

ISTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

**STRUCTURAL WEIGHT OPTIMIZATION
OF A NAVAL SHIP HELIDECK**

**M.Sc. Thesis by
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Department : Naval Architecture and Marine Engineering

Programme : Naval Architecture and Marine Engineering

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**ASKERİ GEMİLERDE HELİKOPTER GÜVERTESİNİN
YAPISAL AĞIRLIK OPTİMİZASYONU**

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ABBREVIATIONS

SMAX	: Maximum Equivalent Stress (Von-Misses)
UMAX	: Maximum displacement (mm)
CNTRINC	: Central inclined column radius
CNTRVRT	: Central vertical column radius
L_H	: Longitudinal girder height
L_T_1	: Longitudinal girder thickness
L_T_2	: Girder flange thickness
L_W	: Girder flange width
RCLMNS	: Rear column radius
SDINC	: Side inclined column radius
SDVRC	: Side vertical column radius
T_H	: Transverse frame depth
T_T_1	: Transverse frame web thickness
T_T_2	: Transverse flange thickness
T_W	: Transverse flange width
TOTVOL	: Total volume of the structure
DV	: Design variable
SV	: State variable
OBJ	: Objective function
OPT	: Optimization
TOLER	: Tolerance
GL	: Germanischer Lloyds of Register
ABS	: American Bureau of Shipping
DNV	: Det Norske Veritas
LR	: Lloyds Register
KR	: Korean Register
MOD	: Ministry of Defence
CFD	: Computational Fluid Dynamics
FEM	: Finite Element Method
ISSC	: International Ship and Offshore Structures Congress
TEU	: Twenty-foot Equivalent Unit
MPa	: Mega Pascal
Hz	: Hertz
MOO	: Multi-Objective Optimization
APDL	: ANSYS Product Design Language
G	: Maximum take-off weight of helicopter
Pe	: Landing force
e	: Helicopter wheels skid distance

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STRUCTURAL WEIGHT OPTIMIZATION OF A NAVAL SHIP HELIDECK

SUMMARY

It is a well-known fact that nowadays optimization studies are being broadly developed and applied into engineering sciences. One of the most influential areas in optimization studies is naval ships optimization. Naval Ships are optimized with their structural, hydrodynamic and stability considerations. It is also a well-known fact that by the help of the developing technology, nowadays, optimization of difficult problems such as naval ships helidecks can be performed successfully via computer programmes.

Based on the projects that have been carried out in School of Marine Science and Technology (UK), it was discovered that there had been examples of structural analysis of helidecks. However, optimization of these structures belongs to a different phenomenon. Due to the nature of optimization and helideck structures, the analysis was performed in the sense of Collaborative Optimization. Stress and displacement in the structure were concerned at the same time in the analysis via collaborative optimization techniques.

This thesis presents the optimization experiments which were performed on Bremen Class German frigates. The structure of helideck was designed by own regarding to the main dimension variables belongs to these special kinds of vessels. Moreover, Germanischer Lloyds of Register (GL) rules were used to check the flight area, structural and general arrangement requirements on flight deck structures in a Bremen Class frigate. Moreover, the helicopter was selected as type Seahawk 70-B and all calculations were done in sense of relevant scantlings.

The objective function of this problem is to find the minimum weight design of the helideck structure which is constrained by equivalent stress and displacement aspects at the same time. ANSYS Finite Element Analysis (FEA) software was used to optimize the structure. Problem consists of 13 independent design variables changing in every loop to find the best design option. Two different design optimization algorithms were used to optimize the weight of the structure. Comparison of these optimization methods and buckling assessment of the columns were given in the thesis as well. Design loads were also selected as the worst scenario which can be applied on this structure from GL rules.

ASKERİ GEMİLERDE HELİKOPTER GÜVERTESİNİN YAPISAL AĞIRLIK OPTİMİZASYONU

ÖZET

Son yıllarda optimizasyon yöntemlerinin sürekli olarak geliştiği ve mühendislik alanında kullanıldığı bilinen bir gerçektir. Askeri gemilerin optimizasyonu sürekli olarak gelişen alanlardan biridir. Askeri gemilerin yapısal, hidrodinamik ve stabilite unsurlarının dizayn optimizasyonları yaygınca yapılmaktadır. Aynı zamanda, gelişen teknolojiye dayanarak askeri gemilerin helikopter güverteleri gibi karmaşık dizayn problemlerinin optimizasyonu da paket programlar aracılığıyla gerçekleştirilmektedir.

Helikopter güvertelerinin yapısal analiziyle ilgili çalışmalar Newcastle Üniversitesinde ve İTÜ'de mevcuttur. Fakat, bu yapıların optimizasyonu farklı bir fiziksel fenomene sahiptir. Helikopter güvertesinin doğasından dolayı yapısal olarak çökme ve gerilme optimizasyonlarının aynı anda kısıtlara uygun olarak yapılması gerekmektedir.

Bu tezde yapısal optimizasyon çalışmaları Alman Bremen tarzı Fırkateynlere göre yapılmıştır. Helikopter güvertesi Bremen tarzı Fırkateyn ana boyutları baz alınarak yeniden dizayn edilmiş ve optimizasyonu yapılmıştır. Uçuş alanının, yapısal elemanların ve genel yerleşimin dizaynında Alman Lloyd kuralları baz alınmıştır. Dizayn yükü olarak güverte yükü haricinde seçilen Seahawk 70-B tipi helikopterin acil durum çarpma yükü uygulanmıştır.

Optimizasyonun hedef fonksiyonu yapısal olarak belirli çökme ve gerilim kısıtlarının aynı anda sağlanması koşuluyla en hafif ve sağlam helikopter güvertesinin dizayn ölçülerini bulmaktır. Yapının optimizasyonu sırasında ANSYS sonlu elemanlar paket programı kullanılmıştır. Problem her döngüde yenilenen 13 bağımsız dizayn kriterinden oluşmaktadır. Optimizasyon metodu olarak 2 farklı algoritma kullanılmış ve yöntemler birbirleriyle karşılaştırılmıştır. Güverte kolonları sistem optimize edildikten sonra burkulma analizine tabi tutulmuştur.

1. INTRODUCTION

The present dissertation study concerns about structural optimization applied to naval ships, with a specific emphasis on weight optimization of a naval ship helicopter deck (helideck) regarding to displacement and equivalent stress constraints and 13 independent design variables. Motivation of this dissertation is presented in Chapter 1 and objectives and aims of the thesis together are outlined in order to give a brief description of each 8 chapters.

1.1 Motivation

Over the past decade we have witnessed a remarkable change in optimization studies applied to engineering fields by the help of developing computer technologies. Day by day engineers are seeking for better designs which are more reliable, safe and ergonomic and more time saving for related problems which they are facing. Optimization area consists of all these developing subjects hence, an optimum design is one that performs the intended function while meeting all design constraints and using the least amount of material. This dissertation study concerns structural optimization of a naval ships helideck under displacement and stress constraints applied at the same time. Safety and reliability of a naval ship is the first priority concerned in a design while there are multiple conflicting criteria like displacement, stress and vibration which must be handled at the same optimization process. This process is called “Collaborative Optimization”, which depends on different objective functions meeting several design constraints at the same time.

Several approaches to find an optimum solution of engineering design problems have been developed in the past. Design teams needed to find an optimum solution or compromise of solutions to solve the optimization problem stated by Parsons (2004). However, due to the complicated nature of structures which was very difficult to find a compromise solution, even a feasible set because of the lack of computer softwares which could handle this process thoroughly. Therefore, optimization studies on ship structures have been studied with only few design variables and constraints in the

past. This approach made the results diverge from the actual structure responses and decreased the accuracy of the solution of optimization. On the other hand, it must be born in mind that more design variables increases the chance of finding a local optimum solution which can be misleading for engineer. However, by the help of new engineering softwares, we can control design variables, state variables and objective functions' approximations and find a compromise solution via weight functions stated by Parsons (2004).

It is obvious that more conventional and simple solutions need to be investigated and adopted in order to improve optimization of naval ship structures. Despite the large amount of published work which exists on optimization of panel structures, analysis which addresses naval ship helideck structural optimization couldn't be fulfilled frequently due to the complex nature of the problem and different design concerns. One such ship panel problem regarding to stress, vibration and ship motions concern was analysed by Huang & Wang (2009). The aim of that study was to provide a static and dynamic collaborative optimization for a ship hull structure and to obtain a better design.

To meet today's naval ship requirements vessels need to travel faster, with increased operability and reach required strength requirements. However, all these requirements make the solution to be appeared generally in infeasible region and even inaccessible due to the level of complexity and large numbers of design variables involved in the problem. In order to simplify the optimization a multi-level process can be used stated by Featherston & Watson (2008). This process gives a chance to apply different methods and increases the efficiency of the analysis.

The most notable contribution to find the minimum weight naval ship helideck design process was the proceedings of the ISSC (2009) which concerns the uncertainties in modelling techniques for naval ships regarding to structural design methods. Different classification society rules were considered and compared to each other. In order to assess the operational considerations of the naval ship, which affect the loading and boundary conditions, GL rules are applied in the design and analysis process to ensure the coherence.

In conclusion, the facts stated above presents the motivation of the study. Although, the lack of papers on naval ship structural optimization, this paper consists of many

solution techniques applied to find the best solution to find the global optimum of this weight minimization process.

1.2 Aims and objectives

Within the framework outlined in Section 1.2 the following goals and objectives are met to satisfy to find the best feasible set “the global optimum” solution of weight optimization process of a naval ship helideck which meet the design constraints.

The first objective is to perform a literature review to assess the basic requirements in the naval ship structural optimization and assess the regulations especially emphasized on naval ship helideck structures and also show the relevance and importance of the current research.

The second objective is to model a new design of helideck structure regarding to the Bremen Class German Frigates scantlings, which will give a comparison chance for the first design and the final optimized design whereby an existing ships example to prove the reality.

The third objective is to investigate the optimization database and assign design, state variables and objective function. In addition, third objective also includes finding first responses of structure regarding to displacement and stress constraints and finding the final minimum weighted design via collaborative optimization.

The fourth objective is to investigate the results of the optimization process and determine about if the global optimum of the problem has been reached. Moreover, fourth objective embraces making a comparison of different optimization tools in ANSYS and their pros and cons.

1.3 Layout of the thesis

Following this introduction and explanation of the aims and objectives Chapter 2 presents a literature review on the main research area of structural panel optimization applied to naval ships, regular vessels and aerospace structures. Although, these studies have been accomplished for different environments, they present the same philosophy of structural optimization. Only the design concerns including loading and boundary conditions and regulations differ from the ship structures.

Chapter 3 discusses the philosophy behind the optimization basics and gives a general knowledge about penalty functions, steepest descent methods, weighted sum approach, design and state variables and objective functions.

Following a brief review on literature review related to structural optimization and optimization philosophy, Chapter 4 presents a specific emphasis on structural optimization and the optimization tools in ANSYS. Moreover, Chapter 4 presents the approximations which are used for assumptions and solution techniques in ANSYS. Design, state variables and objective function tolerances are also concerned in this chapter. In addition, restart mechanism which is used to find new search directions for the optimization database to find the global optimum and gradient, sweep tools which are used to find local and global sensitivity are also concerned in this chapter.

Chapter 5 presents the review of regulations and calculations depending on Naval Ship design rules of Germanischer Lloyds Register (GL). Not only, helideck design requirements are addressed in this chapter, but also loading and boundary conditions are also conducted. Special requirements about flight areas, specifications and scantlings of Seahawk 70-B Helicopter are also issued in Chapter 5.

In Chapter 6, the analysis of helideck structure takes place. Different kinds of optimization techniques and approaches are carried out. By the help of restart mechanisms, final set of response data is forced to find a new search direction in database to be ensured that the global optimum has been reached. Sub-problem optimization method and First Order method are compared regarding to their solution time consumption namely “computational cost” and accuracy aspects.

In Chapter 7 the results of the analysis are taken place. Interpretations about different solution techniques, global and local sensitivity studies and conclusion of the analysis are done. All results are shown in graphical figures to ensure what factor effects the most of the structural response of helideck under determined loading and boundary conditions in advance.

1.4 The contribution of the thesis

This study aims to occupy the gap in the naval ship structural optimization area especially emphasised on helideck optimization. As mentioned above, in the past decade due to the lack of softwares and technology and due to the complex nature of

naval ship structures, few studies have done on this area. Hopefully this study will be beneficial for latter studies will be done on this area.

1.5 Summary

The first chapter identified the context for naval ship helideck design optimization research and highlighted the solution techniques. In this chapter a brief review of structural optimization studies, optimization basics and tools in ANSYS, regulations and rules which have to be applied on naval ship helideck structures, structural analysis, optimization and results are identified. A detailed breakdown of the aims and objectives has been given together with review of the content and layout of the thesis.

2. LITERATURE REVIEW

Little information exists on the design and structural optimization of the naval ship helicopter decks in the current literature. Therefore, main objective of this chapter is to review the literature on naval ship helidecks with a special interest on design process and optimization methods.

Following the introduction, Section 2.1 gives the general knowledge about multi-objective optimization with a special emphasis on weighted sum method. A survey of existing ship structural optimization papers are presented in Section 2.2. Section 2.3 reviews design process on of naval ships. Moreover, a review of buckling assessment is given in Section 2.3 focusing on the Ministry of Defence (MOD) rules. Finally, conclusions are given in Section 2.4.

2.1 Multi-objective optimization features

Most of the marine optimization problems contain multiple conflicting constraints and objective functions. In order to explain the main idea behind the multi-objective optimization, it is beneficial to define multi criterion and multidiscipline optimization features in advance. According to Parsons (2004), multi criterion optimization is defined as more than one objective functions to be concerned at the same time to make an optimization decision. However, multidiscipline optimization is depicted as an overall philosophy concerning entire design instead of subsystem optimization within each objective function. Entire design optimization can be defined as optimizing different disciplines at the same time, such as computational fluid dynamics (CFD) with structural analysis in finite element method (FEM). Conceptual design process are generally performed with multidisciplinary optimization methods due to the complexity of the nature of marine structures, stated by Parsons (2004). Moreover, multi criterion optimization can be defined in the following equations.

$$\text{Min } F_x = (f_1(x), f_2(x), f_3(x), \dots, f_k(x)) \quad (2.1)$$

$$X = [x_1, x_2, x_3, \dots, x_N]^T$$

While the equality and inequality constraints can be stated as:

$$\begin{aligned} h_i(x) &= 0 & i &= 1, 2, \dots, I \\ g_i(x) &\geq 0 & i &= 1, 2, \dots, J \\ x_i^l &\leq x_i \leq x_i^u \end{aligned} \quad (2.2)$$

Where $K \geq 1$ is the multi optimization criteria from $f_1(x)$ to $f_k(x)$ and N is the number of unknown design variables and l and u define the lower and upper bound of each design variable.

Moreover, multi criterion optimization is generally defined as *Pareto optimum*. In general, no solution vector X exists that minimizes all the k objective functions simultaneously. Therefore, the *Pareto optimum solution* is used in the solution of multi objective optimization problems. A solution is Pareto optimal if it is not possible to change the point in the design space and at least one of the objective functions is improved without any worsening within the other objective functions, stated by Arora (2009). In other words, a feasible solution X is called *Pareto optimal* if there is no other feasible solution Y such that $f_i(Y) \leq f_i(X)$ for $i = 1, 2, \dots, k$ with $f_j(Y) < f_j(X)$ for at least one j . According to Arora (2009), if it is not possible to move from the optimum point and improve all objective functions simultaneously, it is defined as *Weakly Pareto optimal*. For instance, if the objective functions are given by $f_1 = (x - 3)^4$ and $f_2 = (x - 6)^2$, their graphs are shown in Figure 2.1. For this problem, all the values of x between 3 and 6 (points on the line segment PQ) denote Pareto optimal solutions.

Design teams determine which criteria are the most important for their design intend. According to Parsons (2004), design teams are always looking for a compromise solution in the Pareto optimal set.

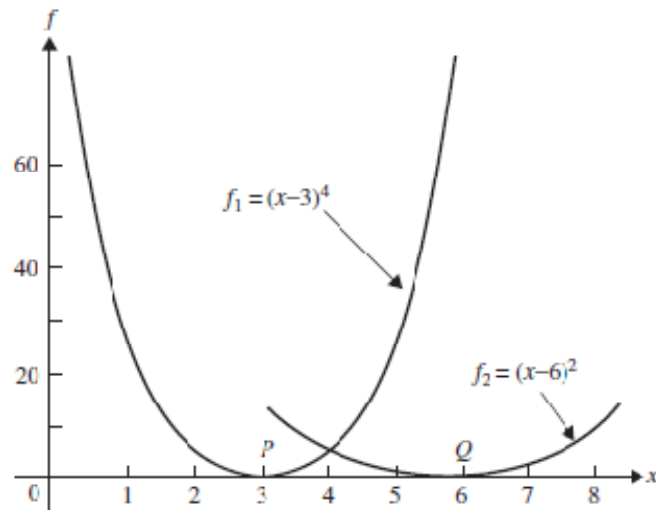


Figure 2.1 : Pareto optimal solutions

In order to perform optimization, different methods are adopted to solution techniques in the literature. One of these methods is depicted as *weighted sum method*. Weighted sum method to perform multi-objective optimization (MOO) is widely used for optimization problems. It provides multiple solution sets by altering weights and a single solution point reflecting references which are incorporated in the selection of a single set of weights, stated by Arora (2009). Solutions for MOO problems are performed via Pareto optimality. Compromise comprises the basis of multi objective optimization. According to Messac and Mullur (2006), compromise between the design criteria results in achievement of an optimum solution of multi criterion optimization. An example in design objective space of two criterion problem is shown in Figure 2.2.

