell plating will still keep a certain level of load-carrying capacity in the direction parallel to the crack. Wang et al (2000) proposed a plate perforation model for estimating the strength of punctured plate. However, no parameter for fracture has been included in their formulation. Simonsen and Lauridsen (2000) proposed analytical and semi-analytical solutions for plates under indentation by a sphere including parameters of fracture.





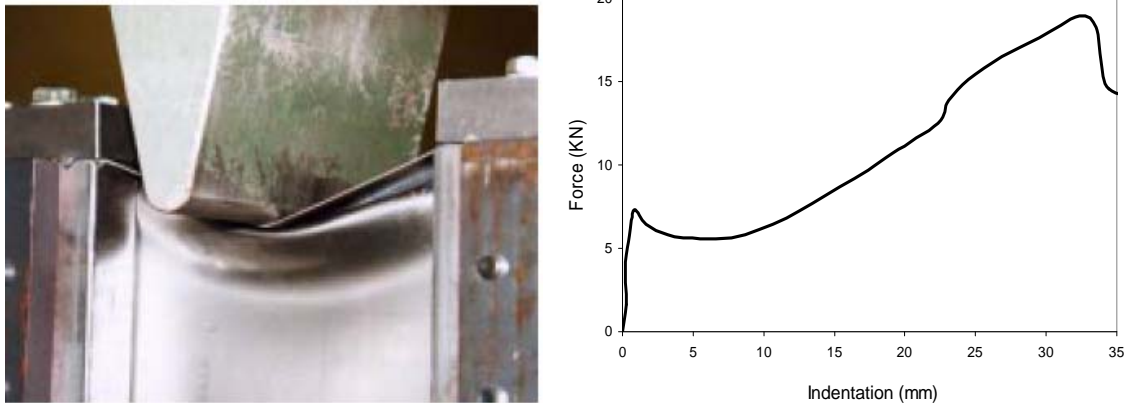
**Figure 2-5:** A lateral indentation test for ship panel at NTNU (Alsos and Amdahl, 2008).



**Figure 2-6:** Indentation of a bare plate (a) before fracture, (b) after fracture (Alsos and Amdahl 2008).

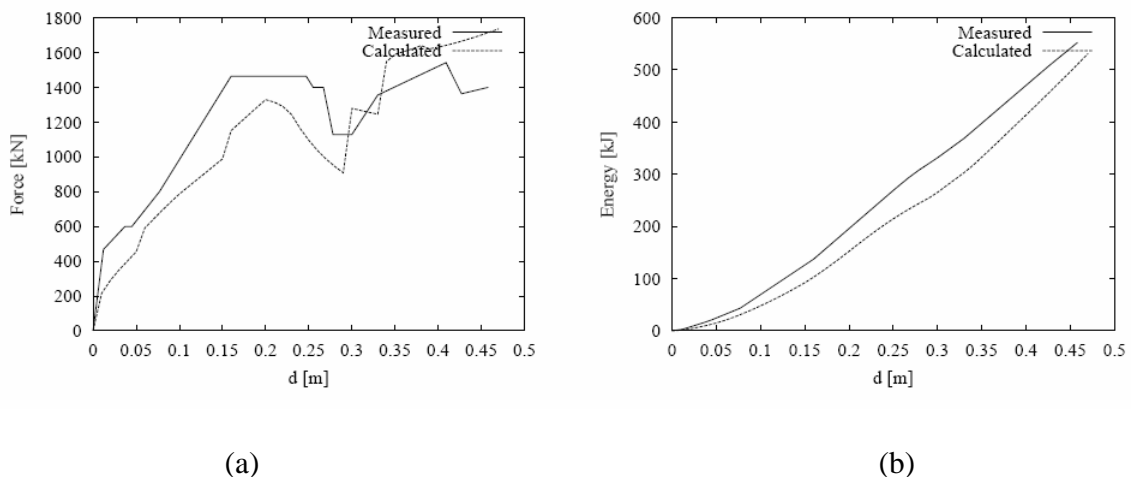
- *Denting of web girders:* The deformation mode of local denting of web girders is widely experienced during ship collision and grounding. Stringers, bulkheads, main decks and frames may suffer from this type of deformation when loaded in the plane of the web. The web plate bulges out of its original plane and forms some wrinkles (Figure 2-7). Wierzbicki and Driscoll (1994) did a pioneering study on the behavior of web girders under in-plane loads. Choi et al (1994) proposed an empirical method for predicting the crushing resistance for shallow web girders based on a series of experiments at MIT. Wang and Ohtsubo (1997), Simonsen (1997) and Zhang (1999) developed analytical formulations for local denting of web girders successively adopting similar mechansim. Simonsen and

Ocakli (1999) proposed a somewhat different model on the basis of a series of experiments carried out at *DTU*. Hong and Amdahl (2008) compared all existing models, and proposed a denting model with two folding elements.



**Figure 2-7:** A web crushing test at *DTU* and a typical load deflection curve.

Based on the theoretical models and simplified analytical solutions, fast and reliable analysis of ship collisions is possible. Wang and Ohtsubo (1999) estimated the collision force from a supply vessel. Lützen (2001) formulated simple calculation procedures for struck ship side and striking bow involved in collision applying existing simplified analytical methods. Figure 2-8 shows an example of how the predicted results compares with the experimental results. Regarding the simplicity of the method, the correlation is good, though discrepancy is exhibited.

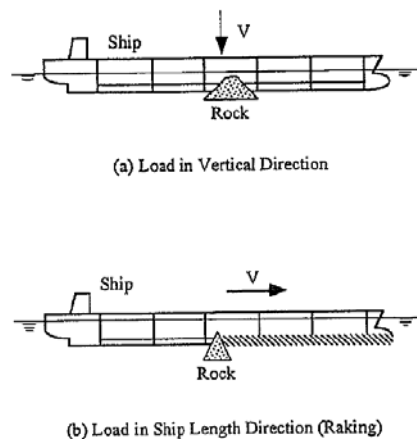


**Figure 2-8:** Comparison of prediction based on simplified analytical methods with double hull penetration test: (a) force-penetration; (b) energy dissipation. (Lützen 2001).

Wang (1995), Sano et al (1996), Ohtsubo and Wang (1996), Lützen et al (2000), Suzuki et al (2000), Yamada and Pedersen (2007) applied the simplified analytical methods for quick estimation of damage and energy absorption of striking and struck ships during collision. Amdahl (1983) and Kierkegaard (1993) evaluated the collision force from ship bow impact. Amdahl's method was later improved by Pedersen et al (1993), Lehmann and Yu (1995).

#### 2.4.2 Plastic methods in ship grounding

The grounding process has been drastically interpreted by Wierzbicki et al (1993) by examining the evidence from grounding incidents, notably from the grounding of *Exxon Valdez*. Generally, there are two types of grounding: vertical action referred to as “*stranding*” and horizontal action referred to as “*powered grounding*” (Simonsen and Friis-Hansen 2000), decelerating the ship. As illustrated in Figure 2-9, if grounding over hard and sharp rock is of concern where bottom plating will be torn open, the process is referred to as “*raking*”. If there is no tearing on the bottom structure, the process may be termed as “*sliding*”.

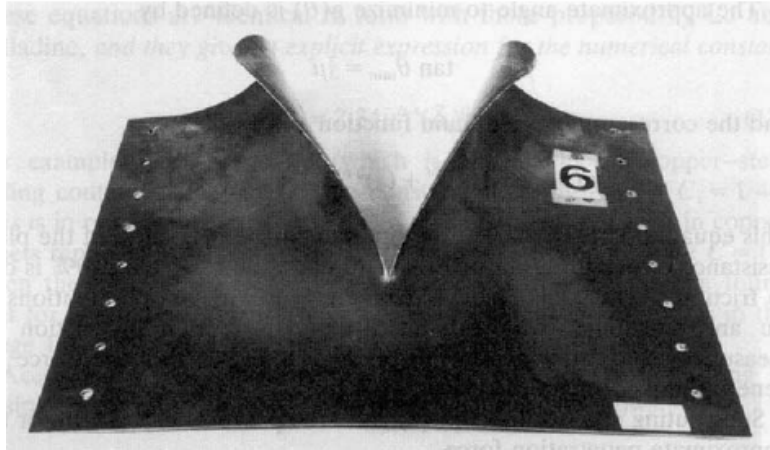


**Figure 2-9: Grounding phenomena of ships (Wang et al, 1997).**

Ship bottom structures during stranding behave somewhat similar with ship side structures subjected to a right-angle collision. Consequently, the deformation/failure modes identified and theoretical models developed for ship collision can be applied for ship bottom structure during stranding consistently. The behavior of bottom structures during “*powered grounding*” is, however, quite different from that of stranding.

By far, for powered grounding, enormous studies have been dedicated to the problem of plate cutting. Figure 2-10 shows the result from a bare plate cutting experiment. The ship bottom plating is subjected to horizontal grounding force from a single seabed obstruction which is commonly represented by either a wedge-shaped or a cone-shaped rock. In such

condition, the bottom plating could be easily torn open. Ship grounded over multi-rocks has been considered by Zhu et al (2002).

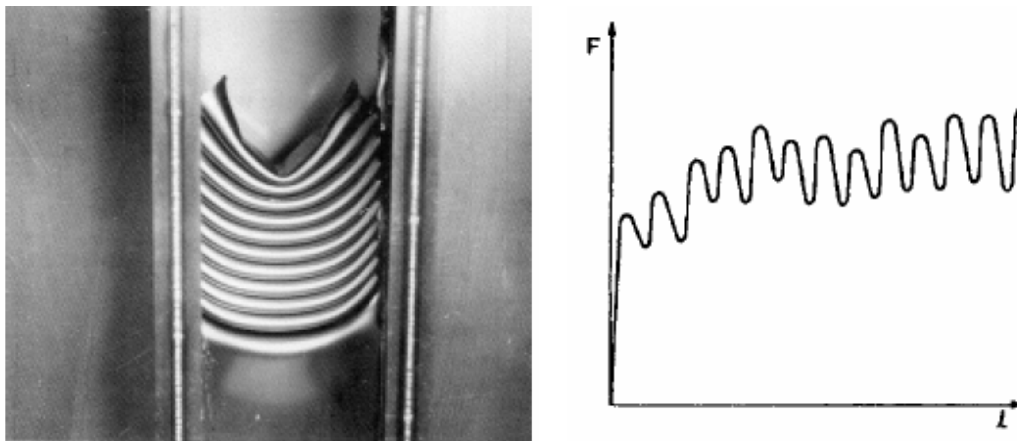


**Figure 2-10:** A bare plate after cutting (Thomas, 1992).

The mechanics of the cutting process is quite complicated as it involves fracture, friction, bending and membrane deformation. A group of empirical formulae have been formulated on the basis of plate cutting experiments (Vaughan 1978, Vaughan 1980, Woisin 1982, Jones and Jouri 1987, Lu and Calladine 1990, Paik 1994, Shen et al 1998). Most studies are concerned with cutting and tearing of a bare plate by sharp rock. An experimental study by Paik (1994) showed that the longitudinal stiffeners on the ship panel can be treated by equivalent thickness method without losing accuracy. Regarding simplified analytical methods for plate tearing, there may be distinguished between initiation phase and steady-state phase (Little et al 1996, Wang et al 1997, Paik and Wierzbicki 1997, Simonsen and Wierzbicki 1997, Simonsen 1997). It is observed that the tearing force increases in the initiation phase as the cutting proceeds until a steady-state with constant resistance is attained. Wierzbicki and Thomas (1993), Ohtsubo and Wang (1995), Zhang (2002) proposed plastic methods for plate cutting in the initiation phase. Zheng and Wierzbicki (1996), Simonsen and Wierzbicki (1997), Wang et al (1997) presented solutions for steady state plate cutting, where the shoulder of the wedge goes into the plate. From the experimental observations of Thomas (1992) and Lu and Calladine (1990), the formulae for initiation of cutting may be extended in steady-state cutting after a certain penetration. It is also noted that the steady-state solution may be applied to the entire cutting process because the influence of transition from initiation phase to steady-state phase is considered limited. In addition, Simonsen (1997), Simonsen (1998) developed tearing model for plate cutting by a cone which has been recognized as a more general representation for seabed obstructions.

Apart from the plate tearing mode, in some of the plate cutting experiments (Astrup 1994, Yahiaoui et al 1994), the plate was observed to pile up in front of the wedge after it ruptured at remote clamped boundaries (Figure 2-11 **Error! Reference source not found.**). This failure mode is called *concertina tearing*. Simplified analytical method for concertina tearing was developed by Wierzbicki (1995). Zhang (1999) considered the concertina tearing as a consecutive failure mode for denting after the web ruptures. As a result, Zhang extended the theory for local denting to concertina tearing.

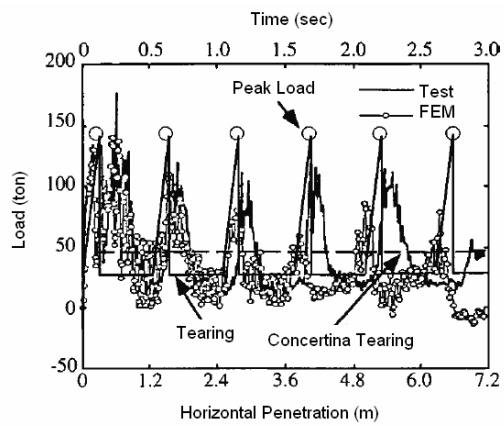
Whether the plate tearing mode or the concertina tearing mode shall be applied depends on the parameters of the cutting object and plate dimensions. It is evident from experiments that a critical region exists where either of these two failure modes may be provoked. In a study by Wang et al (1997), it is shown that the bottom strength is underestimated by using the tearing mode. On the contrary, the concertina tearing mode will overestimate the bottom strength to some extent, refer Figure 2-12.



