FINITE ELEMENT ANALYSIS OF WARSHIP STRUCTURES

A Thesis

submitted by

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DECLARATION

I do declare that the thesis titled "FINITE ELEMENT ANALYSIS OF WAR SHIP STRUCTURES" submitted to Cochin University of Science and Technology, in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy is a bonafide record of research work carried out by me. The contents of this thesis have not been submitted and will not be submitted to any other university or institute for the award of any degree.

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This is to certify that the thesis titled "FINITE ELEMENT ANALYSIS OF WAR SHIP STRUCTURES" submitted by Sunil Kumar P.G. to Cochin University of Science and Technology, in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy is a bonafide record of research work carried out by him under my supervision. The contents of this thesis have not been submitted and will not be submitted to any other university or institute for the award of any degree.

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ABSTRACT

KEY WORDS: Warship Structure, Finite Element Analysis, Ultimate Strength Analysis, Reliability Analysis, Linear Static Analysis, Nonlinear Static Analysis, Geometric Nonlinearity, Material Nonlinearity

Warships are generally sleek, slender with V shaped sections and block coefficient below 0.5, compared to fuller forms and higher values for commercial ships. They normally operate in the higher Froude number regime, and the hydrodynamic design is primarily aimed at achieving higher speeds with the minimum power. Therefore the structural design and analysis methods are different from those for commercial ships. Certain design guidelines have been given in documents like Naval Engineering Standards and one of the new developments in this regard is the introduction of classification society rules for the design of warships.

The marine environment imposes subjective and objective uncertainties on ship structure. The uncertainties in loads, material properties etc.,. make reliable predictions of ship structural response a difficult task. Strength, stiffness and durability criteria for warship structures can be established by investigations on elastic analysis, ultimate strength analysis and reliability analysis. For analysis of complicated warship structures, special means and valid approximations are required.

Preliminary structural design of a frigate size ship has been carried out . A finite element model of the hold model, representative of the complexities in the geometric configuration has been created using the finite element software NISA. Two other models representing the geometry to a limited extent also have been created – one with two transverse frames and the attached plating alongwith the longitudinal members and the other representing the plating and longitudinal stiffeners between two transverse frames. Linear static analysis of the three

models have been carried out and each one with three different boundary conditions. The structural responses have been checked for deflections and stresses against the permissible values. The structure has been found adequate in all the cases. The stresses and deflections predicted by the frame model are comparable with those of the hold model. But no such comparison has been realized for the interstiffener plating model with the other two models.

Progressive collapse analyses of the models have been conducted for the three boundary conditions, considering geometric nonlinearity and then combined geometric and material nonlinearity for the hold and the frame models. von Mises – Illyushin yield criteria with elastic-perfectly plastic stress-strain curve has been chosen. In each case, P-Δ curves have been generated and the ultimate load causing failure (ultimate load factor) has been identified as a multiple of the design load specified by NES.

Reliability analysis of the hull module under combined geometric and material nonlinearities have been conducted. The Young's Modulus and the shell thickness have been chosen as the variables. Randomly generated values have been used in the analysis. First Order Second Moment has been used to predict the reliability index and thereafter, the probability of failure. The values have been compared against standard values published in literature.

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NOMENCLATURE

AFOSM	Advanced First-Order Second-Moment
ALS	Accidental Limit State
B	Breadth of the Ship
B_{mld}	Moulded Breadth
C_B	Block Coefficient of the Ship
CDF	Cumulative Distribution Function
D	Depth of the Ship
EMRC	Engineering Mechanics Research Corporation
FEM	Finite Element Method
FLS	Fatigue Limit State
FORM	First-Order Reliability Method
FOSM	First-Order Second-Moment
GNLA	Geometric Nonlinear Analysis
ISO	International Standards' Organisation
L_{BP}	Length Between Perpendiculars
LEA	Linear Elastic Analysis
LRS	Lloyd's Register of Shipping
MCS	Monte Carlo Simulation
MGNLA	Material and Geometric Nonlinear Analysis
NES	Naval Engineering Standards
NISA	Numerically Integrated elements for System Analysis
PDF	Probability Distribution Function
RINA	Royal Institution of Naval Architects
RPST	Random Polar Sampling Technique
SLS	Safe Limit State
SNAME	Society of Naval Architects and Marine Engineers
SORM	Second-Order Reliability Method
SSC	Ship Structure Committee

SWBM	Still Water Bending Moment
T	Draft of the Ship
ULS	Ultimate Limit State
USBP	Unsymmetrical Bulb Plate

GREEK SYMBOLS

α	Subtending angle
β	Reliabilty Index
δx	Coefficient of variation of the design variable
μ_R	Mean value of response
μ_s	Mean value of load
ν	Poisson's ratio
ϕ	Cumulative distribution function of the standard normal variable
σ	Compressive stress in the section
σ_{CR}	Critical buckling stress
σ_E	Elastic stress
σ^2_S	Variance of the load
σ^2_R	Variance of the response
σ_Y	Yield stress of the material
σ_{YP}	Yield stress of material for shell-plating
σ_{YS}	Yield stress of material for stiffener
σ_∞	Ultimate stress
τ_d	Applied Shear Stress
τ_{sc}	Critical Elastic Shear Buckling Stress

CHAPTER 1

INTRODUCTION

1.1 General.

Floating vessels are used to transport men and materials overseas and it has applications in warfare as well. Warships are the chief instruments for a nation to extend its military might, by protecting own interests like fleet and offshore platforms against enemy attack. They prevent the enemy from using the sea to transport their military forces and are also used in blockade - i.e., in attempts to prevent an enemy from importing by sea the commodities necessary for his prosecution of the war by blockading / attacking the enemy's merchant shipping. Offensive actions against the enemy's military installations, ports and economic/strategic targets form another important role.

The operations to be performed by a warship make it necessary that it has to be sleek and fast moving besides being of high maneuvering capabilities. When these features are considered as the basic requirements, the resulting structure will have to be light, and at the same time it has to withstand weapon imparted loads like impact due to recoil, blast, explosions etc.,.

1.2 Categorisation of Warships

In order to accomplish the above functional objectives, naval ships have been designed to be faster and structurally stronger than merchant ships and to be capable of carrying offensive weapons.

Modern combat ships have generally been classified into five major categories:

(a) Ships with landing/take off facilities and hangars for aircraft – viz., aircraft carriers and landing platforms.

(b) Vessels that fight primarily with guns or with rocket-propelled missiles and guns which form part of the carrier escort force. Corvette which is a small single-screw ship designed for convoy duties; A frigate is a longer and improvised version of a corvette; destroyers which are fast and slender and generally equipped with torpedoes, antisubmarine equipment, medium-calibre and antiaircraft guns and guided missiles as their chief weapons, Cruisers which are large, fast and moderately armed and displacement in between that of aircraft carrier and the destroyer are the examples.

(c) Ships which take part in active combat and perform miscellaneous tasks like anti-submarine warfare, amphibious operations etc.,.

(d) Submarines that mainly operate from underwater using mines, torpedoes, and depth charges, and missiles.

(e) Miscellaneous ships like, fleet tankers, survey vessels etc.,.

1.3 Structural Features of Warships

Warships above 60 m in length are usually longitudinally framed, with transverse frame at every standard frame spacing. Special quality steels like B quality steel conforming to NES 791, 10XSND, DS40, AK 25 and, HY 80 are used for the construction of warships. The structure should withstand shock and blast loads in addition to the conventional loads.

1.4 Structural Behaviour and Failure Modes

The possible modes of failure caused by slamming in heavy seas can be divided into two groups: primary failures, where the ship's survival is threatened and secondary failures, where the continuance of the voyage in the normal mode of operation is impaired. Primary damage modes consist of local yielding of forefoot plates due to excessive bending at hard points and rupture of welded joints, plastic buckling of bow and forefoot plates, yielding of frames in the highly-loaded areas of the hull, yielding and possible rupture of hull girder plates caused by the severe vibratory motion of the entire ship and low-cycle fatigue in the highly stressed locations. The possible secondary modes of failure can be shock damage to navigational and communication systems, shock damage to piping and electrical transmission systems etc.,. Due to the high speed of the warships, the effects of slamming are much more profound than those compared to slow moving merchant ships.

For structural components, many basic types of structural failure are considered and the more important ones are yielding and local plasticity, structural instability (or buckling), fatigue cracking related to cyclic loading, ductile or brittle fracture, given fatigue cracking or pre-existing defects and excessive deformations. Among these, the possible modes of failure are yielding and plastic flow and instability (buckling).

Failure due to yielding and plastic flow can be investigated using Plastic Collapse Moment, Shakedown Moment and Initial Yield Moment methods. Buckling failure can occur in three different ways such as failure of plating between stiffeners, panel buckling failure mode (flexural buckling or tripping of longitudinal) and overall grillage failure mode.

1.5 Design Philosophy

The motto of fighting ships all around the world is 'To Float, To Move and To Fight'. The naval design spiral commences with the threat analysis for developing a variety of conceptual solutions, ranging from the conservative to the abstract and encompassing the latest technological advances and developmental research.

Warships are generally sleek, slender with V shaped sections and block coefficient below 0.5, compared to fuller forms and higher values of in the range of 0.8 to 0.9 for tankers, around 0.75 for general cargo ships etc.,. The ratios like L/B, L/D, B/D, B/T etc.,. of a warship also vary significantly from a commercial ship. Warships normally operate in the higher Froude number regime, and the hydrodynamic design of the hull is primarily aimed at achieving higher speeds with the minimum power.

In case of damage in action or otherwise, it is desirable that the ship retains some fighting ability, or at least allows sufficient time for the crew to disembark safely. This is achieved by ensuring sufficient post-damage stability and watertight integrity; and minimising the weapon impact through ballistic protection, shock protection *and the likes*. The objective is realized by maintaining structural integrity through design based on ultimate strength techniques, use of box girder structures and appropriate materials of construction and outfit.

The conventional methods of performing structural design of ships make use of accumulated experience from previously built ships of similar size and function. The accumulated experience is mostly expressed in the form of semi-empirical formulae contained in classification society rules and design specifications. Many years of design experience have shown that by using appropriate empirical margins for strength over expected load, the unknowns can be accounted for and ships with acceptable risk or probability of failure levels can be designed. The designs resulting from this approach are uncertain as to the degree of structural adequacy they can afford, however the ship designs based on these approaches have given acceptable service. The uncertainty stems from the assumptions made regarding parameters affecting the environment and the strength of the ship.

With the advent of new ship types, and the resultant lack of "accumulated experience" on vessels of similar size and function, it has become a professional responsibility to look into a more scientific and rational approach to structural analysis of ships. In this context, various investigators in the ship research community have adopted probabilistic structural analysis procedures from mechanical and civil engineering fields. In the probabilistic approach, the quantitative values of factors affecting the strength of the structure and the magnitude of the load are statistically determined and hence, the resulting measure of the adequacy of the design is also statistical in nature.

The demands for efficient, faster, lighter and cheaper warships are strongly linked to the philosophy and procedures of ship structural design. The economic success and safety of warships rely heavily on intelligent structural design that optimizes the use of new materials, improved fabrication procedures, and efficient life-cycle maintenance and environmental issues. All these demands place increasing emphasis on the structural design process, based on rational ship structural analysis, which derives its strength and scope from modern computing procedures and devices.

Structural designs of Indian warships are conforming to Naval Engineering Standards (NES). NES 154 [30] defines the structural strength standards in the design, construction and modification of surface warships and the basis for approval and acceptance. So far, no clear recommendations or guidelines based on probability method are prescribed in NES.

Introduction of classification society rules is the latest development in warship design [42]. The rules are based on the concept that the structural integrity and watertightness general safe operation of the ship should not be compromised by static and dynamic loads experienced during normal operating conditions. The formulae in the rules for the scantlings of structural members like stiffeners, beams, girders, etc.,. are normally based on elastic or plastic theory using simple beam models supported at one or more points and with varying degrees of fixity at the ends, associated with an appropriate concentrated or distributed load.

1.6 Idealisation and Analysis of Ship Structure

Structural configuration of ships is so complex that the analysis of the structure by treating it as a single unit is tedious. Instead, analyses of subunits are usually performed. An ideal structure is always a single unit. The selection of the substructure is made without compromising on the idealisation of the structural behaviour and the estimation of structural response. The substructures interact with each other and the analysis procedure should be able to account for this mutual interaction. The substructure should be sufficiently small, regular and cohesive. At the same time, it should be sufficiently large and sufficiently autonomous in its response. So each substructure has to be a complete segment of the hull, called hull module [Hughes]. If all modules are of reasonable length, the overall failure will occur totally within a module. The interactions between individual modules can be minimized by locating the boundaries at main transverse bulkheads. In order to analyze the modules in isolation, they should be defined such that a complete set of boundary conditions can be generate for it from hull girder analysis. The boundary conditions and the correct representation of hull girder response decide the minimum length of a module.

Global strength evaluation is estimation of the stress levels/deflections related to the hull beam idealisation, considering the main global loads due to both wave and still water conditions acting on the hull like longitudinal bending moment, both hogging and sagging, shear force and torsion moment.

Local strength evaluation can be interpreted as the structural analysis of a limited part of the structure subjected to the loads directly applied on it and also the analysis of a limited part of the structure or what happens in a well defined structural detail when the whole ship structure is subjected to the global load effects.

A structure can be designed as a single unit, exhibiting its structural identity. Hence irrespective of the high computational efforts, attempts have to be made to analyse the ship structure as a hull module rather than approximated structural components or near exact structural identities [Hughes]. The representative structural analysis for a ship is therefore conducted on the hull module.

Classical structural analysis methods like the quasi static beam method are still used for the global analysis of ship structures. Moment distribution method, slope deflection method and matrix methods have applications in transverse strength analysis of the ship treating it as a portal frame. Analysis of ship structural components like decks, bulkheads etc.,. can be performed using the grillage analysis methods.

Numerical simulation using 3D finite element models is one of the powerful methods to predict ship response. The trend is toward one structure description, one model and several applications. The base modeling will be re-used and adapted to perform successively. The main aim of using the Finite Element Method (FEM) in structural analysis is to obtain an accurate calculation of the stress response in the hull structure and sub units like longitudinal plating, transverse bulkheads/ frames, stringers/girders, and longitudinals or other structural stiffeners.

The easiest method available for the hull girder analysis is the one dimensional quasi-static analysis using simple beam theory assuming free-free boundary conditions. For transverse strength analysis, portal frame analysis of the section has been considered. But these idealisations do not truly represent the hull configuration

Analysis of the local behaviour of structures also is equally relevant and essential like the global behaviour estimation. Structural analysis based on the grillage model and orthotropic plate model are common practices. Finite element analysis has been employed for the ship structural analysis from the late sixties.

1.7 Uncertainties in Ship Structural Analysis

The sources of uncertainty of ship structure can be categorized as subjective and objective. The subjective uncertainties are (also called modeling uncertainties) are those resulting from the designer's lack of knowledge or information regarding the wave pattern associated with structural failure. These are usually manifested in the form of imperfect analytical models with basic assumptions to arrive at a tractable solution. Some examples of the uncertainties can be stated as follows [23].

(a) Uncertainties associated with simple beam theory in primary bending of the ship, i.e., plane sections really remain plane or not.
(b) Uncertainties in the effects of initial deformations on buckling strength.
(c) Uncertainties in the amount of plating to consider as acting as an effective flange due to shear lag effects.
(d) Uncertainties associated with using small-deflection plate theory.

The objective uncertainties are those associated with quantities that can be measured and examined. Examples of such quantities are yield strength, fracture toughness, thickness, residual stress, and initial distortion. If enough data could be collected on these quantities, the uncertainties could be quantified by the statistical parameters determined from an analysis of the data. The variations and the resulting uncertainties in the quality/standards of construction Is another factor. Uncertainties in operation in the form of operating errors or change in service adds to the uncertainties. Structural safety is quantified by the margin between the applied load and the capacity of the structure, which is measured by the safety factor. Normally only one safety factor is used and so the flexibility to adjust the prescribed safety margin is limited. This is required to account for factors like variability in the strength loads, modeling uncertainties, and the likelihood of various load combinations.

Reliability methods are now being introduced in ship design. They take into account more information like uncertainties in the strength of various structural elements, uncertainties in loads, and modeling errors in analysis procedures. Probability based design is more flexible and consistent than working stress formats because they provide uniform safety levels over various types of structures.

The uncertainties in loads, material properties etc.,. pose major problem for marine structures. The response of the marine structure to the total combined loads is determined and compared with the resistance or capability of the structure. This comparison may be carried out through one of several reliability methods. Based on these methods, safety indices or probabilities of failure are estimated and compared with acceptable ones. A new cycle may be necessary if the estimated indices are below the acceptable ones.

1.8 Scope and Objectives

Very complex structural system and uncertain loads make ship structural analysis a tedious effort. When it happens to be the structural analysis of a slender ship with which needs to be designed to operate at high speeds and are susceptible to unconventional loads like those generated by explosions, the analyst has to resort to special means and valid approximations. In the present study, approximation in the structural geometry regarding the selection of the hull involved in the analysis has been realized by adopting three configurations viz., hold model, frame model and inter-stiffener model. The scope of this work has been extended to investigations to assess and predict the influence of rotational and longitudinal restraints on the response. In the present study, finite element analysis of warships has been envisaged and the objectives are set as given below.

(a) To design the structural scantlings for a slender ship to suit the special requirements of military loads defined in special rules like the ones promulgated by NES etc.,. and create the finite element model of it to perform the necessary analyses.

(b) To conduct linear elastic analysis and check the adequacy of the structural scantlings.

(c) To conduct geometric nonlinear analysis of the structural configurations and predict the ultimate load.

(d) To conduct combined geometric and material nonlinear analysis and predict the ultimate strength and assess the influence of material strength on it.

(e) To conduct reliability analysis of warship structure based on uncertainties in Young's modulus and the shell thickness on the ultimate strength based on First Order Second Moment method. Reliability index will be predicted based on this analysis which is a measure of the probability of failure.

1.9 Organisation of the Thesis

Chapter 1 presents the structural features of warships and the recommended structural analysis methods of such ships. The scope and objectives of the thesis have been presented here. Chapter 2 describes the structural analysis of warships and provides an introduction to the ultimate strength and reliability of ships' structures. Review of the literature available on ultimate strength and reliability analysis of ship structures has been carried out and reported in Chapter 3. Chapter 4 describes the various analyses conducted on the ships structure under various conditions of boundary restraints and combinations of loads. Chapter 5 summarises the results obtained from the analysis envisaged in the present study and describes the conclusions.

CHAPTER 2

STRUCTURAL ANALYSIS OF WARSHIPS

2.1 Introduction.

Warships have totally different functions to perform during operations than other vessels like merchant ships. Warships are thin and long with a high Froude number, designed for intensive loadings like explosion and blast. Linear elastic analysis method conducted for the determination of displacements and stresses will not be sufficient for realistic and acceptable estimation of the strength of the warships. Nonlinear analysis (both geometric and material) has been recommended for such structures. Owing to the presence of uncertainties in material and geometric features, there is sufficient scope for reliability analysis. For all these analyses, finite element method is considered the essential tool and recommended. Structural modeling of warships, description of the design loads, finite element analysis, ultimate strength analysis and reliability analysis of warships are described under the following subheadings.

2.2 Approximations in Structural Levels of Ships

The action effect levels of ship structure has been described in different sources in different ways. The Primary, secondary and tertiary bending of the hull and resulting stresses (σ_1, σ_2 and σ_3) are depicted in fig 2.1. The primary, secondary and tertiary structures, as defined by ISO Report ISO/CD 18072-2 [18] are identified as indicated in table 2.1.

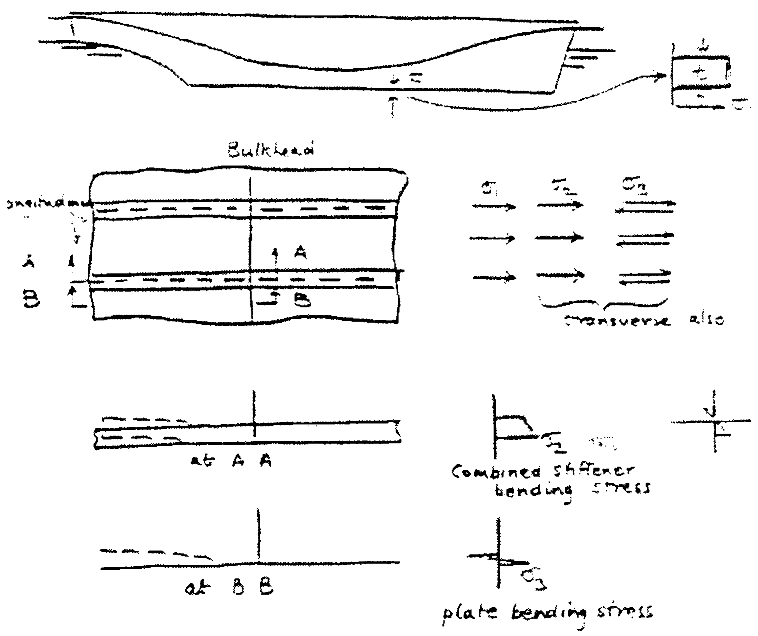

Fig 2.1 - Primary, secondary and tertiary hull bending [13]

Characteristics	Primary Structure	Secondary Structure	Tertiary Structure
Loading	In-plane	Normal	Normal
Stresses	Tension, Compression and Shear	Bending and Shear	Bending, Shear and Membrane
Examples	Hull shell, deck, bulkhead, tank top	Stiffeners on bulkhead, shell	Unstiffened shell
Boundaries	Undetermined	Primary structure	Secondary Structure

Table 2.1 - Classification of Ship Structure [18]

2.3 Structural Modelling

Structural modeling based on different levels of geometric idealisations has been an accepted procedure and has been well utilsed for ship structural analysis from the beginning of the history of strength of ships. A one dimensional beam model for the longitudinal strength estimation, a two dimensional portal frame for transverse strength estimation etc.,. can easily be cited as examples

However, the most ideal structural model for a ship will be the one in which the entire ship with the inclusion of all minor details like stiffeners and structural discontinuities and subjected to a realistic load combination. This is possible only with the support of advanced computing and will be a costly and time-consuming affair. Often, the naval architect is not interested in the absolute values of the response like stresses and displacements, but interested in the range of response values, mainly due to the uncertainties involved in all the stages of structural performance. In this context, it will be the most appropriate to take steps for a realistic solution by analysing a representative part of the ship with appropriate boundary conditions and actual loads, instead of modeling the entire hull. Analysis of part of the structure bounded by main transverse bulkheads can be quoted as an example. Such an attempt of selection of a structural identity of a smaller proportion that will represent the behaviour of the hull will reduce the effort in computation. This can be achieved by the logical and rational selection of 'critical segments' of the hull girder/module. The procedure and criteria for selection of critical segments and hull modules have been thoroughly discussed [Hughes]. Global structure model and the hull module model for the finite element analysis of the ship structure have been presented [ISO]. A slice of any ship cross section between two adjacent transverse frames is widely taken as the extent of the progressive collapse analysis [Paik, 2005].

2.4 Design Loads

The seaway loads on a hull have been classified as global loads which act on the hull girder and local loads which have a localized effect and act only on certain parts of it. Depending on the time domain description, loads can further be classified as static and dynamic and this classification is valid for each of the local and global categories [8]. The general global loads acting on the hull comprises of bending moments arising from still water loads and thermal loads. Low frequency wave induced loads like vertical and horizontal bending and torsional moments and high frequency springing and slamming loads are also treated as global loads. Major constituents of the local loads are external static still water loads, external hydrodynamic pressure due to waves, cargo inertial loads due to vessel accelerations and Internal liquid sloshing loads [Jensen]. Fatigue is fast emerging as a failure mode of ship structures and therefore needs special consideration in the ship structural design.

Wave loads which are the major seaway loads are random in nature and hence probabilistic representations are critical for them. Procedures of extrapolation of these loads to their extreme lifetime values are being exercised. Generally, these loads are dynamic and random and their combinations require the difficult but important analyses for determining the degree of correlation between the individual components. These analyses may be carried out either in a frequency domain or time domain.

Warships are expected to operate in a combat environment and certain loads in this regard have to be considered for their design unlike other ships. The main combat loads to be taken into consideration are underwater explosions/shock, nuclear air blast loading and own weapons effects. The design loads used in ship structural analysis have been discussed under the subheadings of global and local loads subsequently.

2.4.1 Global Loads

In the ship structural design practice, both hydrostatic and self-weight loads can be determined for a given ship condition with a high degree of confidence. The underwater shape of the hull is readily determined from detailed knowledge of the hull offsets and appendages, enabling the buoyancy distribution to be calculated. While buoyancy distribution is known from an early stage of the ship design, accurate weight distribution is defined only at the end of construction. Statistical formulations calibrated on similar ships can be used in the design development to provide an approximate quantification of weight items and their longitudinal distribution on board. The resulting approximated weight distribution, together with the buoyancy distribution, allows computation of shear and bending moment in the still water condition by successive integration. This bending moment is always referred as the Still Water Bending Moment (SWBM).

The evaluation of wave generated hydrodynamic loads, however, is less reliable than the static loads and there is less guidance as to how to handle the dynamic nature of the loading as well as transient effects such as slamming and sloshing. Nonlinear theories and three-dimensional load prediction methods have been introduced but these require greater computational effort and have not yet proven to be significantly more accurate than the two dimensional methods, regarding the design considerations.

The evaluation of wave-induced loads is attained in many practical situations through the quasi-static wave approach. The ship is positioned on a frozen wave of given characteristics in a condition of equilibrium between weight and static buoyancy. The scheme is analogous to the one described for still water loads, with the difference that the waterline upper boundary of the immersed part of the hull a curved surface. This procedure neglects all types of dynamic effects and is rarely used to quantify wave loads. Sometimes, however, the concept of equivalent static wave is adopted to associate a longitudinal distribution of pressures to extreme wave loads derived from long term predictions based on other methods.

Strip theory has been one of the first tools developed to calculate the wave induced forces by treating the hull as a rigid body moving in irregularly disturbed interface of fluid and air. The main drawback of this method is that it considered only regular waves and it neglected the mutual interactions between the various strips, which are of particular importance for certain frequency ranges. However, regular wave loads can still be estimated using strip theory.