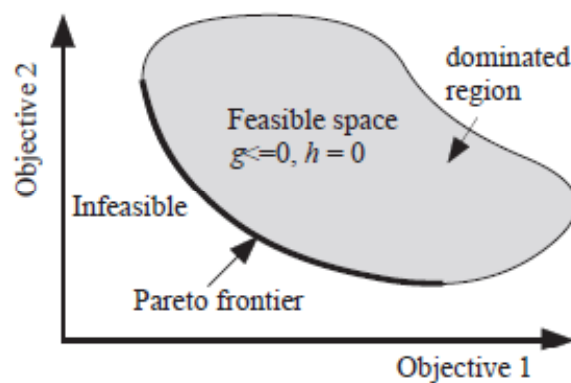


Figure 2.2 : Design objective space for two criterion problem

Moreover, according to Arora (2009), if user denotes preferences and lets the algorithm to find a single solution before performing the optimization, it is called “priori articulation of preferences”. Moreover, if a solution is manually selected within the Pareto optimal set; it is called “posteriori articulation of preferences”.

Scalar weights w_i are selected to minimize the utility function shown in the following equation. Generally, weights are selected as positive in the literature.

$$U = \sum_{i=1}^k w_i F_i(\mathbf{x}) \quad (2.3)$$

In order to minimize the utility function, the entire objective functions and design space must be convex. If a function is convex, Hessian matrix of it must be positive semi definite. In addition, it must be also remembered that, local optimum of a convex function is denoted as its global optimum.

Findings of Arora (2009) related to weight alternation can be summarized below.

- Weights must be considerably related to other weights and responding objective functions if preferences are denoted in advance to optimization.

This is depicted as priori articulation of preferences.

- All criterions must be normalized as they have similar ranges to apply ranking method to adjust weights.
- However, if paired comparison method is used to adjust weights criterions do not need to be normalized.
- Pareto optimum solution depends on the Pareto optimal hyper surface, normalized units of criterions, gradients of the objective functions and the constraints of the Pareto set.

Moreover, user must decide about which MOO method best reflects the characteristics of the analysis. The best method can be selected with a good knowledge about the nature of the problem, in other words pitfalls of it. There are several different methods for MOO and they are summarized with their characteristics in Table 2.1.

Table 2.1 : Comparison of multi objective optimization methods

<i>Method</i>	<i>Always yields Pareto optimal point?</i>	<i>Can yield all Pareto optimal points?</i>	<i>Involves weights?</i>	<i>Depends on function continuity?</i>	<i>Uses utopia point?</i>
Genetic	Yes	Yes	No	No	No
Weighted sum	Yes	No	Yes	Problem type and the optimization engine determines this.	Utopia point or its approximation is needed for function normalization, or in the method formulation.
Weighted min-max	Yes	Yes	Yes	Same as above	Same as above
Weighted global criterion	Yes	No	Yes	Same as above	Same as above
Lexicographic	Yes	No	No	Same as above	No
Bounded objective fun.	Yes	No	No	Same as above	No
Goal programming	No	No	No	Same as above	No

2.2 Review of ship optimization papers

A number of researches have performed optimization of ship hull structure in the last two decades. Huang and Wang (2009) executed a work on optimizing a ship's hull structure with a specific interest in static and dynamic responses of the structure. Collaborative optimization (CO) method is used to integrate static, modal and dynamic responses of a ship panel. Aim of this research is to perform a multi-objective optimization problem of a container ship stern panel. Using CO and bi-level structure approach, optimization is performed efficiently. In order to solve the problem internal penalty functions are used and concurrently all system is divided into two phases.

Firstly, initial scantlings of the frames, which are calculated via classification society rules, are applied to the sub-system level optimization. Next, static optimization of the structure is performed. The aim of this optimization process is to minimize the first objective function (F_1) in other words, the total weight of the ship stern panel. Mechanical properties of materials $\sigma_{\max}$ and $\tau_{\max}$ were determined from classification rules and applied as a constraint to the optimization problem. Secondly, mode analysis of the structure is performed. The aim of the modal analysis is to find the first natural frequency (F_2) of the ship stern panel. Modal optimization consists of maximizing F_2 . Modal constraints are applied as state variables to the sub-problem. While modal constraints are being handled deviation values between first three natural frequencies and excitation frequencies were determined from rules. Thirdly,

objective function of dynamic optimization is to minimize F_3 , which denotes the maximum acceleration of ship hull structure. Finally, system level optimization is performed via standard CO algorithm. Three different objectives are participated in the system level optimization. Therefore, difficulties are encountered during the optimization process due to different units and magnitude orders of the objective functions. Before performing the system level optimization, it will be beneficial to define the global criterion method.

In the global criterion method the optimum solution $\mathbf{X}^*$ is found by minimizing an evaluated global criterion, $F(\mathbf{X})$, such as the sum of the squares of the relative deviations of the individual objective functions from the feasible ideal solutions. Thus

$\mathbf{X}^*$ is found by minimizing the following equation:

$$F(\mathbf{X}) = \sum_{i=1}^k \left\{ \frac{f_i(\mathbf{X}_i^*) - f_i(\mathbf{X})}{f_i(\mathbf{X}_i^*)} \right\}^p$$

$$g_j(\mathbf{X}) \leq 0, j = 1, 2, \dots, m \quad (2.4)$$

Where p is a constant and $\mathbf{X}_i^*$ is the ideal solution for the i^{th} objective function. The solution $\mathbf{X}_i^*$ is obtained by minimizing $f_i(\mathbf{X})$ subject to the constraints.

The goal of the system level optimization is to minimize the sum of residuary subsystem solutions. The system function is

$$\text{Minimize } \left| \frac{F_1(z) - F_1^*}{F_1^*} \right| + \left| \frac{F_2(z) - F_2^*}{F_2^*} \right| + \left| \frac{F_3(z) - F_3^*}{F_3^*} \right| \quad (2.5)$$

Where, $F_i(z)$ is the i^{th} disciplinary computed solution in the system-level model directly coming from disciplinary analysis F_i^* is the subsystem-level optimum solution in its disciplinary optimization model lonely.

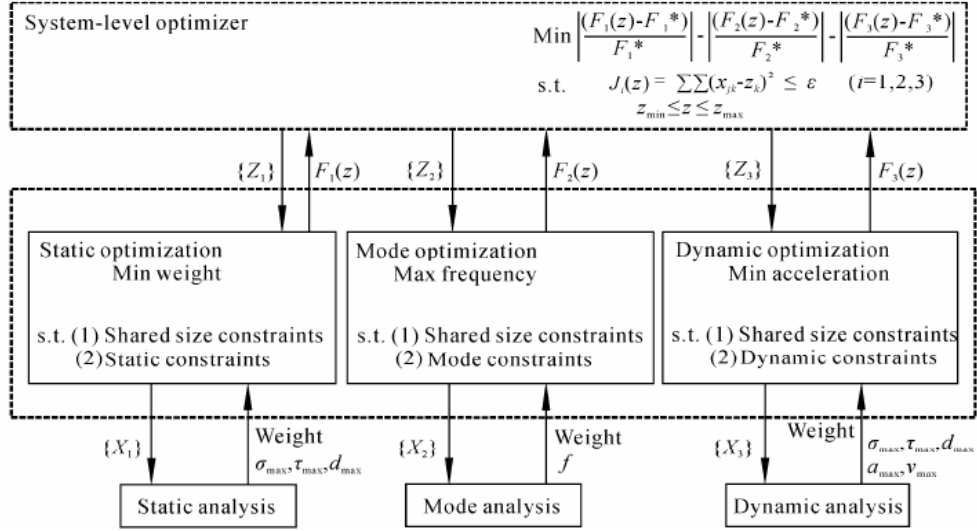


Figure 2.3 : Static and dynamic CO architecture

System level objective function optimization curve and comparison between initial and final design variables of 3100 TEU container ship stern panel is illustrated in Figure 2.4.

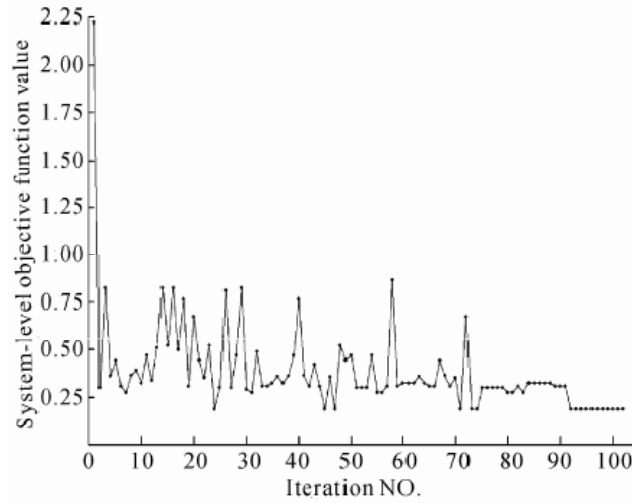


Figure 2.4 : System level optimization values vs. iteration numbers

Table 2.2 : Initial and final dimensions of frames and shell

Design variable		Initial design /mm	Final design /mm
Plate/15mm	x_1	15	11
Plate/12mm	x_2	12	11
L125×80×12	x_3	125	100
	x_4	80	70
	x_5	12	10
⊥ 700×12 250×12	x_6	700	650
	x_7	250	230
	x_8	12	12

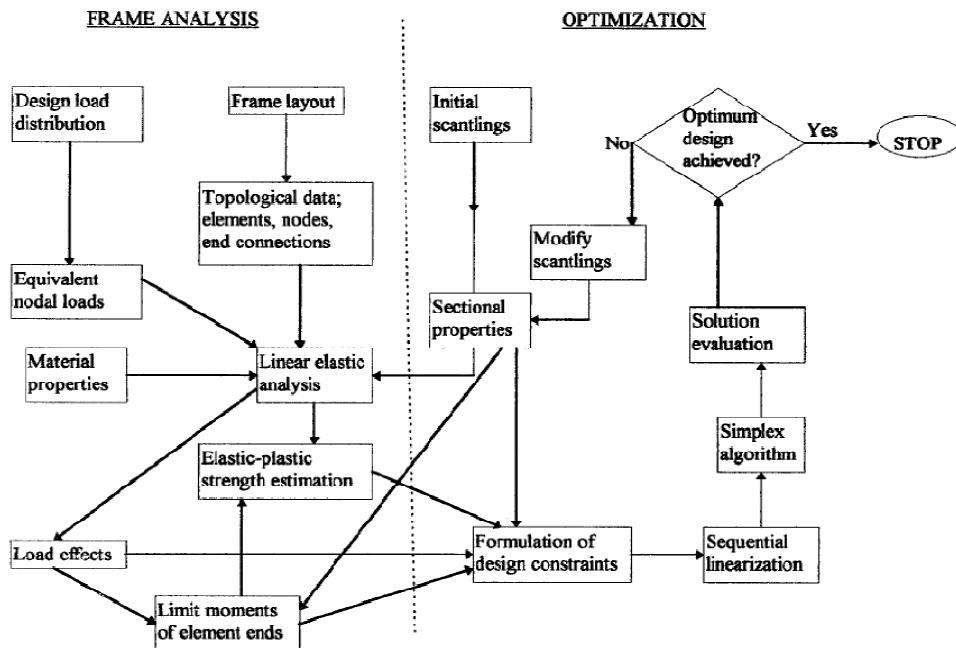
Table 2.3 : Initial and final responses

Design response		Initial design	Final design
Static response	$\sigma_{\max}/\text{MPa}$	126.94	142.99
	$d_{\max}/\text{m}$	0.069	0.073
Mode response	f_1/Hz	11.73	11.90
	f_2/Hz	26.27	26.43
	f_3/Hz	28.84	27.32
Dynamic response	$v_{\max}/(\text{m/s})$	0.002 5	0.002 6
	$a_{\max}/(\text{m/s}^2)$	0.131	0.132
Mass /kg		39 712.96	35 769.18

Findings of the authors can be summarised below.

- CO model is found successful achieving feasibility and reliability in both system and sub-system levels.
- Final responses of the ship stern have satisfied constraints. The maximum von-misses stress is found as 142.99 MPa which is lower than the stress threshold. Moreover, vibration characteristics of the ship are made better, in other words first natural frequency increased in 0.17 Hz.
- Weight of the ship is reduced more than 4 tons which is a percentage of 11%.

Moreover, according to Rahman (1998), frame analysis and optimization flow diagram with their interactions is illustrated in Figure 2.5 for structural computations.

**Figure 2.5 : The frame design and optimization flow diagram with interactions**

Furthermore, Augusto and Kawano (1997) also performed a research on a mixed continuous and discrete nonlinear constrained algorithm for optimizing ship hull structural design. Aim of this study is to optimize constrained design of ship structures using a nonlinear search algorithm. Entire problem formulations are explained such as, design variables, objective function, inequality constraints, equality constraints, local and global solutions.

Moreover, it is also explained that, penalty functions are widely used when a feasible initial point does not exist. Penalty search is fulfilled with an transformation function defined as $\varphi(X, r_k)$, that includes the original objective function, $f(X)$, and a penalty term, $p(X, r_k)$. Penalty parameter r_k is also known as scale factor.

Penalty function can be shown in the following equation.

$$\varphi(X, r_k) = f(X) + p(X, r_k)$$

Penalty factor is altered and a new search is performed if feasible region is not achieved around the optimum found by the algorithm.

In worked examples part, structural design of a Patrol Boat is performed and it is proved to be more efficient than conventional spiral design approach, as stated by Augusto and Kawano (1997).

The dimensions and design variables of the Patrol boat is stated below in Figures 2.6 & 2.7 & 2.8.

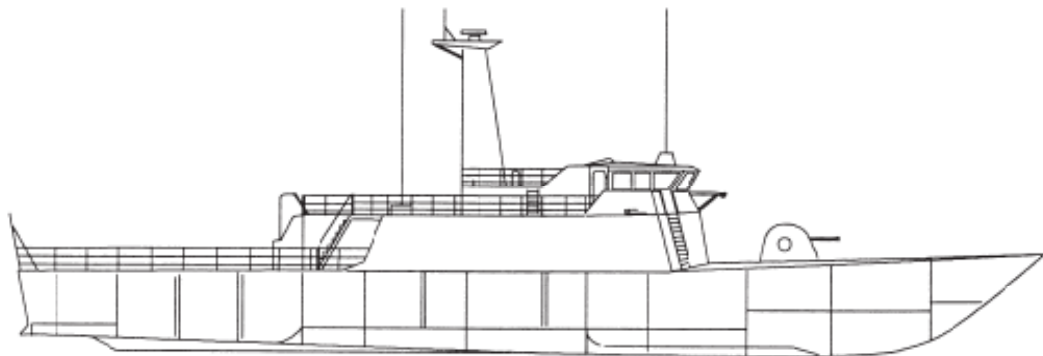


Figure 2.6 : Patrol boat used for optimization

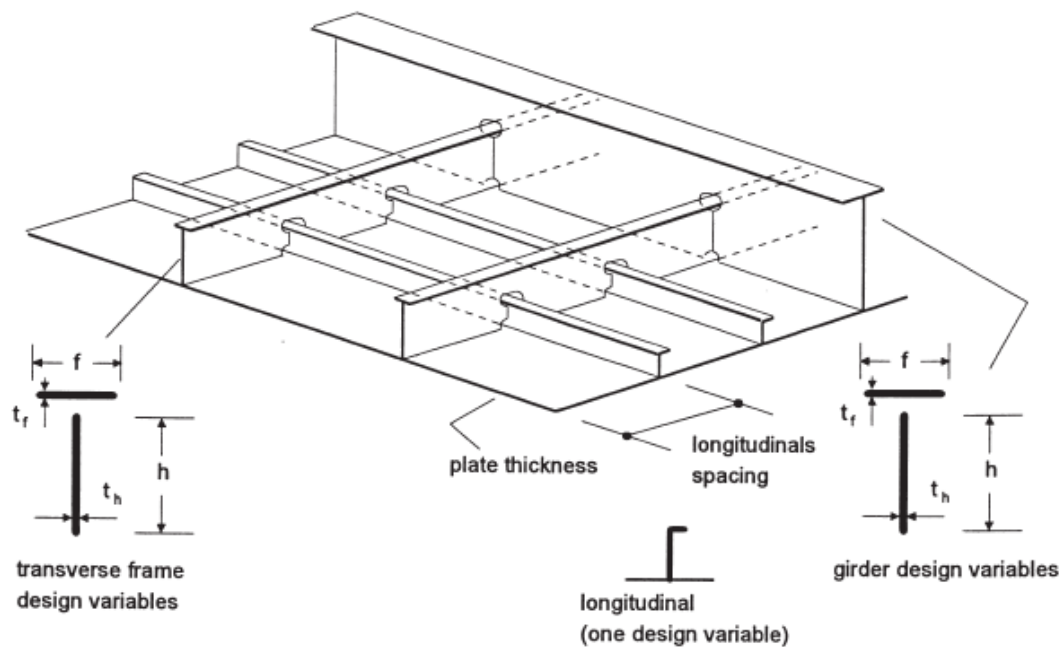


Figure 2.7 : Design variables

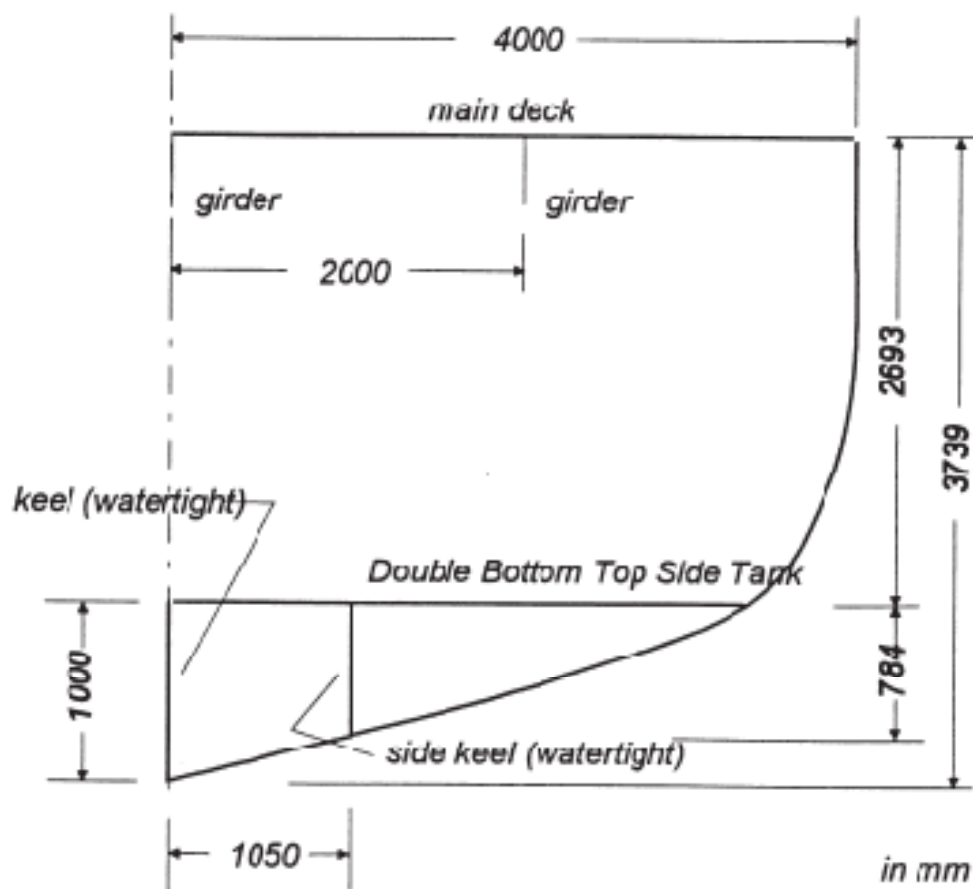


Figure 2.8 : Molded hull section

Finally, weight optimization iterations are illustrated in Figure 2.9.