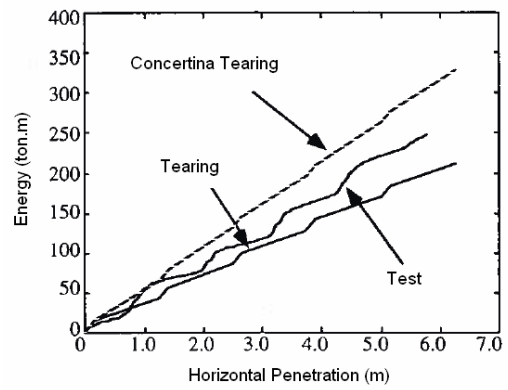
**Figure 2-11:** *Concertina folding of a plate (Yahiaoui, 1994) and a typical force-deformation curve for concertina tearing.*

Besides, the deformation modes such as local denting of web girders, plastic beam model may be applied for the transverse members in ship bottom structures.

Wang et al (1997) developed a simple method for bottom strength analysis including the failure/deformation modes of stretching of transverse members, denting, tearing and concertina tearing of bottom plates. Fairly good agreement is attained from a comparison between simplified prediction and test results for ship raking process, as shown in Figure 2-12. The effectiveness of the method was proved by both experiments and an actual grounding accident. Choi and Park (1997) assessed the bottom resistance of various tanker designs during grounding by using *DAMAGE*. Application of plate tearing model on grounding analysis is also found in Thomas and Wierzbicki (1992), Wang (1995), Ohtsubo and Wang (1996), Simonsen and Wierzbicki (1996), Simonsen (1997), Zhang (2002).



(a)



(b)

**Figure 2-12: Comparison of prediction based on simplified analytical methods with test results for ship grounding: (a) load-penetration; (b) energy dissipation. (Wang 1995).**

## **Chapter 3**

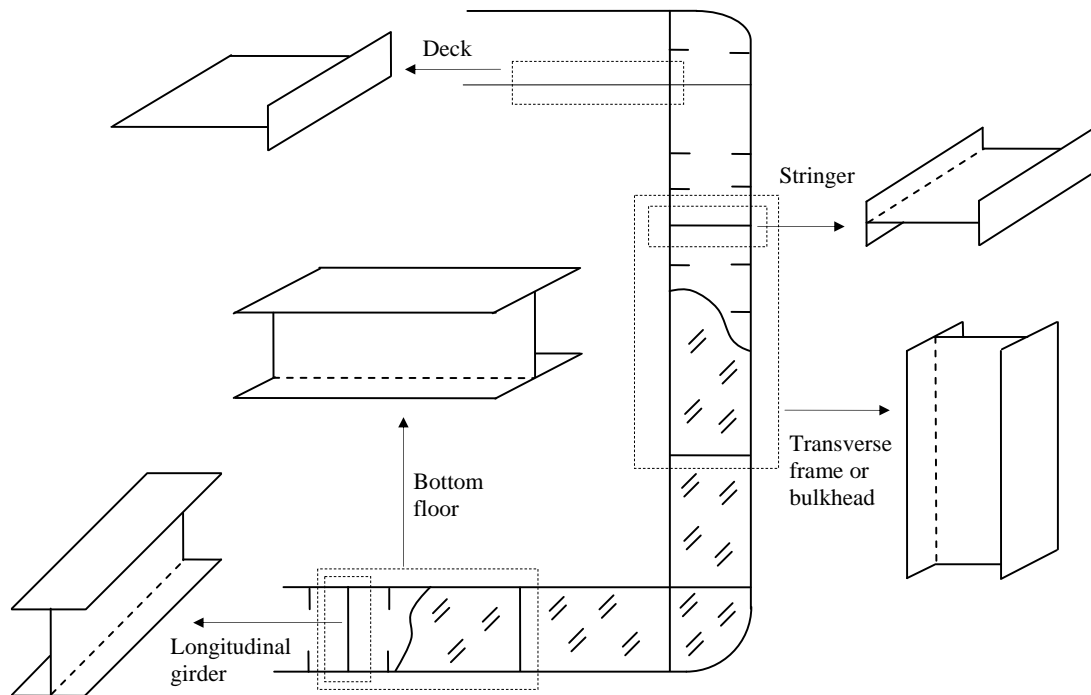
# **Simplified Methods for Web Girders in Ship Collision and Grounding and their Application**

In this chapter, simplified methods based on plastic mechanism analysis for web girders in ship collision and grounding developed in [Article II] and [Article III] are briefly presented, together with their application on grounding analysis of a double bottom structure [Article IV]. The work in [Article II] presents a significant advancement and a thorough study of the deformation mechanism for the local denting of web girders; [Article III] develops the first plastic mechanism for web girders during continuous sliding process. The sliding deformation mode is notably connected to ship grounding over blunt seabed obstruction with large contact surface.

### **3.1 Introduction**

Web girders represent a group of plated structural components which connect shell plating in a double hull ship structure or support the stiffeners in a single hull structure. Figure 3-1 shows major types of web girders in a typical double hull ship structure. The transverse members attached to the bottom shell plating, e.g. primary bulkheads, deep frames in single bottom ships, floors in double bottom ships, the decks, side stringers, frames and bulkheads are uniformly termed as web girders in the present study.

For the establishment of an integrated simplified analysis tool for ship collision or grounding, it is required to understand the behavior of web girders subjected to various loading conditions. Theoretical models will then be constructed based on the observed damage. As described in Chapter 2, a major challenge when developing simplified analytical methods is to construct a kinematically admissible deformation field which may yield the least upper bound solution.



**Figure 3-1: Types of web girders in a double hull ship midsection.**

With regard to the internal mechanics of ship collision and grounding, there is a continuous trend to propose new theoretical models by improving the existing mechanisms on one hand, and identifying new collapse mode on the other hand. For instance, the theoretical model for plate cutting was first proposed by Wierzbicki and Thomas (1993) by assuming a gap between crack tip and wedge tip. Then, the model was reconsidered successively. Ohtsubo and Wang (1995) argued that there is no evidence of cracks extending ahead of the wedge tip and proposed a mechanism with no separation between wedge tip and crack tip. The critical rupture strain enters the simplified formula proposed by Zhang (2002). At the end of the day, the theoretical model for plating cutting problem should approach the real physics and becomes more reliable by verification through various experimental results.

Usually, the mechanisms may be improved through the discovery of new deformation characteristics in one way, and they may also be modified through the justification of simplifications employed previously in another. New deformation modes may be



discovered for the same structural member taking into consideration the variety of loading conditions and accident scenarios.

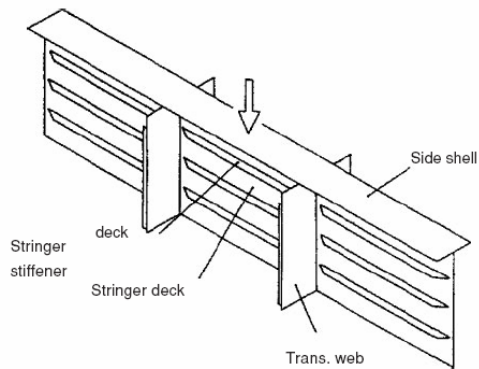
Following this pattern, the response of web girders during collision and grounding is examined comprehensively in [Article II] and [Article III]. For a ship bottom structure, the structural behavior is largely governed by the definition of the accident scenario, among which loading condition and seabed topology are of crucial importance. This also applies to the ship hull during collision.

Two types of deformation modes have been identified, namely local denting and sliding deformation. The local denting mode is observed for frames and floors subjected to vertical actions during ship grounding, and for decks, side stringers and frames subjected to right angle collision. The sliding deformation mode is initially found for longitudinal bottom girders during ship grounding over blunt seabed obstruction with large contact surface, such as “shoal”. The side stringers may also deform in this pattern during sliding collision. The former mode has been studied extensively since Wierzbicki and Culbertson-Driscoll (1995) proposed the first theoretical model. The latter one is only discussed in a few recent papers (Midtun 2006, Samuelides et al 2007a, 2007b, Hong and Amdahl 2008b, 2008c).

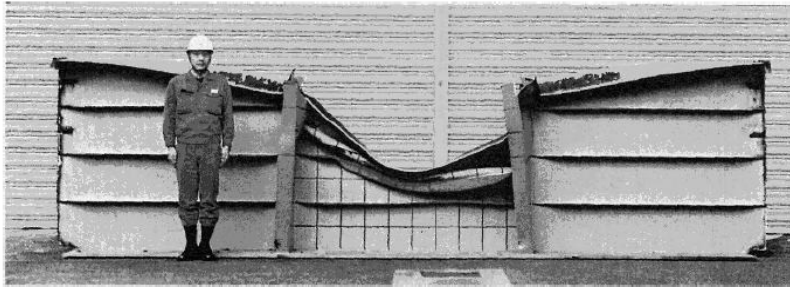
Ultimately, individual structural elements, so-called “super elements”, will be combined to find the aggregate resistance and energy dissipation of an assembled structure adopting the hypothesis that there is no interaction between various structural elements. As an example of application, a simple method is proposed and developed in [Article IV] for ship bottom structure subjected grounding over seabed obstacles with large contact surface such as “shoal”, as defined by Alsos and Amdahl (2007). Both local denting and sliding deformation for web girders developed in [Article II] and [Article III] are applied to the integrated method, encouraging results have been achieved as compared to results of numerical simulations.

## 3.2 Simplified method for local denting of web girder [Article II]

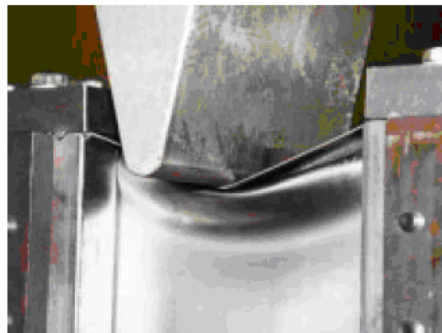
The behavior of web girders under in-plane loads is a relevant subject in both ship collision and grounding process. A new theoretical model is proposed on the basis of a comparative study of the existing simplified methods and the analysis of the progressive deformation process from rational nonlinear finite element simulations. This is described in detail in [Article II]. A significant improvement of this model is that it captures the major deformation characteristics of the girder during in-plane crushing, which have not been captured by any of the existing models.



**Figure 3-2: The model of side collision test by ASIS (Kuroiwa 1993).**



**Figure 3-3: The experimental result of side collision test at 800mm indentation by ASIS.**



**Figure 3-4: Small-scale web crushing test at DTU.**

Figure 3-2 shows a schematic setup for large scale (1:2) side collision test by ASIS (Kuroiwa 1993). A bulbous bow is assumed to collide between two adjacent transverse webs and in the plane of a stringer deck. It is seen from Figure 3-3 that the stringer deck bulges out of its original plane. As the compression proceeds, the bulge will evolve into

folding. In many cases, two folds are established prior to rupture (Wang 2002). The observed collapse mode for the stringer deck before rupture is defined as local denting. Figure 3-4 shows the girder deformation in a small-scale crushing test. Similar deformation pattern is observed.

A variety of simplified methods has been proposed for the local denting mode of web girders. Wierzbicki and Culbertson-Driscoll (1995) performed a pioneering investigation into the collapse modes for girder crushing based on a series of experiments carried out at MIT. Choi et al (1994), Wang and Ohtsubo (1997), Simonsen (1997) and Zhang (1999) progressively developed various analytical formulations by using similar plastic mechanisms. Simonsen and Ocakli (1999) proposed a somewhat different mechanism, with folding elements on both sides of the original plane of the girder plate.

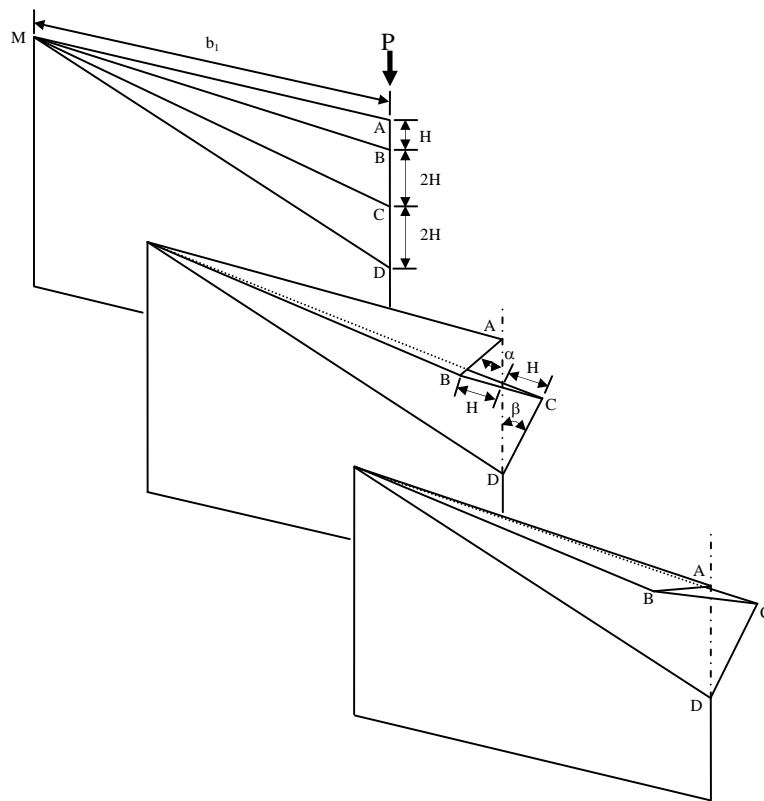
However, from the numerical simulation of the collision test by *ASIS*, several deformation features which differ from the existing mechanisms are observed, see details in [Article II]:

- The girder plate bulges initially to both sides of its original plane with different folding length;
- Not all the deformed plate is flattened when the first fold is completed;
- No hinge will be located on the original plane of the girder plate when the deformed area is flattened, except at the junction of the web and flange.