Panel methods, FE assisted methods etc.,. also can be utilized for estimating loads due to regular waves.

The regular wave results can be extended to short-crested irregular seas, by means of the superposition principle. The basic assumption is that both the irregular waves and the ship short-term responses are stationary stochastic processes. Long-term computations can be made using the spectral approach. Available calculations for limited periods of time in specific irregular sea conditions can be translated to long-term predictions, covering the lifetime of a ship or a fleet of ships. For each pair of values for wave height and period a spectrum can be defined in terms of the spectral ordinates at discrete values of the frequency, ω. In the absence of any actual spectra or observed wave heights and periods, the only way to describe the sea is by means of the wind speed, which can be considered to be the single most important factor in generating waves. The globe is divided into various service areas by different agencies. The classification by Lloyds Register of Shipping [42] has summarily been given below.

Service Area 1 **(SA1)** covers ships having unrestricted world-wide operation. **SA2** is to cover ships designed to operate in tropical and temperate regions, excluding operating in sea areas for which a **SA1** notation is required whereas **SA3** is to cover ships designed to operate in tropical regions excluding operating in sea areas for which a **SA1** or **SA2** notation is required. **SA4** Service Area covers ships designed to operate in Sheltered water, **SAR** Service Area Restricted covers ships that are designed to operate in a predetermined and contiguous area of operation. The environmental wave data for the various service areas are shown in Table 2.2 and the sea service areas are shown in fig 2.2.

Service Area Notation	Wave Height for Service Area (m)	Mean Wave Period (Sec)	Extreme Design Wave Height (m)
SA_1	5.5	8.0	18.6
SA_2	4.0	7.0	13.5
SA_3	3.6	6.8	9.5
SA_4	2.5	6.0	6.0
SAR	To be specially considered		

Table 2.2 - Environmental Wave Data for Various Service Areas [42]

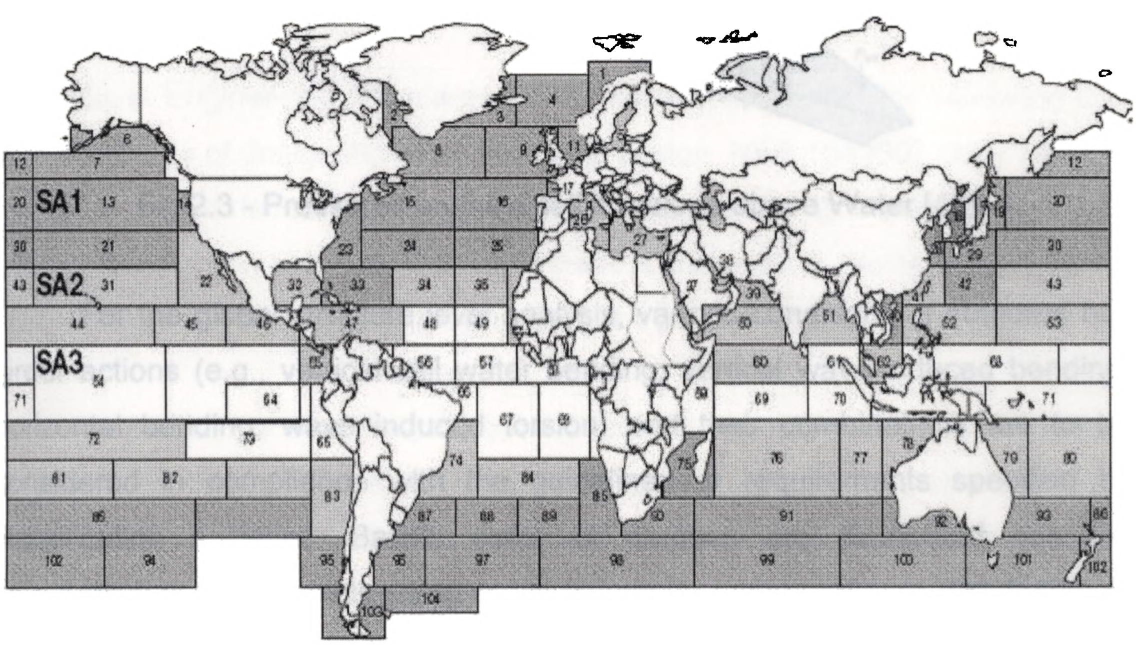

Fig 2.2 – Sea Service Areas indicated by Lloyds Register of Shipping [42]

2.4.2 Local Loads

Local loads consist of external (still water loads, low frequency dynamic pressure and slamming loads) and internal loads (inertia forces of cargo associated with accelerations, sloshing of liquid cargo etc.,.). Fatigue loads are important in the design of local details, which require estimation of stress ranges and number of cycles during the ship life. Internal loads and fatigue have been omitted from the purview of the present study.

The other major local loads are due to equipment, cargo, crash loads (like helicopter crash, vehicles/crane), ice, flooding, docking and pressures on the shell envelope above as represented in fig 2.3.

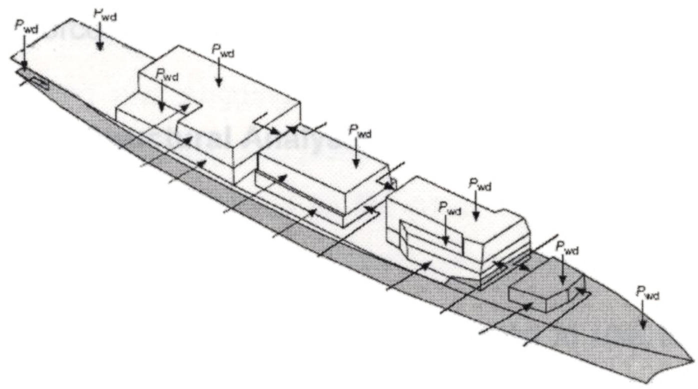

Fig 2.3 - Pressures on the Shell Envelope above Water [42]

For the global structure level analysis, various conditions of standard hull girder actions (e.g., vertical still water bending, vertical wave-induced bending, horizontal bending, wave induced torsion) and their combinations are to be considered in compliance with the guidelines or requirements specified by classification societies. Ballast water or cargoes are distributed into the corresponding nodal points using mass elements. Local pressure distribution of the tanks may not be considered for the global structure level analysis. Static and hydrodynamic external water pressure loads are applied to the external plate shell elements which form the envelope of the ship hull.

The magnitude of pressure actions on the transverse bulkheads are calculated for the worst cases. These pressure actions are applied as equivalent nodal forces at the related nodes. The sectional forces and moments will also be applied at both ends of the cargo hold model. Once the sectional forces and moments at the left end of the model are specified, the corresponding sectional forces and moments at the right end of the model may be determined to satisfy the equilibrium.

A set of the sectional forces and moments are selected from those obtained for various load application, operating conditions and sea states, which give maximum hogging and sagging moments in the cargo hold area and maximum shearing forces at the bulkhead locations.

2.5 Rule Book Based Structural Analysis and Design of Warships

2.5.1 Introduction

Naval Engineering Standards (NES) have been in use for validating the various aspects of design including structural design. NES 154 [30], titled 'Design Standards for Surface Ships' defines the structural strength standards in the design, construction and modification of surface warships. It provides a standard against which ships' structural designs are to be judged and approved.

Introduction of classification society rules in warship design is one of the latest developments, and the first set of draft rules were published by the Lloyd's Register of Shipping in 1999. The main objective of introducing a military arm is to co-operate in areas related to the effectiveness and safe operation of naval ships. Of late, the Indian Register of Shipping also have brought out their own rules. The rules provide a staring point for structural design so that the designer does not have to resort to design from first principles.

2.5.2 Structural Analysis of Ships using Naval Engineering Standards

2.5.2.1 Longitudinal Strength

The criteria put forward by NES on longitudinal strength is that the hogging and sagging design loads due to wave action on the hull at any point along the length of the ship should not exceed the strength at that section throughout the life of the ship. The design load is defined as that vertical bending moment and shear force (both hogging and sagging) that have a 1% probability of exceedance in the life of the ship allowing for weight growth over that period.

The ultimate strength of the hull is defined as the maximum bending moment (both hogging and sagging) that the structure can withstand at any section before collapse. Buckling and plasticity are also to be taken into account. The ultimate strength can be defined as the point in both hogging and sagging where no further longitudinal bending moment can be sustained by the structure for any increase in hull curvature.

The calculation of design loads should consider the sea areas in which the ship is expected to operate, the duration of operation in each area and the expected operating conditions in terms of speeds and headings in different sea states, as mentioned in section 2.4.1. The design loads and their lengthwise distribution along the ship includes an allowance for slamming effects and the effects of the design wave traveling along the hull, as indicated in fig 2.4 and 2.5

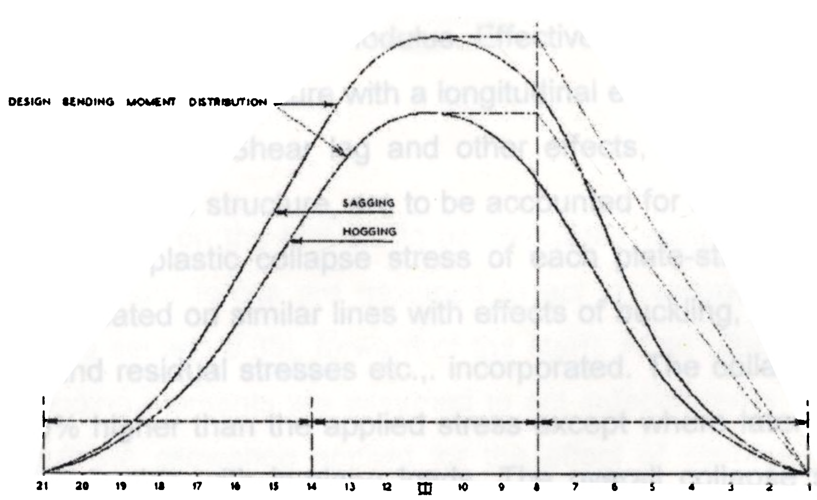

Fig 2.4 Distribution of Design Vertical Bending Moments [30]

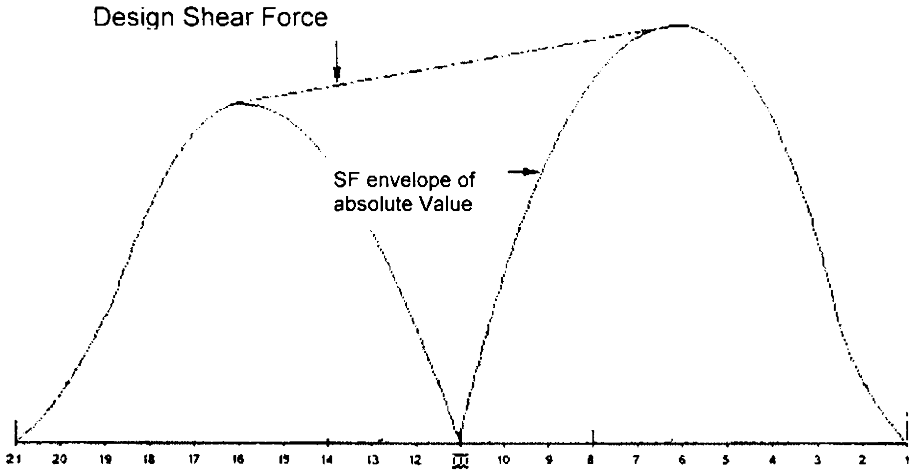

Fig 2.5 Distribution of Design Vertical Shear Force [30]

2.5.2.2 Local In-Plane Strength

In addition to the requirement for the strength of the hull girder, there is also a requirement for strength of individual panels within the hull to resist in-plane loads due to longitudinal bending stipulated by NES. A panel is defined as a section of stiffened plate between horizontal and vertical stiff supports, usually decks and bulkheads but sometimes deep stiffeners as well. The stress in any part of a panel should be calculated assuming the design bending moment, and using simple beam theory taking account only of effective longitudinal structural material in estimating the section modulus. Effective longitudinal material in this context is defined as any structure with a longitudinal extent of more than 10% of the ship's overall length. Shear lag and other effects, which reduce the load carrying efficiency of the structure, are to be accounted for by means of effective breadth. The elasto-plastic collapse stress of each plate-stiffener combination also is to be estimated on similar lines with effects of buckling, plasticity, as-built imperfections and residual stresses etc.,. incorporated. The collapse stress is to be at least 10% higher than the applied stress except where lateral pressure is applied in combination with in-plane loads. The overall collapse stress of the grillage is to be estimated using orthotropic plate theory or finite element analysis and is to be at least 25% higher than the applied stress.

2.5.2.3 Transverse Strength

Transverse strength of the hull is its ability to withstand the effects of hydrostatic and hydrodynamic pressure. The loads to be applied, which allow for the effects of ship motions (not slamming or green seas) are taken as static heads of sea water as illustrated in fig 2.6.

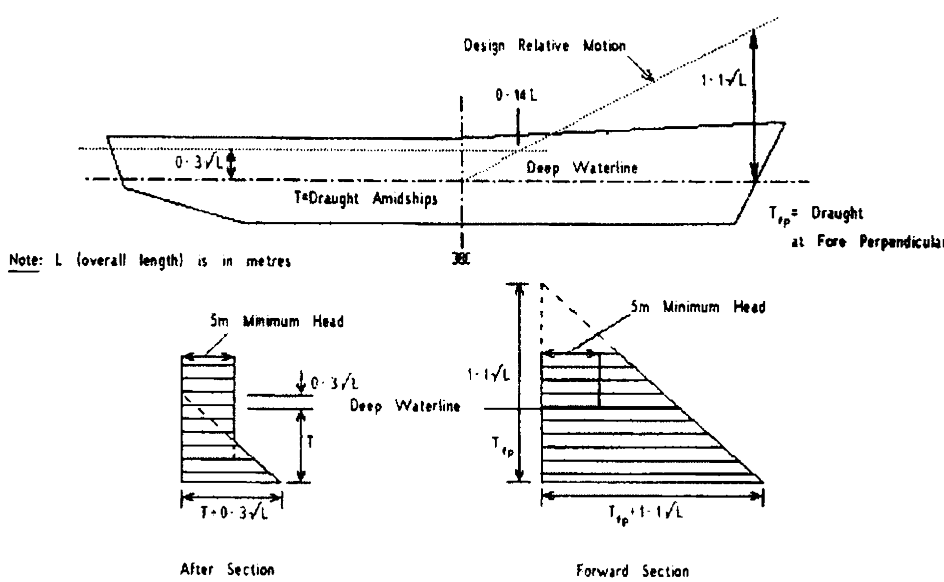

Fig 2.6 - Hydrostatic Heads for the Design of the Bottom and Sides [30]

2.5.2.4 Shear Strength

Shear stresses on the hull are to be calculated using conventional beam bending theory. Shear forces are assumed to act in conjunction with bending moments abaft a section 0.35L forward of the stern. At all other sections shear forces and bending moments are assumed to act independently. In the forward half of the hull the allowance applied for the effect of slamming on bending moments can be assumed to take care of the combined effects of shear force and bending moment.

2.5.2.5 Torsion

Torsion analysis is required for ships with large deck openings, unusual form, proportions, special operating modes.

2.5.2.6 Permissible Stresses

NES 154 prescribes that the maximum tensile or compressive stress at any point in the grillage structure must not exceed 83% of the yield stress of the material. The shear stress limit is 50% of the shear yield stress. When shear force is applied independently, the applied shear stress (τ_d) is to be less than the critical elastic shear buckling stress of the plate panel between stiffeners, and of the critical elastic shear buckling stress (τ_{sc})of the combination of plate and the smaller of the stiffener sets on the plate. If shear stress is applied in conjunction with in-plane loads due to hull vertical bending, the safety factor between total compressive stress (in-plane plus local bending) and the average in-plane collapse stress of each plate-stiffener combination is not to be less than $\tau^2_{sc}/(\tau^2_{sc}-\tau^2_d)$. The shear stresses resulting from torsional loads on the hull due to wave effects are not to exceed 50% of the shear yield stress of the hull material.

2.5.3 Structural Design/Analysis using LRS Rules

The rules apply to ships of normal form, proportions and speed. Although the rules are for steel ships of all welded construction, other materials for use in the construction also will be considered such as use of special materials at select locations, use of cast/forged parts etc.,. Scantlings are generally based on the strength required to withstand loads imposed by the sea, payload, ballast, fuel and other operational loads. The design loads and pressures are defined in the rules. Direct calculation methods to derive scantlings based on maximum allowable stress or other suitable strength criteria also can be used.

Static loads are based on standard conditions. Dynamic loadings are examined for both the local and global structures. Wave induced loads are considered both in the static condition (hydrostatic and pitching pressures), and in the dynamic mode (impact, slamming and hogging and sagging wave loading conditions). It is pertinent that the factors of safety applied in these calculations are not explicitly mentioned.

The rules are formulated to provide for scantling derivation for designs comprising the following structural framing systems.

(a) Primary/secondary stiffener systems. Due to the relative differences in stiffness of the members, the secondary members are considered to act independent of, and are supported by, the primary members.

(b) Grillage systems. The relative stiffness of the orthogonal stiffening is similar and work together to support the applied loads. The grillage system is in turn supported by major structural members such as bulkheads or decks.

Apart from the global considerations, the capability of the structure to resist the military loads imposed upon it also is covered under LRS rules. However, such features like helicopter decks, beach landing or grounding, external and Internal blasts, fragmentation, under water explosion etc.,. are not considered in this rule book.

The general observation is that the scantlings derived from LRS rules are generally higher than those derived by conventional methods. This would result in over design as is happening in most of the cases. Avoiding over design would result in structural weight reduction.

Recommendations of Rule Books (LRS and NES) and the methods suggested by classical theory on the structural analysis of ships are summarized and shown in table 2.3.

METHOD	NES	LRS	CLASSICAL
Longitudinal strength	Based on 1% probability of exceedance. Mainly elastic regime. Local in-plane stress also is considered.	Elastic/plastic regimes. Empirical formulae based on simple beam models with varying degrees of fixity. Direct methods also possible.	Free-free beam balanced on 8 m high waves.
Transverse strength	Based on plate-panel combination in elastic regime. Maximum σpermitted < $0.83\sigma_y$ and $\tau \le \tau_y$.	Empirical formulae based on simple beam models with varying degrees of fixity.	Elastic beam theory in normal cases. Non linear analysis for special cases.
Shear strength	Using conventional beam theory, $\tau_d \le \tau_{sc}$	Shear formula to be used. Limiting value is a function of material.	Shear formula to be used.
Torsion	Using conventional beam theory $\tau \le \tau_y$.	Required for ships with large deck openings, unusual form, proportions, special operating modes. Direct calculations	Calculations using direct procedures
Dynamic analysis	Only at local areas of interest	Only at local areas of interest	From first principles

Table 2.3 : Summary of Methods for Ship Structural Analysis

2.6 Finite Element Analysis of Ship Structures

2.6.1 Introduction

Finite element analysis is universally recognised as the most important technological breakthrough in the field of engineering analysis of structures. The development of computer has caused the finite element method to become one of the most popular techniques for solving engineering problems. For analysing a complicated structure like a ship hull, the finite element method is the only tool using which satisfactory results can be obtained.

2.6.2 Ship Structural Models for Finite Element Analysis

Hull structure of ships consists of a steel framework surrounded by steel plating. A hull girder is a three-dimensional framework of beams and stiffened panels. On a hull girder, most of the lateral loads act initially on the plating. Then, through the action of plate bending, the plating transmits the load to the nearby major beams, the transverse frame and longitudinal girders.

When ship structural analysis is carried out using substructures, the results strongly depend on the boundary conditions of the model taken. The more local the model, the stronger is this dependency. The extent of action effect analysis for each model must be large enough so that the structural area of interest will be relatively unaffected by approximations in the boundary conditions. The structural models used for finite element analysis of ships are global structure model, hull module (hold model), grillage model, frame model and local structure model. These models are described in the subsequent sections.

2.6.2.1 Global Structure Model

The global structure model is used to investigate the action effects of the overall ship hull and its primary strength members to both still water and wave-induced hull girder actions. At this level the primary concern is the overall stiffness and the 'global' or 'nominal' stresses of primary strength components along the entire ship length, rather than local or detailed stresses.

The finite element analysis model is usually the full length of the ship. Half symmetry will normally be made use of and that reduces the computational cost and effort. All longitudinal members and all primary transverse members (e.g., bulkheads, cross decks, transverse webs) which contribute to strength are included in the finite element analysis model.

A coarse mesh extending over the entire ship hull length is usually adopted. All primary longitudinal and transverse structural components are best modeled by quadrilateral plate/shell elements, with selective usage of triangular elements. Support members that do not involve a deep web may be modeled by beam elements. Stiffened panels and grillages may be modeled as an assembly of plate-shell elements and beam elements. A set of general guidelines for finite element modeling of ship hull is given elsewhere [Hughes].

2.6.2.2 Hold Model

The hold model is used to examine the response of the primary strength components in a particular portion of the hull girder under the action of internal cargo and external water pressure.

The extent of the cargo hold considered to constitute the finite element model for analysis depends on the ship type, the loading conditions and the degree of symmetry of the hull structure in the longitudinal and transverse directions. A single hold, two cargo hold lengths (i.e., ½ +1+½) or three hold lengths (i.e., 1+1+1) may be used [18]. A half breadth model may be used only if the available finite element program being used can correctly model unsymmetric actions effectively.

The finite element hold model is usually made with a coarse mesh. Girder webs with cut-outs may be modeled by non-cut-out webs with reduced equivalent thickness. Four-noded plate-shell or membrane elements are employed for finite element modeling of the cargo holds. Decks, shell, inner bottom and longitudinal bulkhead plates are modeled by plate-shell elements so that lateral pressure actions can be accounted for. Mixing membrane and plate-shell elements in a three dimensional model is not recommended in this case.

2.6.2.3 Grillage Model

The grillage model is used to investigate overall and/or local strength behaviour of a continuous plated structure supported by both longitudinal girders and transverse frames, subjected to a lateral pressure or other actions that are normal to the plane of the grillage. An idealized structural module evolved out from a flat plate surface with stiffeners - transverse frames and girders, deprived of the plating can be taken as a grillage in ship structural practice. The beams constituting the grillage are flanged ones with flange elements contributed by the effective breadth. Double bottoms, bulkheads and decks are the best bets for this structural approximations. The grillage structure is modeled by conventional three dimensional beam elements.

2.6.2.4 Frame Model

The frame model is related to the action effects of two or three dimensional frame structures such as transverse web frame systems or longitudinal girder systems, including the flanges that are provided by the associated plating. The purpose of these frame analyses is to examine the bending and shear behaviour in the plane of the structure web, and also torsion, for which fine mesh modeling is required. One plate-shell element is typically used to model plating between stiffeners. Three or more elements are required over the height of web frames or girders so that the stresses of plate webs should be readable without interpolation or extrapolation.

2.6.2.5 Local Structure Model

The local structure model is used to investigate the action effects of local or special structural components, and of structural details. An example of a local member is a laterally loaded plate stiffener with its connecting brackets, subject to relative deformations between end supports. A fine meshing which provides a good aspect ratio of the plate-shell elements is generally required to reflect the behaviour of the local structure under large deformations. Three 4-noded plate-shell elements are typically used for the web height of the stiffeners and for plate flanges. At least three plate-shell elements are typically used to model plating between stiffeners, but much more than three plate-shell elements are normally required over the height of web frames or girders.

2.6.3 Finite Elements for Ship Structural Analysis

Ship structure can be considered as a thin walled box section, stiffened with beams, subjected to loads which include flexural shear and torsion in the plating. The ideal finite element for modelling such a structure will obviously be plate shell element. The inherent complexities associated with plate element formulations like conformity, convergence and consistency have to be borne in mind while selecting the element. The typical finite elements selected from the element library of the package used for the analysis have to be tested for convergence and consistency – i.e., the element should be immune to phenomena like shear locking type of drawbacks.

Finite elements employed in ship structural analysis are to be tested against standard problems regarding the applicability of the element to model a particular structural component [5].

One dimensional truss element, with axial stiffness without bending stiffness can be used to model stiffeners with these parameters.

One dimensional beam element, with axial, shear, bending and torsional stiffness can be used to model .beam structures subjected to bending. If beam elements are used to model the stiffeners, eccentric beams (with their neutral axis offset from the attached nodes) should not be used. Appropriate properties of beam elements are assigned by considering equivalent concentric beams. This process is using the effective plate width (i.e., individual space of stiffeners) in the calculation of moment of inertia and assuming the neutral axis being located at the center layer of the attached plate. Attached plates are excluded from the calculation of sectional areas of beam elements.

Two dimensional membrane stress element (plane stress element), with membrane stiffness in the plane, but without out-of-plane bending stiffness, can be used to model the structural parts under in-plane loads. Deck structure in ships is subject primarily to in-plane loads rather than transverse loads. So it is better modelled using membrane elements rather than plate/shell elements,

Two dimensional plate-shell element, with membrane, out-of-plane bending and torsional stiffness, can be used to model the side shell structures. However, if the analysis of deck structure is local in nature and the loading is transverse, then plate bending elements would be required. In this case transverse shear effects may be significant.

Three dimensional solid element. Certain element formulations do not account for shear. If through thickness stresses are considered to be important, then the use of solid elements is prudent.

Boundary and spring elements are used to model supports offered by the stiffeners.

Point or mass elements are used for dynamic analysis.

Combination of bending plates and beam elements is preferable, since computer technology has advanced to the point that computing time is not an issue for the FE analysis. The best option for modeling is to use plate elements for stiffeners also except in the cases of rolled sections like Holland profile, full bulb profile etc.,. Combined use of bending and membrane plate elements is not a common practice. However, this does not preclude the combined use of rod elements (faceplates) and bending plates (web plates) for main supporting structures [3,5,9].

2.6.4 Boundary Conditions

The procedure of finite element methods is such that kinematic boundary conditions are incorporated by suppressing or prescribing translational displacements and/or rotations at the relevant nodes to represent the interaction between structural neighborhood along the boundaries, or to represent the constraints at existing supports.

For the global level analysis, sufficient degrees of freedom (normally six) are constrained to prevent the rigid body motion of the model. The translational supports should be located away from the areas where the stresses are of interest. Forces in the constrained nodes (i.e., translational supports) may be eliminated by generating balanced loads. For lower level analyses, symmetric boundary conditions can be applied considering the symmetry related to structural arrangements and load application. Also, the boundary conditions may be prescribed based on the load effects obtained from a higher level. The (translational or rotational) displacements or forces may be applied at the boundaries of the model.