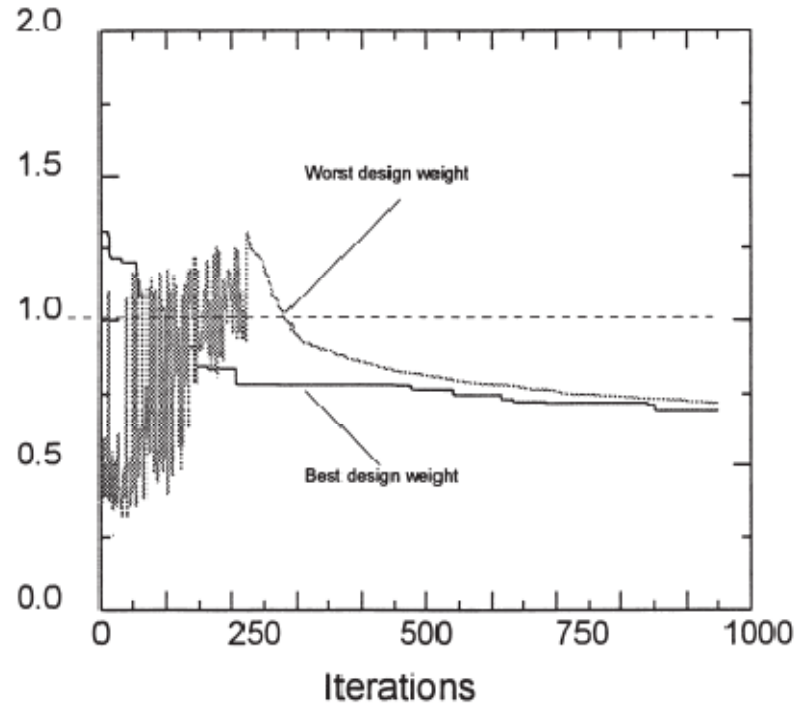


Figure 2.9 : Optimization curve

In conclusion, the algorithm presented is shown to be a powerful tool in performing design tasks where some kind of merit must be optimized. It was used as the heart of a computational system for designing ship structures, but it can also be used in other complex engineering problems.

2.3 Naval vessel design process

In this section structural design process of naval ship is processd in brief. Structural design and optimization of a naval ship is completely different from a merchant ship design and optimization, stated by International Ship and Offshore Structures Congress ISSC (2009). Moreover, blast loading, vulnerability and operational loads must be concerned exceptionally for naval ship design even though; these calculations are not common in merchant ship design. Goal of this research is to explore the aspects of naval structural design. All inspection process during the construction of a naval ship are explained. It is dictated that survey results are changing with different classification societies.

Moreover, structural analysis philosophy was also explained. According to ISSC (2009), while global bending moments are the first concern on large ships such as

frigates; on the contrary, in small ships such as patrol boats local loads are generally concerned. It is stated in ISSC (2009) that, only combat loads such as blast and explosion differ with merchant ships in design concern due to hull damages. Moreover, scantling determinations are performed same as merchant vessels after determining the loads applied on the vessel. Each component is assessed with its yielding and buckling aspects whether it has enough strength or not. It is mentioned in ISSC (2009) that, a full 3-D analysis is required for larger vessels such as frigates and destroyers.

Structural analysis process regarding to applied loads to naval vessels are divided into two sections: process against environmental loads and operational loads. For large ships overall bending moment is considered and scantlings are executed regarding to it because; ship is assumed as a beam to withstand overall bending moment. On the contrary, first local structures are analysed in small ships whose length are lower than 70 m then, local pressures are integrated and hull is assessed for global loads. However, structural analysis against operational loads is performed for extreme conditions. According to ISSC (2009), loads are taken from military load assessments or specified grounding and collision damages. Moreover, ultimate strength analysis is performed with both extreme strength and residual strength bending moments.

Operational considerations make the difference between merchant ships and naval ships. According to ISSC (2009), naval vessels must be capable of withstand to specified sea conditions, without any loss in fighting ability or manoeuvring. Moreover, ships must survive in combat conditions so additional requirements are applied to the design factors. It is also stated that, most of the classification societies defines the naval ship design process in peace and war times differently. Operational considerations are compared in ABS, DNV, GL, LR, BV, KR classification society standards. The role of naval structural research and development in classification societies are defined and current developments in naval ship design and fatigue design concepts are also taken place in that report.

Moreover, a naval vessel namely, DDG-51, design process is defined. Its mid section design process is compared via classification societies rules for the section's final weight. Moreover, vertical bending moment, global mid-ship section properties, local scantlings comparisons are also taken place in this report.

Finally, results, comparisons and conclusions are summarised below for ISSC (2009). It can be observed from Figure 2.10 that, the difference between the final weight differences calculated via six classification societies' rules is found as 30%. According to ISSC (2009), variation in weight is resulted from the conservatism of classification society rules.

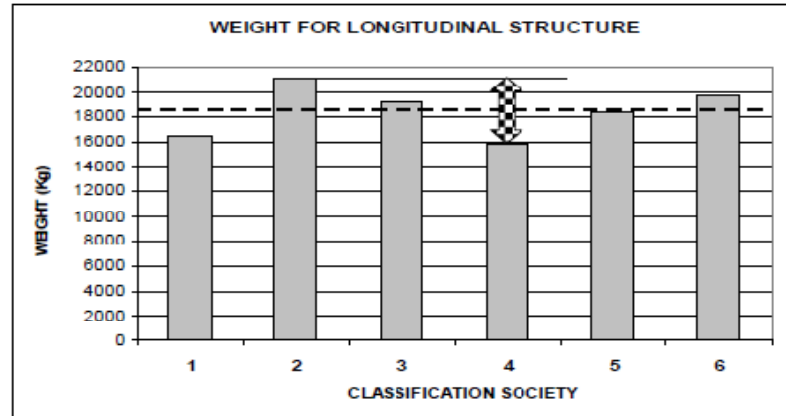


Figure 2.10 : Structural weight comparison

Figure 2.11 illustrated below shows vertical bending moments due to sagging and hogging positions of the vessel. Vessel is considered as it is operating in North Atlantic Sea and subjected to head waves.

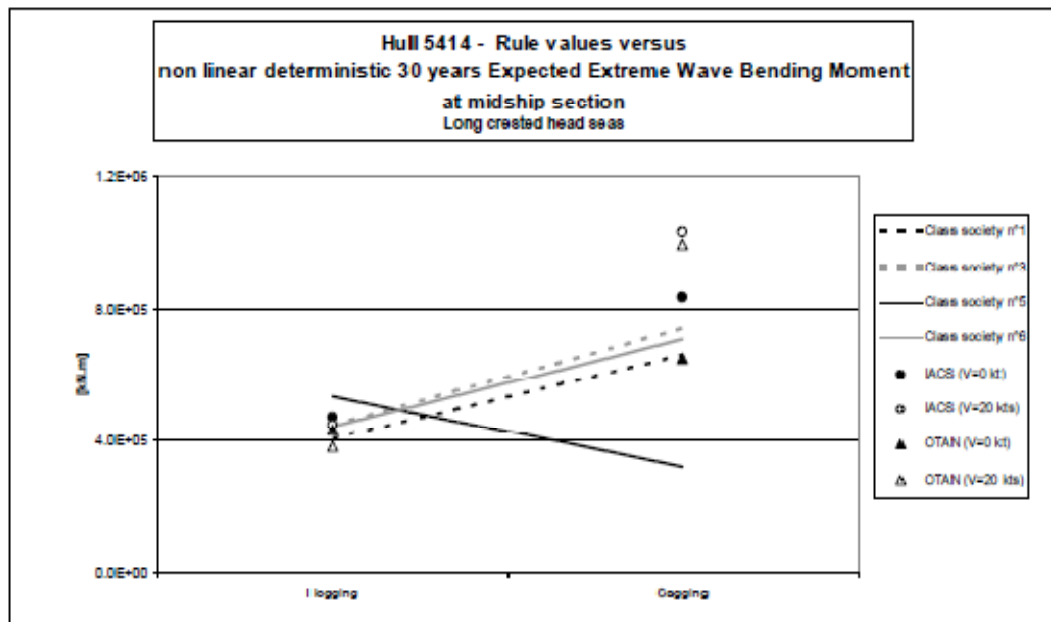
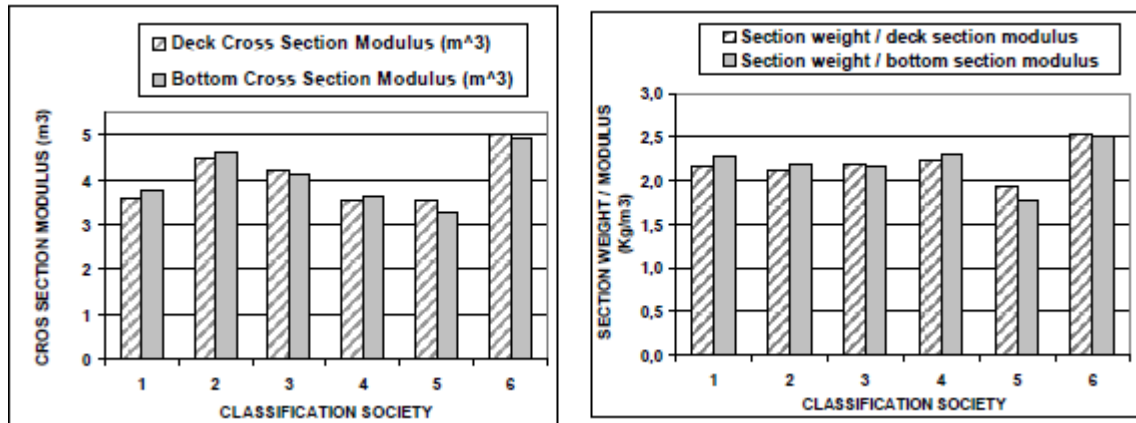


Figure 2.11 : Vertical bending moment at the mid-ship section



a)

b)

Figure 2.12 : Midship section modulus and hull girder strenght per unit weight comparison

Moreover, deck and bottom cross-section modulus in midship section iss compared and results are found consistent in number 1,2,3 and 5 classification societies. Number 2 is found more conservative and number 6 is representing 40% higher weight due to ultimate stress consideration.

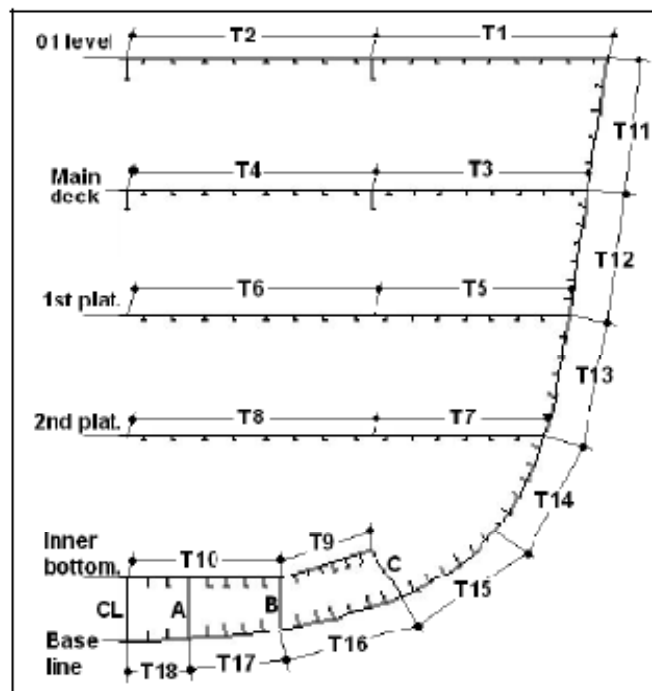


Figure 2.13 : Design divisions of the midship section

Next step is to compare stiffener scantlings with respect to class rules. Before performing the comparison, divisions of the mid-ship section must be illustrated in

Figure 2.13. Comparisons charts shown in Figure 2.14 are performed with respect to the mid-ship divisions and scantlings. Stiffener scantlings are calculated for deck and bottom sections of the vessel. It is stated in ISSC (2009) that, stiffeners at 01 level have a contribution to global cross section properties while; stiffeners which are situated in intermediate decks have a contribution to support local loadings. Therefore it can be observed from rule set number 6 that, it denotes global longitudinal strength.

In the main conclusion, it is stated that, optimization, fatigue and overall design integrations are the main concern nowadays. Moreover, however, the techniques are developing fast and independently in class societies, approaches of them are significantly similar.

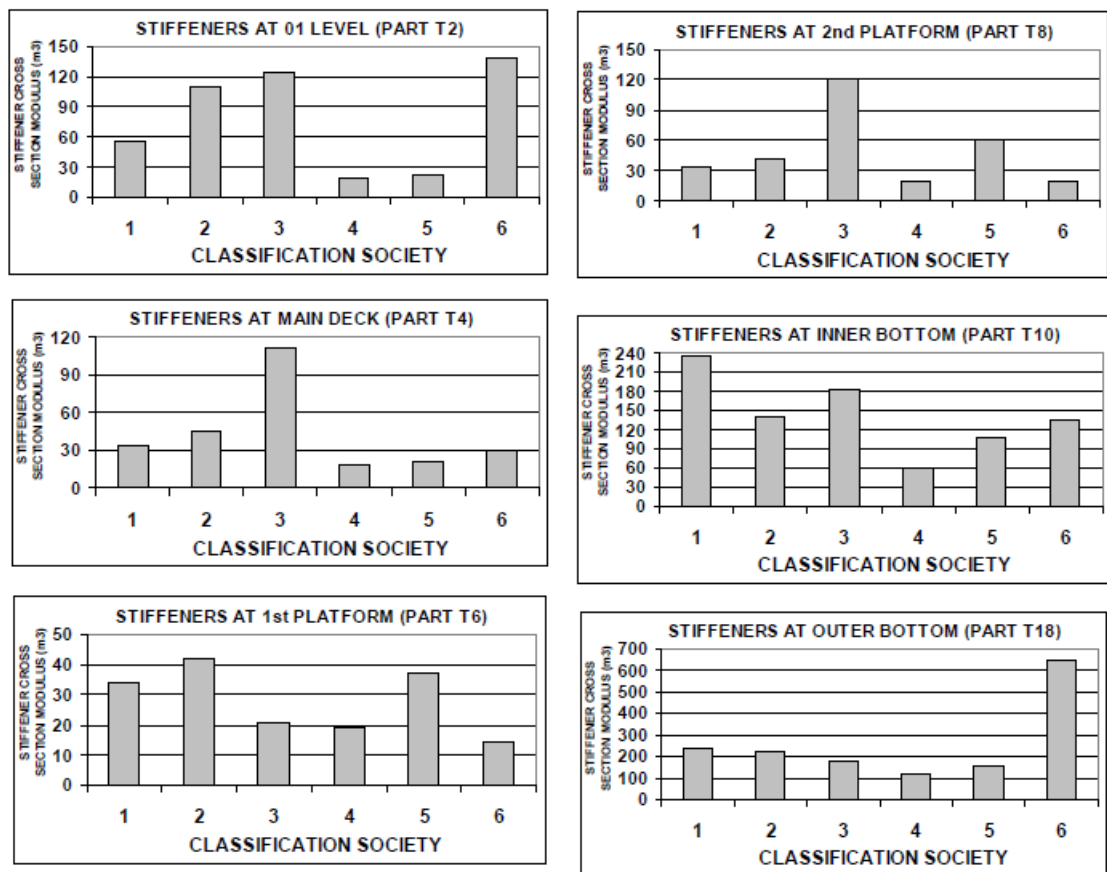


Figure 2.14 : Stiffener scantlings

According to Chalmers (1993), aircraft loads apply to both flight decks and hangar decks. The major loads that applied to hangar and flight decks are parking loads and crash loads in order. Chalmers (1993) also stated that, logical process to design flight

deck is to determine scantlings which are capable to resist crash loads and accidental loads. Therefore, helideck structures are more likely to fail before the ship structures.