These features can also be observed from the DTU experiment (see Figure 3-5). Regarded as the key points of the crushing deformation of the web girder, these characteristics have not been captured by any of the existing simplified methods. Consequently, a new theoretical model is proposed in [Article II] which incorporates the above observations (see Figure 3-6).

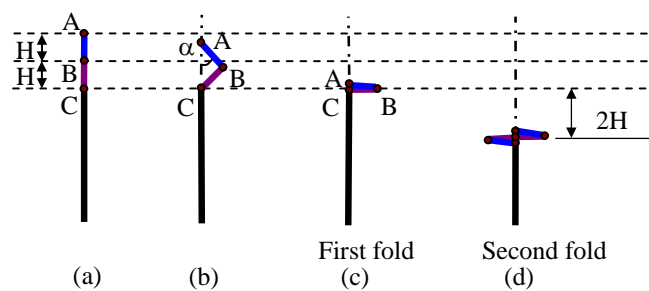


**Figure 3-5: Cross-section profile of web girder after crushing test at DTU (Simonsen and Ocakli 1999).**

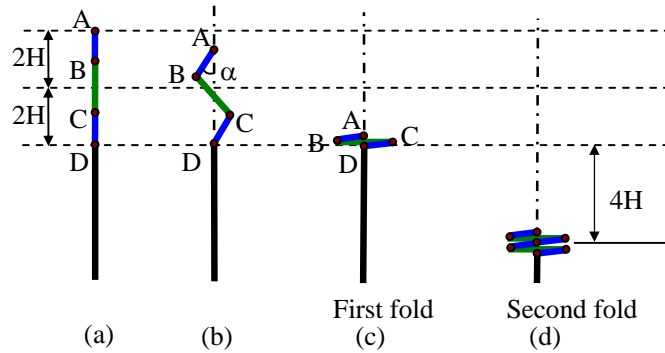


**Figure 3-6: Idealized progressive deformation mode of the girder plate under localized in-plane load.**

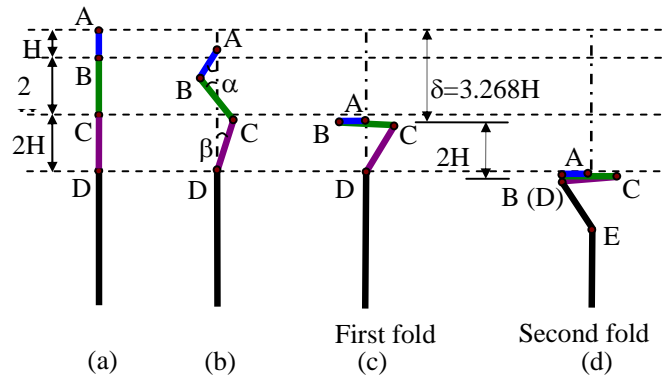
In aggregate, there are three major mechanisms concerning the local denting of web girders, namely *Model I* (by Wierzbicki and Culbertson-Driscoll, 1995), *Model II* (by Simonsen and Ocakli, 1999) and *Model III* [Article II], as illustrated in Figure 3-7.  $H$  is the characteristic crushing distance,  $\alpha$  and  $\beta$  denote folding angles. The closed-form formulae are summarized in Table 3-1.



**(a) Model I**



(b) Model II



(c) Model III

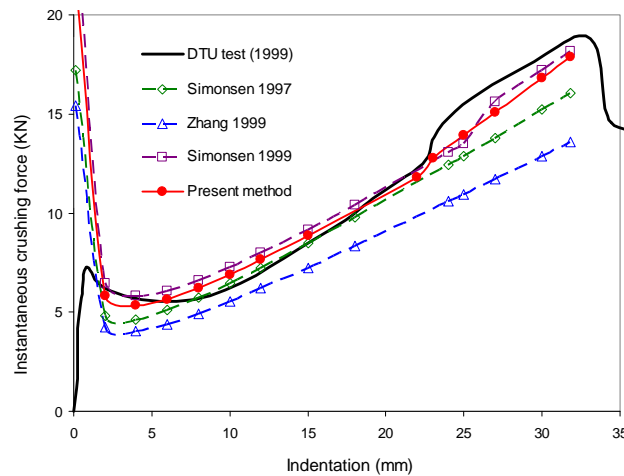
Figure 3-7: Progressive folding of the cross section in the loading plane of various denting modes for web girders (the filled small circles represent plastic hinges).

Table 3-1: A summary of the existing simplified methods for local denting of web girders.

Method	Model	H	$\lambda_0$	$P_m$	$P(\delta)$
Hong and Amdahl 2008	III	$H = 0.395b^{\frac{2}{3}}t^{\frac{1}{3}}$	0.73	$\frac{P_m}{M_0} = \frac{17.0}{\lambda} \left(\frac{b}{t}\right)^{\frac{1}{3}}$	$\frac{P(\delta)}{M_0} = \frac{1.2b}{H\sqrt{1-(1-\frac{0.3\delta}{H})^2}} \left( 2 + \frac{(1-\frac{0.3\delta}{H})}{\sqrt{3+(1-\frac{0.3\delta}{H})^2}} \right) + 22.24\frac{H}{bt}\delta$
Simonsen and Ocakli 1999	II	$H = 0.377b^{\frac{2}{3}}t^{\frac{1}{3}}$	1	$\frac{P_m}{M_0} = \frac{18.72}{\lambda} \left(\frac{b}{t}\right)^{\frac{1}{3}}$	$\frac{P(\delta)}{M_0} = \frac{3b}{H\sqrt{1-(1-\frac{\delta}{4H})^2}} + \frac{22H}{bt}\delta$
Zhang 1999	I	$H = 0.838b^{\frac{2}{3}}t^{\frac{1}{3}}$	0.75	$\frac{P_m}{M_0} = \frac{11.26}{\lambda} \left(\frac{b}{t}\right)^{\frac{1}{3}}$	$\frac{P(\delta)}{M_0} = 4.37t^{-1/6}b^{2/3}\delta^{-1/2} + 4.47b^{-1/3}t^{-2/3}\delta$

Simonsen 1997	I	$H = 0.671b^{\frac{2}{3}}t^{\frac{1}{3}}$	1	$\frac{P_m}{M_0} = \frac{14.76}{\lambda} \left(\frac{b}{t}\right)^{\frac{1}{3}}$	$\frac{P(\delta)}{M_0} = \frac{4b}{H\sqrt{1-\left(1-\frac{\delta}{2H}\right)^2}} + \frac{12H}{bt}\delta$
Wang and Ohtsubo 1997	I	$H = 0.811b^{\frac{2}{3}}t^{\frac{1}{3}}$	0.67	$\frac{P_m}{M_0} = \frac{11.68}{\lambda} \left(\frac{b}{t}\right)^{\frac{1}{3}}$	-

These simplified methods are compared with the results of experiments carried out at *MIT* (Yahiaoui et al, 1994), *DTU* (Simonsen and Ocakli, 1999) and *ASIS* (Kuroiwa, 1993), refer [Article II]. For instance, Figure 3-8 shows the comparison with the result of the *DTU* test. Though good correlation is seen, the proposed mechanism gives the best prediction. The onset of second fold is also well predicted.



**Figure 3-8: Comparison with DTU web girder test.**

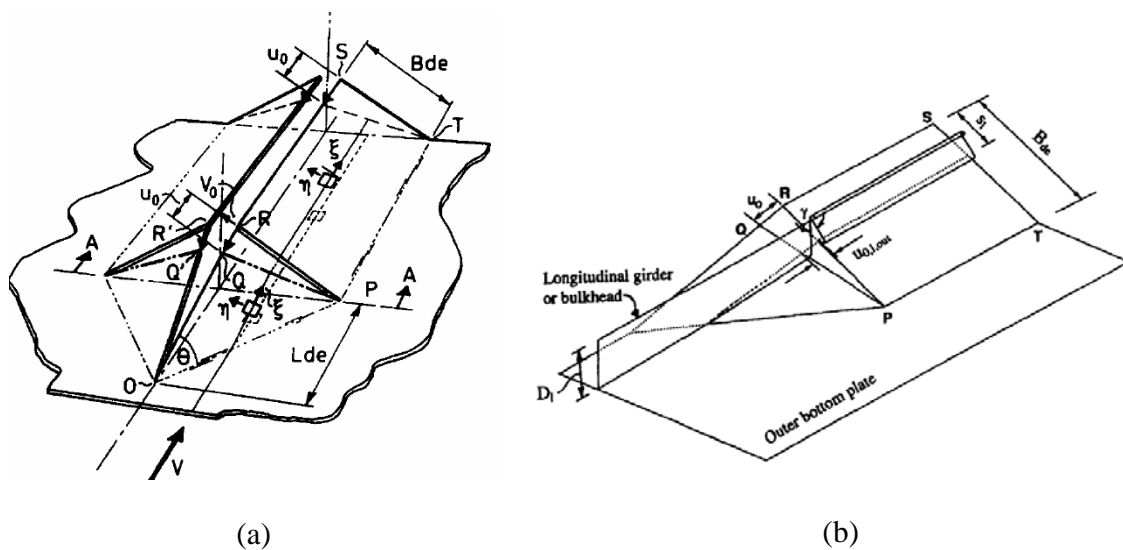
In addition, it is also found that the effective crushing factor plays a significant role in the prediction of the mean crushing resistance of plated structures. It is concluded that the influence of the effective crushing factor is more prominent for thick plates than thin plates, and it can be reasonably assumed to be unity for very thin plates.

### 3.3 Simplified method for horizontal sliding of web girder [Article III]

Different from the local denting deformation mode, a new deformation mode for web girders, namely *sliding deformation*, is observed during grounding when seabed obstacles with large flat contact surface are of concern. The description of the wavy pattern

deformation and the theoretical analysis of the new deformation mode are found at length in [Article III].

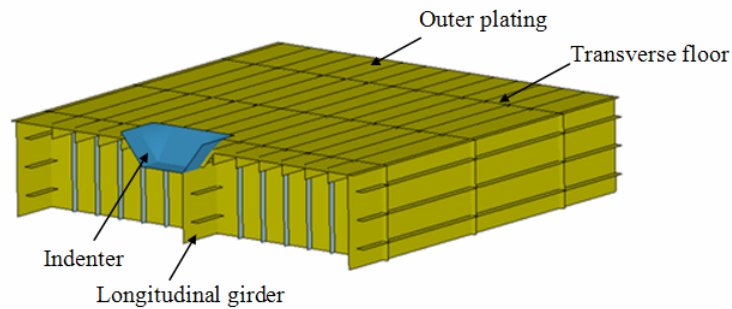
The sliding deformation mode for longitudinal bottom girders is provoked through grounding over large sea floor surface, such as “shoal”. Side stringers during sliding collision may also suffer sliding deformation. In previous studies, refer Figure 3-9, the deformation of the bottom girder is generally assumed to comply with the global deformation of the bottom structure (Thomas and Wierzbicki 1992, Simonsen 1997). In other words, the deformation pattern of longitudinal members has not been investigated when the longitudinal members are directly subjected to horizontal crushing force.



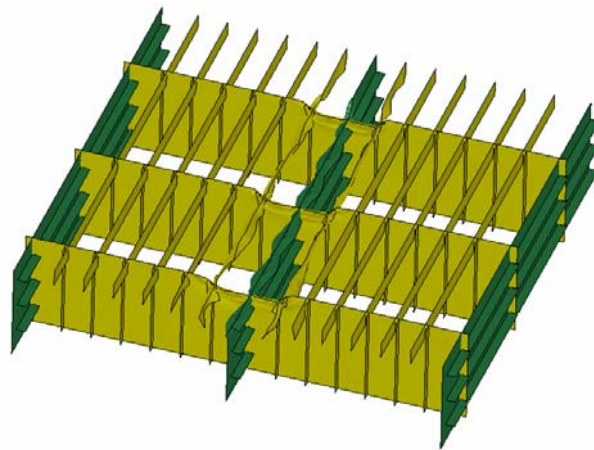
**Figure 3-9:** (a) Global deformation mode for bottom structure; (b) Deformation mode of a bottom longitudinal girder corresponds to the global deformation mode (Simonsen 1997).

Samuelides et al (2007a, 2007b) described the behavior of the longitudinal bottom girders subjected to sliding. Midtun (2006) made the first attempt on the mechanism analysis for bottom girders during sliding. Alsos and Amdahl (2008) proposed a simplified semi-analytical procedure to estimate the resistance of the bottom structure during steady state sliding where the effect of fracture is negligible. Here, sliding refers to grounding over seabed obstruction with large contact surface.