When the half breadth model is used, symmetric conditions are generally applied with regard to the center line. If the model is subjected to uniform lateral loads alone, symmetric conditions can also be applied with reasonable certainty even at the ends, and the additional stresses due to global hull girder bending may be superimposed on the results by the former model analysis. On the other hand, if hull girder bending and shearing forces are applied, distributed displacements or forces which can be obtained from the results of the global structure analysis may be prescribed over the cross section at the ends.

Alternatively, it may be considered that the hull module is supported in the vertical direction by vertical springs along the intersections of the side and the transverse bulkhead, between the inner side and the transverse bulkhead, and between the longitudinal bulkhead and the transverse bulkhead. The spring constants are uniformly distributed along the corresponding intersections. Instead of application of the vertical springs, vertical forces may be applied along the intersections mentioned above, but the displacement of one nodal point at each intersection is additionally fixed in the vertical direction to remove the rigid body motion.

The boundary conditions for the hull module under hull girder loads are different from those under local loads. For hull girder vertical bending, it is often modeled that a simple support condition at transverse bulkhead locations of the hull module is often taken. For vertical shearing forces, the symmetric boundary conditions are often applied at both ends of the cargo hold model. When only a half breadth of the ship is taken and under vertical shearing forces, symmetric boundary conditions are also applied along the center line.

2.7 Finite Element Formulations for Ship Structural Analysis

This thesis addresses the finite element analysis of warships which can be treated as a slender ship subjected to military loads besides the conventional loads. Linear elastic analysis, geometric nonlinear analysis, combined material and geometric nonlinear analysis are envisaged in the present study. Finite element formulations and procedures for these analyses are discussed in the subsequent sections.

2.7.1 Linear Elastic Analysis

As the name indicates, linear elastic analysis is based upon the linear relations between stress and strain and the assumption that the stress field is in the elastic limit and obviously the principle of superposition is valid here. Usually the stresses and deflections obtained from the linear elastic analysis are used to check the rationale of the initial design/scantlings chosen. Normally, classification societies and other agencies insist that ship structures operate only in the elastic regime, with the maximum stress developed limited to 75% to 80% of the yield stress. The shear stress limit is 50% of the shear yield stress. In linear analysis, the response is directly proportional to the load. The basic assumptions are that displacements and rotations are small, supports do not sink/settle, stress is directly proportional to strain and loads maintain their original directions as the structure gets deformed.

The linear elastic analysis using FEM, involves the stiffness matrix and the load vector and the nodal displacements are the outcome of the analysis. The linear elastic stiffness matrix [K] is derived from the linear stress strain relationships and the strain displacement relations relevant for the element into which finite element approximations are put into practice by means of shape functions. Loads may be lumped at the nodes, distributed or evaluated from the 'consistent' concept. The stiffness matrix and load vector which are derived at the element level are transformed to global coordinate system and assembled to yield the structure stiffness matrix and load vector. The displacements are evaluated by employing appropriate numerical procedures for the solution of systems of simultaneous equations like elimination or factorisation schemes.

2.7.2 Nonlinear Analysis

Hull module of the ship being a box structure constituted with stiffened panels, it falls in the category of thin walled box structures, open or closed depending on the type of the ship. All thin walled structures are susceptible to issues arising from buckling and large deformations. This warrants the need for nonlinear analysis. In general, the two categories of nonlinear analysis, viz., geometric nonlinear analysis and the material nonlinear analysis have applications in ship structural analysis. The source of geometric nonlinearity can be attributed to large deflections and large strains, which are common in thin walled structures. Shipbuilding steels definitely have a nonlinear stress strain pattern. To sum it up, the necessity for geometric and material nonlinear analysis of the hull module is imperative.

Structural nonlinearity may be due to large deflections, large strains and nonlinear constitutive relations. When the displacements and rotations become large requiring the equilibrium equations to be written for the deformed configuration rather than the initial one or part of the structure looses stiffness because of buckling, it is called geometric nonlinearity. When elastic material becomes plastic or material does not have linear stress strain relationship at any stress level, it is called material nonlinearity. When the loads do not maintain their original directions, it is environmental loading nonlinearity.

The scope of the nonlinear structural analysis is spread over buckling analysis, ultimate strength analysis and analysis of accidental or extreme situations like explosions, collisions, grounding, blast etc.,. These are very useful to understand possible failure modes and mechanical behavior under severe loads.

The material nonlinear analysis predicts plasticity behaviour of the structure. The yield criterion relates the onset of yielding to the state of stress. For shipbuilding steel, the von Mises criterion is commonly used. The hardening rule describes how the yield surface grows and moves as plastic strains accumulate. Metals including steel can be described using the kinematic hardening. In this case, when the von Mises stress reaches σ_y, yielding can be assumed to have begun. The flow rule relates stress increments, strain increments and the state of stress in the plastic range.

Geometric stiffness matrix $[K_G]$ which is derived based on the nonlinear terms in the stress displacement relations are used along with linear elastic stiffness matrix [K] for the geometric nonlinear analysis. The material nonlinearity is incorporated by means of constitutive matrix which already carries nonlinear terms. These matrices will be modified in the iterative procedure at every load step.

2.7.3 Ultimate Strength Analysis

Various definitions of the ultimate strength of a hull have been proposed, but the most acceptable one [18] is as follows:

> "This occurs when a structure is damaged so badly that it can no longer fulfil its function. The loss of function may be gradual as in the case of lengthening fatigue crack or spreading plasticity, or sudden, when failure occurs through plastic instability or through a propagation of a brittle crack. In all cases, the

collapse load may be defined as the minimum load which will cause this loss of function."

The stiffened panels of the hull module are normally sufficiently strong such that the mode of compressive collapse is not elastic panel buckling but falls in the inelastic regime [Hughes]. The hull module being a 3D structural identity composed of plates and stiffeners, its collapse involves combination of plate deformation and inelastic buckling. Hence an investigation on ultimate strength is a necessity for the hull module. It has been discussed elsewhere [Hughes] and established that there only two independent models of overall collapse for the hull module, viz., the longitudinal collapse and the transverse collapse. And also that longitudinal collapse will occur only between two adjacent frames. The identification of the critical segment is the hull module and rigorous analysis procedures for the determination of the ultimate strength are the crucial steps in this.

The performance of a ship structure and its components are described on the basis of specified limit states that separate desired states for the structure from its undesired states. Limit states can be classified into four categories [18], as follows:-

(a) Serviceability limit states (SLS) which represent exceedance of criteria governing normal functional or operational use.

(b) Ultimate limit states (ULS) which represent the failure of the structure and its components usually when subsequent to maximum or near maximum values of actions or action effects.

(c) Fatigue limit states (FLS) which represent damage accumulation (usually cracking damage) under repetitive actions.

(d) Accidental limit states (ALS) which represent situations of accidental or abnormal events.

The various limit states are considered against different levels of safety margin. The actual level of safety margin for a particular type of limit state is a function of its perceived consequences and ease of recovery from that state to be incorporated in strength assessment. For the ULS assessment, the safety margin of a structure or its components are determined as a ratio of the ultimate strength to the extreme action or action effects, both measured consistently, e.g., stress, deformation, force or moment. Therefore the calculations of both the ultimate strength and the extreme action or action effect are of primary tasks for the ULS assessment. ULS typically occurs under maximum or near maximum action effects and result in either local or global failure. Before local failure leads to global failure, the ratio of applied action effects to maximum action effects corresponding to global failure shall be determined.

2.8 Reliability Analysis

The rationale behind a satisfactory structural design is to ensure safety and performance. When the design parameters are under the shadow of conditions of uncertainty, probabilistic analyses are needed to propose a reliability based design [25].

The initial proposals of reliability formulation of ship hulls date back to the early 70's. However, they have not been widely used by the industry. Classification societies also have not used them systematically to formulate and to calibrate their rules for ship structural design.

In general a quantitative analysis needs to be used in the risk analysis, considering all uncertainties that affect the risk in the life cycle. In this process, the effects of aging and the role of inspections and maintenance must be anticipated in an integrated manner. However, if the risk assessment is limited to structural failures induced by natural and man-made hazards resulting from normal operations, structural reliability analysis (SRA) can be applied. Such a methodology can be used to calibrate safety factors in semiprobabilistic design approaches [27].

Structural engineering deals with load (S) and strength (R) in terms of forces, displacements and stresses acting on the structures. Structural design codes commonly specify loads, strength and appropriate safety factors to be used. Structural reliability theory is about the evaluation of the failure probability taking into account the uncertainties in loads and strength.

A structural component can fall into safe or failure state. The border line (or surface) between the safe and failure states is named as limit state, and expressed as g(Z) = R -S . The following conditions describe the possible states of a structural component.

g(Z)<O represents a failure state where loads S exceeds the strength R.
g(Z)>O represents a safe state since strength R is larger than loads S.
g(Z)=O represents the limit state line (or surface).

Fig 2.7 shows the concept of limit state sketchily

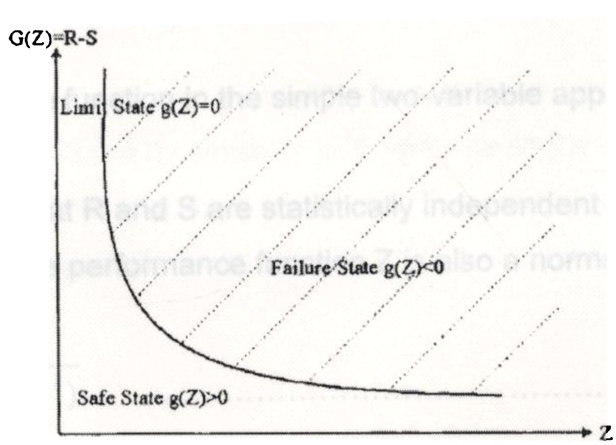

Fig 2.7 – Limit State Concept [4]

For marine structures, the limit states are defined in accordance with the different requirements, such as serviceability, ultimate strength, etc

First-Order Second Moment Method is used to assess the reliability of structural components. FOSM method is also referred to as the Mean Value First-Order Second-Moment method (MVFOSM). Based on a first-order Taylor series approximation of the performance function linearised at the mean values of the random variables, it uses only up to second-moment statistics (mean and covariance) of the random variables.

The method only depends upon the mean and variance of individual random variables. Information about the distribution types of random variables is not required, which leads to easy computation.

When the performance function is approximated to be linear, significant errors may be introduced due to the higher order terms neglected. Since the method does not use the distribution information about the variables even when it is available, the accuracy of the results get reduced. The reliability index fails to be constant under different but mechanically equivalent formations of the same performance function, which leads to violation of invariance.

A performance function in the simple two-variable approach can be defined as

Z= R-S. Assuming that R and S are statistically independent normally distributed random variables, the performance function Z is also a normal random variable, i.e.,

$$N(\mu_R - \mu_S, \sqrt{\sigma_R^2 + \sigma_S^2}) \quad \text{.......} \quad (2.1)$$

Where μ_R = mean value of strength R

μ_S = mean value of the load effect S

σ_R = standard deviation of strength R

σ_S = standard deviation of the load

The event of failure is r<s, or z<0. The probability of failure can be evaluated as pf = p(z<0)

$$p_f = \phi\left(\frac{-(\mu_R - \mu_S)}{\sqrt{\sigma_R^2 + \sigma_S^2}}\right) \tag{2.2}$$

or

$$p_f = 1 - \phi\left(\frac{(\mu_R - \mu_S)}{\sqrt{\sigma_R^2 + \sigma_S^2}}\right) \quad \ldots\ldots \tag{2.3}$$

where ϕ is cumulative distribution function (CDF) of the standard normal variable.

The probability of failure depends on the ratio of the mean value of Z to its standard deviation. The ratio is known as Reliability Index and is defined by

$$\beta = \frac{\mu_Z}{\sigma_Z} = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \quad \ldots\ldots \tag{2.4}$$

$$p_f = 1 - \phi(\beta) \quad \ldots\ldots \tag{2.5}$$

The corresponding reliability is given as

$R=1-p_f$ .... (2.6)

Finite element nonlinear analysis for combined geometry and material nonlinearities is carried out by keeping 10% variance in the values of modulus of elasticity and 5% in the side shell thickness. The reliability factor is calculated based on ultimate strength load factor predicted using this finite element analysis.

2.9 Summary

Ship structure is primarily a box structure composed of stiffened plates. It possesses longitudinal symmetry but never remains prismatic. It is primarily subjected to static loads like hydrostatic pressure, cargo loads etc.,. and wave induced dynamic loads. The structural behaviour of ships basically is flexure of a nonprismatic thin walled beam. The shells or plate of ship structure will be under tensile or compressive stress resultants and the failure modes can broadly be identified as yielding or buckling, which opens the necessity for nonlinear structural analysis. The ultimate strength analysis of various structural configurations of ships using finite element methods have widely been attempted and extensive research has been published in this regard. A similar attempt has been proposed in this study for slender warships. Uncertainties in ship structural analysis are related to material and geometric features like yield strength, fracture toughness, thickness, residual stress, and initial imperfections and above all the wave induced loads. Reliability methods are now being introduced in ship design to take care of such uncertainties. There are published work in this regard and in the present study, First-Order Second Moment Method based reliability analysis is conducted based on the ultimate strength prediction.

CHAPTER 3

LITERATURE REVIEW

3.1 INTRODUCTION

The thesis addresses structural analysis of warship structures using finite element methods. Literature available in the field of ship structural analysis has been reviewed and those pertaining to the ultimate strength analysis and the reliability analysis of ship structures have been presented here.

3.2 ULTIMATE STRENGTH

Mansour and Thayamballi (1980) analysed the limiting conditions beyond which a ship's hull girder will fail to perform its function with the objective of determining the ultimate strength of a hull girder. The ship has been considered to be subjected to a realistic loading consisting of vertical and lateral bending moments and torsional moment. Buckling and instability of the hull stiffened plates, the fully plastic yield moments, and the shakedown moments have been developed in a procedure for estimating the ultimate capacity of the hull. Interaction relations for the ultimate strength of ships subjected to combined moments have been developed. The results have been validated using a 200,000 ton displacement tanker

An efficient theoretical approach has been developed by Paik et al (1995) which calculates the pre and post-collapse response of plated structures under static/dynamic compressive loads. The analysis has been of complex plated structures, and each plate element composing the structure has been modeled as one plate unit. Theoretical formulations for the two principal models, one elastic model for the analysis of the ultimate strength and the other rigid-elastic model for analysis for the crushing load of the plate unit subjected to static/dynamic loads are presented. These models are formulated for quasi-static loading condition, but dynamic effects are included by taking into account the influence of the strain rate sensitivity in the material model. The procedure has been verified by the comparison of experimental and other theoretical results.

Gordo et al (1996) have presented a method to estimate the ultimate moment based on a simplified approach to represent behavior of stiffened plate columns. As hull girder strength assessment is based on the strength of stiffened panels, the modeling of the ship's structure consists of discretizing the hull into stiffened plate elements.

Rahman and Chowdhari (1996) described a methodology for computing the ultimate value of the longitudinal bending moments at any cross section of the ship or a box girder. The cross section has been discretized into a number of stiffened panels (one stiffener with its associated effective plating). Both tensile and compressive limit states for these panels are modeled in an appropriate manner. Since the ultimate strength of the girder section has been largely governed by the behavior of the panels under compression, the authors have paid special attention in modeling the collapse as well as post–collapse behavior of these panels. The complete procedure has been coded in FORTRAN and verified using a number of box girders and an actual ship for which the true behavior has already been known. The results have been quite satisfactory and good correlation has been established when compared with the results obtained by more complex and rigorous analytical methods. The strength assessment of a very large crude carrier is performed and the moment at failure in hogging has been compared with the values obtained from other methods. A computationally inexpensive procedure to assess the ultimate longitudinal strength with adequate accuracy has been presented and the developed software is able to predict the moment-curvature relationship for several conditions heeling, levels of corrosion, residual stresses and distortions, and also to deal with the effect of load shedding after the buckling of the panels on the ultimate bending moment of the section.

Gordo and Soares (1996) have developed a method to estimate the ultimate moment of a ship hull section based on a simplified approach represented by the collapse strength of beam columns. An approximate method to model the load shortening behaviour of plate stiffener assemblies has been used to evaluate the flexural behaviour of the hull girder. This model has been extended to represent the behaviour of all elements in a ship cross section and to account for the contribution of each to the bending moment developed in the cross section. The predictions have been compared with the results from three independent sets of experiments. Most of the experiments have been conducted on small scale models which is not the best way of testing this approximate method, because the initial assumptions become less applicable when the number of elements belonging to a panel decreases. In spite of this, the experimental results are reproduced with very good accuracy. Comparisons with experimental results of box girders, small scale models of box girders and a 1/3 .frigate model are performed. Comparison with results of other approximate methods and finite elements codes has also been made.

Paik et al (2000) have presented a summary of recent research and development in areas related to advanced buckling and ultimate strength design of ship plating, jointly undertaken by the American Bureau of Shipping and the Pusan National University. The behavior of ship plating normally depends on the variety of influential factors, such as geometric/material properties, loading characteristics, initial imperfections, boundary conditions and deterioration arising from corrosion, fatigue cracking and accidental dents. The problem areas which are confronted in the buckling and ultimate strength analysis procedures are identical and the definite need for sophisticated methods of analysis has been emphasized. This paper covers the studies as characteristics of the plate buckling with elastically restrained edge conditions, strength equations for ship plating under combined static loads including biaxial compression/tension, edge shear and lateral pressure and characteristics of the plate capacity under slamming induced lateral impact pressure loads. Results, important insights and conclusion developed from the studies have been summarized and recommendations have been made.

Byklum and Amdahl (2000) have developed a computational model for buckling and post buckling analysis of stiffened panels which provides fast and accurate results for use in design of ships and offshore structures. It can accommodate in-plane compression or tension, shear force, and lateral pressure loads. Deflections assumed through trigonometric functions, and the principle of minimum potential energy has been employed for solutions. Geometrical nonlinearities are accounted for using large deflection plate theory whereas material nonlinearity is not taken into account, since the onset of yielding is taken as the capacity limit. Various computations have been performed for verification of the proposed model, and comparisons are made with nonlinear finite element methods.

Belenkiy and Raskin (2001) have examined plastic behavior of typical ship structural components such as beams, grillages, and plates subjected to predominantly lateral loads. The ultimate loads, determined on the basis of the theorems of limit analysis are evaluated using nonlinear finite element plastic analysis. The relationships between analytical and finite element models for prediction of ultimate loads of the structural components have been illustrated. It has been shown that the ultimate loads obtained from the theorems of limit analysis can be successfully used for strength assessment of stiffened ship structures subjected to lateral loads. The effect of shear force on ultimate load also has been analyzed using the finite element method. This paper confirms that in the case of beams and grillages under lateral loading, the ultimate load may characterize the threshold of the load at which a ship's structure fails by the development of excessive deflections. It has been reported that for plate elements, the plastic deflections represent the permissible limit of external load better than the ultimate limit load.

Paik et al (2001) have developed and reported advanced design formulations for the ultimate strength of ship plating. Ultimate strength of plates subject to any combination of the four load components like longitudinal compression/tension, transverse compression/tension, edge shear, and lateral pressure loads have been addressed. The formulations developed herein have been designed to be more sophisticated than the based simplified methods based on theoretical concepts. The influence of post-weld initial imperfections in the form of initial deflections and residual stresses has been taken into account. The adequacy of single ultimate strength interaction equation to represent the ultimate limit state of long/and wide plates under all possible combinations of load components has been felt earlier and subsequently, the present study derives three sets of ultimate strength formulations for the long and/or wide plating under the corresponding primary load by treating lateral pressure as a secondary dead load. The ultimate strength interaction formula under all of the load components involved is then derived by a relevant combination of the individual strength formulae. The validity of the proposed ultimate strength equations has been investigated by comparison with nonlinear finite-element analyses.

Paik et al (2001) have carried out analysis of warping stress and hatch opening deformation for ship hull with large deck opening like that of a container vessel or large bulk carrier. It has been of important for such hull forms to understand the ultimate torsional strength characteristics of ship with large hatch opening. The primary aim of this is to investigate the ultimate strength characteristics of ships with large hatch openings and a procedure for calculating warping as well as shear stresses which are developed for thin walled beams with open cross sections subjected to torsion has been developed. ---By theoretical and numerical analysis, it has been shown that the influence of torsion induced warping stresses on the ultimate hull girder bending strength is small for ductile hull materials while torsion induced shear stresses will of course reduce the ship hull ultimate bending moment.

Ziha et al (2001) have published a review paper which reveals for Croatian readers the basic issue and the history of ultimate strength and conclusions according to the International Ship Structure Committee. It briefly recapitulates the practical method for ultimate strength analysis according to common rules of classification societies and presents a computer program, ULTIS, implemented at the Faculty of Mechanical Engineering and Naval Architecture at Zagreb, based on IACS recommendations. Subsequently, benchmark studies of ultimate strength of a bulk carrier built in a Croatian shipyard employing ULTIS are attached to illustrate the stepwise yielding and buckling scenario of hull elements both for deck and bottom structures in sagging and hogging conditions, as well as the effect of higher tensile steel during the ship bending. Finally, the paper investigates a possible increase of the ship's hull ultimate strength by strengthening longitudinal structure elements after their failure sequence under bending.

Hu et al (2001) have analysed a typical bulk carrier is using a simplified method to determine the ultimate longitudinal strength. The moment curvature curve, the ultimate bending moment and the location of the instantaneous neutral axis at ultimate state have been calculated for both hogging and sagging conditions under vertical bending. The stress distribution over the hull cross-section at ultimate state has also been obtained. The ultimate strength of the ship hull under combined vertical and horizontal bending moments has further been investigated. An interaction curve has been obtained using the results of a series of calculation for the hull subjected to bending conditions with different angles of curvature. It has been found that the interaction curve is asymmetrical because the hull cross-section is not symmetrical about the horizontal axis and the behavior of the structural members under compression is different from that under tension due to the nonlinearity caused by buckling. The angle of the resultant bending moment vector and that of the curvature vector have been different in general cases. An interaction equation suitable for bulk carriers has been proposed based on the results of the analyzed ship.

A new computerised design model for the buckling strength assessment of stiffened panels has been presented by Steen et al (2002).The overall formulation has been very general and any type of stiffening arrangements of open or closed profile type, corrugations etc.,. can be analysed. The model has been based on an orthotropic version of Marguerre's nonlinear plate theory. The stiffened panel has been treated as an integral unit, allowing for internal redistribution of membrane stresses between component plates, while preventing overall buckling and permanent deformation. By using nonlinear plate theory, the strength model has been more theoretically consistent than existing formulations, which are mainly based on empirical curve fitting to a limited number of numerical and experimental results. Complicated items such as bi-axial loading combined with in-plane shear loads and nonlinear mode interaction problems are dealt within a sound physical framework, and empirical approximations are reduced to a minimum. The model also provides a set of reduced anisotropic/orthotropic macro material coefficients that can be used in refined global FE analysis of ship hulls to reflect the increased membrane flexibility experienced by compressed stiffened panels. This area of application allows for redistribution of loads between gross elements such as stiffened panels and frames. The model has been used to constitute the basis for a DNV procedure for the buckling analysis of stiffened panels.

Strength of individual ship plates plays a significant role in the ultimate strength analysis of ship structures.. Cui et al (2002) presented a simplified analytical method to deal with combined load cases on ship's plating. This analytical method predicts the ultimate strength of unstiffened plates with imperfections in the form of welding-induced residual stresses and geometric deflections subjected to combined loads. It has also been reported that the comparisons with experimental results have shown that the procedure has sufficient accuracy for practical applications in design.

Paik and Kim (2002) have developed advanced and design-oriented ultimate strength expressions for stiffened panels subjected to combined axial load, in-plane bending and lateral pressure. The collapse patterns of a stiffened panel have been classified into six types and the collapse of the stiffened panel is deemed to occur at the lowest value among the various ultimate loads corresponding to each of the collapse patterns. Provisions for associating the post-weld initial imperfections viz., initial deflections and residual stresses have been made in the panel ultimate strength formulations as parameters of influence. The validity of the developed formula has been confirmed by comparing with the mechanical collapse tests and nonlinear finite element analysis. This method has been validated with theoretical solutions from the Det Norske Veritas classification society design guideline.

A simple design equation for predicting the ultimate compressive strength of unstiffened plates with misalignment, initial deflection and welding residual stresses has been developed by Masaoka and Mansour (2004). A nonlinear finite element method is used to investigate the ultimate strength of the imperfect plate. The method incorporates both geometric and material nonlinearities. Buckling and plastic behavior of the plate can be expressed using this finite element system. The results from the finite element method and analytical method using large deflection and rigid plastic theory are compared. It has been found that the analytical method using large deflection and rigid plastic theory is not always accurate. Reduction factors of the ultimate strength due to initial imperfections are generated from the results of the nonlinear finite element method. A new equation for ultimate strength of imperfect plates has been developed using these reduction factors. The accuracy of the proposed new equation is confirmed by comparing it with the finite element results.

Paik and Seo (2005), established the ultimate limit state approach as a much better basis for design and strength assessment of ships and offshore structures. It has been pronounced in this paper that the practice of determining the realistic margin of safety using the traditional allowable working stress approach on the basis of linear elastic method solutions together with buckling strength checks adjusted by a simple plasticity correction may not truly represent the collapse behaviour. The collapse behaviour of the stiffened panel has been identified into six modes such as overall collapse of plating and stiffeners as a unit, collapse under predominantly biaxial compression, beam – column type collapse, local buckling of stiffened web, tripping of stiffener and gross yielding. The study outlined a scheme based on nonlinear theory, viz., Analysis of Large Plated Structures (ALPS) theory for ultimate limit state assessment of ship structures and a software has been developed for this purpose. Application of ALPS program to ultimate limit state assessment of plates, stiffened panels and ship hull girders have been presented. A benchmark study has been made by a comparison with the ALPS solution with other methods including class rule formulae, nonlinear finite element methods and experimental results. Future trends on ultimate limit state assessment of ship structures have been addressed.