In addition, according to Jackson and Frieze (1980) plate thickness must be calculated separately from stiffener scantlings due to elastic-plastic method consideration under accidental loads. However, these loads are applied rarely and it may be conservative to design all structure elastically stated by Jackson and Frieze (1980).

It is beneficial to define patch loads, which are applied on an area lower than the plate size but more than a single point stated by Chalmers (1993). It can be shown via three non-dimensional parameters in following equations

$$C_p = \frac{P \cdot E}{b^2 \sigma_y^2}$$

$$C_{sp} = \frac{s_p}{b} \cdot \sqrt{\frac{E}{\sigma_y}} \quad (2.5)$$

$$C_{sp} = \frac{b}{t} \cdot \sqrt{\frac{\sigma_y}{E}}$$

Where P is the applied load, β is the plate slenderness ratio. Tyre print pressure dimensions are a_t and b_t for lateral and longitudinal distances in order. Plating design curves can be observed from Figure 2.15 with axis of C_{sp} and b/b_t parameters and slenderness ratio can be read from it. Grillage nomenclature is illustrated in Figure 2.16 for the terms used.

Meanwhile, plate and slenderness ratio is stated by Smith (1983). He recommends that plate slenderness ratio $\beta = (b/t) \sqrt{(\sigma_y/E)}$ must be ideally less than 2.0 and must not be more than 2.5. In addition, the column slenderness ratio $\lambda = (a/\pi k) \sqrt{(\sigma_y/E)}$ must be between 0.45 to 0.55. In these formulas b is the effective width of the stiffeners, t is the thickness of the plate and k is the radius of gyration. Chalmers (1993) used these formulas for buckling of columns and panels. One of the column buckling diagram for average imperfections in the material is shown in Figure 2.17.

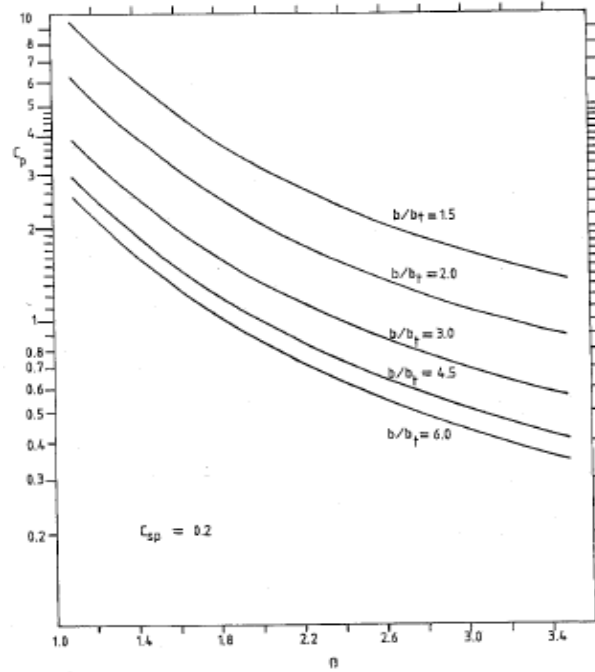


Figure 2.15 : Plating design curve

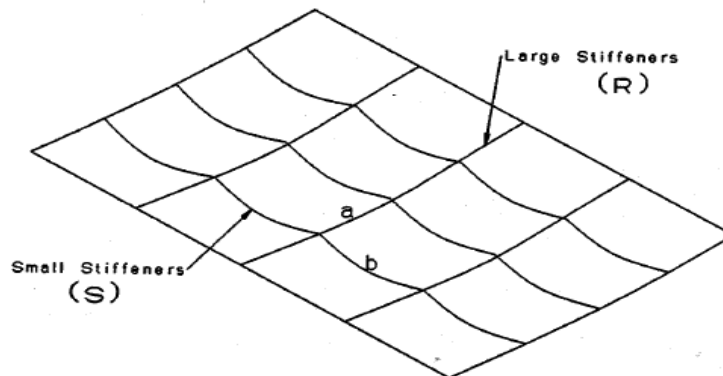


Figure 2.16 : Grillage nomenclature

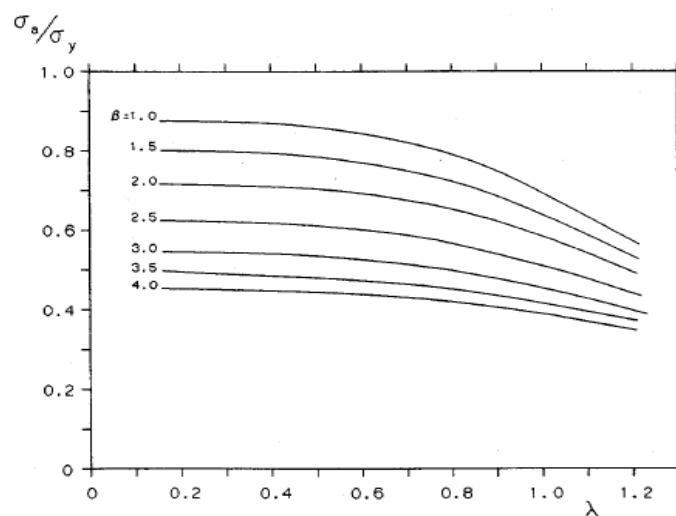


Figure 2.17 : Column buckling curves for average imperfections

2.4 Conclusions

Chapter 2 presented literature review on the main design features of naval ships with a specific emphasis on used optimization methods. In addition, recently performed structural optimizations examples are explained. Finally, it is beneficial to summarize what have been done in the section 2.

- Multi-objective function basis was explained with a special interest on weighted sum methods. Moreover, most of the MOO methods were compared to each other and finding about weight alternation method was explained in detail.
- Literature review about former ship optimization studies was executed and their algorithms and solution methods are explained. Moreover, optimization and static analysis flow diagrams were illustrated.
- Structural analysis process of naval ships was explained and an example of frigate mid-ship section design calculation and its comparison with six different classification societies was performed.
- Flight deck design principles for compressive loads were explained from MOD naval ship design book with diagrams to execute proper calculations.

3. OPTIMIZATION FUNDAMENTALS

Chapter 3 composes the optimization fundamentals of the helideck design and optimization process. Therefore, aim of this chapter is to provide general knowledge about decision maker algorithms which are used in the optimization background of the ANSYS programme. Main information about ANSYS optimization tools will be presented in Chapter 4 in detail.

To satisfy this objective firstly, penalty functions and their properties are presented in Section 3.1. Moreover, two different kinds of penalty functions are explained and the derivations of them are clarified. Secondly, steepest descent methods are presented in Section 3.2 to denote the design direction search to find the optimum of the main function. In addition, steps of the method are explained in detail. Finally, summary of the chapter is presented in Section 3.3.

3.1 Penalty functions

In order to use sub-problem and first order method, which will be explained in next chapters in detail, general knowledge about penalty functions is required. Both of the methods stated above uses penalty functions to find the optimum solution in constrained optimization problems. The method is very important because; constrained problem statement is transformed into an unconstrained one via penalty functions. Derivatives are formed for the objective function and the state variable penalty functions, leading to a search direction in design space. An unconstrained version of the problem is formulated as follows.

$$Q(\mathbf{x}, q) = \frac{f}{f_0} + \sum_{i=1}^n P_x(x_i) + q \cdot \left(\sum_{i=1}^{M_1} P_g(g_i) + \sum_{i=1}^{M_2} P_h(h_i) + \sum_{i=1}^{M_3} P_w(w_i) \right) \quad (3.1)$$

Where;

Q is the dimensionless, unconstrained objective function. P_x , P_g , P_h , and P_w are the penalties applied to the constrained design and state variables. While, f_0 is the reference objective function value that is selected from the current group of design

sets. Constraint satisfaction is controlled by a response surface parameter, q . Exterior penalty functions (P_x) are applied to the design variables. State variable constraints are represented by extended-interior penalty functions (P_g , P_h and P_w). In the internal approach, a feasible start point is required so that the starting point is ‘internal’ to the feasible solution space. However, in the external approach, the penalty only applies when the solution strays into the infeasible region and guides the solution back towards the feasible solution space. For example, for state variable constrained by an upper limit the penalty function is written as:

$$P_g(g_i) = \left(\frac{g_i}{g_i + \alpha_i} \right)^{2\lambda} \quad (3.2)$$

Where, λ is a large integer so that the function will be very large when the constraint is violated and very small when it is not. Moreover, the functions used for the remaining penalties are of a similar form. As search directions are devised a certain computational advantage can be gained if the function Q is rewritten as the sum of two functions. Defining:

$$Q_f(x) = \frac{f}{f_0} \quad (3.3)$$

and

$$Q_p(x, q) = \sum_{i=1}^n P_x(x_i) + q \cdot \left(\sum_{i=1}^{M_1} P_g(g_i) + \sum_{i=1}^{M_2} P_h(h_i) + \sum_{i=1}^{M_3} P_w(w_i) \right) \quad (3.4)$$

Then, Equation 3.1 takes the form:

$$Q(x, q) = Q_f(x) + Q_p(x, q) \quad (3.5)$$

The functions Q_f and Q_p relate to the objective function and the penalty constraints, respectively.

Penalty function can be illustrated below in Figure 3.1. Penalty function is given by Rao (2005) as stated below. It must be reminded that both of the equations 3.5 and 3.6 are similar in process. Formulation of the penalty function also explains how it achieves the optimum solution.

$$P(x, r_k) = f(x) + r_k \cdot 1/g(x) \quad (3.6)$$

Penalty term can be denoted as $1/g(x)$, which becomes larger while boundary of the constraint is approached in other words, while $g(x)$ becomes smaller in value. When the constraint boundary is approached $1/g(x)$ becomes a positive large value due to the positive selected $g(x)$. Concurrently, r_k is just a positive scaling factor controlling the magnitude of the penalty term. The first term in P is the objective function to be minimised and the second term is the penalty term. The first term decreases and the second term increases as the constraint boundary is approached, resulting in a U-shaped function P .

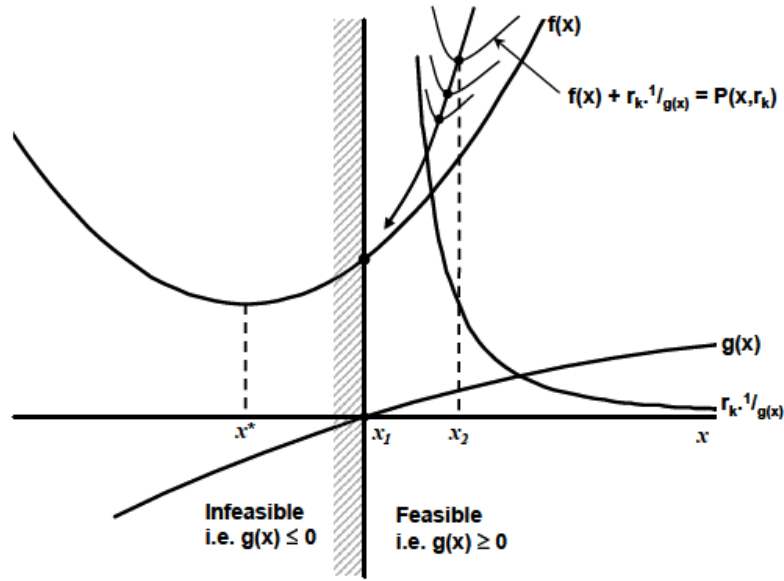


Figure 3.1 : Internal penalty function

3.2 Steepest descent method

In first degree method various steepest descent and conjugate direction searches are performed during iteration until convergence is reached. All iterations are composed of sub-iterations that include search direction and gradient computations. The steepest descent method or the gradient method is the simplest and the most convenient method for unconstrained optimization. The aim of this method is to find the direction search direction d at the current iteration in which the main function $f(x)$ decreases most rapidly, at least locally. The steepest descent method is a *first-order method* since only the gradient of the main function is calculated and used to evaluate the search direction. Steps of the steepest descent algorithm can be summarised as follows:

Step 1. Estimate a starting design $\mathbf{x}^{(0)}$ and set the iteration counter $k = 0$. Select a convergence parameter $\varepsilon > 0$.

Step 2. Calculate the gradient of $f(\mathbf{x})$ at the point $\mathbf{x}^{(k)}$ as $\mathbf{c}^{(k)} = \nabla f(\mathbf{x}^{(k)})$.

Step 3. Calculate $\|\mathbf{c}^{(k)}\|$. If $\|\mathbf{c}^{(k)}\| < \varepsilon$, then stop the iterative process because $\mathbf{x}^* = \mathbf{x}^{(k)}$ is a minimum point. Otherwise, continue.

Step 4. Let the search direction at the current point $\mathbf{x}^{(k)}$ be $\mathbf{d}^{(k)} = -\mathbf{c}^{(k)}$. While $\mathbf{c}$ is stated as:

$$\mathbf{c}^{(k)} = \mathbf{c}(\mathbf{x}^{(k)}) = \left[\frac{\partial f(\mathbf{x}^{(k)})}{\partial x_i} \right]^T \quad (3.7)$$

Step 5. Calculate a step size α_k that minimizes $f(\mathbf{x}^{(k)} + \alpha \mathbf{d}^{(k)})$. Any one-dimensional search algorithm may be used to determine α_k .

Step 6. Update the design as $\mathbf{x}^{(k+1)} = \mathbf{x}^{(k)} + \alpha_k \mathbf{d}^{(k)}$. Set $k = k + 1$, and go to Step 2.

3.3 Conclusions

In Chapter 3 the philosophy behind the optimization process in ANSYS was presented. In order to use tools in ANSYS the methods running behind the programme must be known exactly. Findings of Chapter 3 can be summarized below.

- Penalty function methodology was presented for both sub-optimization and first order method tools used in ANSYS. Differences between internal and external penalty functions were discussed. Moreover, derivation of the penalty function in ANSYS was proven as well.
- Steepest descent method was presented for first order method due to the direction decision process performed in this method. In order to use the method, steps of the steepest descent algorithm were explained step by step to avoid incoherence.

4. OPTIMIZATION METHODOLOGY IN ANSYS

The key aspect of this chapter is to explain the processes that have been performed in ANSYS optimization tool. In order to explain the steps of the optimization process, all the details of optimization process, including tools and techniques, are executed to reach feasible results.

The objective of Chapter 4 is to show briefly how to perform an optimization process in ANSYS. In order to present the goals, Section 4.2 presents the procedures to build a parametric model as well as to create analysis file and to retrieve data from the optimization database. Section 4.3 describes the procedures to find an optimum design, to use restart mechanisms and to demonstrate responses of the structure in optimization process. Optimization tools in ANSYS and investigation of the analysis file are presented in Section 4.4 in detail to perform a better analysis. In section 4.5, two different algorithms are described to optimize the design while their approximation functions and requirements are explained in detail. In addition, guidelines on assigning design, state variables and objective function are described in Section 4.5. Conclusions are provided in Section 4.6.

4.1 Building a parametric model

Accurate estimation of a structural response optimization requires conducting careful analysis and harmonization of the existing parameters. In order to explain how to build a parametric model, first the definition of the parametric model and its purpose is explained.

A parametric model is a representation of a structural model in terms of design variables in lieu of numbers. The purpose for building a parametric model is, simply changing the design variables in every loop to build a new structure.

ANSYS allows the user to parameterize several characteristics in a structure. These characteristics include geometry modelling, material specifications, loading and boundary conditions, number of constraints, maximum vertical displacement and maximum stress etc. The basic requirement is that quantities to be used in design

variables (DV's), state variables (SV's) and objection function (OBJ) must be assigned to parameters.

4.2 Definition & Purpose of Parametric Model

Parametric model is compulsory while performing an optimization in ANSYS. Analysis file is the output of parametric design and also input of the optimization process. The general flow diagram of optimization process is shown briefly in Figure 4.1:

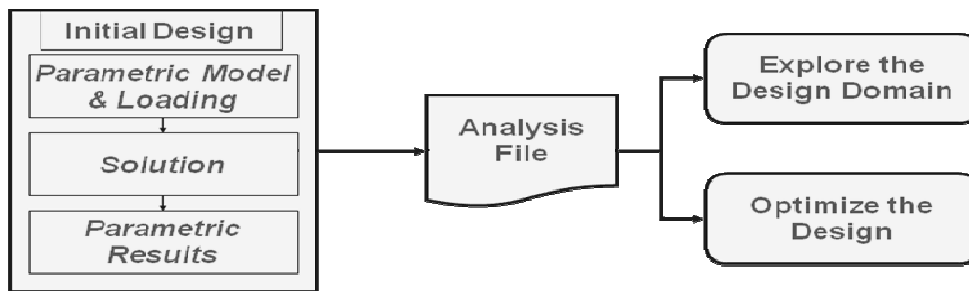


Figure 4.1 : General Optimization Procedure in ANSYS

Analysis file is comprised of modelling, loading, solution and results review sections in advance to perform a complete loop of optimization process. The optimizer uses analysis file several times with new design variable values assigned in each loop.

ANSYS Parametric Design Language (APDL) provides the user to assign input model dimensions, material properties etc. in terms of parameters. Moreover, it provides to retrieve data results from the optimization database and performs mathematical calculations through parameters.

In order to define a parameter, steps shown below must be performed;

Utility Menu>Parameters>Scalar Parameters

It must be kept in mind that, after using the parameters, ANSYS commutes values shortly in the log file.

Following the parametric modelling and solution process, results data must be retrieved from the database by *GET functions. These retrieved results data is stored as parameters and used by the optimizer in each loop after assigning new values to the design variables. In order to retrieve a data from the database, steps shown below must be performed. Data retrieval process is shown in Figure 4.2 below.

Utility Menu > Parameters > Get Scalar Data...