Figure 3-10 shows a schematic arrangement of a bottom structure subjected to grounding. Seabed obstruction with large surface is represented by a rigid indenter with flat contact surface and trapezoidal cross-section. The impact force is directly transmitted to the middle longitudinal girder. Figure 3-11 depicts the deformation of the bottom structure. It is apparent that the girder deforms sequentially to both sides of its original plane.



**Figure 3-10: Bottom structure with longitudinal girders subjected to grounding.**

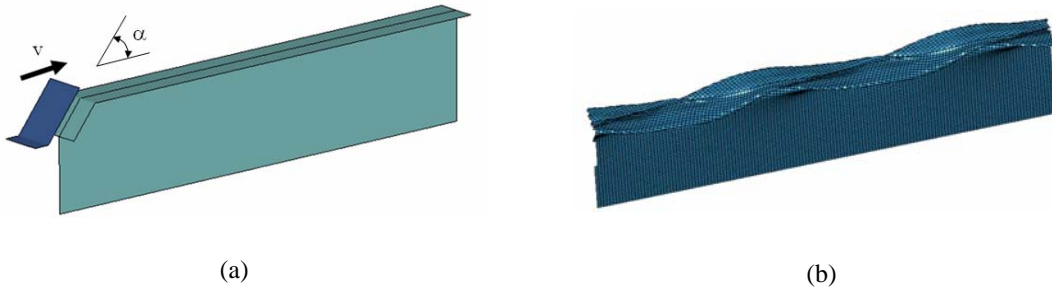


**Figure 3-11: Deformation of the bottom structure after horizontal indentation.**

A simple girder model has been used in [Article III], see Figure 3-12. Some major findings of the sliding deformation are concluded from a series of numerical simulations:

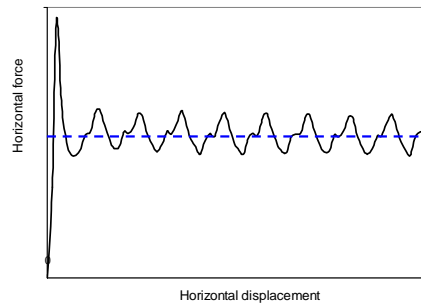
- In the steady state, a repetitive deformation pattern is developed with the wave switching from one side to the other side;
- The wavelength, the amount of vertical crushing and the transverse wave extension are constant in a certain case;
- A horizontal movement of the intersection between girder and flange plating is observed;
- The upper line (intersection between web girder and flange plating) and lower line (where the crushing action ends) remain lengthwise straight before and after crushing.





**Figure 3-12:** (a) Simple model for longitudinal girder subjected to sliding; (b) Deformation of web girder after continuous crushing.

A typical horizontal force-displacement curve of the girder is shown in Figure 3-13. The force-displacement curve exhibits a repetitive wave pattern corresponding to the formation of consecutive folding waves of the web girder. The sliding resistance of the girder can, therefore, be represented by a mean crushing force (the dashed line in Figure 3-13).



**Figure 3-13:** Characteristic horizontal force-displacement curve of web girder.

The deformation pattern is rather complicated. It consists of a combination of bending, stretching, compression or shearing. The mechanism, illustrated by paper folding, is shown in Figure 3-14. The deformation is assumed to be localized in the shaded quadrilateral area. An apparent advantage of this mechanism is that the top edge of the girder displaces horizontally a distance. This is a natural consequence of the bending action over oblique yield lines. It agrees favorably with the behavior observed in the NLFEA. In [Article III], the mechanism is described in detail alongside with the theoretical derivation. The total internal energy dissipated in one half-wave due to the proposed mechanism is derived as

$$E_{\text{int}} = M_0 \pi H \left( 1 + 2\sqrt{1 + \tan^2 \theta} \right) \cdot \frac{1 - \tan^2 \theta}{\tan \theta} + \frac{4N_0 H^2}{\sqrt{3}} \sqrt{\frac{1}{4} + \tan^2 \theta} . \quad (3.1)$$

The mean horizontal crushing resistance is obtained by dividing Eq. (3.1) by  $L$

$$P_{mH} = M_0\pi\left(1 + 2\sqrt{1 + \tan^2 \theta}\right) + \frac{4N_0H}{\sqrt{3}} \frac{\tan \theta}{1 - \tan^2 \theta} \sqrt{\frac{1}{4} + \tan^2 \theta} . \quad (3.2)$$

$H$  is the vertical crushing distance,  $L$  is half wavelength,  $\theta$  represents the crushing wave angle. According to the upper bound theory, it is postulated that the free parameters should adjust themselves in the deformation process to obtain the least energy dissipation. Theoretically, they should be determined by minimization to get the closed-form solution. However, due to the complexity of the problem, it is not possible to get analytical solutions for  $H$  and  $\theta$  according to the present theory. This means that the mechanism proposed is not a true upper bound. Even so, such approach still has been proved to work well in a large number of simplified analyses, see for example Wierzbicki and Culbertson-Driscoll (1995). The expression for  $H$  and  $\theta$  will thus be formed empirically rather than analytically, see [Article III].



**Figure 3-14:** *Sliding deformation model for web girders during sliding reproduced from paper folding.*

The crushing resistance and energy absorption predicted by the proposed theory are compared with results from numerical simulations. Table 3-2 shows an example of such comparison. More results can be found in [Article III].

**Table 3-2:** Comparison of energy dissipation and mean horizontal resistance according to the proposed mechanism and FEA for series 1,  $t=20\text{mm}$ .

$\alpha$	$E_{\text{proposed}}(\text{MPa})$	$E_{\text{FEA}}(\text{MPa})$	$R_E(\%)$	$P_{\text{mH-proposed}}(\text{MN})$	$P_{\text{mH-FEA}}(\text{MN})$	$R_{\text{mH}}(\%)$
30°	1.69	1.77	-4.6	1.04	1.04	0.3
35°	1.64	1.55	5.8	1.17	1.07	9.3
40°	1.61	1.56	3.4	1.30	1.27	2.2
51°	1.59	1.47	8.1	1.58	1.51	4.9
59°	1.59	1.47	8.5	1.79	1.63	9.5
67°	1.60	1.52	5.1	1.97	1.80	9.5
75°	1.61	1.49	8.0	2.13	1.86	14.5
80°	1.61	1.51	7.0	2.21	1.93	14.5
89°	1.62	1.55	4.2	2.31	2.07	11.6

Although some discrepancy is observed, the theory agrees with the FE results with reasonable accuracy considering that the complicated deformation has been treated in a

relatively simple manner. The mechanism should be verified further, not only by finite element analysis, but also by carrying out relevant model- or full-scale experiments. Nevertheless, the present work represents a significant forward step of the sliding deformation analysis.

### 3.4 Strength assessment of a ship bottom structure [Article IV]

In the rational design procedure for ships against collision and grounding suggested by Amdahl et al (1995), it is of paramount importance that the accident consequences can be quantified within short time. Taking into account the numerous potential accident scenarios, calculation tools with high efficiency are required. It is summarized in Chapter 2 that the analysis tool which is constituted by simplified methods based on plastic mechanism analysis is the most advanced and appropriate method. It provides reasonable accuracy with a very limited computational effort.

As an application example, the performance of a ship bottom subjected to grounding is evaluated through a simple analysis procedure in [Article IV]. In the proposed simple method, both local denting and sliding deformation for web girders developed in [Article II] and [Article III] are implemented. It is especially noticed that the simple method is developed for ship grounding over sea floor with large contact surface where the effect of fracture is of little importance. This type of grounding, which can be termed as “*sliding*”, has been somehow overlooked for decades, see Amdahl et al (1995), Wang et al (2000, 2002).

Three types of seabed topologies have been outlined in the stranding scenarios by Alsos and Amdahl (2007), namely “*rock*”, “*shoal*” and “*reef*” (refer Figure 1-5). Different deformation mechanisms may be triggered by seabed obstructions with different shape and size. Most studies on ship grounding to date are concerned with the “*rock*” type seabed obstacle, expressed in form of wedge or cone (Vaughan 1978, Jones and Jouri 1987, Thomas and Wierzbicki 1992, Ohtsubo and Wang 1995, Simonsen and Wierzbicki 1996, Simonsen 1997, Simonsen 1998, Wang et al 1997, Zhang 2002).

Indeed, the sharp rock may cause earlier penetration of the bottom plating, and result in very unfavorable consequences such as compartment flooding. This is exemplified by the high profile accident of “*Exxon Valdez*”. On the contrary, the bottom plating may not be fractured when moving over a blunt type sea floor with large contact surfaces. This has been seen in actual grounding incident, such as the grounding of *MS Sveafjell* on the coast close to *Trondheim, Norway* as reported by Alsos (2004). Refer Figure 3-15, in both grounding accidents, the ship bottom is dented as it slides over the large sea bottom. The damage spreads over a large part of the ship bottom which may threaten the global hull

bending resistance (Pedersen 1994, Alsos and Amdahl 2008b). Figure 3-16 shows an example that the global hull girder capacity is exceeded after the container ship, *Fowairret*, running aground during ebb tide near her terminal *Antwerp*. Taking into consideration the severity of such damage pattern, a study is needed for the ship bottom subjected to grounding over large contact surface.



(a) Bottom damage of *MS Sveafjell* ran aground on the coast close to Trondheim, Norway (Photo Courtesy of Alsos, H.S.).



(b) El Paso Paul Kayser – an LNG carrier in dry dock after grounding in Straits of Gibraltar (Photo Courtesy of BP).

**Figure 3-15: Ship bottom plating damage due to grounding over relatively large sea floor surface.**

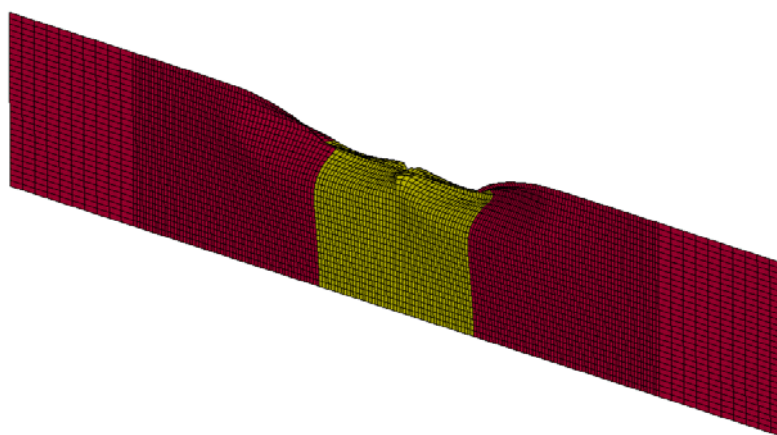


**Figure 3-16: Hull collapse of a container ship (Courtesy of [www.shipspotting.com](http://www.shipspotting.com)).**

A ship bottom structure similar to Figure 3-10 is applied in this study. The response of the ship bottom can be considered periodic because of the repetitive arrangement of structural members. Three types of structural components are of major concern during the grounding process:

1. longitudinal girder;
2. transverse member;
3. bottom plating.

The mechanisms for different structural components are described in [Article IV], and they are summarized in short here. For longitudinal bottom girder, the sliding deformation mode developed in [Article III] is used. The response of the transverse member is divided into two parts: the central part which has the same breadth as the contact surface from the indenter and the remaining part (Figure 3-17).



**Figure 3-17: Transverse floor after horizontal crushing.**

The crushing behavior for the central part is similar to the axial crushing of a cruciform, but with a horizontal displacement component. To simplify the problem and proceed to the establishment of the simple assessment tool, the existing theory for axial crushing of intersections from Amdahl (1983) is applied to the central part of the transverse floor. The response of the rest of the transverse member may be calculated by the denting mode proposed in [Article II]. The local denting mode was proposed for plates subjected to a load which moves in the plane of the plate. In a sliding process, the indenter moves in the longitudinal direction perpendicular to the plane of the plate. Despite the difference, the denting mode can be consistently applied to the present analysis.

A significant part of the energy will be consumed by the plastic deformation of ship bottom plating. Rather than being torn open by sharp rock type obstacle, the bottom plate is dented horizontally by blunt seabed. The energy is dissipated through three major mechanisms:

1. plastic bending at longitudinal hinge lines;
2. membrane stretching of the material between the longitudinal hinge lines;
3. plastic rolling of the plate in contact with the front surface of the indenter.

Further, the effect of friction is considered and included in the simplified method due to its significant influence during horizontal sliding. As general, it is postulated that the external work equals the total internal work due to plasticity, friction, and fracture where applicable

$$F_H \cdot V = F_{H,plasticity} \cdot V + F_{H,fracture} \cdot V + \mu V \int_S p dS . \quad (3.3)$$

$F_H$  is the total horizontal resistance of the structure,  $V$  is relative velocity between ship and obstruction,  $F_{H,plasticity}$  and  $F_{H,fracture}$  denotes the plastic resistance due to plasticity and fracture respectively,  $V'$  is the relative velocity between contact surface and obstruction,  $p$  is the pressure distribution on the contact surface,  $S$  is area of the contact surface.