Naar (2006) has investigated the ultimate strength of the hull girder for large passenger ships with numerous decks and openings. In this study, a theory of nonlinear response of a coupled beam method has been presented where each deck in the superstructure and also in the main hull can be considered as a thin-walled beam with nonlinear structural behaviour. These beams are coupled to adjacent beams with nonlinear springs called vertical and shear members, modeling the stiffness properties of the longitudinal bulkheads, side shells and pillars. Special emphasis has been placed on the modeling of the shear members. A semi-analytic formula of the load-displacement curve has been developed by the help of the nonlinear finite element analysis. Also, the load-end shortening curves under axial load taken from the literature have been validated with the finite element method. The reverse loading options are included into the behaviour of the structural members. It allows calculation of the normal stresses and vertical deflections at any arbitrary locations of the hull girder. Average longitudinal displacements and deflections of deck structures and shear stresses in the side structures have been estimated as well. The ultimate strength of the hull girder has been investigated with nonlinear finite element method. The prismatic hull girder of a Panamax passenger ship has been chosen as a case study. The ultimate strength has been estimated both in hogging and sagging loading with coupled beam method and with finite element method. The results of these two different methods, presented in the form of the bending moment versus the deflection of the hull girder, show good correlation upto the area where the moment starts to decrease. In both loading cases, the failure starts by the shear collapse in the longitudinal bulkhead. The ultimate stage of the strength has been reached in the sagging when the failure progressed to the lower decks. Correspondingly in the hogging loading when the bottom structures failed showed that the shear strength of the longitudinal bulkheads and side structures has been a very important issue on the ultimate strength problem.

Karvinen and Pegg (2006) have shown that the application of pre-determined failure equations, derived from nonlinear finite element analyses, is effective in determining failure of structural components in a simpler linear finite element analysis. An analysis method called simplified failure analysis has been presented, which involves the nonlinear determination of a component's failure limit and the corresponding failure load is applied on a linear coarse-meshed finite element model of the component. The resulting linear stress distribution is a 'representative failure stress' for the component because it is in equilibrium with the applied failure load. This 'failure stress' is then used in simpler linear analysis to provide a representative failure limit. This method is verified by an analysis of a structural grillage.

Box columns are often used as main strength members of various types of thin-walled structures such as ships, ship-shaped offshore structures, and aerospace structures. The maximum load carrying capacity of box columns depends on progressive failures of individual components and their interacting effects. Paik and Kim (2007) have demonstrated a method for the progressive collapse analysis of thin-walled box columns in terms of computational efficiency and accuracy. Short, medium and long box columns in length have been studied in terms of interacting effects between local component failure modes and global system failure modes. The effect of unloaded edge conditions of individual plate elements has also been studied. A comparison of the method with more refined nonlinear finite element method computations has been made.

Paik et al (2008) have analysed the methods useful for ultimate limit state assessment of marine structures that have been developed in the literature during the last few decades. Such methods are now mature enough to enter day-by-day design and strength assessment practice. Some benchmark studies of such methods on ultimate limit state assessment of (unstiffened) plates, stiffened panels, and hull girders of ships and ship-shaped offshore structures, have been conducted using some candidate methods such as ANSYS nonlinear finite element analysis (FEA), DNV PULS, ALPS/ULSAP, ALPS/HULL, and IACS common structural rules (CSR) methods. As an illustrative example, an AFRAMAX-class hypothetical double hull oil tanker structure designed by CSR method has been studied. The ultimate limit state assessment of unstiffened plates under combined biaxial compression and lateral pressure loads has been emphasized using the above methods, and the results have been compared. The plate ultimate strength behavior has been found to be significantly affected by various parameters such as plate initial deflection shape and boundary conditions as well as loading conditions thereby underlining the importance and necessity of using nonlinear finite element methods

Paik et al (2008) have analysed the methods for the ultimate limit state assessment of stiffened panels under combined biaxial compression and lateral pressure on the bottom part of an AFRAMAX-class hypothetical double-hull oil tanker structure designed by IACS common structural rules (CSR) method. Three methods - ANSYS nonlinear finite element method, DNV PULS method, and ALPS/ULSAP method, have been employed. It has been concluded that DNV PULS and ALPS/ULSAP are useful for the ultimate limit state assessment of stiffened plate structures in terms of the computational effort and the resulting accuracy.

3.3 RELIABILITY

Existing probabilistic structural design methods have been reviewed by Daidola and Basar (1981). The most promising probabilistic analysis techniques have been identified. Factors influencing strength in terms of uncertainties in ship strength distribution have been reviewed and different methods proposed to obtain coefficients of variation for various types of data on the uncertainties. Sample calculations are performed for a number of ships using an approximate probabilistic method and yielding safety margins for each. This method requires only the coefficients of variation of the strength and load be known. A computer program has been developed to perform this calculation for any ship subjected to any load or mode of failure.

Mansour (1990) has provided an introduction to the state-of-the-art in structural reliability theory directed specifically towards the marine industry. Comprehensive probabilistic models are described for the environment, wave loads acting on a marine structure, its failure modes, reliability under extreme load, system reliability, and fatigue reliability. Application examples of various models are presented including the necessary information required to perform such reliability analyses. A computer program for calculating the reliability level of a marine structure is provided as an appendix.

Mansour et al (1993) have attempted a demonstration on the use of probability based ship structural design methods and have enumerated the benefits in comparison to traditional methods. Two basic demonstrations are provided. The first illustrates the development and calibration of design criteria that produce uniform safety over a wide range of basic parameters involved in design. The second applies to the state of the art reliability techniques to determine safety levels of existing vessels, taking into consideration uncertainties in loads, strength and calculation procedures. In addition, structural reliability terminology, limit states and load extrapolation techniques pertinent to ships are defined and described.

Mansour et al (1993) have investigated several aspects of loads and load combinations for reliability based ship design. These include identification of relevant hull girder and local loads, models for load calculation, procedures for extreme loads and load combinations, treatment of combined load effects for fatigue, and modeling errors related to loads, response and structural analysis. Impact of operational factors such as heavy weather countermeasures on design loads is discussed. Load combination procedures of two levels of complexity are provided such as those suitable for design use, and more elaborate ones for detailed analysis. A new design oriented probabilistic load combination factor method for steady state wave induced load effects, and a time domain method suitable for combining vertical wave induced bending and transient slam effects has been proposed.

Soares et al (1996) have developed different methods for practical applications of reliability based design of ship structures. The publication deals with the primary strength and thus with the hull behaviour under longitudinal bending, in particular with the design of the midship section, New probabilistic models of still-water load effects have been developed for tankers and containerships. New results have been presented for non-linear wave induced load effects and the corresponding long-term formulations. Methods to combine linear and nonlinear components of wave induced load effects have been developed and checked by alternative methods. These improved models have been used for the reliability assessment of the primary hull structure of several tankers and containerships. The results of the reliability analysis were the basis for the definition of a target safety level which was used to assess the partial safety factors in a new design rules format to be adopted in modern ship structural design. Finally, recommendations have been produced for the longitudinal strength requirements in the Rules of Classification Societies. The proposed formulation has been to first advance the state of the art of the load effect models, and the strength criteria, then deal with the reliability analysis and reliability based design and code formulation. Having identified the new formulations, these have been applied to 357 typical cases of containerships and tankers, demonstrating how a coherent set of rules had been developed and applied to ships with various loadings and structural behaviours. A set of simplified procedures and formulae have been developed to predict the design loads and the assessment of the strength of primary structural components. Prototype software packages have been developed to quantify loading, response and strength of components of primary ship hull structures. A methodology for probability based rule development and guidance notes for reliability based ship structural design have also been established.

A detailed approach has been developed for assessing structural safety and reliability of ships by Mansour et al (1997). The methodology provides a means for determining reliability levels associated with failure at hull girder, stiffened panel and unstiffened plates. Procedure for estimating the nonlinear extreme sea loads and structural strength required for the reliability analysis has been developed. Fatigue reliability of structural details has also been addressed and developed. The method has been demonstrated on four ships - two cruisers, a double hull tanker and a containership. Reliability levels with each mode of failure of these ships have been determined and compared. Sensitivity analysis has been conducted to provide sensitivity of safety index to variations in design variables associated with extreme loading conditions as well as with fatigue loads. Recommendations regarding the target reliability levels for each ship type and failure modes have been made. Design variables that have the highest impact on reliability have been identified and some guidelines are provided for improving design criteria.

Leheta and Mansour (1997) have developed a methodology for structural optimization of stiffened panels based on reliability. The stiffened panels, typical of those found in the deck or bottom of longitudinally stiffened ships have been assumed to be under stillwater and wave induced loads, resulting in predominantly compressive loads. Both serviceability and collapse limit states have been considered. The design problem has been formulated as a nonlinear programming problem that aims at minimizing weight with behaviour constraints on reliability and physical constraints on the dimensions. The safety index is calculated using a First Order Reliability Method (FORM). Then the representative failure modes and the system safety index are determined. Finally, a numerical example has been carried out to demonstrate the applicability of the design methodology and the results have been presented and discussed.

Assakkaf et al (2000) summarized the strength prediction models of stiffened and gross panels that are suitable for Load and Resistance Factor Design (LRFD) development for ship structures. Monte Carlo simulation has been used to assess the biases and uncertainties for these models and recommendations for the use of the models and their biases in LRFD development are provided. The first-order reliability method (FORM) has been utilized to develop the partial safety factors (PSF's) for selected limit states. The use of partial safety factors has been demonstrated through an example.

Assakkaf and Ayyub (2004) presented strength limit states for various modes of ship panels. The objective of this paper is to summarize strength prediction models of stiffened and gross panels that are suitable for LRFD development for ship structures. Monte Carlo simulation has been used to assess the biases and uncertainties for these models. Recommendations for the use of the models and their biases in LRFD development are provided. For each limit state, commonly used strength models have been collected from different sources for evaluating their limitations and applicability and to study their biases and uncertainties. Wherever possible, the different types of biases resulting from these models have been computed. The bias and uncertainty analyses for these strength models are needed for the development of LRFD rules for stiffened and gross panels of ship structures. The uncertainty and biases of these models have been assessed and evaluated by comparing their predictions with ones that are more accurate or real values.

Fang and Das (2004) have introduced a relationship between the risk evaluation and structural reliability, while reviewing the evolution of structural reliability of ships. The limit state function of a damaged ship due to collision and grounding has been presented. Based on the Monte Carlo simulation techniques, the failure probabilities of the damaged ship have been presented under different damage and loading conditions and subsequently, some salvaging measures have been recommended to reduce the risk of a damaged ship.

Moan et al (2006) have analysed the recent efforts to establish ship rules and especially a framework for a reliability-based *Ultimate Limit State* (ULS) and *Fatigue Limit State* (FLS) criteria for ships and implementation of such an approach for trading vessels and FPSOs. The relevant characteristic features of design code formulations, the reliability methodology as well as the rule calibration approach were kept in the purview of the formulae. Procedures for quantification of load and load effects have been evaluated and the measures for the uncertainties inherent to load effects and resistance for relevant limit states have been established. Finally, the procedures for calibrating safety factors for a design format have been discussed. The main challenge in implementing reliability-based codes is adequate measures of stochastic variability and uncertainty and the main focus has been on uncertainty measures, which requires analyses one level beyond that in design processes themselves. The estimation of the risk associated with the life cycle of structure is based on methods which account for the relevant hazards and failure modes.

Ultimate strength analsyses of ships have been attempted by maby researchers at a local level like the collapse analysis of panels. Paik attempted the pre and post-collapse response of plated structures under static/dynamic compressive loads (1995), followed by studies related to advanced buckling and ultimate strength of ship plating as characteristics of the plate buckling with elastically restrained edge conditions under various loads (2000). This was followed by formulations for the ultimate strength of ship plating which were found to be more sophisticated than the simplified methods based on theoretical concepts (2001a). Paik further developed advanced and design-oriented ultimate strength expressions for stiffened panels subjected to combined loading (2002), with provisions for accounting the weld imperfections. Paik and Seo (2005) established the ultimate limit state approach based on nonlinear theory, viz., Analysis of Large Plated Structures (ALPS) theory for ultimate limit state assessment of ship structures. Paik et al (2008) have analysed the methods useful for ultimate limit state assessment of marine structures that have been developed during the last few decades. Such methods are now mature enough to enter day-by-day design and strength assessment practice Gordo (1996) presented a method to estimate the ultimate moment based on a simplified approach to represent the behavior of stiffened plate columns. Byklum and Amdahl (2000) developed a computational model for buckling and post buckling analysis of stiffened panels which provides fast and accurate results. Belenkly and Raskin (2001) used limit analysis to examine plastic behavior of ship structural components subjected to predominantly lateral loads, and evaluated the results using nonlinear finite element plastic analysis. Steen (2002) carried out buckling strength assessment of stiffened panels based on nonlinear plate theory. This was used by DNV in their codes. Cui et al (2002) developed an analytical method to predict the ultimate strength of unstiffened plates with imperfections when subjected to combined loads. A simple equation for predicting the ultimate compressive strength of unstiffened plates with imperfections was developed by Masaoka and Mansour (2004), where a nonlinear finite element method was used to investigate the ultimate strength incorporating both geometric and material nonlinearities. Karvinen and Pegg (2006) developed a simplified failure analysis which involves the nonlinear determination of a component's failure limit. They concluded that the application of pre-determined failure equations derived from nonlinear finite element analyses is effective in determining failure of structural components in a simpler linear finite element analysis.

A few attempts have been made on the hull girder like that of Mansour and Thayamballi (1980) who analysed the limiting conditions of a ship's hull girder failure with the objective of determining the ultimate strength of a hull girder with validations on a tanker. Rahman and Chowdhari (1996) described a methodology for computing the ultimate longitudinal bending moments at any cross section of the ship or a box girder. The cross section has been discretized into a number of stiffened panels. Ziha (2001) presented a practical method for ultimate strength analysis according to common rules of classification societies, with validation on benchmark studies of ultimate strength of a Croatian bulk carrier. Hu et al (2001) analysed a typical bulk carrier to determine the ultimate longitudinal strength. The moment curvature curve, the ultimate bending moment and the location of the instantaneous neutral axis at ultimate state were determined and stress distribution over the hull cross-section at ultimate state was obtained. Paik and Kim (2007) demonstrated a method for the progressive collapse analysis of thin-walled box columns.

4 Conclusions

Analysis of the available literature on the ultimate strength and reliability analyses ship structures has revealed the following aspects.

Many of the investigations at local level have been validated with experimental results (Gordo (1996), Ziha (2001), Cui (2002) and Paik (2002, 2005, 2007)). Some of the computational models have been compared with non-linear finite element methods Byklum (2000), Masaoka (2004), Naar (2006), Karvinen (2006), Paik (2007)). Paik (2001b) and Naar (2006)) considered the effect of large deck openings of merchant ships on the ultimate strength. Nonlinear finite element methods are the commonly adopted tools in estimating the ultimate strength of ship structures. In many cases, only panels have been analysed and the scope of investigations have been limited to the buckling behavior of plates.

Hull of the ship is essentially a thin walled box structure constituted with stiffened panels, open or closed depending on the type of the ship. Like all thin walled structures, ship structures are also susceptible to issues arising from buckling and large deformations, warranting the use of nonlinear finite element analysis for prediction of ultimate strength and structural reliability. Modelling the entire hull girder is a costly and time consuming effort. As the analyst is normally not worried about the exact value of stresses and deflections but only in the order of values, the response of the primary strength components can be assessed by analyzing a typical hull module, chosen to meet the requirements. The results of any finite element analysis strongly depend on the boundary conditions. A module between two main transverse bulkheads may be analysed for all possible boundary conditions to analyse the effect of restraints.

Reliability applications have been attempted in ship structural analyses since 1981. Contributions from Mansour (1990, 1993, 1994) primarily deals with loads and load combinations at local level. Bulk carriers (Ziha (2001)) and tankers and container hips (Soares (1996)) have been attempted, but published data on reliability predictions warship structures are very few.

It has been envisaged in the present study to preserve the identity of the hip structure as a multilevel box between bulkheads and to predict the ultimate trength using nonlinear analysis.The prediction of ultimate strength using non-linear nite element analysis and subsequent evaluation of reliability index warship structures bjected to loading prescribed by NES has therefore been attempted in this study. In such a scenario, the module may be analysed with effects of cargo and external water pressure. In order to analyse the effect of extent of the model, lower levels of structure like frame and girder model and a model of the structure between two transverse ames also may be analysed with all the possible boundary conditions.

CHAPTER 4

NUMERICAL INVESTIGATIONS ON WARSHIP STRUCTURES USING FINITE ELEMENT METHOD

4.1 Ship Details

Structural scantlings of a warship have been designed in accordance with the provisions for structural design of ships published by the Rules and Regulations for the Classification of Naval Ships of Lloyds Register of Shipping [42]. The ship parameters used in the design are given in table 4.1. The ship has three decks, spaced 2.4 m apart between the main deck and the inner bottom.

L_{BP}	132 m
B_{mld} (at Waterline)	15.2 m
B_{mld} (at Main Deck)	16.3 m
D	9.2 m
T	4.5 m
C_B	0.49
Speed	32 kn

Table 4.1 – Ship Details

Material of construction has been chosen as DS 40 steel with σ_Y = 390 MPa and σ_U = 590 MPa

The scantlings are finalised as per the formulae enumerated in LRS rules and the results are summarised and given below.

Spacing of transverse stiffeners – 1500 mm
Spacing of longitudinal stiffeners – 800 mm
Double bottom height - 1200 mm

Plate Thickness has been calculated as per provisions given in table 3.2.1, Vol I, Part 6, Ch 3, Section 2 of LRS rules. Scantlings for the longitudinal stiffeners have been calculated as per the provisions of table 3.3.2, Vol I, Part 6, Ch 3, Section 3. Primary transverse stiffeners include the side and deck transverses and the scantlings have been calculated as per the provisions of table 3.3.4 of Section 3. The calculated plate thicknesses and other scantlings are shown in table 4.2.

Ser	Item	Scantlings
(a) Plate Thickness (mm)		
1	Keel plate	11
2	Bottom and inner bottom	6
3	Side shell	5
4	Centre girder	10
5	Side girder and floor	7
(b) Secondary Members		
6	Bottom longitudinals	Unsymmetrical Bulb Profile (USBP) 14A
7	Side longitudinals	USBP 12
8	Inner bottom longitudinals	USBP 12
9	Upper deck longitudinals	USBP 14A
10	No 2 and No 3 deck longitudinals	USBP 7
11	No 1 Deck centreline girder	500x10+100x12 'T Girder'
12	No 2 and 3 decks centreline girders	280x7+120x12 'T Girder'
(c) Primary Members		
13	Side transverse, No 2 deck, No 3 deck and No 4 deck transverses	280x7+120x12 'T Girder'
14	No 1 deck and bottom transverses	320x8+150x13 'T Girder'

Table 4.2 – Scantlings of Midship Section

The structural configuration of the midship section is shown in fig 4.1.

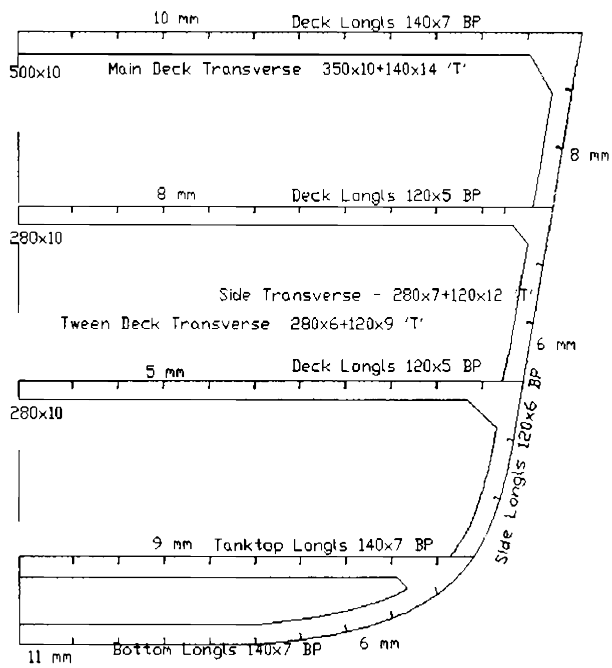

Fig 4.1 Midship Section of the Hull Girder

4.2 Types of Analysis

In the present study, numerical investigations related to linear elastic analysis, nonlinear analysis and reliability analysis of warship structures have been envisaged. Linear elastic analysis is carried out to check the rationale of the initial design/scantlings chosen. Normally, classification societies and other agencies insist that ship structures operate only in the elastic regime of stresses, with the maximum stress developed being limited to 75% to 80% of σ_Y. Hull girder/module of the ship being a box structure constituted with stiffened panels, are susceptible to issues arising from buckling and yielding. Nonlinear analysis being necessary to arrive at buckling and ultimate strength, this analysis has been carried out in this study. The strength of the hold model is affected by the uncertainties in several production and fabrication factors besides those in load estimation. A realistic study of the uncertainties and the subsequent considerations of the risks can be made possible by resorting to the reliability based analysis and design. In the reliability analysis, the strength of the hold model is taken as a function of material properties like the modulus of elasticity and Poisson ratio and geometric properties like the plate thickness.

4.3 Description of the Finite Element

NISA (Numerically Integrated elements for System Analysis) is a general purpose finite element program to analyse a wide variety of problems in engineering mechanics, which has been developed and marketed by EMRC and this has been extensively used in the present study. This program is composed of different types of analysis modules, which are completely integrated through an interactive graphical interface DISPLAY III [31]. The DISPLAY III is used for the geometric and finite element modeling. The software uses frontal solver techniques, iterative solver techniques and sparse matrix methods for solving the equation system. Elemental stresses can be estimated at the nodal points, centroidal points and integration points. A comprehensive library of elements is available in NISA. Each element in the library is uniquely identified by two variables; NKTP, which specifies the element type and NORDER, which specifies the element shape. In the finite element analysis of warship structures considered in the present study, a linear quadrilateral general shell element NKTP = 20 and NORDER = 1 has been adopted. The element has 6 degrees of freedom per node. The element reference guide is given in table 4.3 and the geometry of the element is shown in fig 4.2.

Element Type	3D General Shell Element (NKTP=20)
Analysis Types	Linear Static, Nonlinear Static, Buckling, Dynamic
No of Nodes/Order	4 Nodes / NORDER = 1
Degrees of Freedom	6 per node :- U_X, U_y, U_z, R_X, R_y, R_z
Real Constants	Nodal Thickness (Same as number of nodes)
Material Properties	Young's Modulus (EX), Poisson's Ratio (NUXY), Density (DENS), Plasticity (PLASTIC)
Dynamic Capabilities	Consistent or Lumped Mass, Eigen Value Analysis
Nonlinear Capabilities	Geometric Nonlinearity, Large displacement and rotation, total Lagrangian formulation, deformation dependent loads, Material nonlinearity

Table 4.3 Element Reference Guide for 3D General Shell Element (NISA)

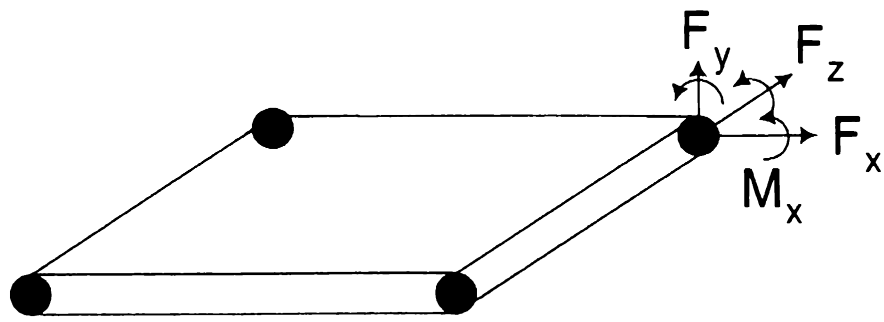

Fig 4.2 - 3D General Shell Element [31]

Four noded quadrilateral thin shell elements have been mainly used in the analysis except where the geometric complexities call for the use of three noded triangular elements. This finite element has been accepted for the analysis after comparing the performance of three (T3), four (Q4), six (T6) and eight (Q8) noded thin shell finite elements in the prediction of deflections and the stresses of thin plates subjected to lateral loads. Comparison of the results of this analysis the solution available in Timoshenko [45] is presented in fig 4.3(a) and 4.3(b), which indicate that 4 noded elements provide the best results as far as deflections and stresses are concerned.

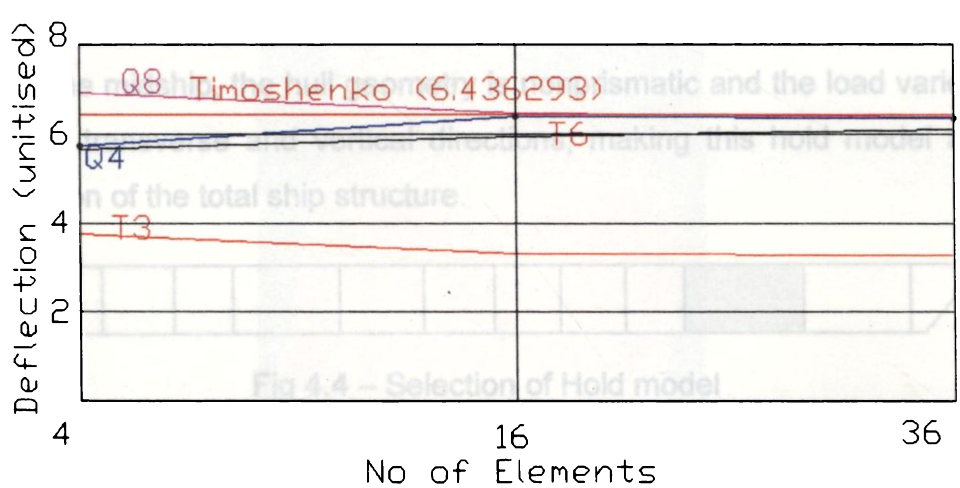

Fig 4.3 (a) – Convergence Check of Elements (Deflection)

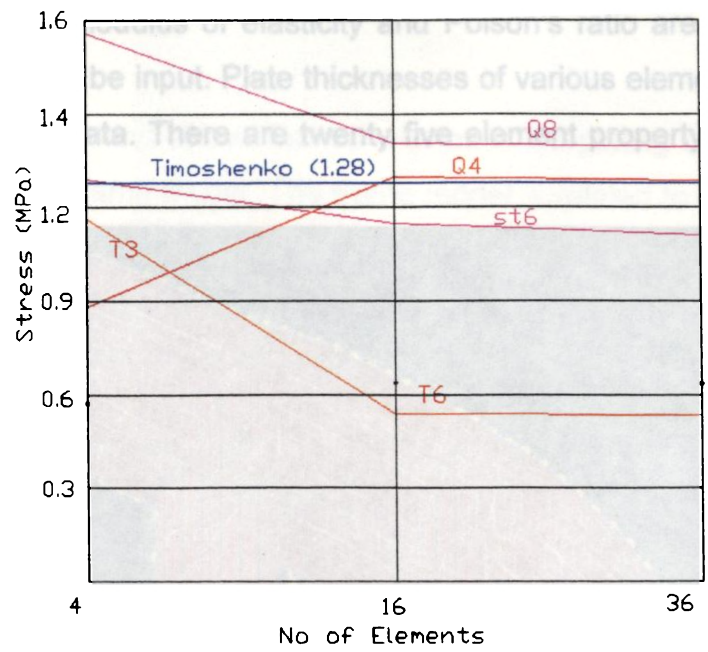

Fig 4.3 (b) – Convergence Check of Elements (Stress)

4.4 Structural Models for Analysis

4.4.1 Hold Model.

In accordance with the method suggested by Hughes [18], the longest compartment of the ship is selected as the hold model (15 m length) for finite element structural analysis of warships, as shown in fig 4.4. In this region which is forward of the midship, the hull geometry is nonprismatic and the load varies in the longitudinal, transverse and vertical directions, making this hold model a critical representation of the total ship structure.