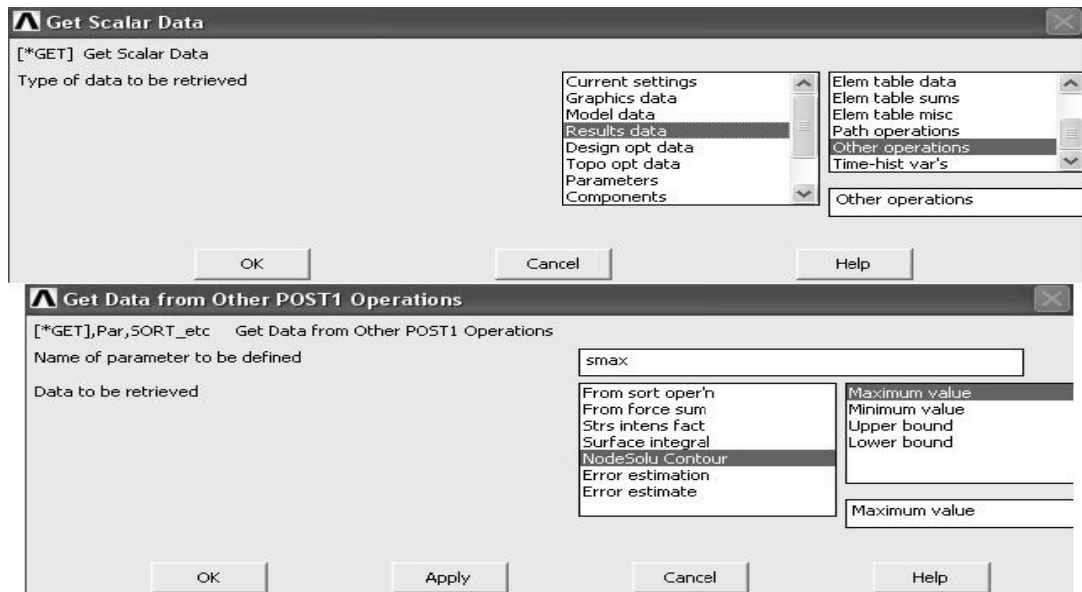


Figure 4.2 : Retrieving data in ANSYS

Commands on the analysis file can be presented by the progression stated below briefly. Analysis file creation is shown in Figure 4.3 below as well.

- 1- Parameter definitions
- 2- Geometry commands
- 3- Meshing commands
- 4- Loading and Boundary conditions commands
- 5- Solution commands
- 6- Retrieval of results data commands

In order to create an analysis file the steps shown below must be performed:

Utility Menu > File > Write DB Log File

It must be also kept in mind that, the created analysis file must be tested to ensure there is not any error in it. ANSYS reads the analysis file in each loop again with new parameter values assigned to it and after a limited amount of warnings are received program closes itself immediately. This can cause unrealistic results. To test the analysis file, the_input must be read from the database as shown below:

Utility Menu > File > Read Input from...

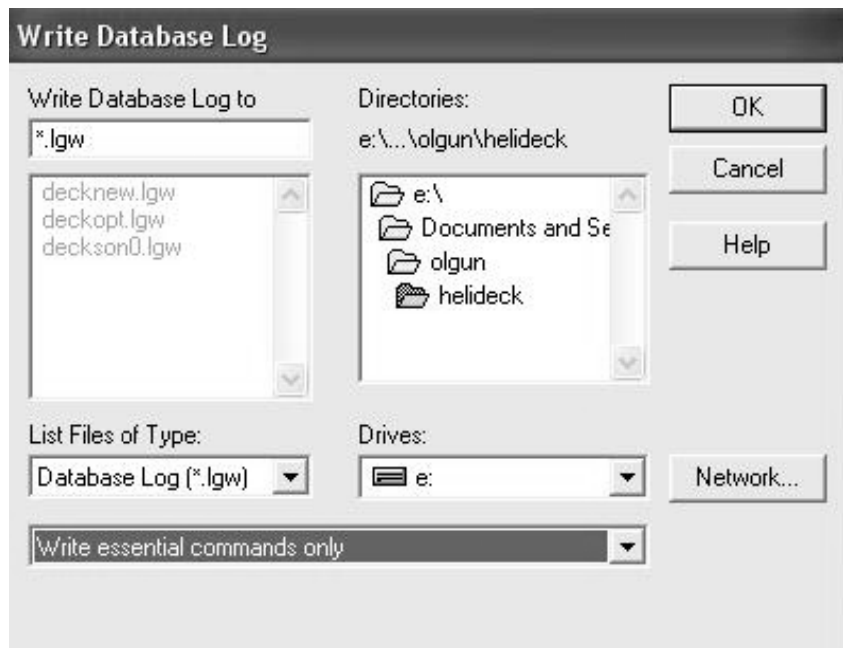


Figure 4.3 : Creating analysis file in ANSYS

4.3 Optimizing the design

Achieving the best design under given constraints is the subject of optimization art, stated by Rao (2009). An optimum design is one that performs the intended function, meets all constraints and uses the least amount of material. It must be reminded that in order to perform optimization, an analysis file must be created in advance. Supposing that the analysis file is created, there are four main steps can be listed to optimize the design. They are;

- 1- Assign analysis file
- 2- Identify the optimization variables DV's, SV's and OBJ function.
- 3- Run optimization
- 4- Review results

First three steps of this optimization process situated under the main optimization menu and can be reached as shown below.

Main Menu > Design Opt

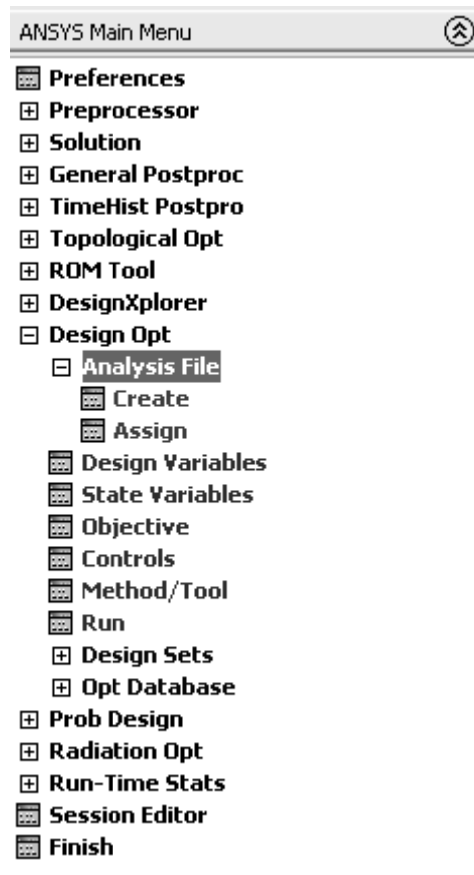


Figure 4.4 : Creating analysis file in ANSYS

4.3.1 Identifying the Analysis File

Analysis file contains the input required to fulfil one complete loop of the optimization run. To identify the analysis file, use the main menu options as demonstrated below:

Design Opt > -Analysis File- Assign...

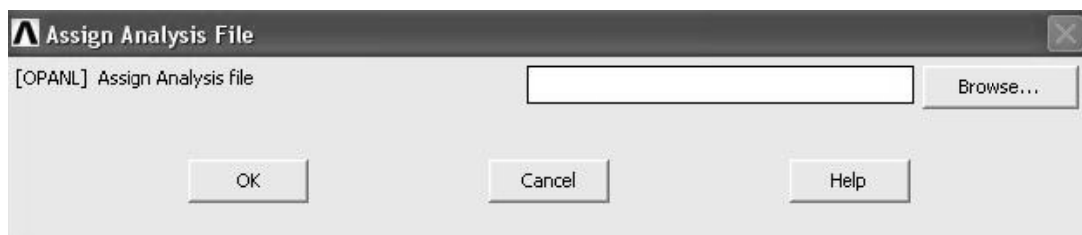


Figure 4.5 : Assigning analysis file

4.3.2 Identifying Optimization Variables

This step involves choosing appropriate parameters and designating them as DV's, SV's and objective function. Design variables (DV's) are design characteristics that are allowed to change the geometry in order to minimize or maximize the objective function.

Design variables can be identified and assigned to parameters in the design optimization menu as shown below in Figures 4.5 & 4.6:

Design Opt > Design Variables... > Add

It must be reminded that, ANSYS permits to define up to 60 DV's. It is always suggested that limiting DV's up to 10 or 20. Otherwise, it will result to arriving to a local optimum solution. DV's are restricted to positive values and maximum (MAX) of a DV must be greater than zero. If the minimum (MIN) of a DV is not identified, ANSYS defaults it to $0.001 \cdot \text{MAX}$ value.

The tolerance (TOLER) is the acceptable limit between the loops for convergence criteria. It uses the same units as DV and it is neither a percentage nor fraction. ANSYS defaults it to $\text{TOLER} = 0.01 \cdot (\text{MAX} - \text{MIN})$.

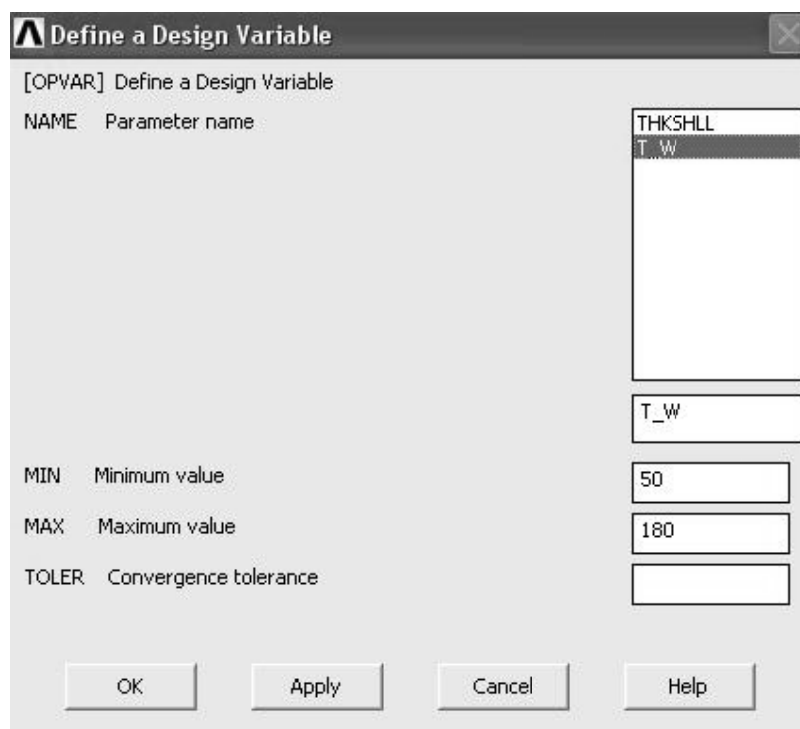


Figure 4.6 : Defining design variables

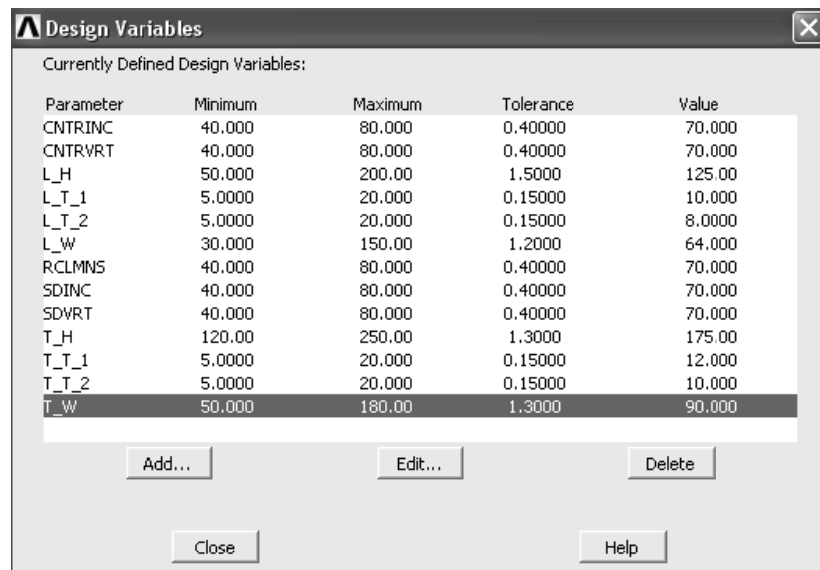


Figure 4.7 : Defined design variables

State variables (SV's) are the constraints on the design such as maximum stress or deflection. In order to identify SV's the same procedure in the optimization menu must be performed. The procedure is shown above and below in Figures 4.7 & 4.8:
 Design Opt > State Variables... > Add...

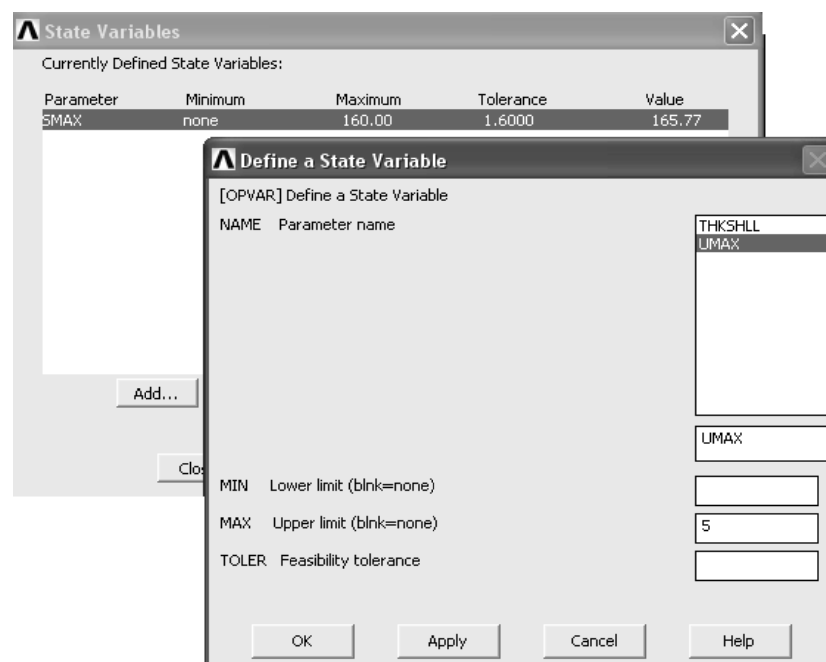


Figure 4.8 : Defining state variables

ANSYS permits up to 100 SV's to be defined. Tolerances specify the areas of feasibility, in other words they are the elastic barriers in front of the infeasible regions. Figure of feasible and infeasible regions scale is shown in the Figure 4.9. It

must be reminded that the same TOLER sensitivity rules as DV's are applied to SV's tolerances. ANSYS defaults tolerances to $0.01 \cdot \text{MAX}$ and $0.01 \cdot \text{MIN}$ for one sided SV's and $0.01 \cdot (\text{MAX} - \text{MIN})$ for two-sided SV's as well.



Figure 4.9 : Defining state variables

Objective function (OBJ) is the parameter to be minimized by the optimizer. It must be reminded that ANSYS always **minimizes** the OBJ. If the objective function is needed to be maximized, assume parameter y , it must be specified like $1/y$ to maximize it. Moreover, it is also suggested that OBJ remain positive for feasible results.

The TOLER is the acceptable change in OBJ between loops for convergence. TOLER is defaulted to $0.01 \cdot \text{current iteration result}$.

In order to identify the objective function, the main optimization menu must be used as it is shown in Figure 4.10:

Design Opt > Objective...

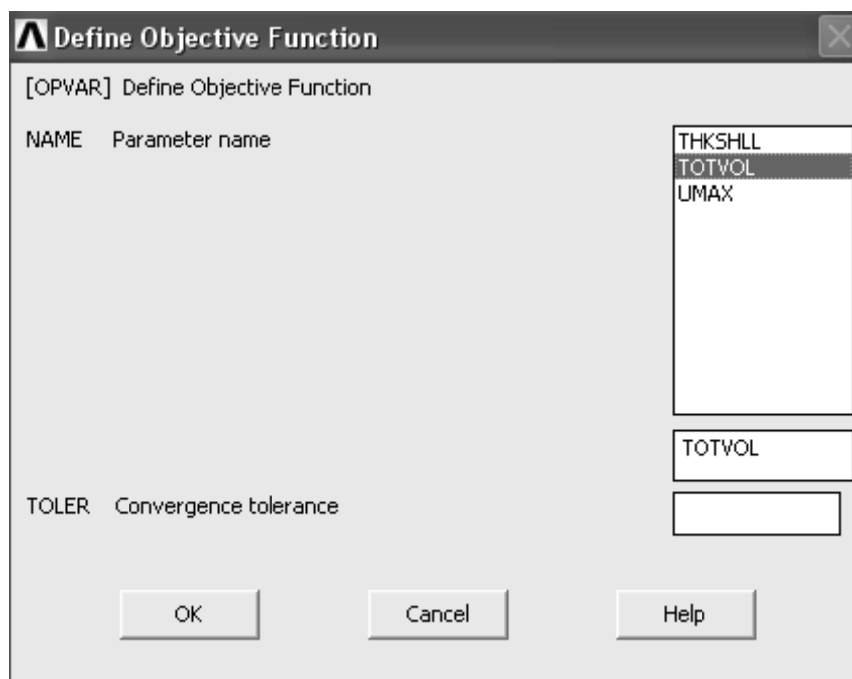


Figure 4.10 : Defining the objective function

4.3.3 Run the Optimization

This step involves specifying run-time controls, choosing the exact optimization method, saving the optimization database and initiating the optimization run. Run-time controls covers optimization database file name which is **jobname.opt** in default. In addition, it controls the optimization looping, how to read the analysis file and also controls the printout options. The most important feature of run-time controls is that, it saves the best design set and best result set upon request. In order to use this tool, save-best-design option must be activated in advance. Following this activation, program saves the best design and result data occurred up date in default name **jobname.bdb** and **jobname.brst** for best design and result in order. It is shown briefly in Figure 4.11 below;

Specify run-time controls

[OPDATA] Specify file to write optimization data
FNAME File name
(default is deckson.opt)

[OPLOOP] Specify controls for reading analysis file
READ Read from
DVAR Parameters used as DVs
PARMS Parameters to be saved

[OPPRNT] Activate summary printout during looping
KEY Printout option

[OPKEEP] Save database + result
- for best design to deckson.bdb + .brst

OK Cancel Help

Figure 4.11 : Specifying the run-time controls

It must be noted that if multiple analysis are desired to be performed, such as stress followed by vibration, only the last results file will be copied to results file. To overcome this situation, /ASSIGN function must be considered in order to copy different results.