Combining Eq. (3.3) and the requirement of equilibrium, both the total horizontal resistance and vertical resistance which include the effect of friction are obtained

$$F_H = g(\mu, \alpha) \cdot F_{H,plasticity} , \quad (3.4)$$

$$F_V = k(\mu, \alpha) \cdot F_H = k(\mu, \alpha) \cdot g(\mu, \alpha) \cdot F_{H,plasticity} , \quad (3.5)$$

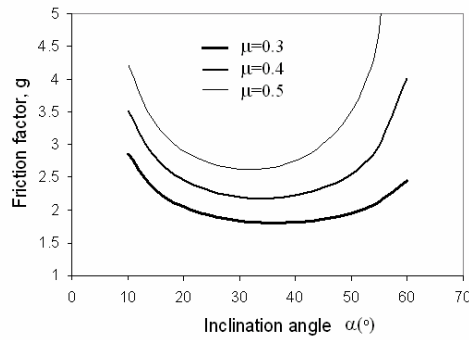
in which  $\alpha$  is the inclination angle of the flat indenter relative to the bottom plate. The friction factor  $g(\mu, \alpha)$  is derived as

$$g(\mu, \alpha) = \left( 1 - \frac{\mu}{(\sin \alpha + \mu \cos \alpha) \cos \alpha} \right)^{-1}. \quad (3.6)$$

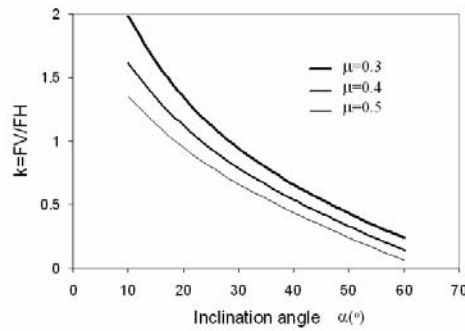
The ratio of vertical resistance to horizontal resistance,  $k(\mu, \alpha)$  is

$$k(\mu, \alpha) = \frac{F_V}{F_H} = \frac{1 - \mu \tan \alpha}{\tan \alpha + \mu}. \quad (3.7)$$

It is found that the vertical resistance,  $F_V$ , is independent of the friction coefficient  $\mu$  with reference to  $F_{H,plasticity}$ , which is evident from the product of  $g(\mu, \alpha)$  and  $k(\mu, \alpha)$ . This is also in accordance with the observations from numerical simulations.



(a) friction factor as a function of  $\alpha$  and  $\mu$



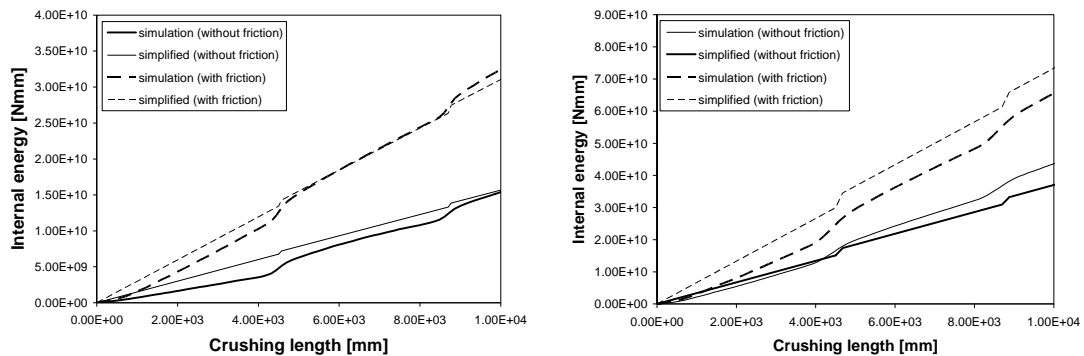
(b) ratio of  $F_V$  and  $F_H$  as a function of  $\alpha$  and  $\mu$

Figure 3-18: Illustration of friction factor  $g$  and ratio of  $k=F_V/F_H$ .

As illustrated in Figure 3-18(a) for friction factor, if  $\mu=0.3$  is assumed,  $g$  will be 2.05, 1.84 and 1.94 for  $\alpha=20^\circ$ ,  $30^\circ$  and  $50^\circ$  respectively. This indicates a prominent increasing for the

total horizontal resistance due to the effect of friction. Figure 3-18(b) shows  $k$  as a function of  $\alpha$  and  $\mu$ . For large inclination angles, the vertical component of the frictional force dominates over the normal force. The total vertical force acting on the ship may become negative for very large inclination angles.

Subsequently, simplified formulae for longitudinal girders, transverse floors and bottom plating are assembled and applied to a simple ship bottom structure. The main parameters for the bottom structure are given in [Article IV]. Energy dissipation curves obtained from numerical simulations and predicted from the simplified method are compared in Figure 3-19. The simplified method agrees well with the results of numerical simulations in these cases. However, it overestimates the total energy dissipation in some cases especially when the friction effect is taken into account which implies further improvement of the present model for considering friction effect. The increased strength due to transverse members is reasonably captured. However, the strength predicted by simplified method tends to increase slightly later. This is mainly due to the neglect of the interaction between longitudinal girder and transverse member. It is found that the bottom plating and the longitudinal girder absorb significant amount of energy during the sliding process. Whereas the energy consumed by transverse members is much lower. This indicates that further improvement of the present method should be focused on the bottom plating and the longitudinal girder. More results are presented in [Article IV].



Case 3:  $\alpha=51.3^\circ$ ,  $D=150\text{mm}$

Case 4:  $\alpha=51.3^\circ$ ,  $D=450\text{mm}$

(a)

(b)

**Figure 3-19: Simplified method vs. numerical simulation in terms of total bottom energy absorption.**

Despite of the discrepancies, the results are encouraging. However, further studies are required to fully understand the structural response of ship grounding over large flat contact surface. Further improvement and more verification examples are needed before the model is generally accepted.



The proposed method is, however, still considered to be a rational analysis tool. When coupled with a model for external dynamics, the presented theory can be used to calculate ship motions and damage in a given grounding scenario. An example of such coupling has been conducted by Simonsen and Wierzbicki (1996). The present method is considered to contribute substantially to the establishment of efficient methods for fast and reliable assessment of the outcome of accidental grounding events. It is also essential for probabilistically based formal safety assessment procedures or quantitative risk analysis (Friis-Hansen and Simonsen 2002, Bogaert and Boon 2007). The method may in turn be incorporated into decision support tools (Amdahl and Hellan, 2004) for crisis handling in emergency situations, such as tankers in disabled conditions.

## Chapter 4

# Simplified Methods for Ship Plating under Patch Loading

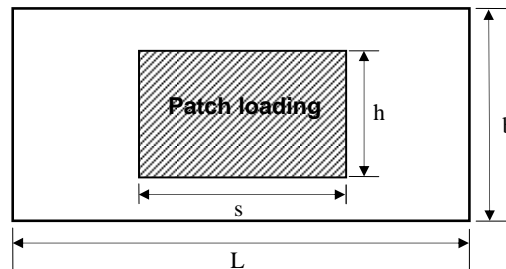
The response of ship plating under patch loading is a relevant topic in the study of ship collision or stranding due to the fact that generally the ship suffers only local damage. Plastic methods developed in [Article I] and [Article VI] for ship plating under patch loading may be adopted for collision resistance design. A prominent contribution of the present work is the inclusion of membrane effect and the development of a new yield line model for plates under patch loading.

### 4.1 Introduction

The stiffened plate is a basic structural component in ships and other marine structures. Plates may deform between various supporting members, such as frames, longitudinals, decks or stringers, which are generally designed to have sufficient strength to support shell plating for the design loads and should preferably not fail prior to shell plating.

Usually, fairly uniform lateral load, in the form of hydrostatic or dynamic pressure dominates in many parts of the ship structures. Initially, it is for the purpose of strengthening the ships navigating in ice that calls for the analysis of plates under the so-called “patch loading”. Comparing to uniform loading, a patch load means the load does not span over the whole area of the plate, but in a restricted area within the plate (see Figure

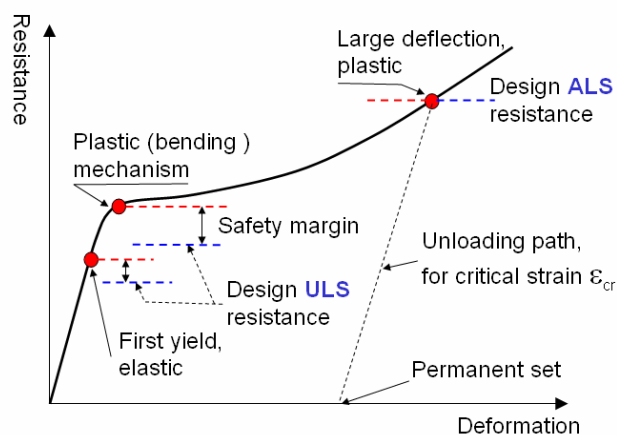
4-1). A frontier work concerning ice loads of limited vertical extension is done by Johansson (1967).



**Figure 4-1: A plate subjected to general patch load.**

During ship collision, it is generally recognized that the damage is local. The evolution of impact force obtained by simulation of bow colliding against rigid wall reveals that the impact force is distributed over a limited area of the ship side structure (Hong and Amdahl 2007b, Hong et al 2007). In this sense, the collision force may be beneficially represented as a patch load acting on the plating because in this manner it becomes simple to implement the impact force into design formulations. Therefore, if design against collision is aimed at, the plate should be designed taking into account the patch loading condition.

Also, in other cases, for example wheel loads of vehicles or landing aircrafts, inner bottom loaded by steel coils on a wooden support, wave slamming loads, falling objects, these loads are all likely to take place over limited area of the plate. Consequently, the structural behavior of ship shell plating under patch loading is of particular interest.



**Figure 4-2: Plate response curve.**

A typical curve for the plate response is depicted in Figure 4-2. The plate is elastic until first yield and the plastic mechanism is more or less fully developed at the top of the “knee” of the response curve. Most often the ship plating is designed according to linear elastic theory. However, the plastic behavior has been recognized to be essential in a rational ship design method in recent years (Daley et al 2007).

The reason why ships designed according to elastic theory appear to withstand not only the design loads, but overload condition as well, is due to the considerable strength reserve during plastic deformation before fracture. However, this is not explicitly reflected in present ship design rules. Therefore, there is a trend by the design rules to explicitly recognize and reflect the strength reserve capacity in ship plating. This will result in better design with improved safety and economy.

The ice design rules, especially the design for *Polar Class*, tend to accept a certain level of permanent deformation for the side shell plating (Wiernicki 1987, Furness and Aksu 1997, Wang and Wiernicki 2006). Figure 4-3 shows the side shell plating damage of a ship navigating in ice (Hänninen 2003). It is observed that the side shell has experienced substantial plastic deformations between adjacent frames as a “hungry horse” pattern. The “hungry horse” look is prohibited in *ULS* (ultimate limit state) design and need to be repaired. However, if *ALS* (accidental limit state) design is aimed at, this may be considered acceptable, provided that the structural integrity is not impaired and sufficient post-accident strength is reserved.



**Figure 4-3: Side plating damage of ships navigating in ice (Hänninen 2003).**

In the present study, the development of the plastic method for plates under patch loading is divided into two steps. In the first step, the patch load is assumed to span over the entire stiffener spacing, but spread over limited length with respect to the frame spacing [Article I]. In the second step, a general patch load which is restricted in both directions is considered [Article VI]. Focus is placed on predicting the load-carrying capacity when permanent deformation of considerable magnitude is developed. A comparative study has been carried out in [Article VI] on various formulations for patch loaded plates with the aid

of NLFEA. By allowing a certain amount of permanent deformation, significant plate thickness reduction can be achieved. The present formulation may be used as a versatile tool for predicting the resistance of plates under various types of patch loads, notably when finite, permanent deformations are accepted, e.g. in *ALS* design.

## 4.2 Plastic analysis for plates under patch loading [Article I, VI]

In this section, the development of simplified method for plates under patch loading is presented by using plastic methods of analysis. The detailed derivations are given in [Article I, VI].

Comparing to the plate under uniform loading, the response of the plate under patch loading is affected by the restricted length and height of the load. The height and length of a ship plate generally refer to stiffener spacing and frame spacing, respectively. Consequently, the formulation may be considered to be built up by three components: the capacity of a plate strip subjected to uniform loading and two factors representing the influence from finite length and finite height of the patch load, respectively. This is the basic idea behind the formulation developed for plates under general patch loading.

When applying plastic method to plates under pressure, the concept of yield line is employed to construct the collapse mechanism. It was first introduced by Wood (1961) in the design of concrete slabs and plates for the case of fully clamped condition. Sawczuk (1964) included the membrane effect for large deflections. The usefulness of yield line theory has been proved for design of ship plating by, e.g. Kmiecik (1995).

First, consider a patch load which spans over the stiffener spacing, but spreads over limited length with respect to the frame spacing. Although the classical yield line mechanism is used for rectangular plates subjected to uniform load, it can be extended to plates subjected to lateral patch load, see Figure 4-4. Other mechanisms are also developed, for example the parallel hinge line model proposed by Nyseth and Holtmark (2006).

Adopting the “roof-top” mechanism, Delay et al (2001) derived the prediction formulae for patch loaded plates introducing some significant simplifications. The accuracy should thus be investigated. These simplifications are removed in the present study. A factor which represents the influence of patch load of finite height on the plate resistance is derived. More importantly, the increased resistance attributed to the membrane effect when plates undergo large deformations is included in the present formulation. This is especially useful when significant permanent deformation is considered acceptable. It provides also insight into the reserve strength of the plate, although the load-carrying capacity beyond yielding or plastic bending may not be used explicitly.