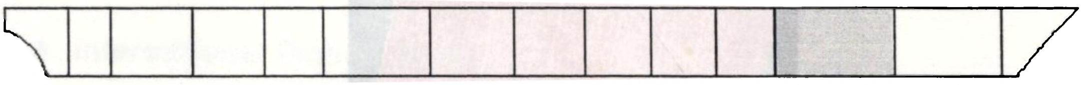

Fig 4.4 – Selection of Hold model

Transverse stiffeners of the side shell and decks which are T girders are modeled using thin shell elements. The longitudinals which are USBPs are modeled with plate and shell elements after converting them as equivalent flat bars. The hold model is used as the vehicle to examine the response of the primary strength components in a particular portion of the hull girder under the action of internal cargo and external water pressure. The finite element model is indicated in fig 4.5. Modulus of elasticity and Poison's ratio are the two material properties required to be input. Plate thicknesses of various elements are to be fed in as the geometric data. There are twenty five element property sets provided in the present analysis.

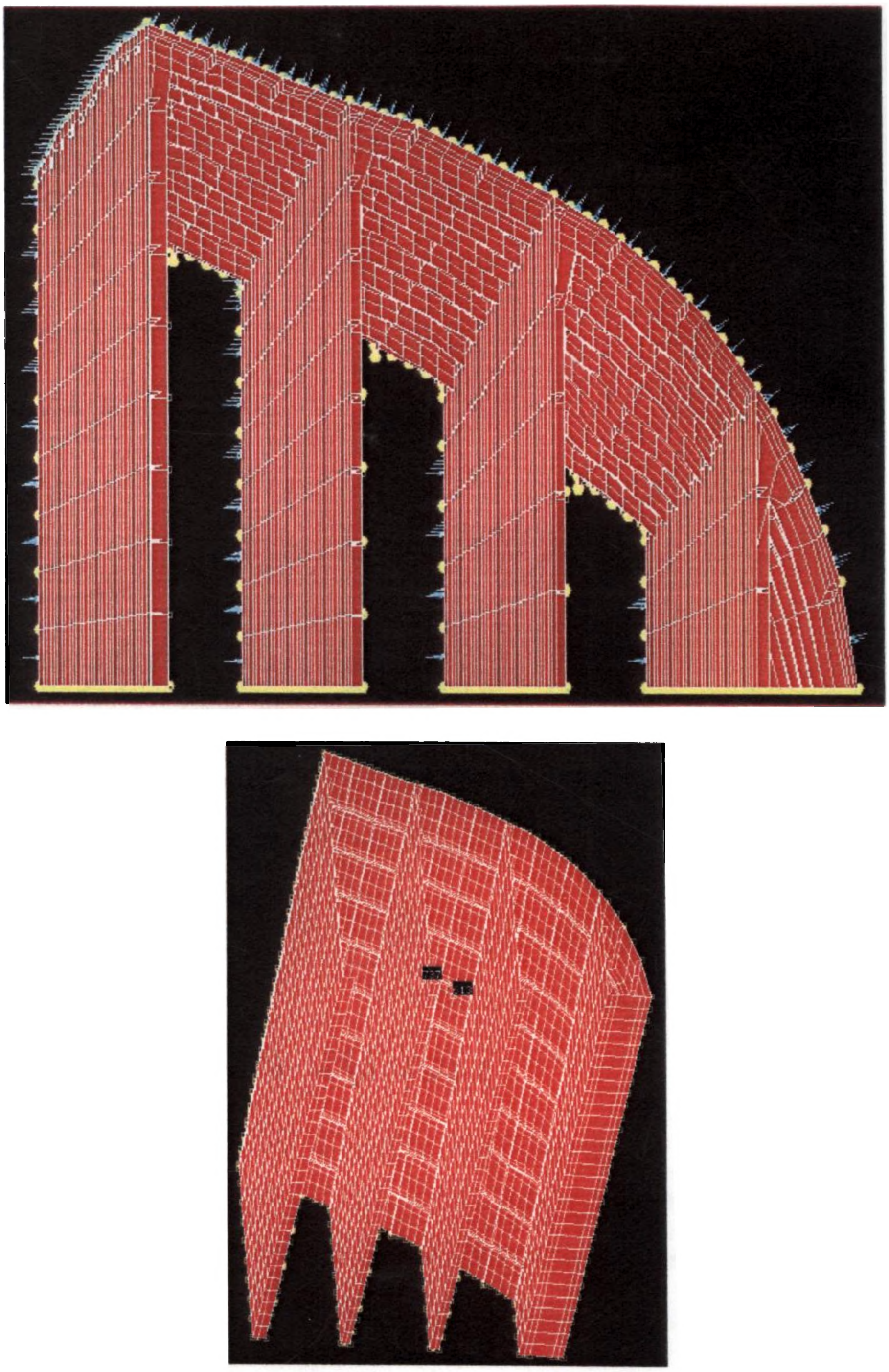

Fig 4.5 – Finite Element Model of Hold model

4.4.2 Frame Model

A section consisting of two frames with attached plating on either side has been chosen for the frame model. The frame model is related to the action effects of two or three dimensional frame structures such as transverse web frame systems or longitudinal girder systems, including the flanges that are provided by the associated plating. The finite element model is shown in fig 4.6.

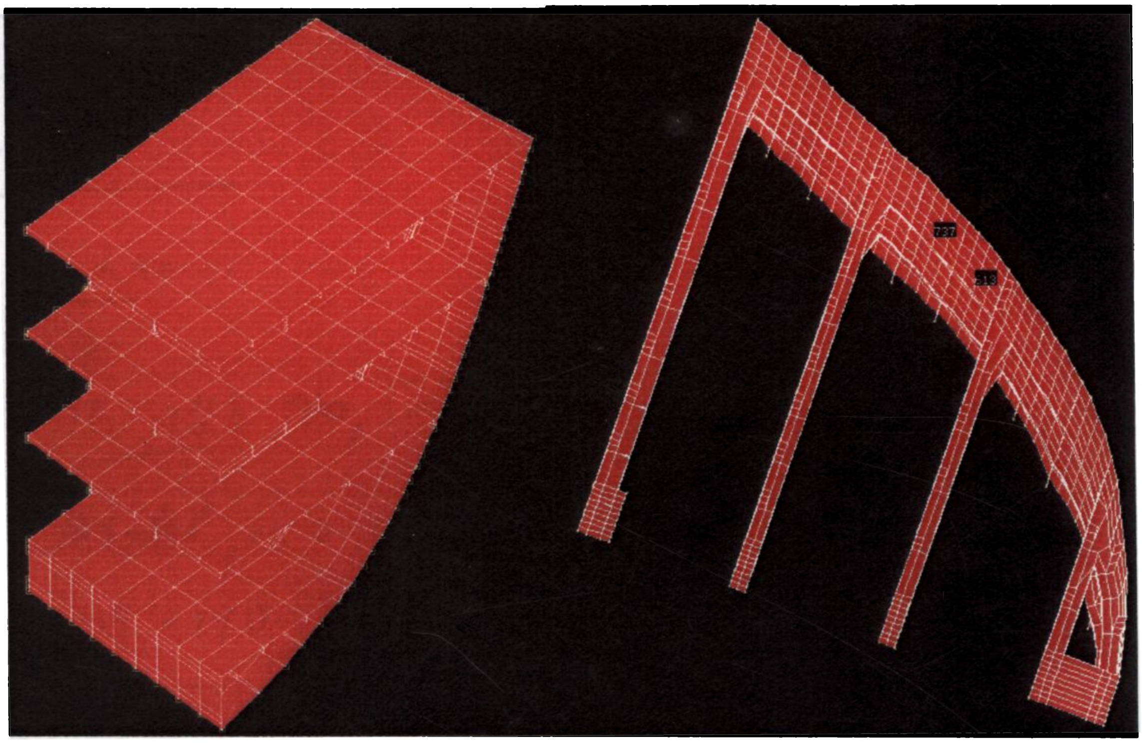

Fig 4.6 Frame Model

4.4.3 Interstiffener Plating Model

A model consisting of plating between two frames has been referred as interstiffener plating model and has been indicated in fig 4.7. This model consists of the side shell extending from bottom to the shear strake, all the decks and the associated longitudinal members between two transverse frames.

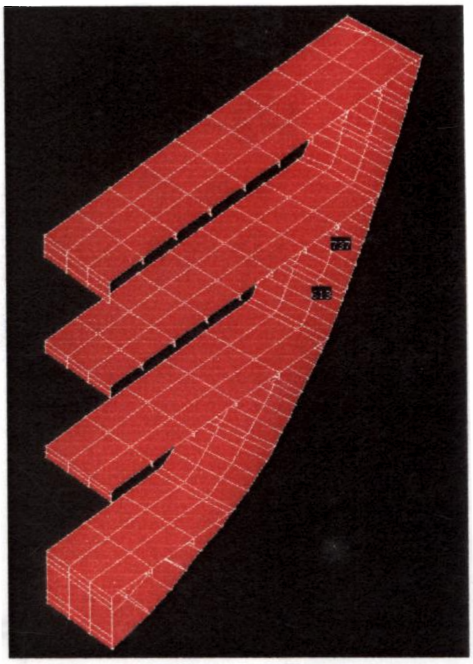

Fig 4.7 - Interstiffener Plating Model

4.4.4 Boundary Conditions.

The structural models presented here for finite element analysis are treated with three end conditions regarding the kinematic degrees of freedom falling at the ends. In the first case, all the degrees of freedom are arrested at the end nodes and is referred as the fixed boundary condition. In the second case, rotational degrees of freedom are released whereas the translations are arrested along the end nodes and is referred as the simply supported boundary condition. The third category referred as the clamped is the same as the fixed case except that the longitudinal translations at the boundary nodes are permitted. Symmetry boundary conditions have been applied along the centerline plane, considering the symmetry related to structural arrangements and load application, where translations normal to the plane of symmetry and rotations in the plane of symmetry are arrested.

4.5 Loads.

4.5.1 Loads on the Shell Plating

Equivalent pressure loads representing the total load on the hull, which allow for the effects of ship motions, in accordance with NES 154 [33] has been considered as static heads of sea water as illustrated in fig 4.8. Values of the design load for the problem considered herein are listed in table 4.4.

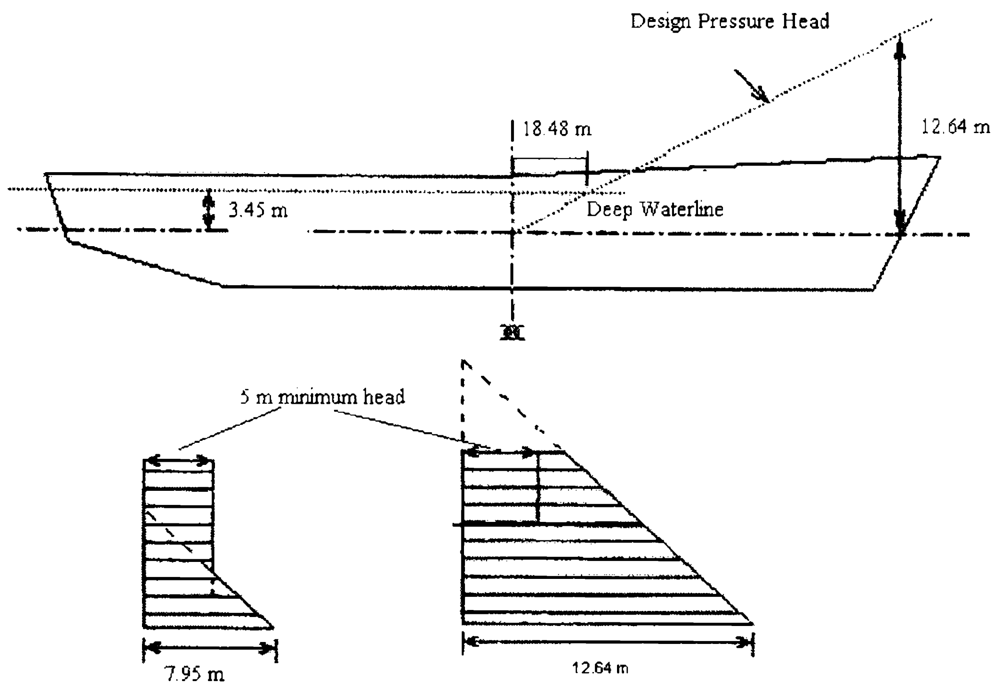

Fig 4.8 – Equivalent Static Loads [33]

Between Frames ↓	Between Decks→			
	1-2	2-3	3-4	4-bottom
9-10	5.03E+04	6.03E+04	8.25E+04	1.04E+05
8-9	5.03E+04	6.13E+04	8.40E+04	1.07E+05
7-8	5.13E+04	6.49E+04	8.90E+04	1.09E+05
6-7	5.23E+04	6.74E+04	9.15E+04	1.12E+05
5-6	5.33E+04	7.09E+04	9.53E+04	1.15E+05
4-5	5.53E+04	7.34E+04	9.70E+04	1.17E+05
3-4	5.78E+04	7.74E+04	1.02E+05	1.20E+05
2-3	5.93E+04	8.09E+04	1.06E+05	1.23E+05
1-2	6.03E+04	8.30E+04	1.08E+05	1.25E+05
0-1	6.18E+04	8.60E+04	1.10E+05	1.28E+05

Table 4.4 – Design Pressure Loads in Pa

4.5.2 Loads on the Deck

Main decks will need to be designed to withstand vertical loads like cargo loads, stores etc.,. as well as inplane loads due to hull bending. In the absence of precise data, NES 154 suggests the following loads for the design of decks.

(a) Upper deck forward of the bridge front—25kPa

(b) Other exposed areas of decks up to and including the first tier of superstructure —25kPa

(c) Exposed decks above the first tier of superstructure — 15kPa

(d) Living spaces and passageways—5kPa

(e) Workshops and offices—10kPa

(f) Storerooms—10kPa

The above loads are extreme values and are unlikely to be exceeded. Those on exposed parts of the decks are to be applied independently of the effects of inplane loads but those on internal decks are continuously applied and are therefore to be combined with the inplane loads.

The main combat loads are underwater explosions/shock, nuclear air blast loading and own weapons effects. These loads have been omitted from the current study.

4.6 Linear Static Analysis

Linear static analysis deals with static problems in which the response is linear in the cause and effect sense and loads are time independent. Linear static analysis is generally carried out to check the adequacy of the structure.

4.6.1 Input and Output

The three finite element models described in section 4.3 have been chosen for analysis. Once defined, the same models have been used with the three different boundary conditions which are applied at the ends to analyse the effect of end restraints on structural response. Loads applied are in the form of elemental pressures. The pressure is uniform for the decks as indicated in section 4.4. For the side and bottom shell structures, a pressure envelope is applied, wherein the pressure varies in the longitudinal, the transverse and the vertical directions. The average pressure is worked out between the frames in the longitudinal direction and between the decks in the vertical direction and applied over the patch of elements.

The output of the analysis contains information on all six components of displacements, stresses, three components of principal stresses alongwith the corresponding direction cosines, the equivalent von-Mises stress etc.,. Stress values at the top, middle and bottom layers of the shell elements have been provided in the output file. The effective resultant displacement at a node and the average displacement at a section can be worked out. Alternatively, the values can be obtained from the post processing phase of NISA.

4.6.2 Hold model

Linear static analysis of the hold model has been carried out for the design loads, under the three different boundary conditions as explained in section 4.3.4. Principal stress and von-Mises stress and deflections at all the nodes have been evaluated and the maximum values have been tabulated in table 4.5. The contour plots of these responses are indicated in figs 4.9, 4.10 and 4.11. The stresses are within the limit of permissible stress of 328 MPa. The scantlings are found to be sufficient. The corresponding values in the simply supported case are also approximately the same and are represented in fig 4.12 to 4.14. The contour plots for the clamped boundary conditions are shown in fig 4.15, 4.16 and 4.17 respectively.

Edge Condition	Deflection Shell (mm)	Deflection Deck (mm)	Principal Stress (MPa)	von-Mises Stress (MPa)
Fixed	19.2	56.3	279	308
Simply Supported	19.178	56.4	279.4	308.8
Clamped	17.12	86.83	324.4	327.4

Table 4.5 - Summary of Results – Linear Static Analysis of the Hold Model

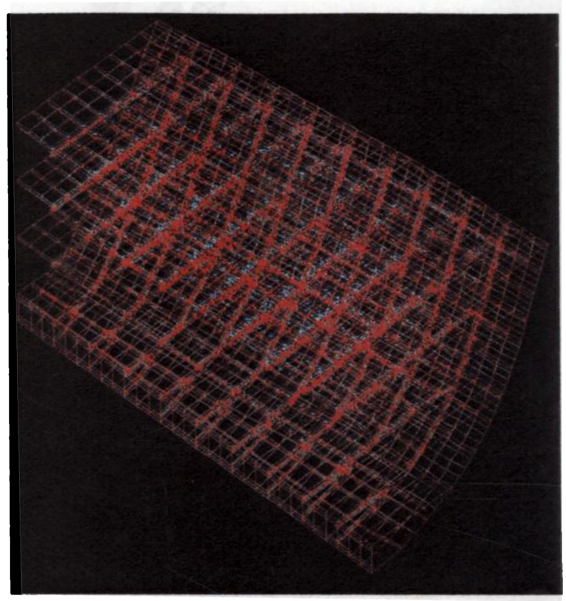

Fig 4.9 – Deflected Profile of the Hold Model for Fixed Boundary Conditions

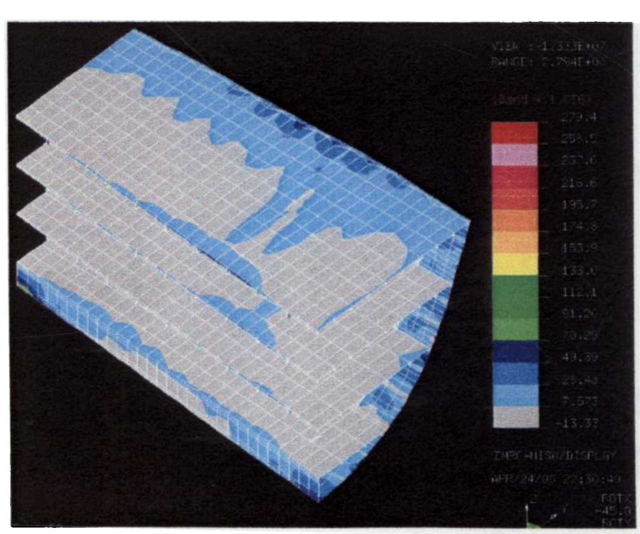

Fig 4.10 – Contour of Principal Stress of the Hold Model for Fixed Boundary Conditions

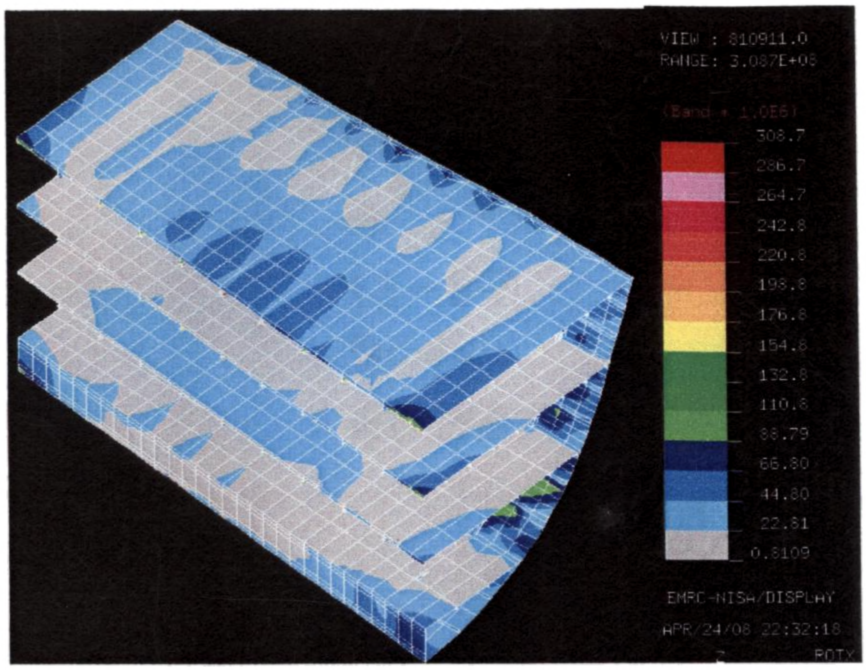

Fig 4.11 – Contour of von-Mises Stress of the Hold model for Fixed Boundary Conditions

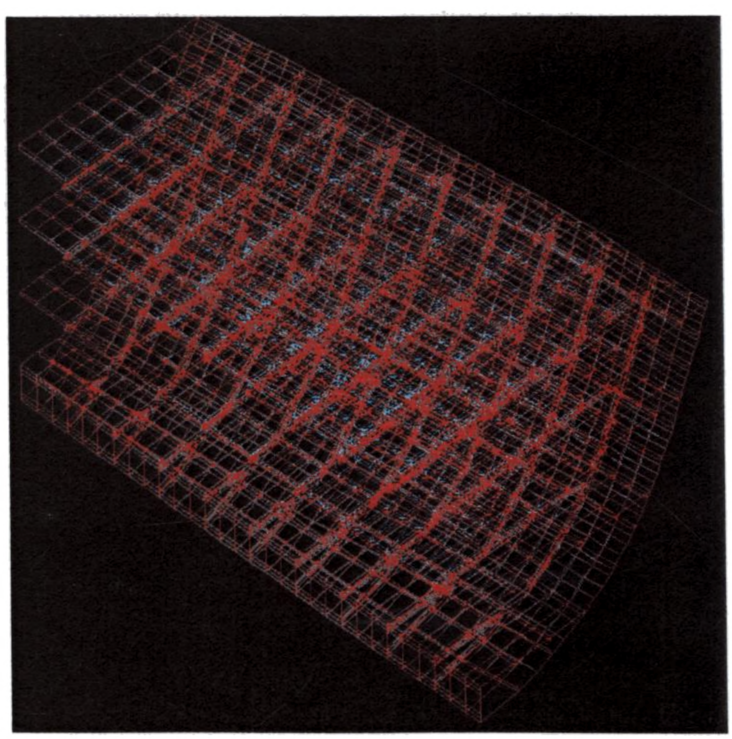

Fig 4.12 – Deflected Profile of the Hold model for Simply Supported Boundary Conditions

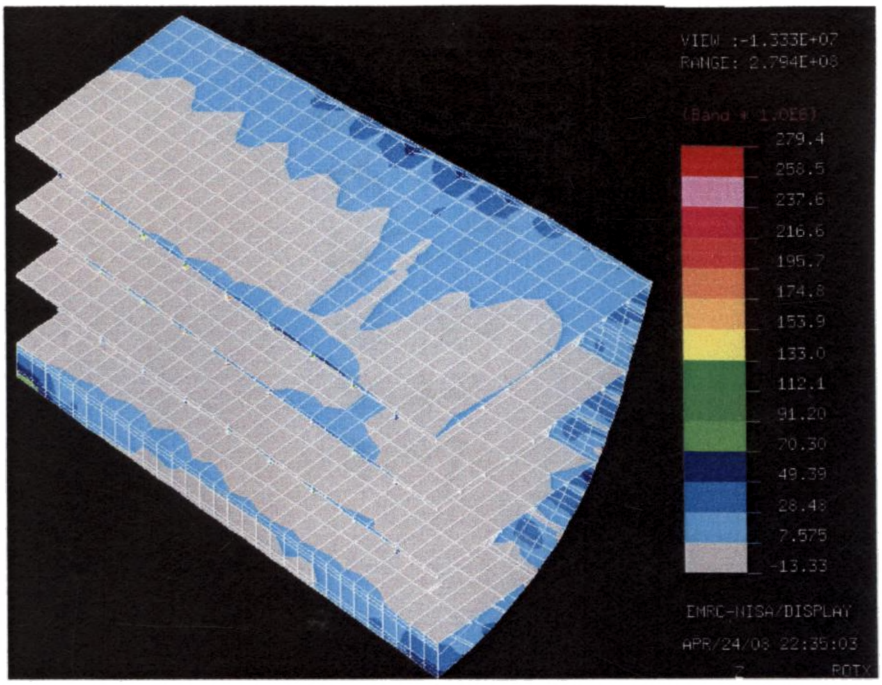

Fig 4.13 – Contour of Principal Stress of the Hold model for Simply Supported Boundary Conditions