Utility Menu > File > ANSYS File Options...

Generally there are two main optimization methods exist in ANSYS.

- 1- Sub-problem optimization method
- 2- First degree method

These methods will be presented in detail later. In order to select an optimization method, methods section from the optimization menu must be selected as it is shown in Figure 4.12:

Specify Optimization Method

[OPTYPE] Specify Optimization Method/Tool
MNAME Select Method/Tool

☐ Single Run
☐ Random Designs
☐ Factorial
☐ Gradient
☐ DV Sweeps
☒ Sub-Problem
☐ First-Order
☐ User Optimizer

OK Cancel Help

Controls for Sub-problem Optimization

[OPSUBP] Controls for Sub-problem Optimization

NITR Maximum iterations 50

NINF5 Max infeasible sets 40

[OPEQN] Curve-fitting controls

KFOBJ For Objective Quadrtrc + X-Term

KFSV For state variables Quadratic

KWGHT Weighting Scheme Compound Weights

KOPPR Print frequency 0

INOPT Reform frequency 0

OK Cancel Help

Figure 4.12 : Specifying optimization method and controls

The optimizer works with its own database which consists of DV's, SV's and OBJ specifications, analysis file name, optimization method and controls and parameter values of each design generated up to date. At the end of each iteration, ANSYS automatically saves this information in the OPT database file specified in the Run-Time Controls dialog (which defaults to *jobname.opt*).

Saving the OPT database before initiating the optimization run allows user to resume from this point conveniently if needed. Following the saving option, to initiate the optimization, “run” must be selected from the optimization menu. The analysis file will be looped through the analysis until it reaches a feasible solution and satisfies the convergence criteria.

In ANSYS it is stated that, a design is converged to an optimum if it is feasible and one of the following four conditions is true:

1. The change in objective function between the current design and the best feasible design is less than the tolerance.

$$|OBJ_{\text{current}} - OBJ_{\text{best}}| < TOLER_{\text{obj}}$$

2. The change in objective function between the current design and the previous design is less than the tolerance.

$$|OBJ_{\text{current}} - OBJ_{\text{current-1}}| < TOLER_{\text{obj}}$$

3. The change between the current design and the best feasible design is less than its tolerance for each DV.

$$|DV_{\text{current}} - DV_{\text{best}}| < TOLER_{\text{dv}} \text{ for all DVs}$$

4. The change between the current design and the previous design is less than its tolerance for each DV.

$$|DV_{\text{current}} - DV_{\text{current-1}}| < TOLER_{\text{dv}} \text{ for all DVs}$$

4.3.4 Review of the Results

This step involves restoring the optimization database, listing design sets, plotting graphs and restoring the geometry and results for the best design. Restoring the optimization database is only required when the ANSYS optimization tool is exited after the optimization process. In order to restore the optimization database resume option in the OPT database menu must be selected.

Design Opt > -Opt Database- Resume...

In order to review parameters for a specified design, design sets must be listed. All design parameters can be selected from the menu shown in Figure 4.13 and the steps have to be done to open this menu are;

Design Opt > -Design Sets- List...

It must be noted that, the best design set is shown in asterisks (*SET_1*) and all design sets are featured whether they are feasible or infeasible during the optimization run.



Figure 4.13 : Listing design sets

Optimization variables can be plotted versus design set number or other features to observe the optimization process. Restoring the best design geometry and results are the former phase of restart mechanism. This process is performed to obtain the best results and geometry and to start with this set to new iteration process and to find a better solution aiming the global optimum. To do this, simply exit the optimizer and resume the file *jobname.bdb* (best db). Steps required to call back the best design set is presented below:

Main Menu > Finish

Utility Menu > File > Resume from...

Utility Menu > Plot > Elements

Main Menu > General Postproc > Data & File Opts...

4.3.5 Restart Mechanism

This step presents how to resume the previous optimization run starting from the feasible sets or from the best design set to obtain better design sets. The purpose of this process is, to find a new optimum in the optimization process by changing the tolerances of the design variables and force the optimizer to find a different optimization “path” by starting from feasible set of designs. This process can be shown in Figure 4.14 below:

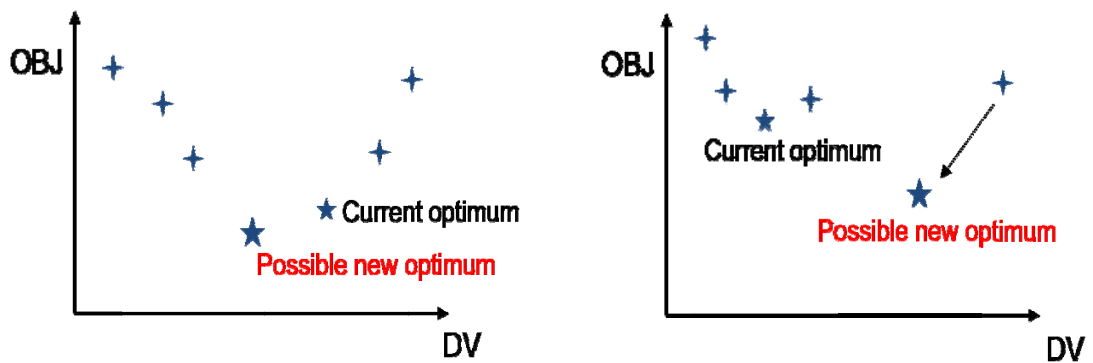


Figure 4.14 : Restart mechanism

Typical restart mechanism consists of four steps to be fulfilled to arrive new feasible design sets. They can be listed in order, saving the OPT database to a named file, selecting feasible set's subsets or the best design set subset, modifying the optimization variables tolerances and limits and running the optimization. It was shown in the former stages how to save the OPT database hence, descriptions of starting from the selecting subsets step will be explained. It is presented in Figure 4.15 below how to select subsets from the all design space. It must be reminded that selecting a subset removes the unselected design sets from the database. Hence, it is always suggested to save the database before each optimization run process. Moreover, tolerances and limits of DV's , SV's and OBJ can be adjusted for restarts. It must be reminded that tightening the OBJ tolerance may force the convergence based on DV tolerances. In addition, changing the SV's tolerances allows the user to increase or decrease the treshhold of feasibility.

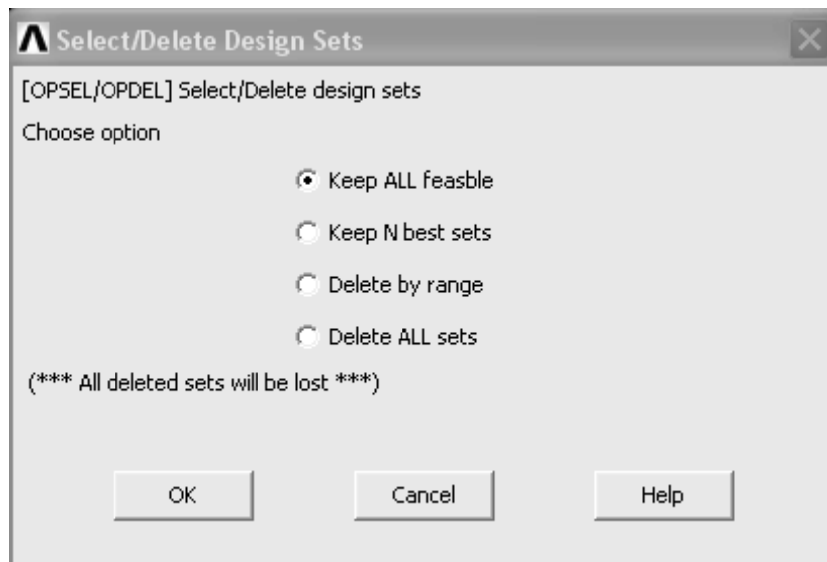


Figure 4.15 : Selecting subsets

4.4 Optimization tools

ANSYS optimizer provides several optimization tools to explore the design domain. It is helpful to remind that Sub-problem optimizer generates $N+2$ random sets by its own while N stands for the number of design variables. These tools are also a good way to generate initial sets for the sub-problem optimizer. Optimization tools are summarised in the diagram in Figure 4.16.

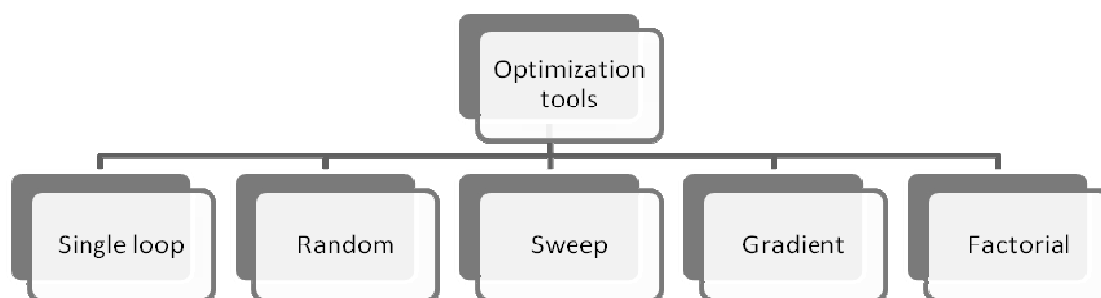


Figure 4.16 : Optimization tools in ANSYS

4.4.1 Single Loop

Single loop process one complete loop through the analysis file. It investigates about the questions related to “what if” scenarios such as in helideck optimization problem “what-if the central inclined columns are eliminated from the design?”

4.4.2 Random tool

Random designs are generated by random tool to start the analysis with few good designs. Sub-optimization method includes random tool in itself.

4.4.3 Sweep tool

Sweep tool sweeps through the entire range of design variable values for each DV. It is very useful for **Global Sensitivity** studies showing how a given design responds over the entire range of values of a given DV. Briefly, the Sweep Tool uses a specified design as a reference point and increments each DV through its entire range while holding the others constant. It must be kept in mind that to use sweep tool existing sets must be specified. In Figure 4.17 sweep tool is shown below:

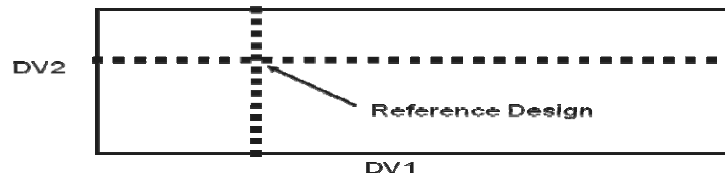


Figure 4.17 : Sweep to

4.4.4 Gradient tool

Gradient tool generates designs in the neighborhood of a reference design by changing each DV by a small amount. It is very useful for **Local Sensitivity** studies presenting how a given design responds to small changes in DV's. In addition another important information must be given is the amount of perturbation **DELTA**, specified as a percent forward difference. Each DV is changed by the amount:

$$\pm DELTA * (MAX - MIN) / 100$$

It must be reminded that this tool is automatically applied at the end of Sub-problem optimization run to observe whether the design is stable or unstable. In Figure 4.18 Gradient tool is shown briefly:

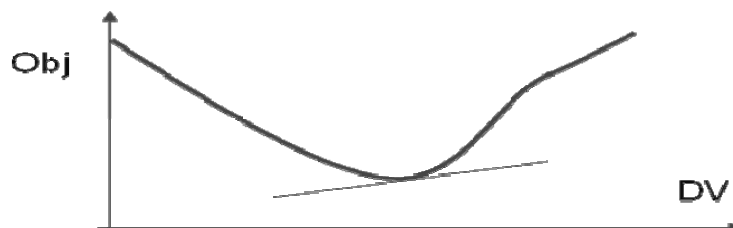


Figure 4.18 : Gradient tool

4.4.5 Factorial tool

Factorial tool is a well-known algorithm derived from factorial method which is widely used in interpretation of experimental results. It is useful for observing not only the effect of each DV on the design, but also the interaction of two-three variables. It samples extreme points of each DV in design database such as maximum and minimum points. Factorial tool can be explained via Figure 4.19:



Figure 4.19 : Factorial tool

4.5 Optimization methods

ANSYS provides two different optimization methods, or algorithms, to optimize the design properly. They are sub-problem and first order methods which are mentioned before. It is useful starting from Sub-problem optimization method.

4.5.1 Sub-problem Optimization Method

Sub-problem method can be explained as an advanced zero-order method which requires only the design variable values not their derivatives. There are two key factors playing important role in the method: approximations of the state variables and the objective function. Approximations are used to locate SV's and OBJ in the design space. A least squares fit of all available design sets is used to form the approximations:

$$\begin{array}{c} \underbrace{\hspace{10em}} \\ \text{Linear} \\ \underbrace{\hspace{10em}} \\ \text{Quadratic} \\ \underbrace{\hspace{10em}} \\ \text{Quadratic + cross terms} \end{array} \quad (4.1)$$

While the notations can be expressed as stated below:

H = approximation of objective function or state variable

X_n = design variable n

a, b, c = coefficients

N = total number of design variables

ANSYS uses quadratic + cross terms approach default for objective functions (OBJ) and quadratic approach for SV's. Users can also adjust approximations of response variables (SV's and OBJ) to quadratic + cross terms approach if linear fit and quadratic approach perform imprecise results.

The relationship between the OBJ and DV's is developed by curve fitting. This is performed by computing the objective function for several sets of DV values and performing a least square fit between the data points meanwhile the SV approximations are used to constraint design. Each optimization loop generates a new data point and the OBJ approximation is updated as well. Briefly, this approximation is minimized instead of the actual objective function. The flow diagram of Sub-problem algorithm can be shown in Figure 4.20:

Figure 4.20 : Flow diagram of Sub-problem algorithm

The sub-problem optimization method is widely used because of its generalized approach and speed to arrive an optimum quickly.

4.5.2 First Order Method

First order method converts the problem to an unconstrained one by adding penalty functions to the objective function. However, unlike the sub-problem approximation method, the actual finite element representation is minimized not an approximation. Hence, the method is more accurate. Method uses gradients of the dependent variables with respect to the design variables. In order to perform each iteration, gradient calculations (which may employ a steepest descent or conjugate direction method) are performed in order to determine a search direction, and a line search strategy is adopted to minimize the unconstrained problem. Therefore, each iteration is composed of a number of sub-iterations that include search direction and gradient computations. Flow diagram of First Order Method can be shown in Figure 4.21 below:

Figure 4.21 : Flow diagram of First Order Method algorithm

It must be remembered that in First Order Method, convergence concern is quite different. Convergence is said to be achieved when both of these conditions are met:

1. Change in objective function between the current design and the best feasible design is less than the tolerance.

$$|\text{OBJ}_{\text{current}} - \text{OBJ}_{\text{best}}| < \text{TOLER}_{\text{obj}}$$

AND

2. Change in objective function between the current and previous designs is less than the tolerance.

$$|\text{OBJ}_{\text{current}} - \text{OBJ}_{\text{current-1}}| < \text{TOLER}_{\text{obj}}$$

Moreover, another requirement for convergence is that the final iteration must use a steepest descent search. Otherwise, additional iterations are performed.

This method is used when the accuracy of Sub-problem algorithm is imprecise and when the accuracy of the results is the first priority. However, the method is not suggested when the speed is essential.

4.5.3 Guidelines for DV's, SV's and OBJ function

This section gives a general knowledge about guidelines for DV's, SV's and OBJ functions. In order to arrive a global optimum quickly, it is beneficial to use the suggestions listed below:

- Symmetry option must be used as much as possible because the smaller the model size is the better.
- Density must not be assigned as much as possible. Assigning it will increase the time required to calculate the mass matrix in every loop.
- In order to avoid arriving to a local optimum, start from a proper design and use Sweep Tool to arrive a global optimum.
- In order to avoid arriving to a local optimum keep the number of DV's to minimum. More than 20 variables are not suggested.
- Eliminate some DVs by expressing them in terms of others.
- If the structure deflects in the -Y direction, and maximum Y deflection is a state variable, retrieve the maximum of *absolute* values or the *minimum* of real values.
- If singularities exist, such as a point load or a re-entrant corner, the maximum stress will always be at that location. Consider unselecting such regions before retrieving the maximum stress.

- Avoid tight bounds on two-sided state variables, especially when using the Sub-problem method.
- Remember that ANSYS always *minimizes* the objective function.
- In order to maximize the objective function, namely y , specify $1/y$ as the objective function.
- Ensure that OBJ should remain positive.

4.6 Conclusions

Chapter 4 presented the optimization methodology in ANSYS to ensure the reader understands next chapters thoroughly. All the steps required to perform an optimization run are explained in detail including parametric modelling, optimization procedures, restart mechanisms and optimization tools. The adopted approaches in the methods section were presented in detail to demonstrate the background of the program. Furthermore, general guidelines for design, state variables and objective function were presented. Main findings of this chapter are:

- Building a parametric model was presented. The section consisted of how to build a model in terms of parameters, how to create an analysis file and how to retrieve data from the optimization database. Moreover, all rules and regulations in ANSYS related to parametric modelling were explained clearly for readers.
- Procedures to find an optimum design, to use restart mechanisms and to demonstrate responses of the structure in the optimization process were explained in detail to avoid future mistakes to be done while performing the analysis.
- Optimization tools and their utilizations were explained thoroughly in the section 4.4.
- Two different optimization methods, algorithms, were presented and their flow diagrams were also presented and explained. Moreover, guidelines about assigning DV's, SV's and OBJ were also presented.