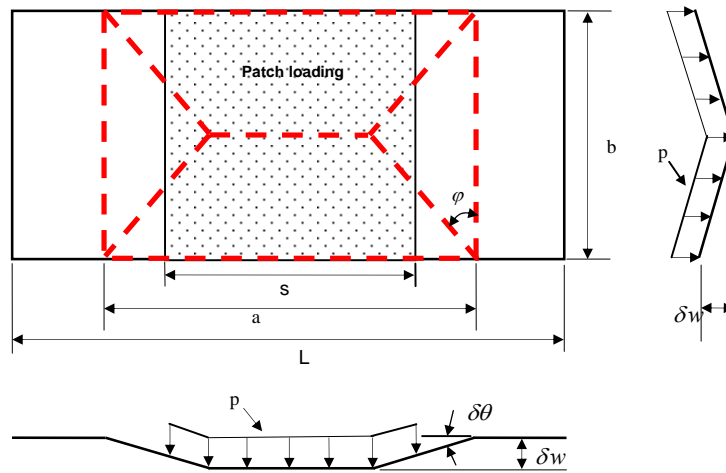


Figure 4-4: “Roof-top” or “envelope” type mechanism for laterally patch loaded plates.

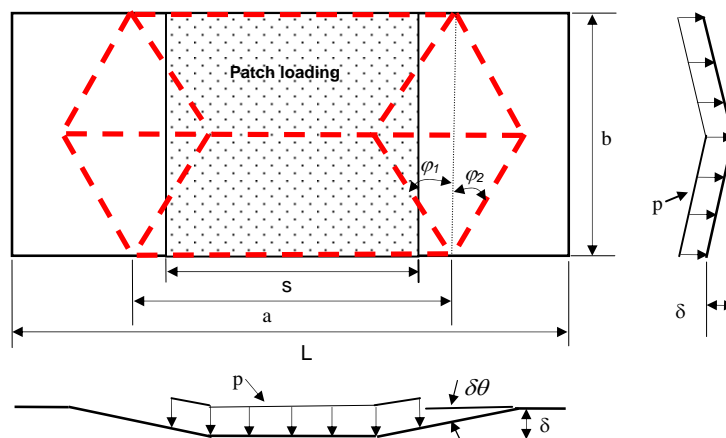


Figure 4-5: “Double-diamond” collapse mechanism for laterally patch loaded plates.

It is found that the plastic bending capacity (when small deformations are considered) is overestimated to some extent according to the conventional “roof-top” mechanism. An alternative mechanism for patch loading, named as “double-diamond” model (Figure 4-5), which gives better prediction than “roof-top” mechanism in the plastic bending phase, is proposed in [Article I]. The triangular hinge formations of short edges are replaced by diamond hinge formations. The proposed model increases the rate of external work, and reduces the rate of internal work, resulting in a somewhat lower collapse load in bending. However, due to the relative complexity of the “double-diamond” mechanism, the basic prediction formula is maintained in order to be consistent with the derived simplified formulation from “roof-top” mechanism. Instead, a correction factor,  $f_B$  is employed to adjust the prediction of the plastic bending capacity.

Second, consider a general patch load (Figure 4-1, in which  $h < b$ ,  $s < L$ ). In this case, the load is restricted in both height and length directions. A factor which represents the influence of patch load of finite length on the plate resistance is employed, refer [Article VI].

Finally, the resistance of plates subjected to general patch loading is formulated as

$$p = \frac{16M_p}{b^2 K_h} \cdot K_l \cdot K_m \cdot f_B, \quad (4.1)$$

in which,  $K_l$  represents the influence factor of finite length,  $K_m$  denotes the membrane effect, and  $K_h$  is the factor representing the finite height of the load, and expressed as

$$K_l = 1.0 + 1.3 \frac{b}{s} + 0.18 \left( \frac{b}{s} \right)^2, \quad (4.2)$$

$$K_h = \frac{h}{b} \left( 2 - \frac{h}{b} \right), \quad (4.3)$$

$$K_m = 1 + \frac{1}{3} \left( \frac{w}{t} \right)^2 \frac{-\left( \frac{b}{s} \right)^2 + 9 \frac{b}{s} - 16 + 36 \frac{s}{b}}{-\frac{b}{s} + 12 + 12 \frac{s}{b}}, \text{ when } z \leq 1, \quad (4.4)$$

$$K_m = 2 \frac{w}{t} \left[ 1 + \frac{\left( \frac{b}{s} \right)^2 - 12 \frac{b}{s} + 52}{-4 \frac{b}{s} + 48 + 48 \frac{s}{b}} \left( \frac{1}{3 \left( \frac{w}{t} \right)^2} - 1 \right) \right], \text{ when } z \geq 1, \quad (4.5)$$

$$f_B = 1 - 0.075 \left( \frac{s}{b} \right)^{-0.5}. \quad (4.6)$$

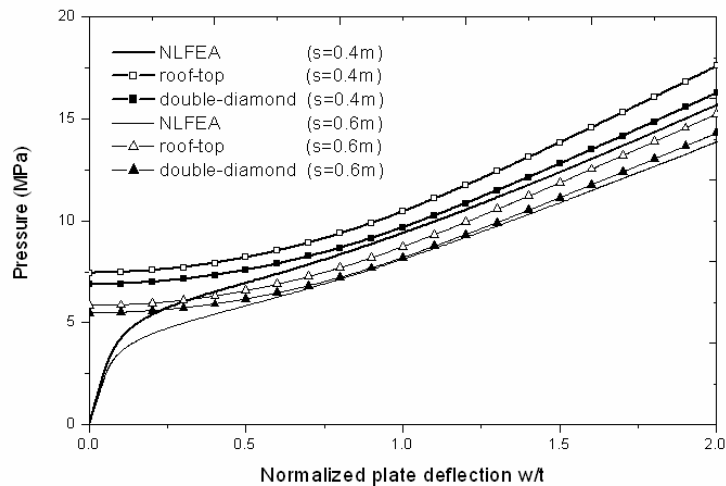
$w$  represents the plastic deformation of the plate. The above plate response equation can be inverted to obtain the plate thickness design equation on the condition that an acceptable deformation  $w$  has been defined:

$$t = 500b \sqrt{\frac{p}{\sigma_y}} \cdot \sqrt{\frac{K_h}{K_l K_m f_B}}. \quad (4.7)$$

It is noted that the development of the present formula for plates under general patch load is under the condition  $s/h \geq 1$ . If  $s/h < 1$ , the yield line pattern changes its orientation. A similar

formulation can be constructed with the inter-change of the value of  $s$  and  $h$ . In addition, a plate length restriction factor is introduced when the free formation of the entire collapse mechanism is restricted by the finite length of the plate, i.e.  $L < a$  in the “roof-top” yield line model, refer [Article I] for detail.

The proposed formula is verified by NLFEA, using the progressive collapse analysis software USFOS (Sørense et al 1988). Figure 4-6 shows an example of a comparison of the predicted resistance and the simulation results. The present formulation predicts the resistance quite well in the range of large permanent deformations, where a substantial increase of the resistance is experienced. It is also found that the IACS requirement (IACS 2006) developed on the basis of Daley et al’s (2002) work - in spite of the simplifications introduced - gives surprisingly comparable results on the plastic bending resistance when the plate is sufficiently long to support the mechanism, refer [Article I].



**Figure 4-6: Resistance for a 400mm×2000mm plate according to the present formulation and NLFEA.**

### 4.3 A comparative study

The resistance of plates under patch loading has been studied extensively, notably due to the increasing demand for ice strengthening structures in relation to the increasing interest of transportation and resource exploitation in Arctic area.

According to the utilization of the plasticity, all the formulations concerning plates under patch loading may be classified into two groups: with and without consideration of large permanent deformations. The design formulations of the classification societies are usually established from the elastic response up to the level of plastic bending where finite permanent deformation is explicitly not allowed. It is just a matter of how well the plastic



bending resistance is predicted which significantly relies on the realism of the mechanism constructed.

When the resistance from large deflection is included, there may be distinguished between formulations for general patch load (Hong and Amdahl 2008c, Zhang 1994) and for patch load which is restricted in one direction (Hong and Amdahl 2007, Ranki 1986, Riska 2002).

Comparative studies for formulations of each group are carried out in [Article VI]. From the comparative studies, it is observed that the present formulation gives comparable results with those of the methods developed by Zhang (1994), Daley et al (2001) and Nyseth and Holtmark (2006) when no significant permanent deformation is allowed. When large deformation is developed, both the method by Zhang (1994) and the present method can predict the resistance satisfactorily. Nevertheless, in all cases when compared to the results of NLFEA, the present method always gives better results.

It should be mentioned, however, that a direct comparison with the design requirements from rules is generally not feasible. The inherent safety level in a design formulation depends upon the mechanical response model, the return period of the loads as well as the partial safety factors adopted. These factors are often not explicitly stated in ship design rules.

It is observed that once structural plasticity is explicitly taken into account, significant weight savings can be achieved. For instance, under the same design load condition, if the allowed deformation is set equal to plate thickness, the required plate thickness according to the present method may be reduced up to 22% by contrast to *IACS* unified requirement. On the other hand, permanent deformation in the form of “hungry-horse” look is generally not desired by the ship owners/operators. It is probably sound to not accept significant permanent deformations for plate designed according to frequently occurring loads, i.e. loads with a return period from 1 year to (at maximum) 100 years. In conjunction with design of offshore structures in arctic conditions this event is denoted *ELIE* (Extreme Level Ice Event) according to Draft ISO/CD 19906 (2007).

For offshore structures it is, in addition, common practice to consider rare actions with a return period in the range of 1,000- 10,000 years, denoted *ALIE* (Abnormal Level Ice Events), refer e.g. Draft ISO/CD 19906 (2007). This is also required for ship type structures involved in offshore activities (e.g. *FPSOs*). For such rare loads it is considered acceptable to allow permanent deformations of considerable magnitude and design the plating in the *ALS* format. The present formulation is especially geared to such analyses. Care should be exercised if the formulae are used for *ULS* design, as the phase from first yield to fully developed plastic bending mechanism is not very accurately predicted.

## Chapter 5

# A Direct Design Approach for Ship Side Structures against Collision

A direct design approach which follows the principles of *ALS* (accidental limit state) and strength design is proposed in this chapter, for ship side structures, notably ship-shaped FPSO, against large impact loads such as from collision with offshore supply vessels. The approach and some application examples are described in [Article V]. The attractiveness of the design approach is it based on closed-form solutions for plating and stiffener besides the simple manner of representing the collision force as a design load.

### 5.1 Introduction

Supply vessels, passing merchant vessels and shuttle tankers are regarded as the major threat for floating production, storage and offloading units, known as *FPSO* (Moan et al, 2003). Figure 5-1 demonstrates an *FPSO* in tandem offloading condition. There is identified potential collision between *FPSO* and the shuttle tanker. Figure 5-2 shows the potential damage of an *FPSO* side structure because of high-energy collision. The accident statistics from the report, OTO 1999 052 (HSE 1999), shows that the majority (66%) of ship collisions with installations involve supply/support vessels. The offshore collision accident is exemplified by the Mumbai High North platform accident in 2005, where a collision with a stand by support vessel and the production platform, caused a devastating fire and total loss of the production platform.



*Figure 5-1: FPSO and shuttle tanker in tandem offloading situation ([www.ntnu.no/cesos/](http://www.ntnu.no/cesos/)).*

Ship collision has been a major concern for a long time in the offshore industry. Consequently, the *ALS* design concept has been applied. In the Norwegian sector of the *North Sea* the standard design event is a supply vessel of 5,000 tons displacement sailing into a platform with a speed of 2m/s. For design purposes, the force-deformation curves for bow, side and stern impact according to Appendix A of *NORSOK* standard N-004 (2004) may be used.



*Figure 5-2: Side structure damage of a tanker resulting from a collision (Wang et al 2003).*

As compared with platforms, there is limited experience for operating FPSOs. The total cumulative operating experience for FPSOs is estimated to be in the range of only 500-600 years. Whereas, for fixed platforms, they have over 100,000 years of combined operating experience. The first FPSO was introduced into the Norwegian Continental Shelf in 1986 only for testing. It was until 1997 that “Norne” FPSO (Figure 5-3) was permanently installed for production. Currently, a large part (approximately 65%) of the operating FPSOs is converted from trading tankers. In this context, Wang and Spong (2003) did extensive data collection effort and proposed to make use of the experience from conventional trading tankers as a starting point for the structural design of FPSOs.

However, it is not fully justified to apply the experience of trading tankers to the design of FPSOs largely due to its site-specific characteristic (Paik and Thayamballi 2007). Moreover, for offshore structures it is common practice to consider rare actions with a return period in the range of 1,000- 10,000 years, refer e.g. Draft ISO/CD 19906 (2007). This is also required for ship-shaped structures involved in offshore activities (e.g. FPSOs). For such rare loads it is considered acceptable to allow permanent deformations of considerable magnitude and design the plating in the ALS format.



Figure 5-3: “Norne” FPSO operating on site ([www.offshore-technology.com](http://www.offshore-technology.com)).

Another but important design principle is the “*strength design*” principle adopted by *NORSOK* standard for design of offshore steel structures against accidental loads.