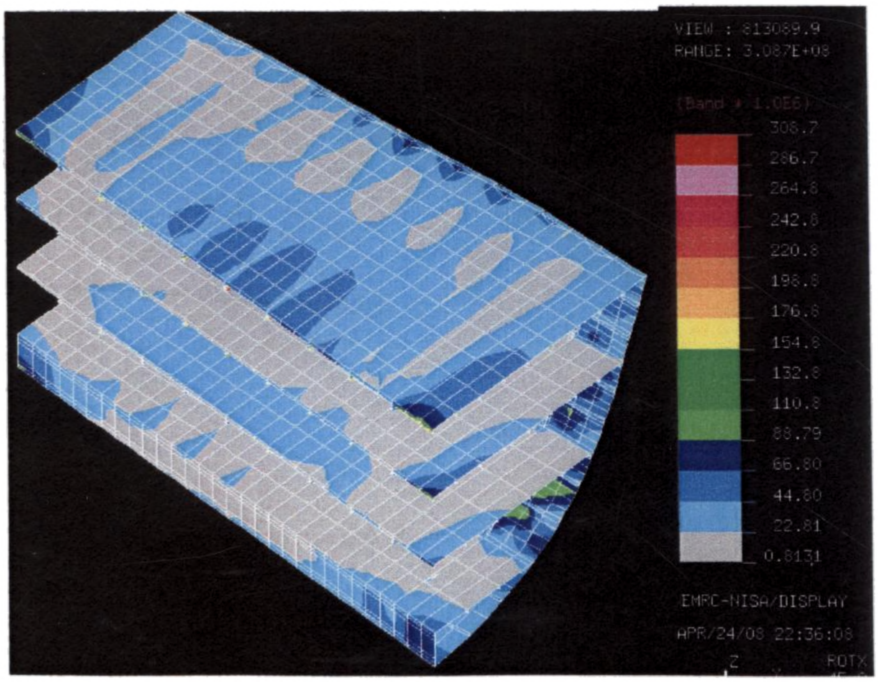

Fig 4.14 – Contour of von-Mises Stress of the Hold model for Simply Supported Boundary Conditions

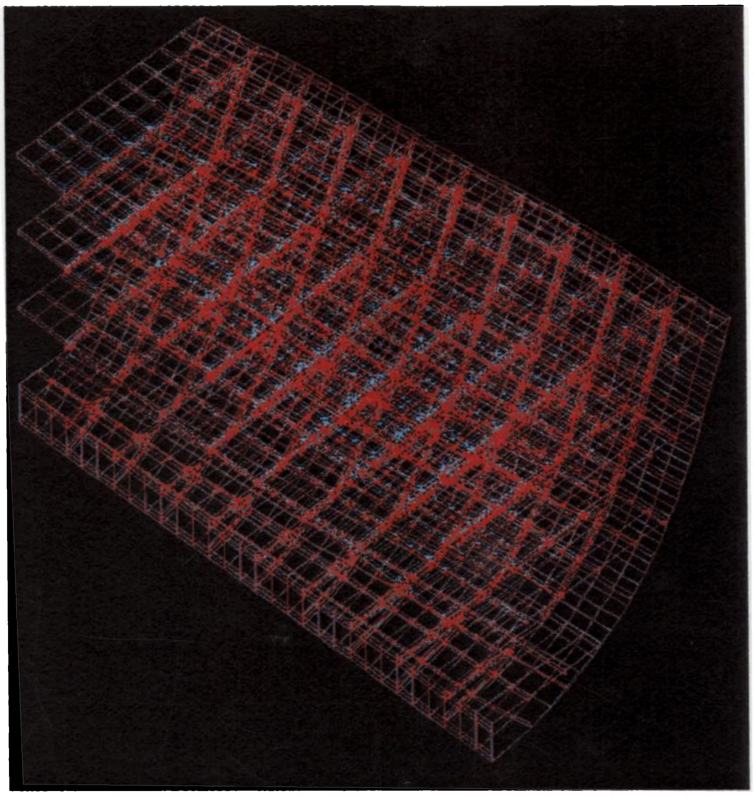

Fig 4.15 – Deflected Profile of the Hold model for Clamped Boundary Conditions

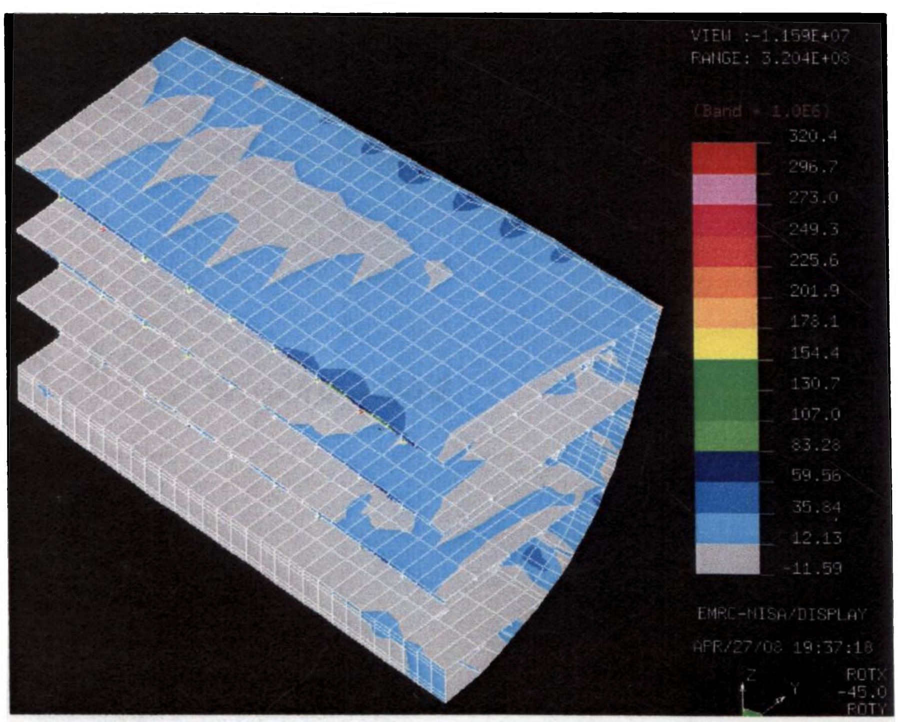

Fig 4.16 – Contour of Principal Stress of the Hold model for Clamped Boundary Conditions

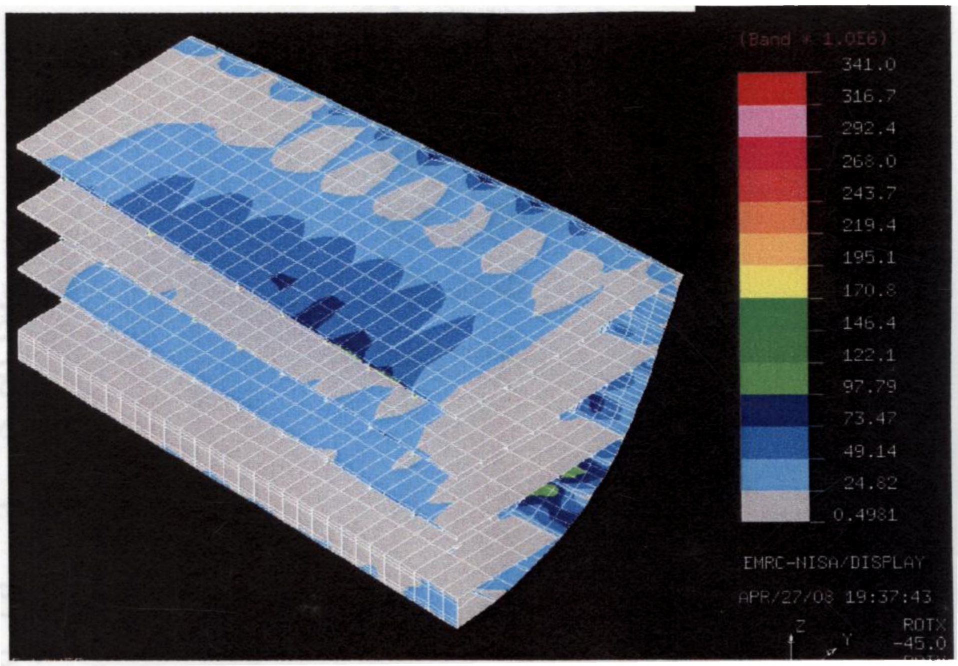

Fig 4.17 – Contour of von-Mises Stress of the Hold model for Clamped Boundary Conditions

4.6.3 Frame Model

The linear static analysis of the frame model shown in fig 4.6 has been conducted in the linear elastic regime under the design loads as per table 4.4, with the three different boundary conditions along the edges. The maximum principal stress, von-Mises stress and deflection of the shell and deck for the model with the three boundary conditions are summarized in table 4.6 and the stress contours and the deflected shape of the model for all boundary conditions are presented in fig 4.18 to 4.26.

Edge Condition	Deflection Shell (mm)	Deflection Deck (mm)	Principal Stress (MPa)	von-Mises Stress (MPa)
Fixed	12.07	8.28	136.4	144.2
Simply Supported	12.07	8.23	138.05	146.89
Clamped	12.01	8.571	158.3	158.2

Table 4.6 - Summary of Results – Linear Static Analysis of the Frame Model

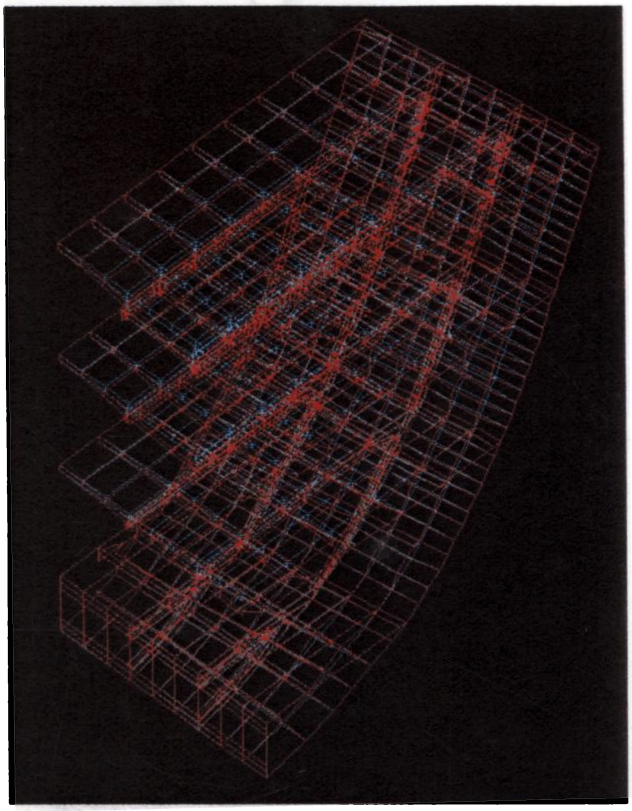

Fig 4.18 – Deflected Shape of Frame Model for Fixed Boundary Conditions

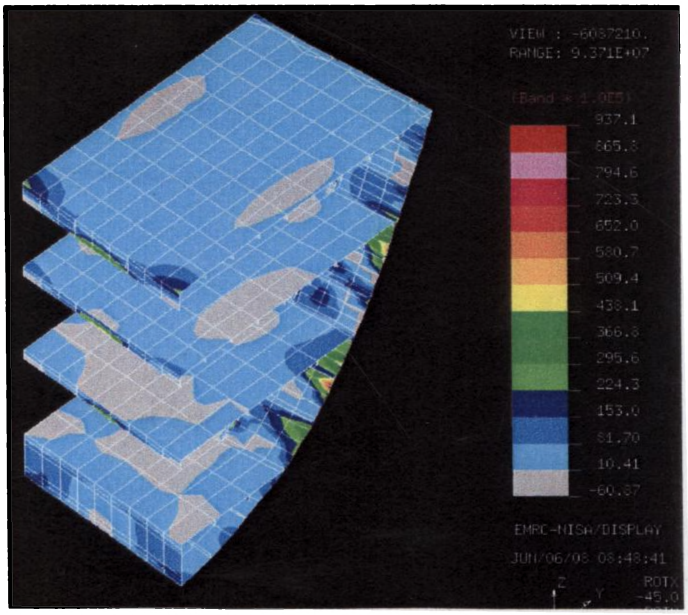

Fig 4.19 – Contour of Principal Stress of the Frame Model for Fixed Boundary Conditions

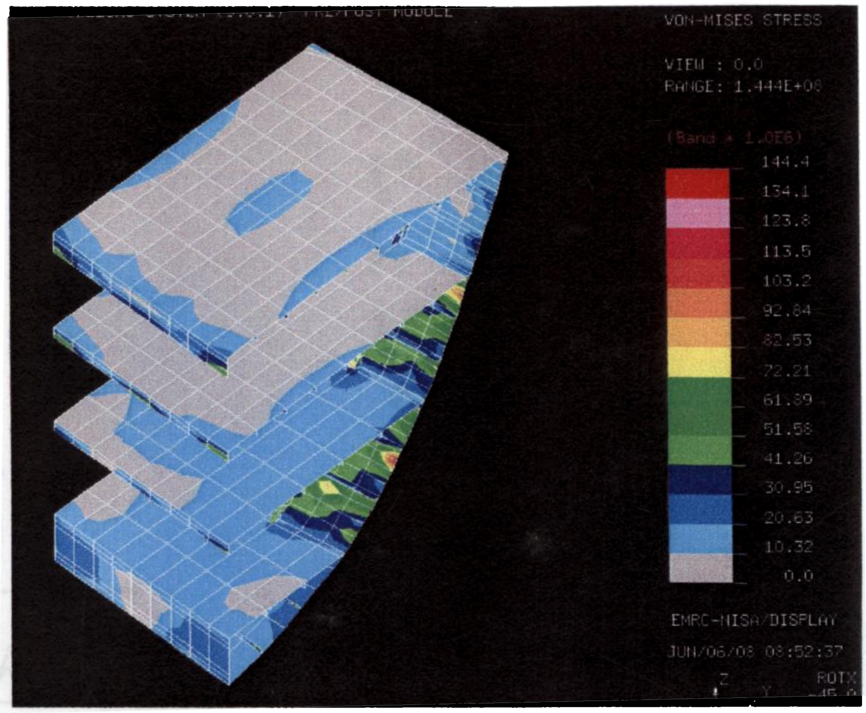

Fig 4.20 – Contour of von-Mises Stress of the Frame Model for Fixed Boundary Conditions

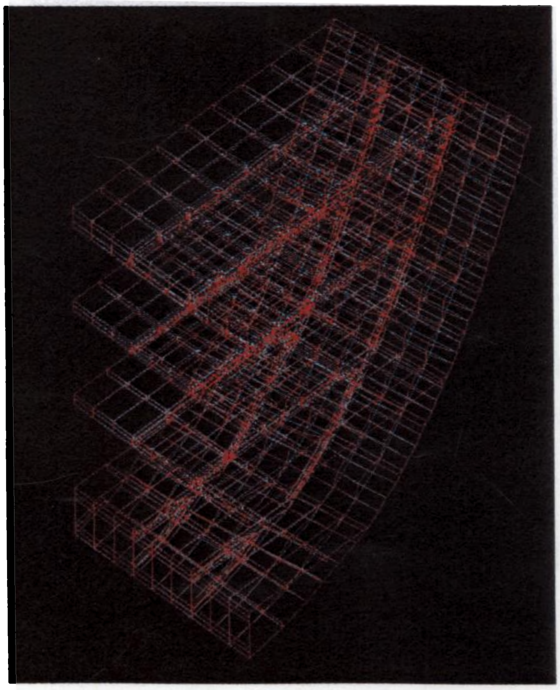

Fig 4.21 – Deflected Profile of the Frame Model for Simply Supported Boundary Conditions

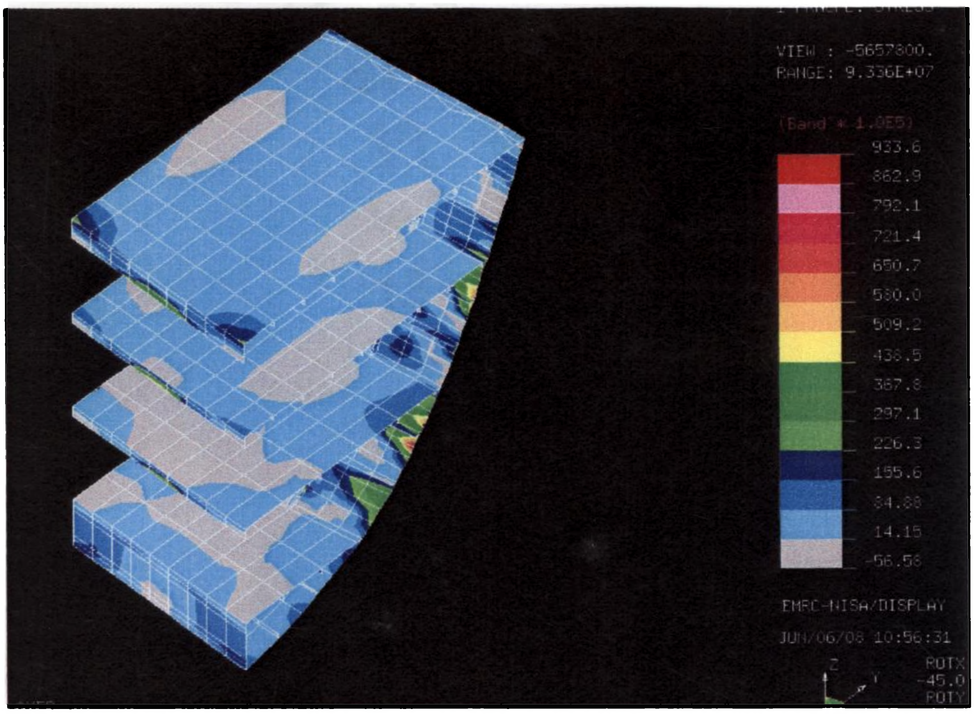

Fig 4.22 – Contour of Principal Stress of the Frame Model for Simply Supported Boundary Conditions

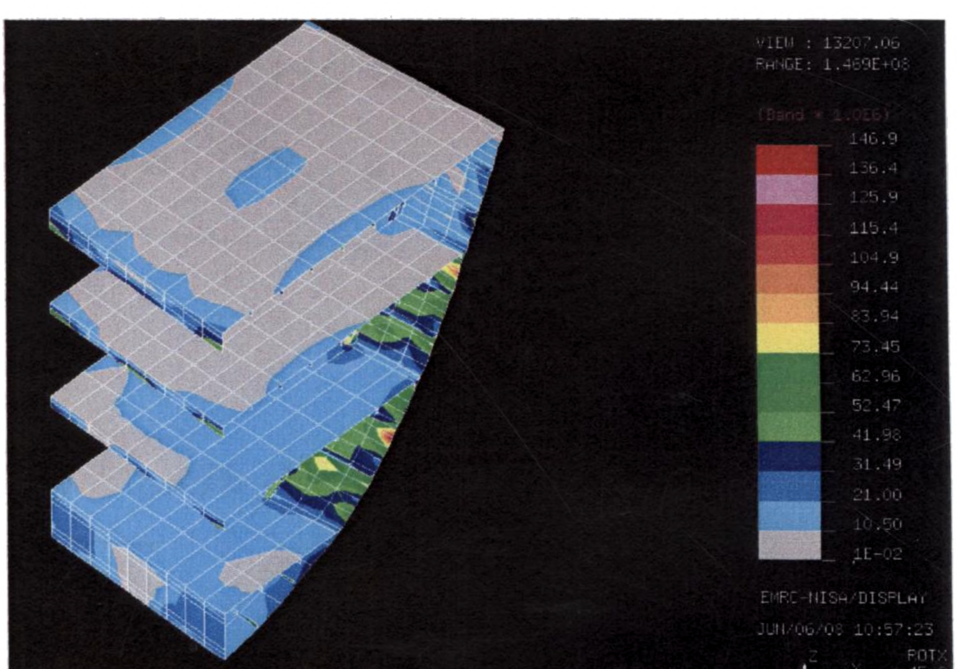

Fig 4.23 – Contour of von-Mises Stress of the Frame Model for Simply Supported Boundary Conditions

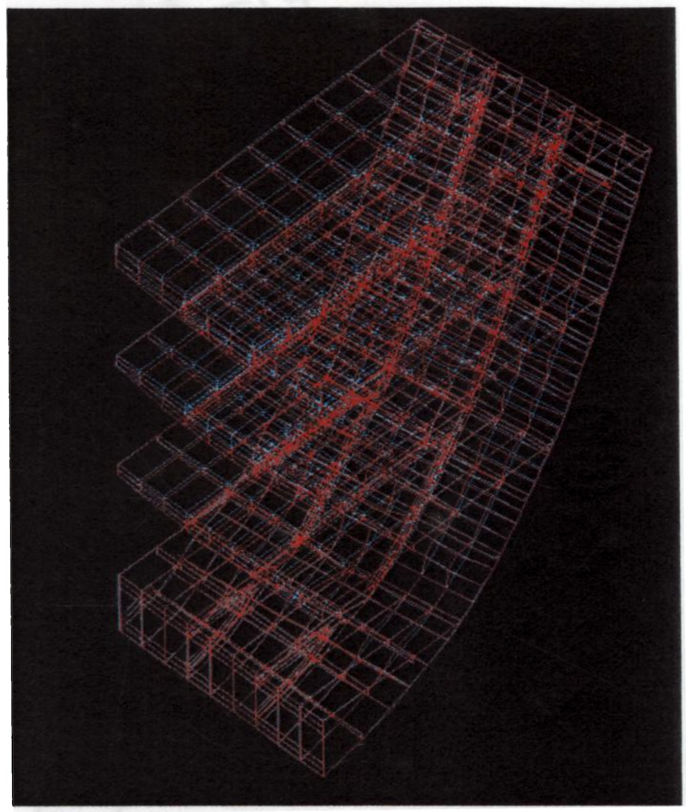

Fig 4.24 – Deflected Profile of the Frame Model for Clamped Boundary Conditions

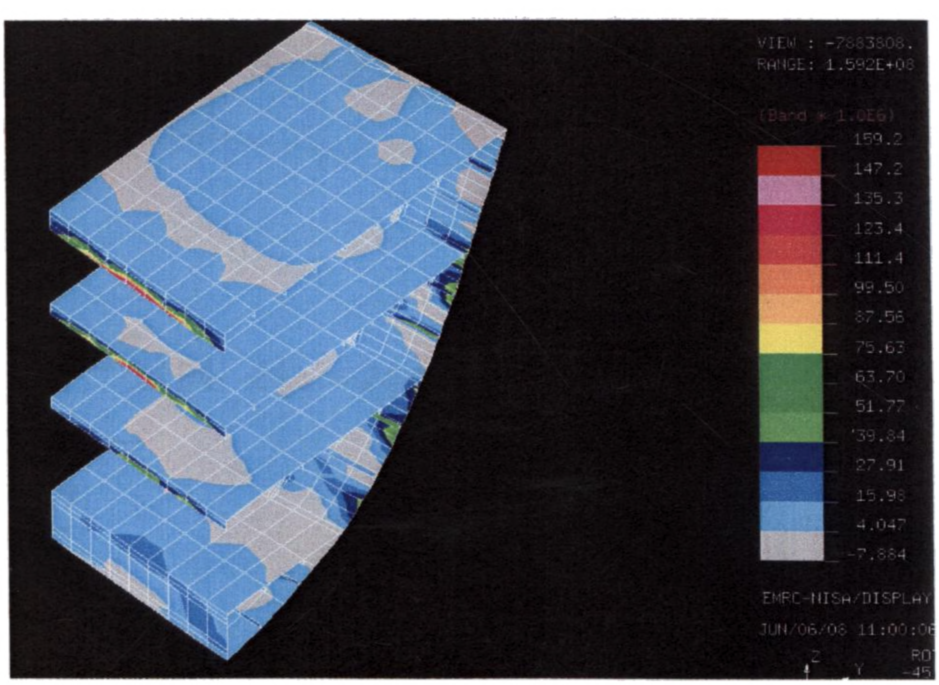

Fig 4.25 – Contour of Principal Stress of the Frame Model for Clamped Boundary Conditions

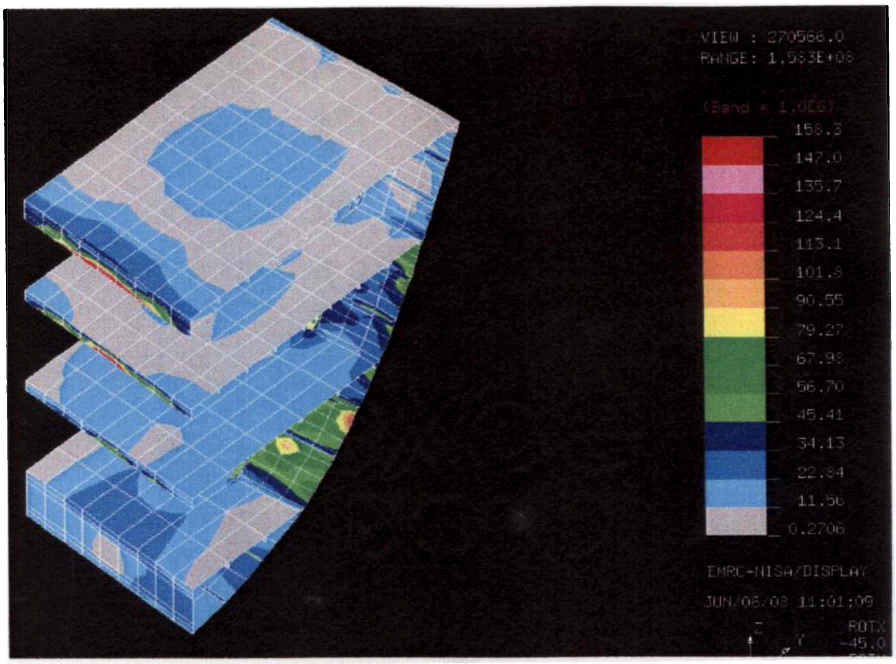

Fig 4.26 – Contour of von-Mises Stress of the Frame Model for Clamped Boundary Conditions

4.6.4 Interstiffener Plating Model

The interstiffener plate model described in section 4.3.3 has been analysed for the design loads under the three different boundary conditions. The maximum values of principal stress, von-Mises stress, shell deflection and deck deflection for three boundary conditions are summarized and presented in table 4.7. The stress contours and deflected shape for various cases are presented in fig 4.27 to 4.35