5. REGULATIONS AND CALCULATIONS

When building a new structure, classification societies provide valuable rules and convenient methods of determining the scantlings and limits of the structure. However, naval ship design rules are different from the regular vessels' due to the operational loads and extreme environmental conditions occurred during the voyages. This chapter presents the rules which are taken from Germanischer Lloyd (GL) for naval ship design. Moreover, helicopter landing decks need more attention when they are being designed because of the landing loads applied on it in addition to static deck loads according to GL rules (2006). Therefore, the objective of this chapter is to conduct strength calculations of the designed helideck structure regarding to GL rules and investigate whether the structure is safe or not.

In order to perform required calculations, specifications of the selected frigate and helicopter are given in Sections 5.1 & 5.2 in order. Section 5.3 describes the general design principles of Naval Ships; Section 5.4 describes the design loads occurred during the operation of the vessel. Section 5.5 presents the provisions for flight operations. Section 5.6 gives the conclusions of the chapter.

5.1 Specifications of the frigate

The GL rule calculations were applied to Bremen Class Frigate of German Naval Forces. It must be kept in mind that, helideck is designed regarding to Bremen class frigate scantlings. Specifications of the vessel is summarised in Table 5.1 and the picture of the frigate is shown in Figures 5.1:

Table 5.1 : Specifications of the frigate

Displacement (tons):	3680 full load
Main Dimensions (m):	130 x 14.5 x 6.5
Speed (knots):	30, 20 on diesels
Range (miles):	4000 at 18 knots
Complement :	219
Helicopters:	Seahawk 70-B
Main machinery:	CODOG (38 MW) and Diesels (8.14 MW)



Figure 5.1 : Bremen Class frigate

5.2 Specification of the helicopter

One of the most important concerns while performing helideck structural design is the knowledge about the helicopter dimensions and weights. Helidecks are designed to specific kinds of helicopters for operation. Hence, in this dissertation study Sikorsky Seahawk 70-B helicopter is selected to observe the response of the structure due to the operational loads. It will be beneficial to give the specifications of Seahawk 70-B helicopter for the analysis below in Table 5.2:

Table 5.2 : Sikorsky Seahawk 70-B helicopter specifications

Maximum take-off weight :	9926 kg
ASW configuration weight :	8055 kg
ASuW configuration weight :	7771 kg
Empty weight :	6895 kg
Useful load :	3031 kg
Length with rotors:	19.75 m
Width with rotors :	16.36 m
Overall height:	5.2 m
Folded length :	12.5 m
Folded width :	3.2 m
Folded height :	4.1 m
Wheelbase-tread :	2.7 m
Cabin length :	3.2 m
Cabin width:	1.8 m
Total take-off power:	2818 kW

Aircraft dimensions are plotted below in Figure 5.2 to perform future calculations about landing area arrangements and tire print pressures. Folded length and width dimensions are used for the design of hangar area general arrangements.

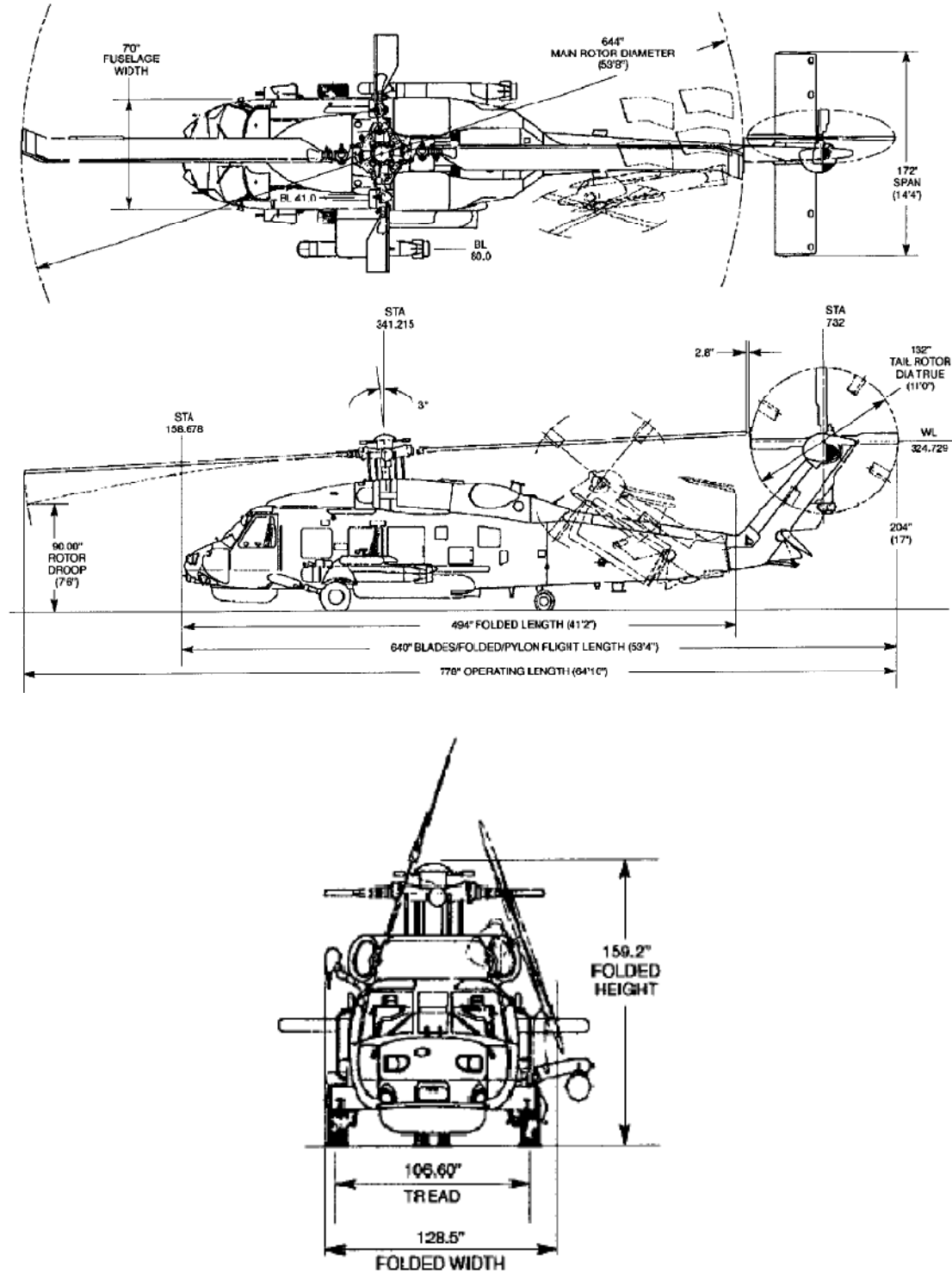


Figure 5.2 : Seahawk 70-B dimensions

5.3 General design principles of naval ships

This section includes main hull structural calculations and design principles of naval ships. It must be noted that, due to the huge amount of calculations in naval ship design, general principles which will be presented in this section are related only with the helideck design. Hence, the basic calculation principles presented below includes the foundation part of strength estimations of helideck design process.

There are several definitions in principles section. It is useful to start with partial safety factors which is used for load calculations on the helideck.

5.3.1 Partial Safety Factors

Naval ship design subject includes several load cases. According to GL Naval Ship Design Rules (2006), generally four different load cases are applied to naval ships. In order to calculate the dimensions of the structure, partial safety factors of these load cases which are shown in Table 5.3 must be determined in design process.

Table 5.3 : Partial safety factors for load cases

Load case	LCA	LCB	LCC	LCD
Factor for structural resistance γ_m	1,1	1,1	1,0	1,1
Load factor γ_{stat}	1,5	1,05	1	1
Load factor γ_{dyn}	2	1,4	1	1
Combination factor Ψ_i				
Ψ_{imin}	0,75	0,7	0,75	0,7
Ψ_{imax}	1	1	1	1

In this table LCA stands for permanent and cyclic loads on the undamaged structure, LCB for static and cyclic loads in extreme operation conditions, LCC for fatigue estimation in regular static and cyclic loading conditions of undamaged structure, and LCD for static and cyclic loads in a damaged structure

5.3.2 Webs and Flanges

Rules for webs and flange dimensions must be satisfied in the design. Rules consist of the ratio web depth to web thickness and/or flange breadth to flange thickness. They are all valid for normal and higher strength hull structural steel. Flange and web dimensions are presented in Figure 5.3.

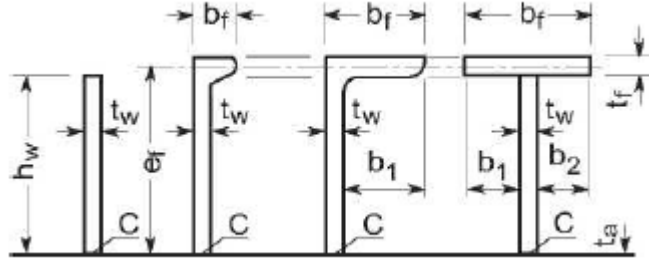


Figure 5.3 : Main parameters of typical sections

Following the main parameters description, sections must satisfy the equations 5.1 and 5.2 stated below for strength calculations:

Angle, tee and flange sections formulations are shown below:

$$\text{Webs; } \frac{h_w}{t_w} \leq \frac{661}{\sqrt{R_{eH}}} \quad (5.1)$$

$$\text{Flanges; } \frac{b_i}{t_w} \leq \frac{215}{\sqrt{R_{eH}}} \quad (5.2)$$

In these equations R_{eH} stands for minimum yielding stress of the hull structural steel. It must be reminded that $R_{eH} = 235 \text{ N/mm}^2$ is applied to all calculations.

5.4 Design loads

This section provides design loads applied to helideck structures to determine the scantlings of the hull structure. Environmental and operational loads are presented in the design loads. However, blast loads are not covered in this section because; military loads are different cases affecting naval ships. It must be remembered that all static loads presented in here are the minimum loads and these rules are valid for mono hull naval ships only.

According to the selected problem, helideck design loads are presented in the following sections.

5.4.1 Helicopter loads

This section provides design loads occurred by helicopter landings to the structure. It was stated in GL rules (2006) that landing, parking and hangar decks must have enough strength for helicopter operation. The structure must be investigated for the worst scenario of landing conditions for the selected specific kind of helicopters.

One of the most important features that must be given in this section is the wheel loads of the helicopter. Wheel loads must be calculated for the maximum take-off weight of the helicopter and also in the crash landing position. In GL rules (2006) it was stated that tire pressure area can be selected as 300mm x 300mm for a single wheel. It is also beneficial that designers must check the data supplied by helicopter manufacturers. In order to find the pressures made by dual wheels or skids, the load must be divided into wheel numbers. Dual wheel landing condition is shown in Figure 5.4.

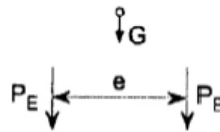


Figure 5.4 : Distribution of static skid loads

In this figure P_E stands for the force applied while the helicopter is landed, G is for the maximum take-off weight and e is the skid distance supplied by the manufacturer.

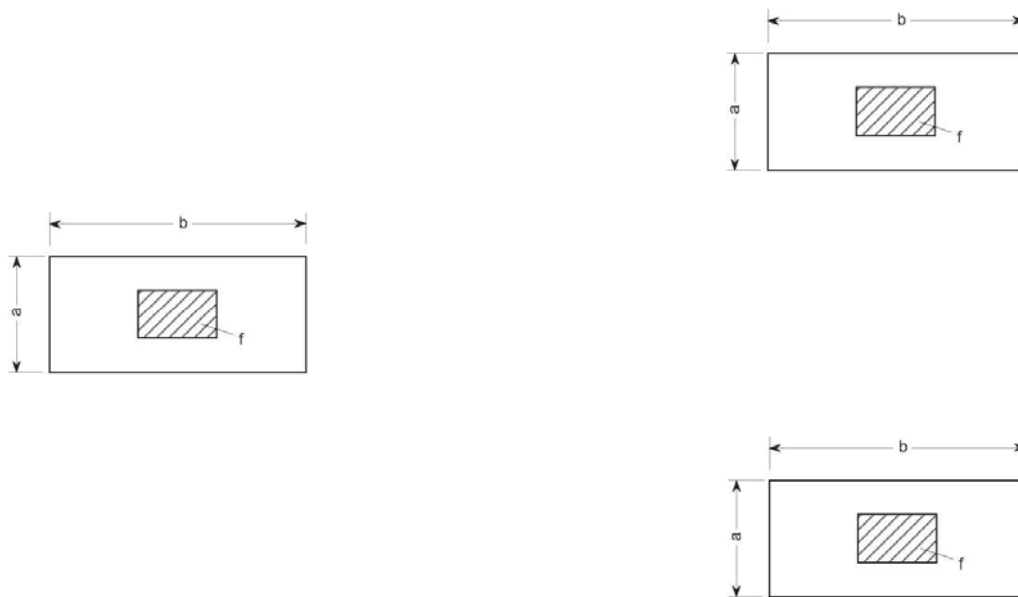


Figure 5.5 : Area of the flat panel influenced by a wheel print

This study presents the loads applied by Seahawk S-70 B helicopter which has three wheels. Due to the wheels, landing equipment and specific weight distribution of the helicopter, landing loads are divided into three. It is calculated as 50% of the total take-off weight is carried by the front wheels, which is divided by 2 due to dual front

wheels, and the remaining 50% of weight is carried by the rear wheel. Weight distribution applied on wheels can be shown in Figure 5.5, for Seahawk S-70B helicopter.

In Figure 5.7 a stands for transverse beam span, b is for girder span. Hence, $a \times b$ dimension stands for the panel and f is the exact area where influenced by a wheel print. It is also stated in GL rules (2006) is that the panel area shown in terms of “ F ” must not be greater than $2.5a^2$.

All of the helideck calculations are performed regarding to crash landing condition which can be stated as;

$$P_E = 3 \cdot G \text{ [kN]} \quad (5.3)$$

5.4.2 Deck thickness calculation

In this section deck thickness calculations are performed regarding to GL rules. Firstly, the selected helicopters’ weight distribution calculations, namely wheel print load calculations, are performed. Moreover, deck thickness is determined for the selected frigate. All the rules and equations stated below are taken from GL rules (2006).

Maximum take-off weight of helicopter:

$$G = 9926 \text{ kg} = 9926 \cdot 9.81 \text{ m/s}^2 = 97,38 \text{ kN} \quad (5.4)$$

Crash landing force is applied for structural calculations:

$$3 \cdot G = 3 \cdot 9926 \text{ kg} \cdot 9.81 \text{ m/s}^2 = 292.12 \text{ kN} \quad (5.5)$$

Weight distributed on one of the front tires:

$$P_E = 0.25 \cdot 3 \cdot G = 73.03 \text{ kN} \quad (5.6)$$

Weight distributed on the rear tire:

$$P_E = 0.5 \cdot 3 \cdot G = 146 \text{ kN} \quad (5.7)$$

Thickness of the deck is to be determined by the following formula:

$$t = c \cdot \sqrt{\frac{P_E \cdot \gamma_m}{R_{eH}}} + t_k \text{ [mm]} \quad (5.8)$$

P_E = total load in [kN] of one wheel or group of wheels on a plate panel $a \times b$.

γ_m = Partial safety factor,

R_{eH} = yielding stress of the ship steel (235 N/mm²)

t_k = corrosion allowance (1,5 mm),

According to the Figure 5.7:

a = width of smaller side of plate panel (in general beam spacing)

b = width of larger side of plate panel

c = factor according to the following formulae:

∴ For the aspect ratio $b/a=1$ and for the range $0 \leq f/F \leq 0.3$,

$$c = 22,9 - 22,5 \cdot \sqrt{\frac{f}{F} \cdot \left(3,4 - 4,4 \cdot \frac{f}{F}\right)} \quad (5.9)$$

∴ In helideck design problem dimension of one panel is 750mm x 1500mm. Hence, calculations of the aspect ratio and the range are shown below:

$$\frac{b}{a} = \frac{1500}{750} = 2 \quad (5.10)$$

$$\frac{f}{F} = \frac{300 \cdot 300}{750 \cdot 1500} = 0.08 \quad (5.11)$$

$$c = 22,9 - 22,5 \cdot \sqrt{0,08 \cdot (3,4 - 4,4 \cdot 0,08)} = 11,79 \quad (5.12)$$

∴ For the aspect ratio $b/a \geq 2,5$ and the range $0 \leq f/F \leq 0.3$,

$$c = 22,5 - 12,25 \cdot \sqrt{\frac{f}{F} \cdot \left(5,2 - 7,2 \cdot \frac{f}{F}\right)} \quad (5.13)$$

$$c = 22,5 - 12,25 \cdot \sqrt{0,08 \cdot (5,2 - 7,2 \cdot 0,08)} = 17,05 \quad (5.14)$$

It is stated in GL rules that, for intermediate values of b/a the factor c can be obtained by direct interpolation. Interpolation calculation is stated below:

$$\frac{c-11,79}{17,05-11,79} = \frac{2-1}{2,5-1} \quad c = 15,3 \quad (5.15)$$

∴ γ_m (the partial load factor) is applied as loading condition LCA, which is stated as permanent and cyclic loads applied to undamaged structure. Hence, $\gamma_m = 1.1$ is applied to the eq 5.8.