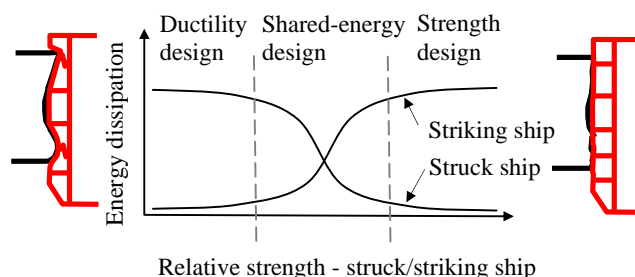


Figure 5-4: *Strength, ductility and shared-energy design* (*NORSOK N-004, 2004*).

According to the relative strength of the striking and struck objects, and consequently the energy dissipation distribution, the design may be categorized as strength design, ductility design and shared energy design in *NORSOK* standard N-004 (2004). Refer *Figure 5-4*, the definitions for these design principles are described as:

- **Strength design** - which implies that the struck ship is strong enough to resist the collision force with minor deformation, so that the striking ship is forced to deform and dissipate the major part of the collision energy.

- **Ductility design** – which implies that the struck ship undergoes large, plastic deformations and dissipates the major part of the collision energy.
- **Shared energy design** – which implies that both the struck and the striking ship contribute significantly to the energy dissipation.

It is noted that *NORSOK* does not require strength design to be adopted. Ductility design is fully acceptable as long as the *FPSO* can resist the direct action of the accidental load without impairment global integrity. In addition the *FPSO* shall have sufficient strength in damaged condition to resist environmental actions with the design return period, which is typically 100 years. The partial safety coefficients are all taken equal to unity in this case. Global integrity is in this context interpreted as no rupture in cargo tanks, no loss of hydrostatic stability due to leakage/flooding and no hull girder collapse in bending or shear. The outer shell panels and girders may undergo large permanent deformations, crushing and rupture.

From calculation point of view, strength design or ductility design is favourable. In such case the response of the “soft” structure can be calculated on the basis of simple considerations of the geometry of the “rigid” structure. In shared energy design, both the magnitude and distribution of the collision force depends upon the deformation of both structures. This interaction gives rise to the complexity of the analysis. It is the current weaker structure that is forced to deform further. The relative strength of the two structures may vary both over the contact area as well as over a period of time.

In most cases, ductility or shared energy design is used. However, strength design may be achieved in some cases with moderate efforts, for instance, adding an intermediate transverse frame to the struck side.

Consequently, the development of a rational design approach considering the accidental load such as collision is of concern in relation to the principles of *ALS* and/or strength design.

Design against accidental loads is to prevent an incident from developing into an accident disproportional to the original cause. The work described in [Article V] is an attempt to develop a rational, direct design procedure for *FPSO* side structure against large impact forces, such as those from collision with supply vessels. The procedure comprises determination and expression of the impact forces, predicting the structural responses by analytical methods, and the consideration of the acceptance criterion.

The approach is considered simple because the design equations are based on closed-form solutions from plastic analysis. Another feature is that it relates the structural design directly to the impact loads. Therefore, such direct design approach should be of significant interest.

## 5.2 Direct Design Approach

During the design process, it is very important that the loads can be defined and represented in an appropriate manner. As shown by, for example, Hong and Amdahl (2007b), Hong et al (2007), compared to the stem of the bow, the bulb represents the major threat to the double hull in the event of a collision. In recent years the size of supply vessels has increased significantly and the use of bulbs is common. A supply vessel fitted with bulbous bow is shown in Figure 5-5. In present work, the impact force from the bulb of a 7,500 tons displacement supply vessel is adopted. A simple pressure-area relation (Eq.1) is derived from the impact force evolution such that it can be implemented practically into the design approach, see [Article V].

$$p = 7.0A^{-0.7} \quad (5.1)$$

Similar pressure-area relationships are typically used to characterize ice action. An identical relationship, but with the coefficient 7.0 in Eq. (2) replaced by 6.24, has been adopted for design against abnormal ice impact with an *FPSO* operating offshore of *Newfoundland*. The coefficient and the exponent in Eq. (1) may vary for impact loads from other striking objects.



**Figure 5-5: A supply vessel fitted with bulbous bow.**

The simplified method developed in Chapter 4 is applied here for the design of the outer plating of an *FPSO* side structure. Since the collision is a rare event, it is natural to allow plastic deformations according to the *ALS* design principle. The question is how much deformation it can sustain. This is an issue argued widely.

In *NORSOK* standard N-004 (2004) Appendix A, a criterion is formulated which relates the permanent deformation to the allowable strain,  $\varepsilon_{cr}$ . The critical strain for rupture is

recommended in NORSOK code to be taken as 20% for grade S235, 15% for grade S335 and 10% for grade S460. The strain levels are significant, but reflect the fact that the expression is based on a continuous strain model. They are therefore considered appropriate for use in design against very rare events; typically accidents or abnormal environmental actions with a return period in the range of 10,000 years. For more frequent events, where the *ULS* (ultimate limit state) or even *SLS* (serviceability limit state) design principles should be adopted, a lower value of  $\varepsilon_{cr}$  should be used. For example, in *ULS* design it is suggested that  $\varepsilon_{cr}$  should be in the order of the strain level corresponding to the end of the yield plateau, i.e., at the onset of strain hardening, e.g.  $\sim 20$  times the yield strain,  $\varepsilon_y$ . For the steel grades listed above such a criterion yields  $\varepsilon_{cr} \sim 2.2\% - 4.4\%$ . For *SLS* design it is probably more appropriate to use permanent deformation rather than strain as the governing acceptance criterion, either from an aesthetic point of view or the practical use or function of the panel could be degraded. Generally, the magnitude of permanent set correlates with the ultimate strain and stiffener spacing. In [Article V], a simple relation between permanent deformation and stiffener spacing is derived as

$$\frac{w}{t} = 0.1 \frac{s}{t} - 0.8, \text{ for } \varepsilon_{cr} = 0.20. \tag{5.2}$$

Assuming that a square patch with side equal to the stiffener spacing is appropriate for local plating design, the following design equation is obtained:

$$t = 18s^{-0.58} \sigma_y^{-1.13}. \tag{5.3}$$

The design equation is extremely simple, it relates the required shell plate thickness directly to the stiffener spacing and material yield strength.

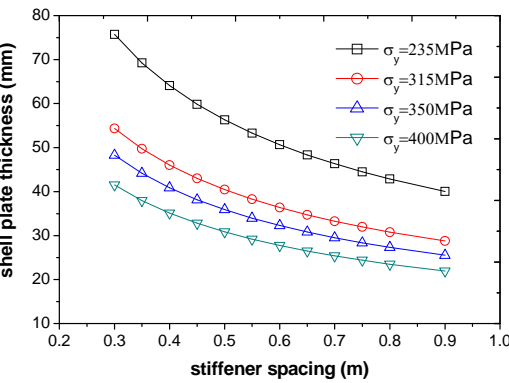
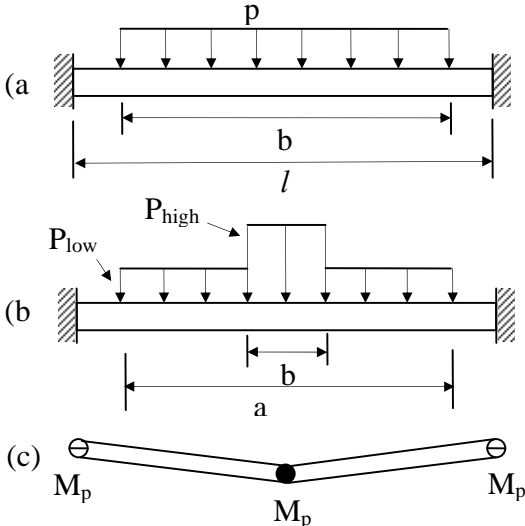


Figure 5-6: Correlation of required plate thickness and stiffener spacing for various materials.

It is perhaps surprising that the required plate thickness increases with decreasing stiffener spacing, but it is a logical consequence because the permanent set decreases with decreasing stiffener spacing which yields less beneficial membrane effect on one hand; the design collision pressure increases with reduced stiffener spacing, refer Eq. (1), on the other hand.

However, it should be noted that the proposed approach is geared for designing against the failure of material rupture in conjunction with accidental/abnormal events, where the basic safety requirement is that the structure should be capable of resisting the direct consequences of the action without impairing the structural integrity and, in addition, have a sufficient post-damage resistance. In more *ULS*-oriented structural design, other considerations may be more dominating than this failure criterion. For example, “large” permanent deformations can be viewed as detrimental to the safety of the vessel. Often, side shell deformations of around 50 to 75 mm are considered as structural damage, which need to be repaired immediately.



**Figure 5-7: Centrally loaded frame and mechanism model: (a) central uniform load pattern; (b) combined high-low intensity load pattern; (c) three hinge collapse mechanism model.**

For stiffener/framing design, two different models may be adopted concerning the pressure distribution over a stiffener with associated plating flange, refer Figure 5-7. One general option is to assume that the pressure,  $p_0$ , is uniformly distributed over the entire plate. Another is to assume that the plate is subjected to a centrally high intensity pressure,  $p_h$ , over a square patch with side equal to the stiffener spacing simultaneously with a low intensity pressure,  $p_l$ , over the remaining plate. For simplicity, it is assumed that the entire pressure within  $s/4$  to the adjacent girders is transferred directly to the girders. The same



assumption has been adopted by *DNV* rules (2001) for stiffener design subjected to ice loading.

In the three hinge mechanism (Figure 5-7c), the central hinge attains the full plastic bending capacity  $M_p$ , and the edge hinges have reduced capacity,  $M_{pr}$ , due to the presence of shear. The full plastic bending capacity is given by  $M_p = Z_p \sigma_y$ , where the fully plastic section modulus is

$$Z_p = Z_w + Z_f = A_w \frac{h_w}{2} + A_f \left( h_w + \frac{t_f}{2} \right). \quad (5.4)$$

The reduced plastic bending capacity reads  $M_{pr} = Z_{pr} \sigma_y$ , where the reduced plastic section modulus is

$$Z_{pr} = Z_f + Z_w \sqrt{1 - \left( \frac{\tau}{\tau_y} \right)^2}. \quad (5.5)$$

This is based on the assumption that the shear force is carried only by the web.

The relation between internal bending moment capacity and external load is obtained through equating the internal and external work. For uniform pressure model, refer Figure 5-7a, there is obtained

$$pbs \left( 1 - \frac{b}{2l} \right) = (M_p + M_{pr}) \frac{4}{l}. \quad (5.6)$$

For combined high-low intensity pressure model, refer Figure 5-7b, it becomes

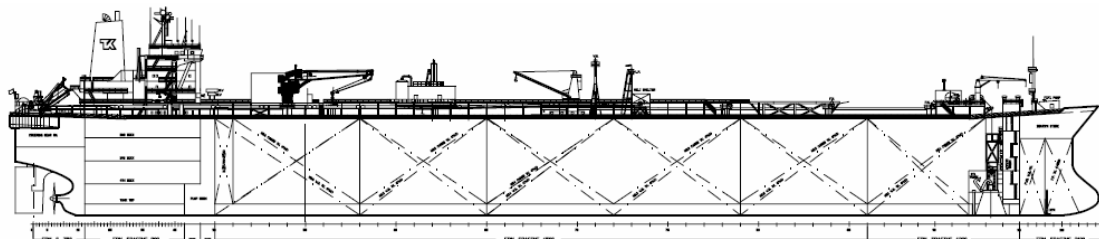
$$p_h bs \left( 1 - \frac{b}{2l} \right) + p_l (a-b) s \left( 1 - \frac{b}{2l} - \frac{a}{2l} \right) = (M_p + M_{pr}) \frac{4}{l}. \quad (5.7)$$

The design equation is given in [Article V]. The formulae contain interactions between shear and bending and thus iteration process is performed until the required plastic section modulus of the stiffener is satisfied, refer Table 2 in [Article V].

### 5.3 Application Example

The proposed design approach is applied to the side structure of an *FPSO* (Figure 5-8). Large-scale collision analyses are carried out for both original and strengthened structural arrangements by using the explicit non-linear finite element code “*LS-DYNA*” which incorporates “*RTCL*” damage model (Törnqvist 2003) for fracture prediction by *Dr. Alsos*

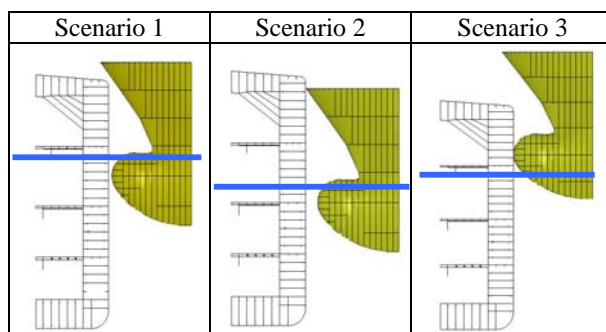
at *NTNU*. The purpose of the analysis is to investigate the relative strength of bow and side structure. It is the current weaker structure that is forced to deform further, whereas the damage of the other structure may remain virtually unchanged.