Edge Condition	Deflection Shell (mm)	Deflection Deck (mm)	Principal Stress (MPa)	von-Mises Stress (MPa)
Fixed	9.36	6.66	80.13	82.23
Simply Supported	10.94	7.28	84.65	79.93
Clamped	13.64	8.44	96.74	99.06

Table 4.7 - Summary of Results – Linear Elastic Analysis of the Interstiffener Plate Model

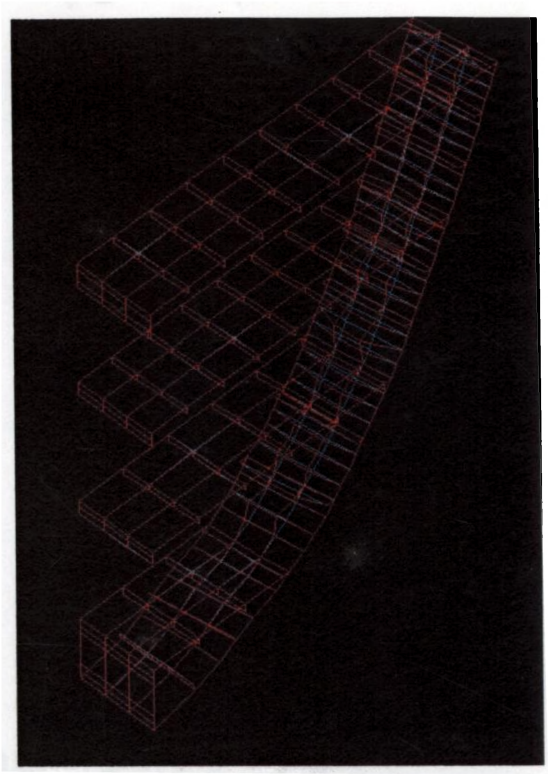

Fig 4.27 – Deflected Shape of Interstiffener Plating Model for Fixed Boundary Conditions

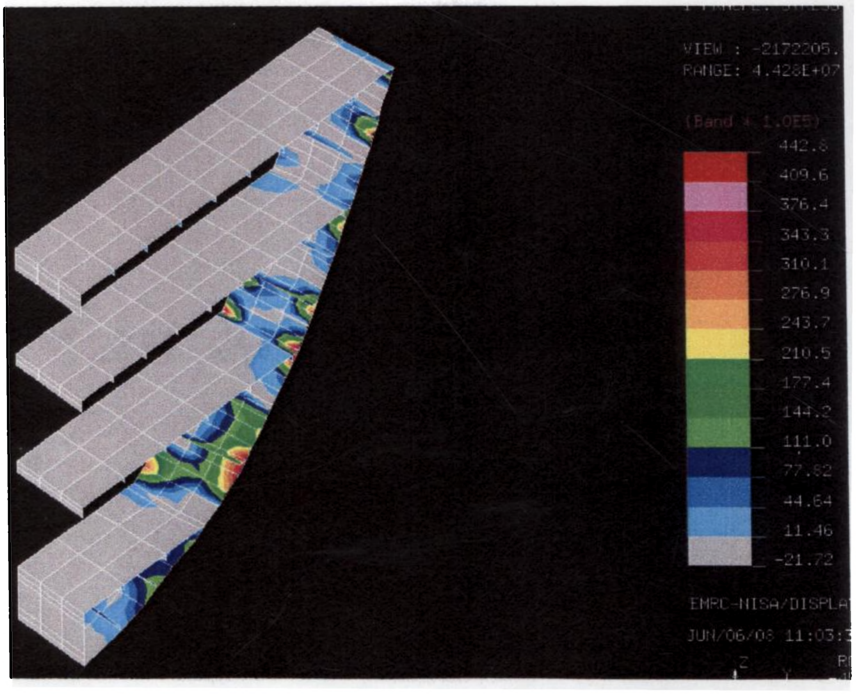

Fig 4.28 – Contour of Principal Stress of the Interstiffener Plating Model for Fixed Boundary Conditions

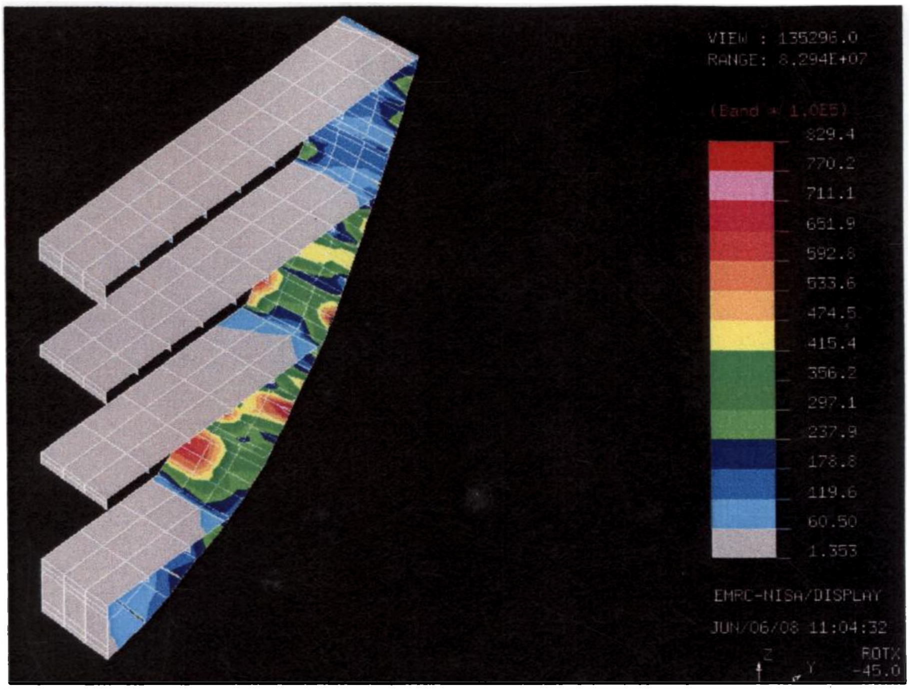

Fig 4.29 – Contour of von-Mises Stress of the Interstiffener Plating Model for Fixed Boundary Conditions

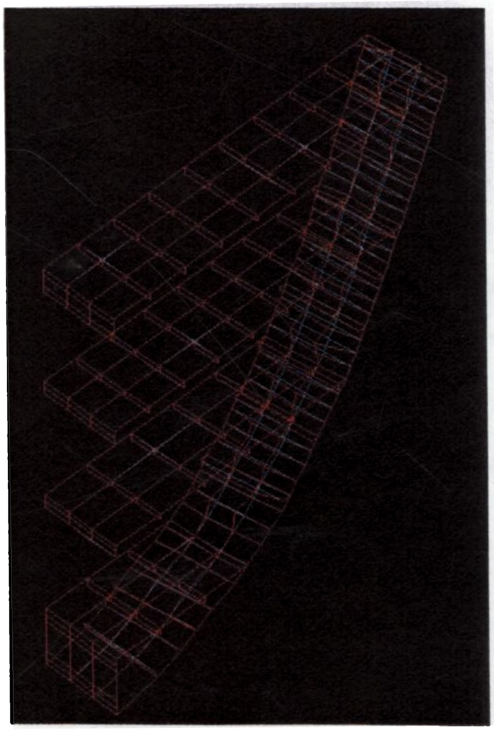

Fig 4.30 – Deflected Profile of the Interstiffener Plating Model for Simply Supported Boundary Conditions

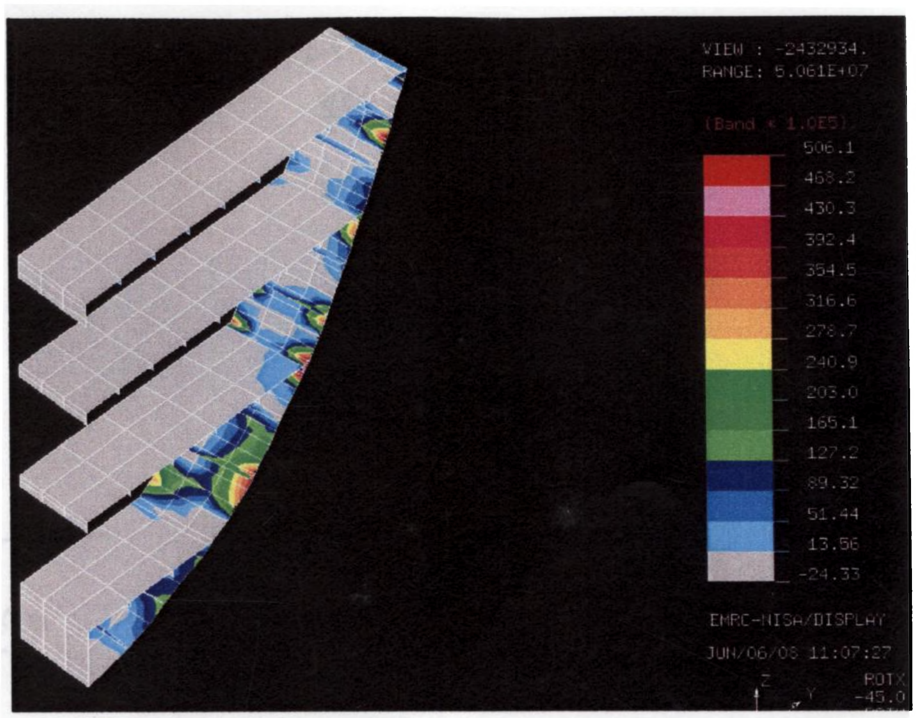

Fig 4.31 – Contour of Principal Stress of the Interstiffener Plating Model for Simply Supported Boundary Conditions

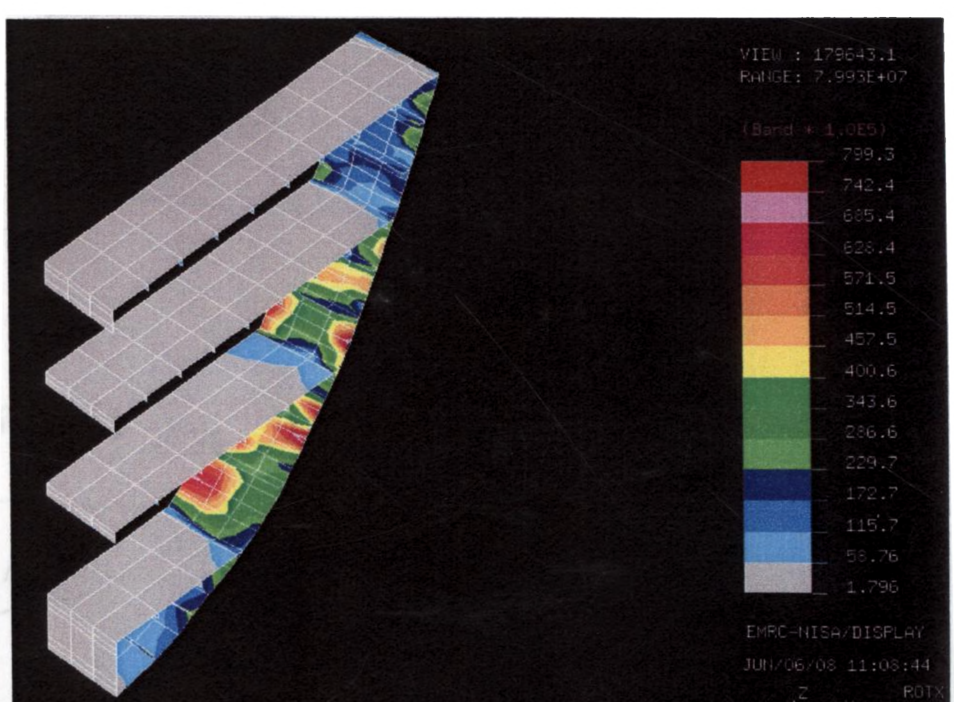

Fig 4.32 – Contour of von-Mises Stress of the Interstiffener Plating Model for Simply Supported Boundary Conditions

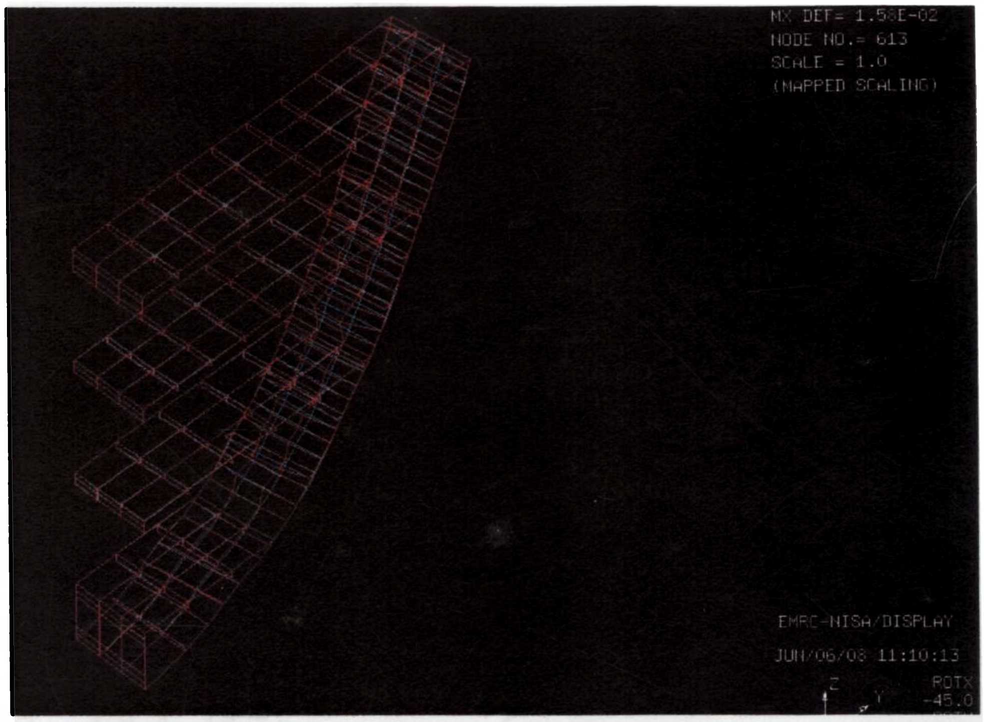

Fig 4.33 – Deflected Profile of the Interstiffener Plating Model for Clamped Boundary Conditions

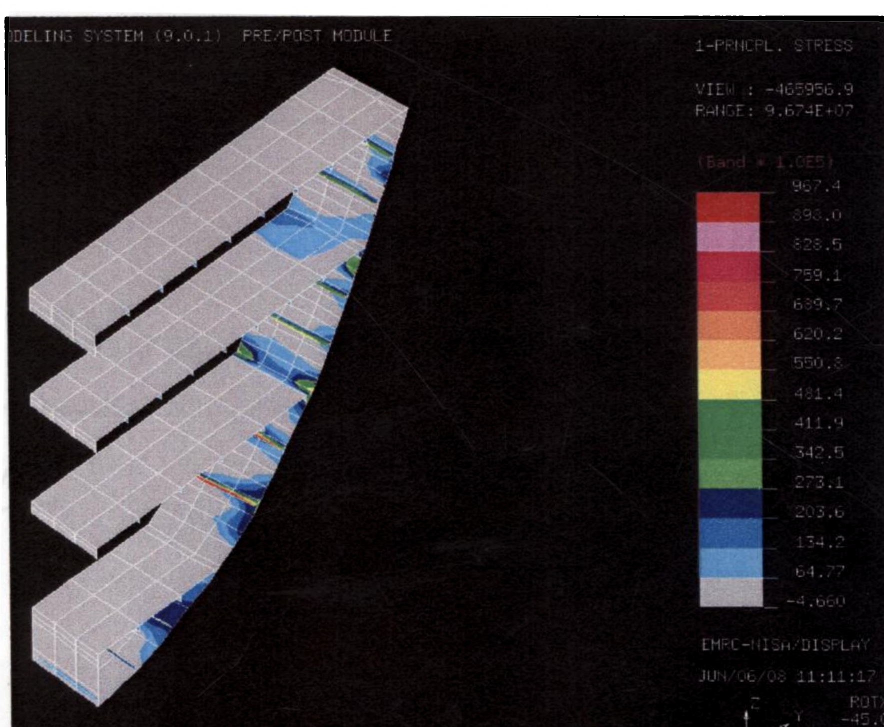

Fig 4.34 – Contour of Principal Stress of the Interstiffener Plating Model for Clamped Boundary Conditions

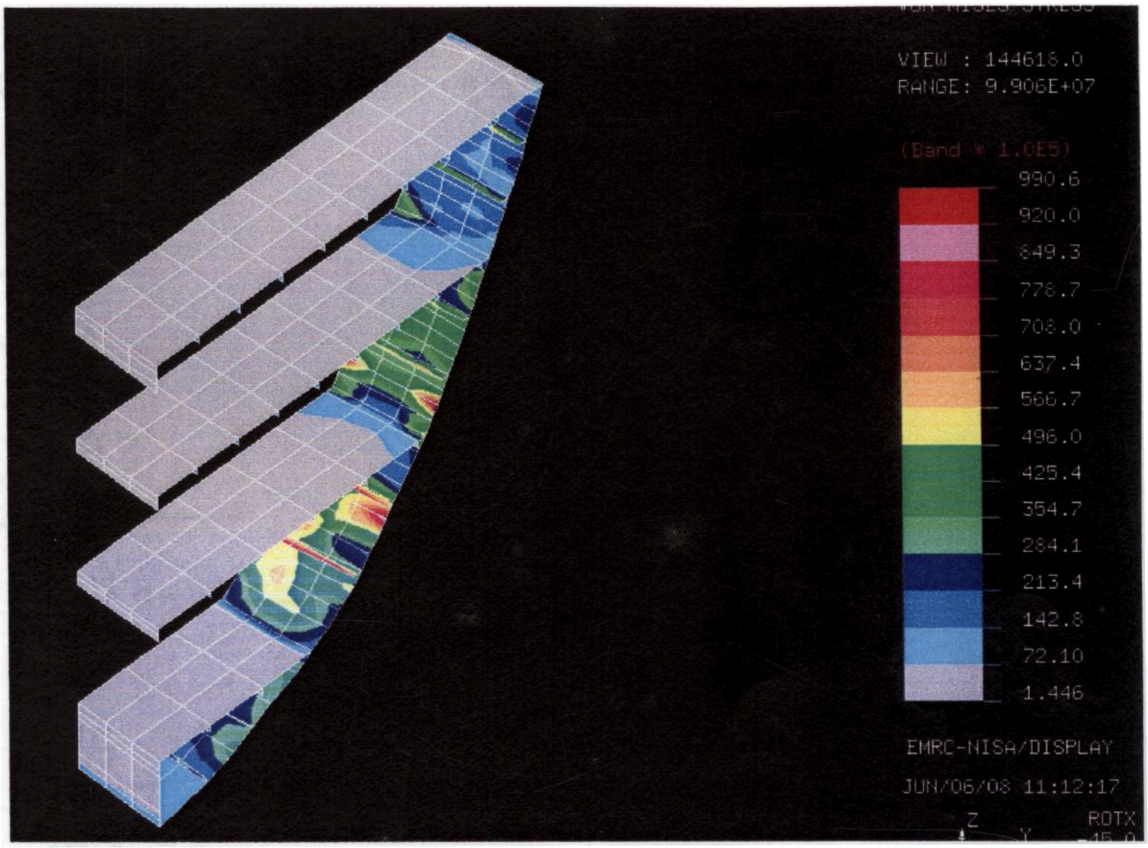

Fig 4.35 – Contour of von-Mises Stress of the Interstiffener Plating Model for Clamped Boundary Conditions

In order to investigate the validity and the range of acceptance of the frame model and the interstiffener plating model with the hold model, maximum values of deflections, von-Mises stress and principal stresses the three boundary conditions are tabulated for all three models vide tables 4.8 to 4.13. The response values are taken for nodes 613 and 737, which are already shown in figures 4.5 to 4.7. The stresses and deflections predicted by the frame model are comparable with those of the hold model, their deviation being ranging from 2% to 6% for deflection, 1.76% to 6.17% for principal stress and 1.17% to 1.68% for von Mises stress. It is evident from the tables that no such comparison has been realized for the interstiffener plating model with the other two models. Therefore further numerical investigations on the interstiffener plating model have not been carried out.

Edge Condition	Hold Model	Frame Model	ISP Model
Fixed	16.206	14.223	10.895
Simply Supported	16.217	14.217	15.811
Clamped	20.443	14.224	12.746

Table 4.8 - Shell deflection (in mm) at Node 613

Edge Condition	Hold Model	Frame Model	ISP Model
Fixed	6.934	7.171	6.389
Simply Supported	6.947	7.171	6.428
Clamped	6.947	7.946	7.695

Table 4.9 - Shell deflection (in mm) at Node 737

Edge Condition	Hold Model	Frame Model	ISP Model
Fixed	56.69	58.36	32.12
Simply Supported	56.67	58.35	37.51
Clamped	77.71	78.88	47.06

Table 4.10 – von Mises Stress (MPa) at Node 613

Edge Condition	Hold Model	Frame Model	ISP Model
Fixed	65.64	66.7	47.09
Simply Supported	65.73	66.79	49.81
Clamped	69.10	79.66	46.31

Table 4.11 – von Mises Stress (MPa) at Node 737

Edge Condition	Hold Model	Frame Model	ISP Model
Fixed	64.24	66.10	28.75
Simply Supported	64.23	66.10	33.68
Clamped	78.13	80.44	44.13

Table 4.12 –Principal Stress (MPa) at Node 613

Edge Condition	Hold Model	Frame Model	ISP Model
Fixed	70.70	72.46	54.11
Simply Supported	70.81	72.57	57.08
Clamped	72.27	78.44	52.22

Table 4.13 – Principal Stress (MPa) at Node 737

4.7 Geometric Nonlinear Analysis

Nonlinear static analysis, which is denoted as NLSTAT in NISA, deals with the nonlinear behaviour of structures under static loading. Nonlinear static analysis (NLSTAT) requires the solution of nonlinear equilibrium equations, for which the program NISA uses conventional Newton-Raphson method, Modified Newton-Raphson Method and the Arc Method. Many problems involve history dependent response, so that the solution is usually obtained as a series of increments, with iteration within each increment to obtain equilibrium.

In the nonlinear analysis, the tangent stiffness matrix is assembled and decomposed repeatedly throughout the incrementation process. Increments must sometimes be kept small (in the sense that rotation and strain increments must be small) to assure correct modeling of history dependent effects, but most commonly the choice of increment size is a matter of computational efficiency – if the increments are too large, more iteration will be required. For most cases, the automatic incrementation scheme is preferred, because it will select increment sizes based on these considerations. Direct user control of increment size is also provided because there are cases when the user has considerable experience with a particular problem and can therefore select a more economic approach.

In the present study, the entire load history for the nonlinear static analysis is divided into events and the pressure values are applied over the elements. Each value of node is associated with a time-amplitude curve. The time-amplitude curve allows a general description of the load history. The value of the applied load at a given time is determined from the load value specified in the corresponding data group, and the referenced time-amplitude curve. For solving the nonlinear equilibrium equations, conventional Newton-Raphson method is used.

4.7.1 Input and Output

The hold and the frame models studied in the linear static analysis have been investigated upon under the same boundary conditions here as well. Loads have been applied on a progressive basis to identify the load at which the structure collapses. Six times the design load has been applied progressively in 50 steps. The number of iterations has been increased to 25 in this study. For solving the nonlinear equilibrium equations, conventional Newton-Raphson method is used. Provisions exist for choosing the quantum of output parameters like averaged nodal stresses, principal stresses and displacements at selected load steps.

The output file for nonlinear analysis contains the values of stresses and displacements at each load step, or at regular intervals desired by the user. After the breaking load is identified, the analyses have been repeated for extracting the desired data.

4.7.2 Hold model

The breaking load is identified as the load level at which the program abruptly terminates. The analysis is repeated for all the three different boundary conditions. The load versus deflection (P-Δ curve) is plotted and is shown in fig 4.36

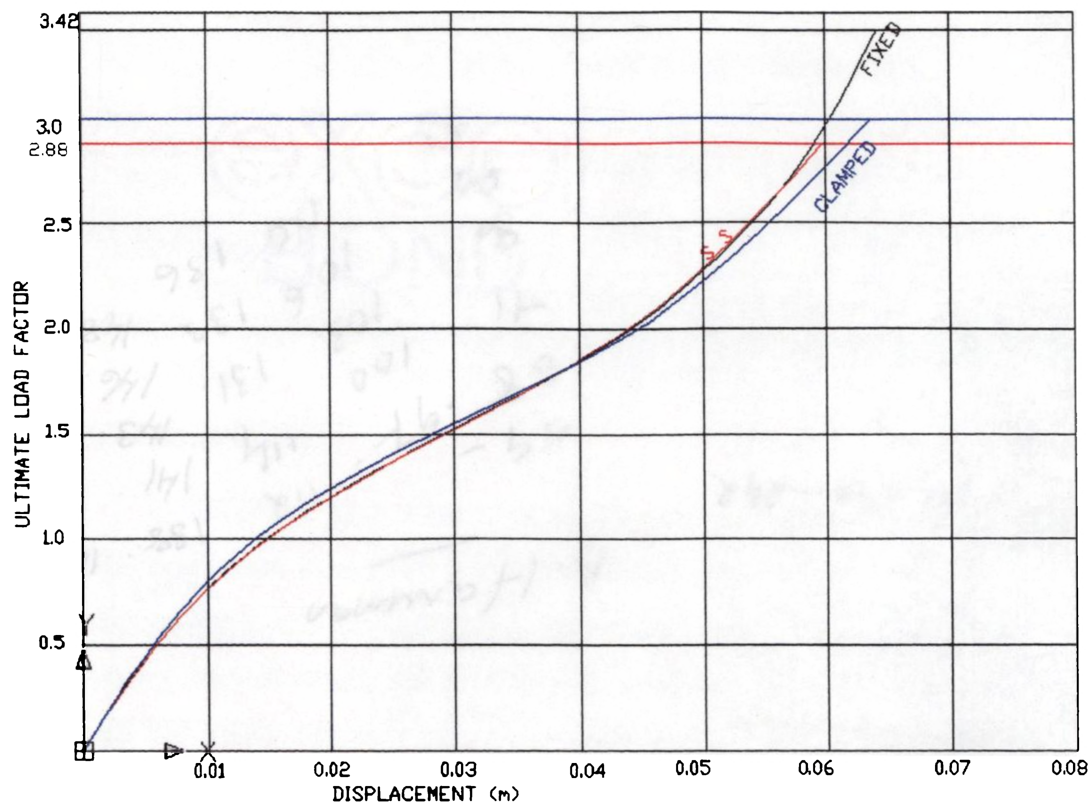

Fig 4.36 P-Δ Curve for Hold Model with Geometric Nonlinearity

For the hold model configuration, the nonlinearity has been found to be initiating at a load level 1.28 times the design loads specified by NES [33], when the kinematic degrees of freedom are fixed at both the ends, and also, while clamped. When the rotational degrees of freedom are released at the ends, the load value has been observed as 1.244 times the design loads, indicating a reduction of 3.1% of design load.