**Figure 5-8: General layout of the reference FPSO.**

Taking into account the relative size of the supply vessel and the *FPSO*, only starboard side of the mid-tank of the *FPSO* is modeled in all analyses. The finite element model of the striking supply vessel and the struck *FPSO* side structure are described in [Article V]. Three collision scenarios (Figure 5-9) are established based on the dimensions of the striking and struck structures, with consideration of draught variations, operational sea-state and motions of the structures. The most severe collision condition considered is a right-angle collision with struck ship at standstill (Kitamura 2002, Yamada et al 2005). This is considered especially appropriate for *FPSOs*.

Scenario 1 refers to the collision when the impact position is located between the side stringers and the transverse frames of the *FPSO*. This is a very likely position. It represents the impact with the *FPSO* in a laden condition and the supply vessel somewhat more than full draught. The definition for Scenario 2 and Scenario 3 is found in [Article V].

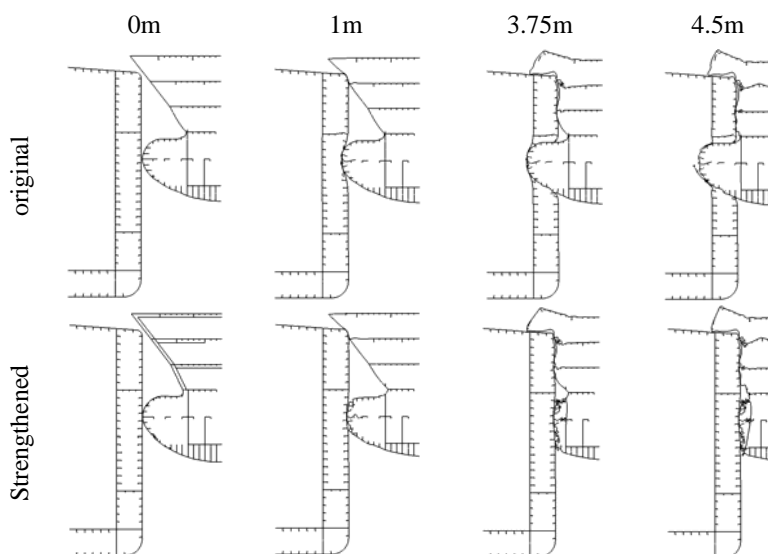


**Figure 5-9: FPSO-Supply vessel collision scenarios.**

In all scenarios where the bow stem is engaged the *FPSO* tank side is strong enough to crush the stem with relatively little deformation of the outer shell. This agrees well with the experience from the “*West Venture – Far Symphony*” collision in 2004 (Pettersen and

Soegaard 2005). On the other hand, the bulb penetrates the inner hull in scenario 1 and 3, and may cause serious consequences such as oil spillage, refer [Article V] for more results.

Applying the proposed design approach, four different scantlings of outer shell and stiffeners are determined in [Article V] which aims at resisting the large impact force from collision with acceptable deformation. It is seen that both the outer shell thickness and the dimensions of the stiffeners are increased substantially, refer [Article V].



**Figure 5-10: Collision process for scenario 1: original design vs. strengthened design.**

The simulations show that all four strengthened designs are capable of resisting the impact from the supply vessel with minor deformation of the tank outer shell. The deformation of the outer shell obtained from *NLFEA* agrees surprisingly well with that calculated from Eq. (2), see Table 6 in [Article V]. The deformation levels would be normally considered dangerous, and result in mandated repair immediately. However, they are considered moderate and fully acceptable in conjunction with *ALS* assessment.

Figure 5-10 illustrates the progressive collision process of the original and the strengthened design for collision scenario 1. The outer shell is penetrated at 1m displacement, the inner shell penetrated at 3.75m displacement for the original design. However, for the design according to the proposed approach, the outer shell is intact during the collision. It is the bulb that collapses. This behaviour can also be identified from the force-displacement curve in Figure 5-11.

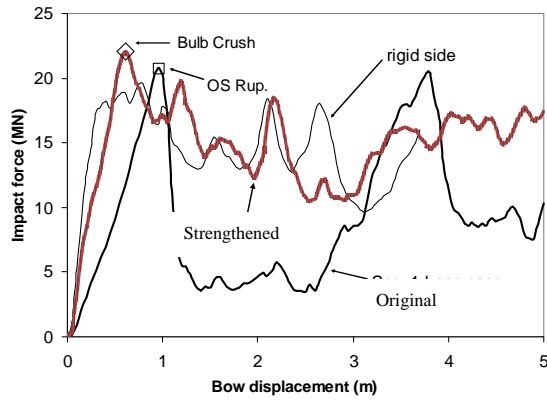


Figure 5-11: Impact force history curve for scenario 1: original design vs. strengthened design.

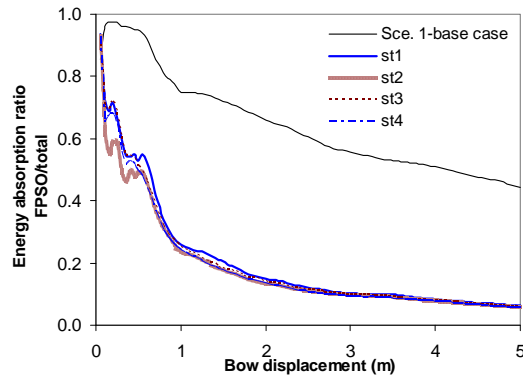


Figure 5-12: Energy absorption ratio for FPSO tank side.

The energy absorption ratio is essential to identify a strength design. The energy absorption ratio of *FPSO* tank side decreases dramatically once the supply vessel bow gets contact with *FPSO* side, refer Figure 5-12. Ultimately, less than 10% of the total energy is dissipated by *FPSO* side structure. It is noted that the response of the side structure is almost identical in view of energy absorption ratio for all strengthened designs.

# Chapter 6

## Conclusions and Recommendations for Further Work

### 6.1 Conclusions

Within the scope of work outlined for the Strategic University Project - *ScenaRisC&G (Scenario-based Approach to Risk Analysis of Ship)*, the present work mainly focuses on developing simplified calculation methods for the structural analysis of ships during collision and grounding, which is considered essential in a rational design procedure for ships against accidental loads. The proposed/developed simplified methods based on plastic mechanism analysis are applied to both structural analysis and the establishment of a direct design approach.

In short, the major contribution of the present work to the analysis and design of marine structures subjected to collision and grounding is constituted by the following items:

1. The structural behavior of ships during grounding is reconsidered with respect to the variety of seabed topologies. It is found that the deformation pattern is quite different for blunt type seabed obstructions such as “shoal” compared to sharp type seabed obstructions such as “rock”. The phenomena of powered grounding is, therefore, classified separately as “raking” and “sliding”.
2. For the existing local denting deformation mode of web girders under large in-plane loads, an improved plastic mechanism model is proposed. The new model incorporates the main deformation features observed in both experiments and numerical simulations which have not been captured by any of the existing models.

The model can be used for deep collapse of decks, frames and stringers during collision, or transverse members, bottom plates and girders during grounding. The model is verified by small and large scale girder crushing tests, from which satisfactory results are achieved.

3. For the first time, a wavy pattern plastic mechanism for longitudinal bottom girders during continuous sliding process is proposed and is accompanied by a in depth investigation of the ship bottom response during sliding. The sliding deformation of web girders is also relevant for stringers in the case of sliding type side collision. Though a closed-form solution has not been obtained due to the complexity of the problem, the semi-analytical solution still gives fairly good results compared to numerical analysis. From the parametric study, it is found that a small indentation angle produces fewer crushing waves with larger transverse deformations. Fewer waves are generated when the indentation depth increases.
4. A simple assessment tool for ship bottom structure during grounding is developed based on simplified plastic methods such as the sliding deformation model of longitudinal girders with special concern on blunt type seabed obstruction with large contact surfaces. The response of the three major bottom structural components, which are bottom plating, longitudinal girders and transverse floors, is considered. [The effect of friction is considered and included in a simple manner. It is found from the analysis that the vertical resistance is free of friction which agrees with the numerical simulation.](#) The resistance of a double bottom predicted by the simple method is verified against large-scale numerical simulations. Encouraging results are obtained.
5. Plastic analysis of laterally patch loaded plates is carried out. This load case is relevant for ship collision and stranding because generally the damage is considered to be local. Extending the classical “roof-top” yield line model for uniform loaded plates to patch loaded plates, a prominent contribution of the present work is the inclusion of the membrane effect and the development of a new yield line model, denoted the “double-diamond” model. A comparative study has been carried out with existing formulations. The present formulation can be used as a versatile tool for predicting the resistance of plates under various types of patch loads such as ice loads, wheel loads from vehicles or landing aircrafts and wave slamming loads, notably when finite, permanent deformations are accepted, e.g. in *ALS* design.
6. A direct and simple design procedure for the side structure of a ship or ship-shaped offshore structure against large impact loads such as collision is proposed. The procedure consists of the four major elements: the determination of collision force for design purpose, shell plating design, stiffener design and consideration of material failure. The major objective of the design procedure is to follow the principle of *ALS* and to comply with the principle of strength design as described by

the *NORSOK* code. The attractiveness of the design approach is that it is based on closed-form solutions for plating and stiffener in addition to representing the collision force in a simplified manner as a design load. The procedure is demonstrated and verified by the design of an *FPSO* tank side structure subjected to collision from a 7,500 tons displacement supply vessel.

7. The acceptance criterion in terms of an allowable permanent deformation for *ALS* design has been discussed extensively in the present thesis. A simple expression relating the stiffener spacing directly to the allowable permanent deformation has been derived. This provides a rational basis for specifying the maximum allowable deformation as opposed to the “rule-of-thumb” type principles used at present. The required plate thickness is simply connected to the material yield strength and the stiffener spacing.
8. Non-linear finite element analysis by using explicit non-linear finite element software *LS-DYNA* is performed and regarded as a reliable tool for analyzing collision and grounding problems. The state-of-the-art of the prediction of initiation of fracture and mesh size sensitivity effect have been implemented into the simulations in the present thesis. Consequently, the results from *NLFEA* are extensively used in the present thesis for the following purposes: investigate the structural deformation pattern; verify simplified methods when no experiment is available; study the relative strength between the two ships involved in collisions.

## 6.2 Recommendations for Further Work

In this section, several considerations which are of interest and of importance in relation to the present thesis are presented. However, they are not conducted due to the time constraints. These may be the subjects for future studies.

1. For the sliding deformation mode of web girders, the complicated deformation pattern is treated in a simplified manner in order to keep the analysis relatively simple and mathematically tractable. No closed-form solution is obtained at present which indicates that the mechanism proposed is not a real upper bound. There may be some minor energy dissipation modes which have been neglected by the simplified analysis. This calls for further investigation. On the other hand, the mechanism proposed should be verified, not only by *NLFEA*, but preferably also by experiments or alternatively by investigating actual sliding grounding incidents, if available.
2. The simplified methods have been integrated and applied to the analysis of a double bottom structure during sliding type grounding, in which fracture is of minor significance. Despite of the discrepancies, the results are encouraging. However, further studies are required to fully understand the structural response of ship

grounding over large flat contact surface. More verification examples are needed before the model is generally accepted. The sophisticated interaction between the transverse and longitudinal members shall be investigated in detail further, from which a new mechanism for the central part of the transverse member may be developed. In addition, the effect of stiffeners on bottom plating and floors should also be studied.

3. For ship grounding problems, it has been recognized that the shape and size of the seabed obstructions are of crucial importance. For the ease of analysis, the sliding object in the present thesis is modeled as a rigid indenter with flat contact surface and trapezoidal cross-section. This may not be fully representative regarding the variety of seabed obstructions. Therefore, to generalize the application of the simplified method, the geometry of large indenters should be defined in a more realistic manner. Cylinder or sphere with large radius may also be considered for the sliding type grounding. The indenter should be able to be represented by simple geometrical parameters.
4. The present thesis focuses on the internal mechanics involved in collision and grounding. In a complete analysis, the internal mechanics should be coupled with the external dynamics. Grounding problems may be studied using the simplified methods for assessment of the resistance to local indentation in conjunction with analysis of the rigid body, dynamic motion. Software such as *VESIM* may be used for this kind of integrated analysis.
5. Grounding forces may become significant compared to the weight of the ship, see Alsos and Amdahl (2007). Considering the degraded hull girder capacity, the forces and bending moments generated by grounding may become critical with respect to hull girder collapse. Therefore, the global hull girder resistance should be checked along with the structural damage during sliding.
6. The plastic method for plates under patch loading developed in the present thesis ranges from plastic bending to predominant membrane resistance. However, it is admitted that the resistance in the plastic bending phase is not so well predicted as compared to the resistance in the plastic membrane stage where permanent deformation of considerable magnitude is developed. Therefore, further studies are still needed for establishing a universal formulation for patch loaded plates where the plastic bending resistance is better predicted. A possible approximation is to use elliptic interpolation between the linear elastic solution and the non-linear plastic solution.
7. The acceptance criterion may need further refinement. It is considered sound to not accept significant permanent deformations for plates designed according to frequently occurring loads, i.e. loads with a return period from 1 year to (at



maximum) 100 years. For offshore structures or ship-shaped offshore structures, it is common practice to consider rare actions with a return period in the range of 1,000-10,000 years. For such rare loads it is considered acceptable to allow permanent deformations of considerable magnitude and design the plating in the *ALS* format.

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# Appended Papers

## PAPER I

Lin Hong and Jørgen Amdahl

PLASTIC DESIGN OF LATERALLY PATCH LOADED  
PLATES FOR SHIPS

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