Execution of the job is terminated on encountering singular stiffness matrix. The load step corresponding to this stage is taken as the ultimate load. The ultimate load factor for the hold model configuration has been found to be 3.42 times, 3 times and 2.88 times the design load for the all-fixed, the clamped and the rotations free end conditions respectively, indicating a difference of 18.5% and 14% for the clamped and simply supported cases over the fixed boundary condition. The deflections, principal stress and the von-Mises stresses corresponding to the ultimate load condition are presented in table 4.14

Edge Condition	Deflection Shell (mm)	Deflection Deck (mm)	Principal Stress (MPa)	von-Mises Stress (MPa)
Fixed	63.59	176.8	584.8	583.8
Simply Supported	59.99	154.6	472.4	488.2
Clamped	63.1	214.7	434.8	494.6

Table 4.14 - Deflections and Stresses from Geometric Nonlinear Analysis of the Hold Model

4.7.3 Frame Model

Incremental progressive collapse analysis has been carried out on the model described in section 4.3.2. The loads worked out in section 4.4 have been multiplied by 6 and are applied in 50 steps on a progressive basis to identify the breaking load at which the program abruptly terminates. The analysis is repeated for all the three different boundary conditions. Typical P-Δ curve for the critical panels/elements have been developed and are presented in fig 4.37.

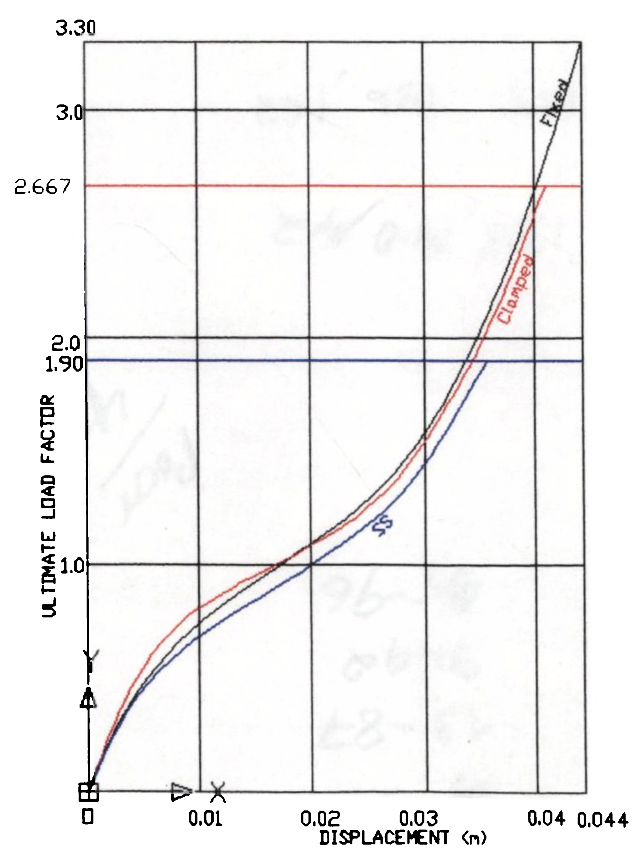

Fig 4.37 P-Δ Curve for Frame Model with Geometric Nonlinearity

For the frame mode, initiation of the nonlinearity has been found to be at a load level 0.85 times the design loads, for the fixed and clamped boundary conditions. When the rotations are released at the ends, the load value has been observed as 0.8 times the design load, indicating a reduction of 5.88%.

The ultimate load for the frame model has been found to be 3.3 times, 2.67 times and 1.8 times the design load for the fixed, clamped and the rotations free end conditions respectively, indicating a difference of 19% and 33% compared to the fixed case for the other cases. The ultimate load is 1.9 times the design load for the clamped condition. The results are summarized in table 4.15

Edge Condition	**Deflection Shell (mm)**	**Deflection Deck (mm)**	**Principal Stress (MPa)**	**von-Mises Stress (MPa)**
Fixed	44.41	43.13	499	443
Simply Supported	35.63	20.27	415.9	393.6
Clamped	41.08	29.29	501	455.7

Table 4.15 - Deflections and Stresses from Geometric Nonlinear Analysis of the Frame Model

4.8 Geometric and Material Nonlinear Analysis

The necessity for incorporation of material nonlinearity in structural analysis is felt when the problem involves nonlinear constitutive relations. Three main material nonlinear models available in NISA are the elasto-plastic, creep, and the hyper elastic or rubber-like material model. In the elasto-plastic material behaviour, various types of yield criteria and hardening rules are available. In the creep model, both general and Oak Ridge National Laboratory material laws can be used. In the hyper elastic or rubber-like material models, various types of strain energy functions with finite compressible or near incompressible behaviours are available. In the present study, von-Mises yield criterion with elastic-perfectly plastic stress strain relations has been used.

4.8.1 Input and Output

390 MPa has been input as the yield stress of the material. Typical stress-strain curve is plotted in fig 4.38.

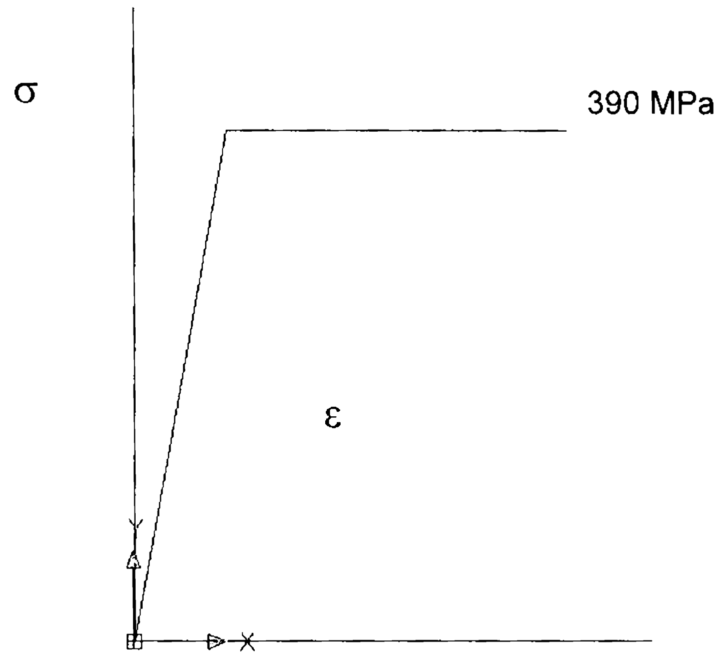

Fig 4.38 – Stress Strain Curve for Elastic-Perfectly Plastic Material

The models have been analysed for the same loads and boundary conditions considered in section 4.6. P-Δ curve for the critical panels/elements has been developed, in the same way as was done for geometric nonlinear analysis.

4.8.2 Hold model

Analyses have been carried out for the hold model under the action of the same loads considered in the case of geometric nonlinear analysis. Three boundary conditions have been considered and the failure loads in each case have been identified. P-Δ curve for the critical panels/elements are presented in fig 4.39.

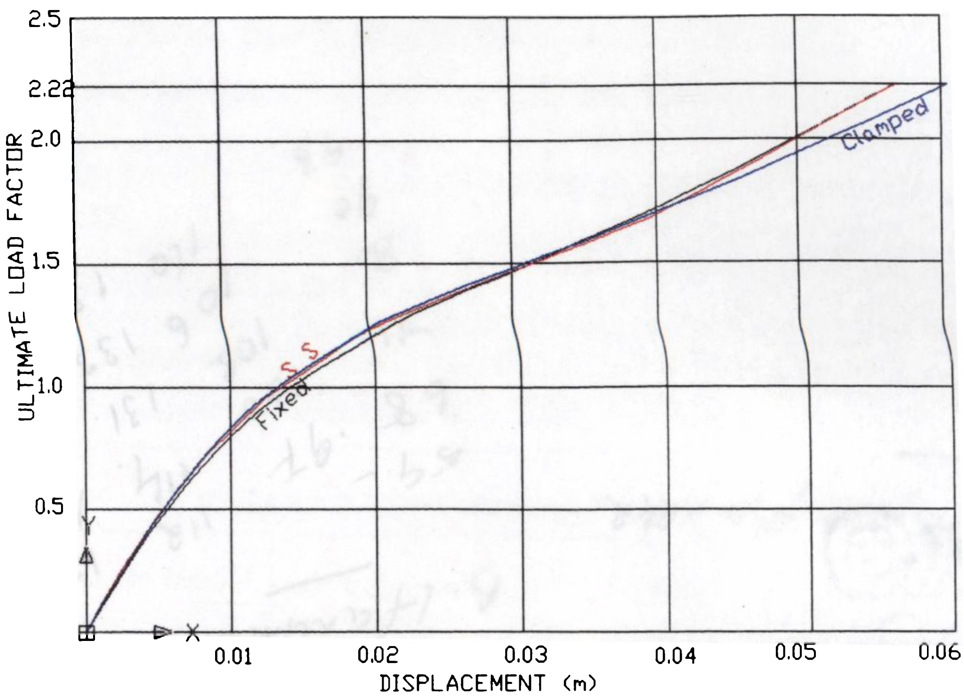

Fig 4.39 P-Δ Curve for Hold Model with Geometric & Material Nonlinearity

For the hold model configuration, the nonlinearity has been found to be initiating at a load level 1.04 times the design loads specified by NES, when the kinematic degrees of freedom are restrained at both the ends. When the rotational degrees of freedom are released at the ends, the load value has been observed as 1.02 times the design loads, indicating a reduction of 1.9%.

The ultimate load for the hold model has been found to be 2.22 times the design load for the all the three cases, as is expected for material nonlinearity. The deflections corresponding to the ultimate load condition at the shell and the deck are presented in table 4.16

Edge Condition	Deflection Shell (mm)	Deflection Deck (mm)
Fixed	56.82	211.53
Simply Supported	56.88	211.61
Clamped	61.19	300.3

Table 4.16 – Deflections from Geometric and Material Nonlinear Analysis of the Hold Model

The ultimate load factors of the hold model for the geometric nonlinear analysis and the geometric and material nonlinear analysis are summarized in table 4.17

Type of Nonlinearity	Fixed	Clamped	Simply Supported
Geometric	3.42	3.00	2.88
Geometric and Material	2.22	2.22	2.22

Table 4.17 – Ultimate Load Factors for Hold Model

4.8.3 Frame Model

The frame model is analysed for the response under conditions of material and geometric nonlinearities for all the cases of boundary conditions. The failure patterns are identified and P-Δ curve for the critical panels/elements have been presented in fig 4.40.

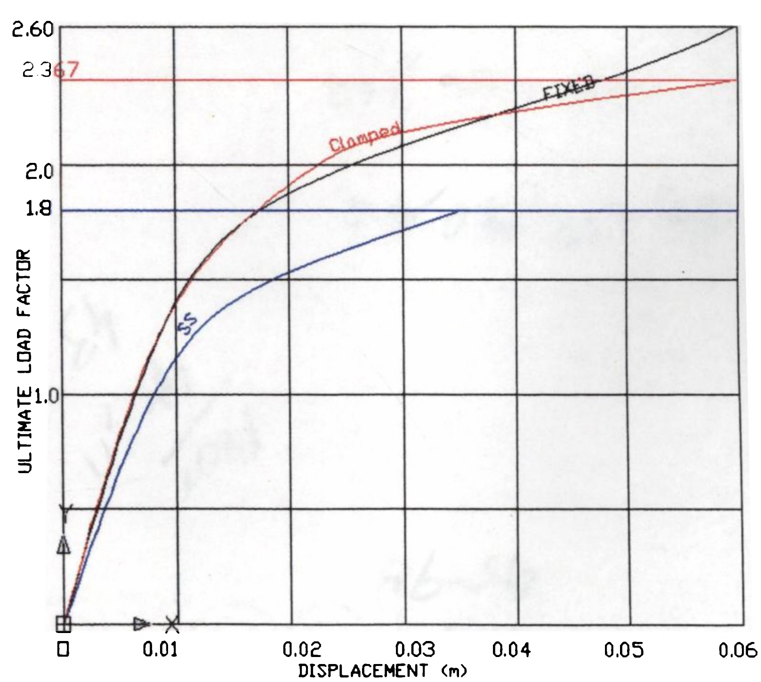

Fig 4.40 P-Δ Curve for Frame Model with Geometric & Material Nonlinearity

For the frame mode; initiation of the nonlinearity has been found to be at a load level 0.85 times the design loads specified by NES, when all the degrees of freedom are restrained at both the ends. When the rotational degrees of freedom are released at the ends, the load value has been observed as 0.8 times the design loads, indicating a reduction of 5.88% of design load.

The ultimate load has been found to be 2.6 times, 2.37 times and 1.9 times the design load for the fixed, clamped and the simply supported conditions respectively, indicating a difference of 8.85% and 19.83% for the latter cases compared to the fixed boundary condition. The deflection values are presented in Table 4.18. The effect of releasing the rotation restraint on deflection has been found as 25.26%. The difference for the clamped case is 33.29%.

Edge Condition	Deflection Shell (mm)	Deflection Deck (mm)
Fixed	58.86	43.13
Simply Supported	35.02	20.47
Clamped	59.58	39.36

Table 4.18 - Deflections from Geometric and Material Nonlinear Analysis of the Frame Model

The ultimate load factors of the frame model for the geometric nonlinear analysis and the geometric and material nonlinear analysis are summarized in table 4.19

Type of Nonlinearity	Fixed	Clamped	Simply Supported
Geometric	3.3	2.67	1.9
Geometric and material	2.6	2.37	1.8

Table 4.19 – Ultimate Load Factors of the Frame Model

The percentage variation of the ultimate load factor for the hold model and the frame model is found to be 3.5% to 34.7% for geometric nonlinear analysis and

5.2% to 18% for combined geometric and material nonlinear analysis for the three boundary conditions.

4.9 Reliability Analysis

4.9.1 General

Reliability analysis of the hold model of the warship based on the ultimate load factor for combined geometric and material nonlinearity has been performed. Young's modulus and the side shell thickness are taken as the random variables. The reliability index β and the probability of failure pf have been estimated by First-Order Reliability Method.

4.9.2 Calculation of Reliability Parameters

Mean Value of the Young's modulus has been taken as 209 GPa and that of the plate thickness as 6 mm between the upper decks and 8 mm between the ower decks. For a covariance of 5%, the Young's modulus varies between 198.55 GPa and 219.45 GPa and the thickness values vary between 5.7 mm and 6.3 mm and 7.6 mm and 8.4 mm. 25 sets of values of these random variables are made available for analysis by generating them using MATLAB. From the combined geometric and material nonlinear analysis, 25 ultimate load factors are evaluated as the response. The value of ultimate load factor for the standard model considered is 2.351, which is taken as the mean value μ_S. It is assumed that there is no deviation for this parameter (σ_S=0). The mean and standard deviation of the response is estimated from the 25 ultimate load factors as 2.10632 and 0.097304 respectively. Using First Order Reliability Method, the cumulative distribution function for normal distribution has been evaluated as 0.994 and the probability of failure as 0.006. The value is comparable with the reported results for similar vessels. The results of the analysis are presented in table 4.20

μ_R	2.10632
μ_S	2.351
σ_R	0.097304
σ_S	0
Reliability Index β	2.51460321
$\phi(\beta)$	0.994
Probability of Failure Pf	0.006

Table 4.20 –Reliability Analysis Results for Geometric and Material Nonlinear Analysis of the Hold Model

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CHAPTER 5

SUMMARY AND CONCLUSIONS

1. Preliminary structural design of a frigate size ship has been carried out using rules for warship structures promulgated by the Lloyd's Register of Shipping. A finite element model of the hull module, representative of the complexities in the geometric configuration has been created using the finite element software NISA. Two other models representing the hull geometry to a limited extent also have been created – one with two transverse frames and the attached plating alongwith the longitudinal members and the other representing the plating and longitudinal stiffeners between two transverse frames.

2. Linear elastic analysis of the three models viz., the hold model, the frame model and the interstiffener plating model have been carried out by keeping three different boundary conditions for each model. The structural responses thus evaluated have been compared with permissible values stipulated in rule books. The structural scantlings have been found adequate in all the cases.

3. On comparing the results of the hold model with frame model and interstiffener plating model, the results from the frame model are found to be closer to those predicted by hold model. The frame model can be employed for he linear elastic analysis of ship structure with reasonable confidence.

4. The influence of boundary restraints, mainly release of the rotational degree of freedom on the end nodes has been found insignificant regarding both stresses and deflections in both hold model and the frame model.

5. Clamped boundary condition has been found to yield fluctuating results irrespective of the investigations carried out and hence no conclusions have been derived and presented based on that.

6. Progressive collapse analyses of all the models have been conducted for the three boundary conditions, considering geometric nonlinearity. Based on the P-Δ curves have been generated in each of the above cases, the ultimate load causing failure has been identified as a multiple of the design loads specified by NES.

7. Combined material and geometric nonlinear analysis has been performed on the hold model and the frame model using von Mises yield criteria with elastic-perfectly plastic stress-strain curve. The effect of material nonlinearity has been demonstrated on comparing the ultimate load factors evaluated in geometric nonlinear analysis and combined geometric and material nonlinear analysis.

8. The ultimate load factor predicted by he frame model shows considerable deviation from that of the hold model in combined nonlinear cases. Hence the frame model is not recommended for nonlinear analysis.

9. Reliability analysis of the hold model based on the ultimate loa factor predicted by combined geometric and material nonlinearities have been conducted, keeping the Young's modulus and the shell thickness as the random variables. First Order Second Moment has been used to predict the reliability index and thereafter, the probability of failure and the values have been compared against standard values published in literature.

Scope for Future Work

1. Finite element analysis of 1-1-1 hold model can be performed and the effect of adjacent holds and bulkheads can be quantified and presented.

2. The scope of reliability analysis can be extended to more random variables and more precise and effective methods like Random Polar Sampling Technique etc.,. can be put into use.

3. Effect of dynamic loads can be investigated in the models presented in this study.

Publications Based on the Research Work

1. Sunil Kumar PG, Nandakumar CG, 'Ultimate Strength Analysis of Slender Ships', Ships and Offshore Structures, (Communicated)

2. Sunil Kumar PG, Nandakumar CG, 'Reliability Analysis of Slender Ships', Journal of Ship Technology, (Communicated)

REFERENCES

1 Assakkaf IA, Ayyub BM and Atua KI (2000) Reliability-Based Load and Resistance Factor Design (LRFD) of Hull Girders for Surface Ships, American Society of Naval Engineers.

2 Assakkaf IA. and Ayyub BM (2004) Comparative and Uncertainty Assessment of Design Criteria for Stiffened Panels, Journal of Ship Research, Vol. 48, No. 3

3 Bathe KJ, Finite Element Procedures, Prentice Hall India Ltd, 2005

4 Bai Y (2003) Marine Structural Design, Elsevier

5 Basu RI, Kirkhope KJ, Srinivasan J (1996) Guidelines for Evaluation of Ship Structural Finite Element Analysis, SSC Report 387

6 Belenkiy L and Raskin Y (2001) Estimation of the Ultimate Load on Structural Members Subjected to Lateral Loads, Marine Technology, Vol. 38, No. 3

7 Byklum E and Amdahl J (2002) Nonlinear Buckling analysis and Ultimate Strength Prediction of Stiffened Steel and Aluminium Panels, Second International Conference on Advances in Structural Engineering and Mechanics

8 Chalmers DW (1993) Design of Ships' Structures, Her Majesty's Stationery Office, UK

9 Cook RD (1995) Finite Element Modeling for Stress Analysis, John Wiley and Sons

10 Cui W, Wang Y, Pedersen PT (2002) Strength of ship plates under combined loading, Marine Structures 15

11 Daidola JC and Basar NS (1981) Probabilistic structural analysis of ship hull longitudinal strength – SSC Report 301

12 Fang C and Das PK (2004) Survivability and Reliability of Damaged Ships after Collision and Grounding. Journal of Ocean Engineering, Aug 2004

13 Fellows DC (1998) Lecture Notes on Ship Structures for M Sc Naval Architecture, Dept of Mechanical Engineering, University College London

14 Gordo JM and Soares CG (1996) Approximate Method to Evaluate the Hull Girder Collapse Strength, Marine Structures 9

15 Gordo JM, Soares CG and Faulkner D (1996), Approximate Assessment of the Ultimate Longitudinal Strength of the Hull Girder, Journal of Ship Research, Vol. 40,No. 1

16 Hu Y, Zhang S, Sun J (2001) Analysis on the ultimate longitudinal strength of a bulk carrier by using a simplified method, Marine Structures 14

17 Hughes OF (1995) Ship Structural Design - A Rationally Based, Computer-Aided, Optimisation Approach, John Wiley and Sons

18 ISO Report ISO/CD 18072-2 (2005) Requirements for Ship structures Ultimate Limit State Assessment

19 Jensen JJ (2001) Loads and Global Response of Ships, Elsevier Ocean Engineering Book Series, Vol 4

20 Karvinen KG and Pegg NG (2006) A simplified method for nonlinear failure analysis of stiffened plates, Marine Structures 19

21 Leheta HW and Mansour AE (1997) Reliability-based Method for Optimal Structural Design of Stiffened Panels, Marine Structures 10

22 Mansour AE, Thayamballi A (1980) Ultimate Strength of a Ship's Hull Girder in Plastic and Buckling Modes, SSC Report 299

23 Mansour AE (1990) An Introduction to Structural Reliability Theory - SSC Report 351

24 Mansour A, Lin M, Hovem L and Thayarnballi A (1993) Probability Based Ship Design Procedures : A Demonstration - SSC Report 368

25 Mansour A and Thayamballi (1994) Probability Based Ship Design : Loads and Load Combinations - SSC Report 373

26 Mansour A E, Wirsching PH, Lucket MD, Plumpton AM and Lin YH (1997) Structural Safety of Ships ,SNAME Transactions

27 Masaoka K. and Mansour A (2004) Ultimate Compressive Strength of Imperfect Unstiffened Plates: Simple Design Equations, Journal of Ship Research, Vol. 48, No. 3

28 Moan T, Das PK, Gu X.K, Friis-Hansen P, Hovem L, Parmentier G, Rizzuto E, Shigemi T, Spencer J (2006) Special Task Committee on Reliability Based Structural Design and Code Development. 16th International Ship and Offshore Structures Congress, August 2006

29 Naar H (2006) Ultimate Strength of Hull Girder for Passenger Ships, Helsinki University of Technology, Department of Mechanical Engineering, Ship Laboratory.

30 Naval Engineering Standards 154 (2000) Design Standards for Surface Ships Structures April 2000, UK MoD

31 NISA User Manual (1997) Engineering Mechanics Research Corporation

32 Paik, JK. and Pendersen PT (1995) Ultimate and Crushing Strength of Plated Structures, Journal of Ship Research, Vol. 39, No. 3.

33 Paik JK. , Thayamballi A, Wang G and Kim BJ (2000) On Advanced Buckling and Ultimate Strength Design of Ship Plating, The Society of Naval Architects and Marine Engineers

34 Paik JK, Thayamballi A and Kim BJ (2001) Advanced Ultimate Strength Formulations for Ship Plating Under Combined Biaxial Compression/Tension, Edge Shear, and Lateral Pressure Loads, Marine Technology, Vol. 38, No. 1

35 Paik JK, Thayamballi A, Pedersen PT and Park Y (2001) Ultimate Strength of Ships Hulls under Torsion, Ocean Engineering, Volume 28, Issue 8, Pages 1097-1133

36 Paik JK and Kim BJ (2002) Ultimate Strength Formulations for Stiffened Panels under Combined Axial Load, In-Plane Bending and Lateral Pressure: A Benchmark Study, Thin-Walled Structures 40

37 Paik, JK. and Seo JK (2005) Ultimate Limit State Assessment of Ship Structures, International Conference on Computational Methods in Marine Engineering, Barcelona

38 Paik JK and Kim BJ (2007), Progressive Collapse Analysis of Thin-walled Box Columns, Thin-Walled Structures.

39 Paik JK, Kim BJ and Seo JK (2008) Methods for Ultimate Limit State Assessment of Ships and Ship-shaped Offshore Structures: Part I — Unstiffened Plates, Ocean Engineering 35

40 Paik JK, Kim BJ and Seo JK, Methods for Ultimate Limit State Assessment of Ships and Ship-shaped Offshore Structures: Part II — Stiffened Plates, Ocean Engineering 35 (2008)

41 Rahman, MK. and Chowdhury M (1996) Estimation of Ultimate Longitudinal Bending moment of Ships and Box Girders, Journal of Ship Research, Vol. 40, No. 3.

42 Rules and Regulations for the Classification of Naval Ships (2002) Lloyds Register of Shipping

43 Soares CG, Dogliani M, Ostergaard C, Parmentier G, and Pedersen PT (1996) Reliability Based Ship Structural Design, SNAME Transactions, Vol. 104.

44 Steen E, Ostvold TK and Valsgard S (2002) A New Design Model for Ultimate and Buckling Strength Assessment of Stiffened Plates, Marine Advisory Services, Det Norske Veritas, Norway

45 Timoshenko SP and Krieger SW (1959) Theory of Plates and Shells, McGraw-Hill International Editions.

46 Yao T (2003) Review Article on Hull Girder Strength, Marine Structures 16

47 Ziha K, Parunov, J and Tusek B (2001) The Ultimate Strength of the Ship Hull