Finally, due to the worst landing scenario, rear wheel landing force, which is 146 kN, is applied to eq. 5.8. Moreover, interim calculations performed are also applied to the equation 5.8 to calculate the deck thickness below:

$$t = 15.3 \sqrt{\frac{146 \cdot 1.1}{235}} + 1.5 = 14.14 \text{ mm} \cong 14 \text{ mm} \quad (5.16)$$

5.5 Provisions for flight operations

In this section the summary of flight operations are presented. A helicopter landing area has to be in the main deck or in higher deck according to GL rules (2006). Moreover, the area must be available of military operational procedures. It is also stated in GL rules that possible approaches should be at least 90° from the both sides of the ships longitudinal axis if the deck is situated in the stern part of the ship. Permanently occupied spaces like crew accommodation, messes and service spaces should be avoided to be designed under the helicopter landing area.

5.5.1 Size of landing deck

According to GL rules (2006), five different zones can be presented as in Figure 5.6:

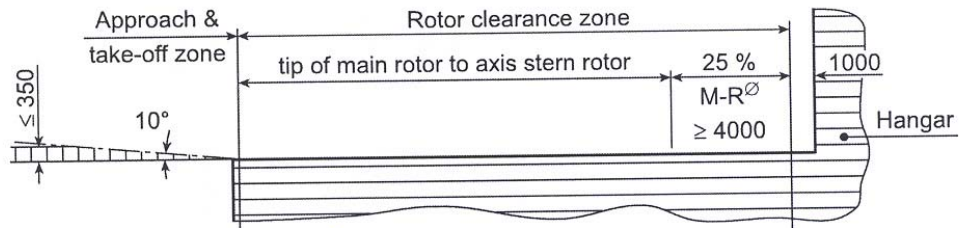
- Aiming circle is an area with a radius equal to the distance between the axis of the main rotor and the seating position of the pilot. The centre of this circle shall have a distance from forward superstructures of at least 75 % of main rotor diameter plus 1m. In this circle there must not be any obstructions for landing. The circumference of the aiming center must be marked.
- Landing zone shall have a length equal to the distance between main and bow/stern landing gear plus 2,5 m fore and aft. Its position is defined by the location of the landing gear to the axis of the main rotor, which is the centre of the aiming circle. The zone reaches from board to board of the ship. No obstructions shall be situated in this zone. Moreover, in this zone the aft rotor centre limit line is situated, which shall be at least 6,0 m before the aft end of the flight deck.
- The rotor clearance zone shall have a length equal to the distance from the tip of main rotor to the axis of stern rotor plus a clearance of the 25 % of main rotor diameter from a 1m passage if superstructures are limiting this zone. The width

of this zone extends from board to board or is defined as the gauge of main landing gear plus 50 % of the diameter of the main rotor. No obstructions shall be situated in this zone.

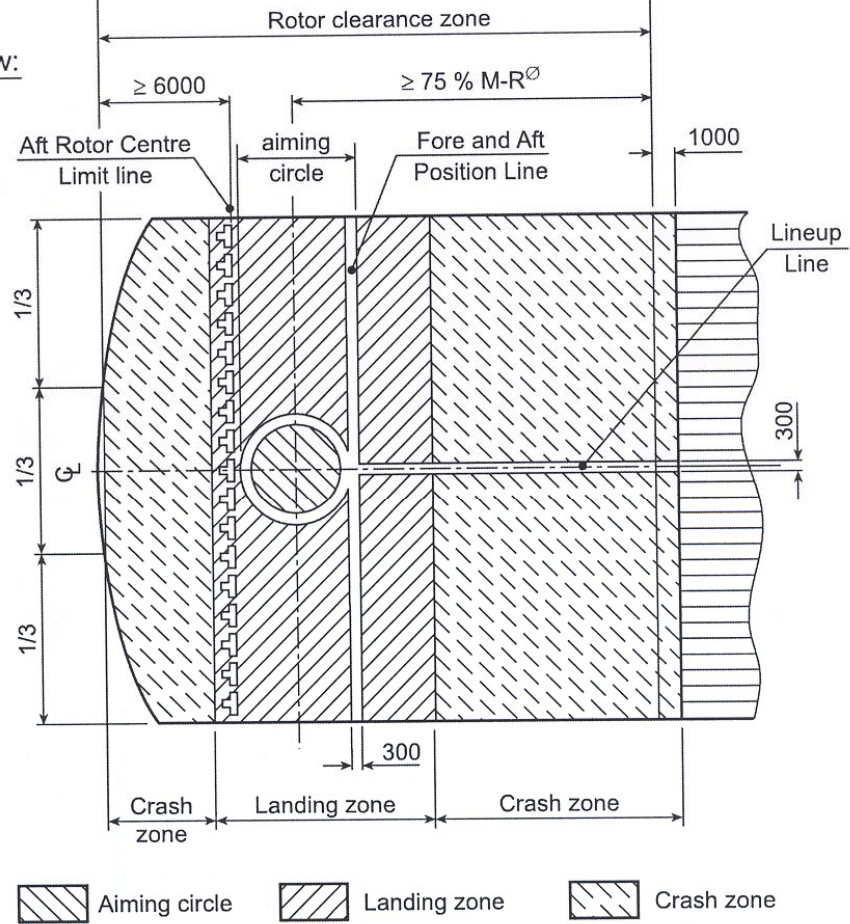
- The approach and take-off zone is extending outside the rotor clearance zone. This zone shall allow approach and take-off manoeuvres within a horizontal range of 180°. Starting from the boundaries of the rotor clearance zone, only obstacles with a height below an area inclined by 10° to the helicopter deck are permissible. In addition the maximum absolute height of obstacles is limited to 350 mm.

All areas outside the landing zone are to be considered as crash zone for the layout of the flight deck.

Longitudinal section:



Plane view:



Transverse section:

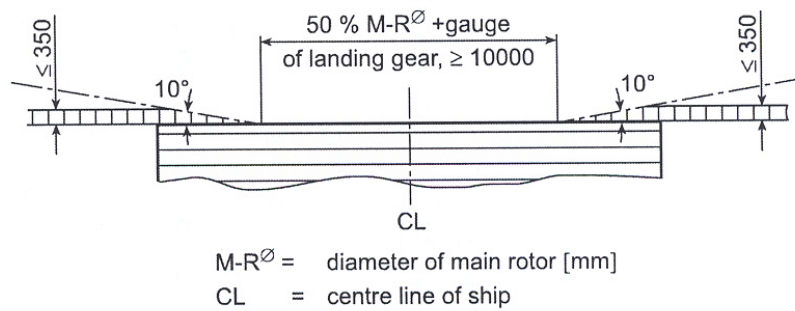


Figure 5.6 : Definition of a helicopter deck

5.6 Conclusions

Chapter 5 presented regulations and calculations for a helicopter landing area. All of the rules and formulas related about helicopter landing areas were taken from GL rules (2006). Finally, the summary of the section is given below:

- Dimensions of the Sikorsky Seahawk 70-B helicopter and the Bremen Class German Naval Forces frigate were described in detail.
- General design principles about naval ships including web and flange dimensions, partial safety factors were explained with their aims and results.
- Loading forces were calculated for the selected helicopter. Moreover, tyre print areas and crash load calculations were also performed.
- Deck thickness calculation was explained step by step. In addition, the calculations of the coefficients affecting the design directly were also performed and at the end deck thickness was found as 14 mm.
- Landing area rules and requirements were taken from the GL rules (2006) for the flight deck and hangar general arrangements. Moreover, all the dimensions of the helicopter deck stated in the regulations were plotted for the design of the helicopter deck.

6. OPTIMIZATION OF HELIDECK STRUCTURE

Little information exists on the design and structural optimization of the naval ship helicopter decks. Structural optimization of a helideck design is an important issue, which has a direct contribution to the weight of the ship. According to Chalmers (1993), the main problem associated with naval ships is; the weight of the ships due to their operation, manoeuvrability and speed requirements. Therefore the main objective of Chapter 6 is to minimize the weight of the helideck via changing several design variables by suitable ANSYS optimization tools. Moreover, two main optimization algorithms, which are sub-problem optimization method and first order method, are compared with each other via their solution times and accuracies. In addition, sweep tool and gradient tool are used to find the global optimum of the problem.

To meet the objective of this chapter background information of the structural analysis and geometric details of the helideck panel have been presented in section 6.1. In section 6.2 elastic static analyses takes place with the adopted techniques stated in advance. In section 6.3 using the validated optimization tools optimization of the structure is performed and plotted in a graphical format. Finally in section 6.4 a set of conclusions extracted from the chapter is included.

6.1 Static analysis background

In order to optimize the structure in ANSYS, static analysis must be performed and saved into the log file in advance because, the optimizer uses this log file several times and loops through the file each time with new design variable numbers assigned. Moreover, evaluation of an optimal design relies on the selection of design approximations, parameters and idealization of the structure in ANSYS. For example, the elements used in the analysis are the idealization of the original structure and they must be compatible of displaying forces and moments accurately in the linear elastic theory. Hence, first set of design parameter values must response in the linear analysis region to fulfil an elastic analysis. Therefore, to perform the

analysis, a good understanding of linear theory and element selection are required. Static analysis details are presented in the next section.

6.1.1 Details of static analysis

In this section details of linear static analysis are presented. It is useful to provide material properties and loads applied to structure in Table 6.1 shown below:

Table 6.1 : Model data specifications

Elasticity modulus (E):	207000 MPa
Poisson ratio (ν):	0.3
Density of steel (ρ):	7.85×10^{-9} ton/mm ³
Minimum Yield Stress of Steel (R_{eH}) :	235 MPa
Allowable Stress:	160 MPa
Rear tyre pressure	1.623 N/mm ²
Front tyres pressure	0.812 N/mm ²
Deck load	0.002 N/mm ²
Hangar load	0.003 N/mm ²

In order to idealize the grillage structure under the name of girders, transverses and columns, BEAM 189 (3-D & 3 nodes) element is selected. The BEAM189 element is suitable for analyzing slender to moderately stubby/thick beam structures. The element is based on Timoshenko beam theory which includes shear-deformation effects. This element has axial direct stress (SDIR) and axial force (F_x) output functions which will be used for column buckling assessment. The geometry of the BEAM 189 element is illustrated below in Figure 6.1:

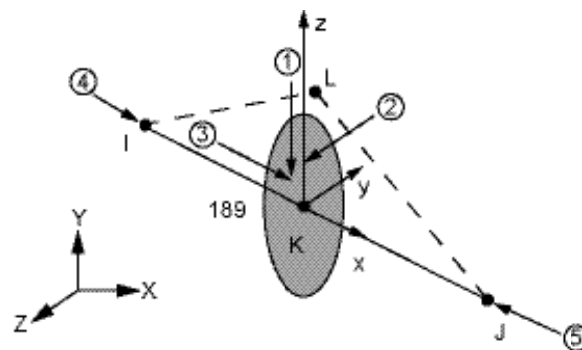


Figure 6.1 : Beam 189 Geometry

Moreover, to idealize the flight deck, SHELL 181 element is used. SHELL181 is suitable for analyzing thin to moderately-thick shell structures. It is a 4-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. SHELL181 is well-suited for linear, large rotation, and/or large strain nonlinear applications. Illustration of the SHELL 181 element is shown below in Figure 6.2:

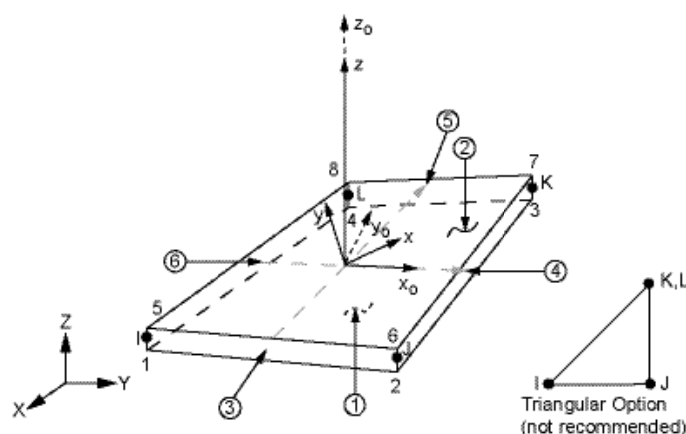


Figure 6.2 : Shell 181 Geometry

After specifying the details of used elements, main dimensions of the helideck are listed in the table 6.2 below:

Table 6.2 : Helideck Main Dimensions

Length:	38 m
Beam :	15 m
Height :	2m from the main deck
Nr of central vertical columns :	15
Nr of central inclined columns :	36
Nr of side vertical columns :	15 on each side
Nr of side inclined columns :	14 on each side
Nr of rear vertical columns :	2

6.1.2 Details of the Geometry

In this section details of the helideck geometry are presented. Flight deck is constructed on the grillage and carried by the columns under the deck. Various element cross-sections are used to define the geometry. Girder, transverse and

column cross-sections can be summarized with assigned initial set of parameters in Figure 6.3 & 6.4 below:

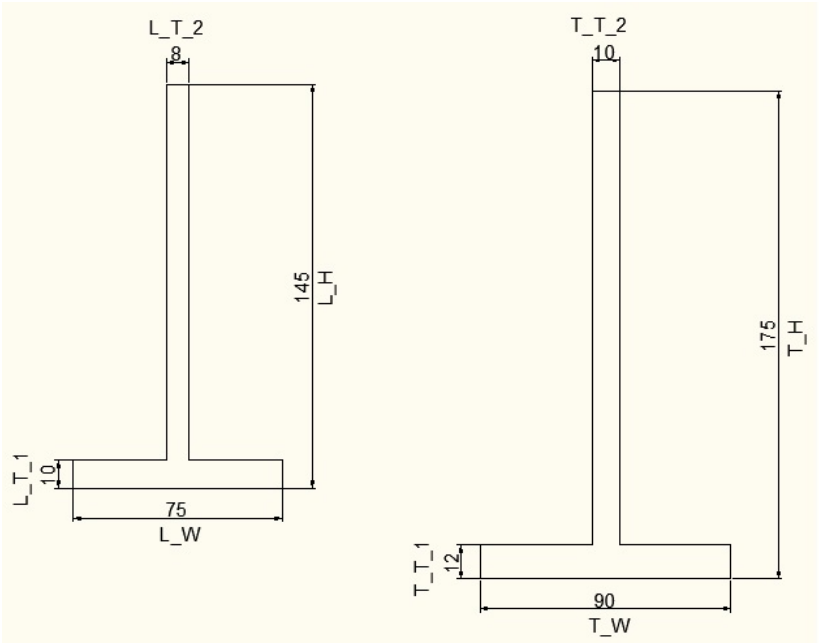


Figure 6.3 : Cross-sectional parameters of girders and transverses

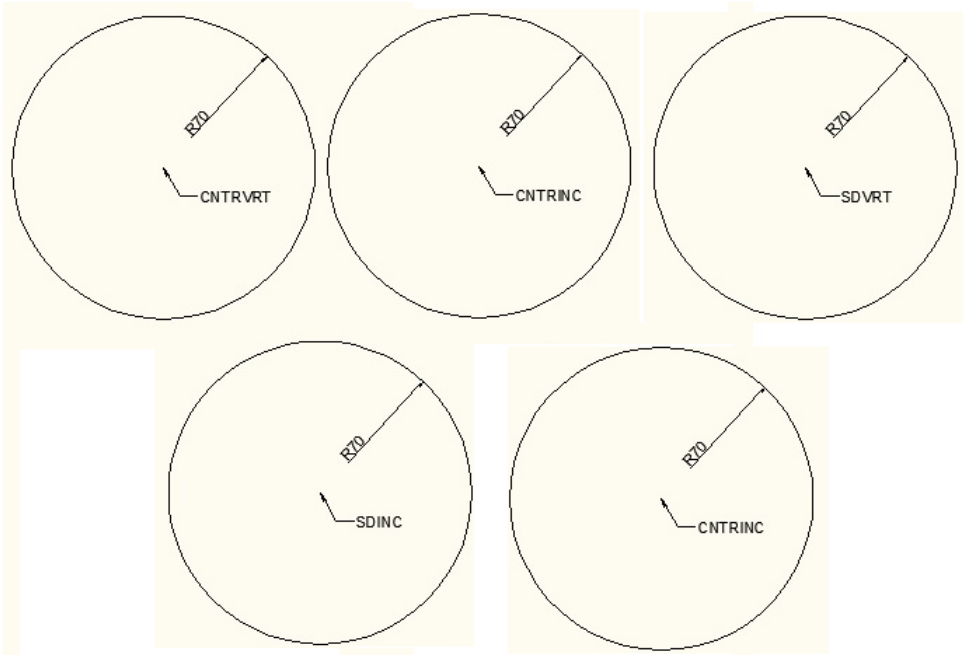


Figure 6.4 : Cross-sectional parameters of columns

Moreover, these parameters, their definitions and assigned first set of values are summarised in Table 6.3 below:

Table 6.3 : Definition of the parameters and the first set values of parameters

Parameters	Definition	Values
L_W	Longitudinal girder width	75 mm
L_H	Longitudinal girder height	145 mm
L_T_1	Girder flange thickness	10 mm
L_T_2	Girder thickness	8 mm
T_W	Transverse height	175 mm
T_H	Transverse width	90 mm
T_T_1	Transverse flange thickness	12 mm
T_T_2	Transverse thickness	10 mm
SDINC	Side inclined column radius	70 mm
SDVRT	Side vertical column radius	70 mm
CNTRVRT	Centre vertical column radius	70 mm
CNTRINC	Centre inclined column radius	70 mm
RCLMNS	Rear vertical column radius	70 mm

In addition, girders and transverses are translated through their mass centres in +z global direction to the bottom of the shell automatically in every loop. The translation is performed automatically because; cross-sectional offset of the elements are also performed with parameters. Aim of this process is to ensure T bars and the shell works together and seems like welded. Below formula defines the process for girders:

$$\text{Offset distance in } +z \text{ direction} = L_H - \frac{L_{T_1}}{2} = 145 - \frac{10}{2} = 140 \text{ mm} \quad (6.1)$$

In order to explain this translation simply, one panel section is shown in Figure 6.5 below. It can be observed that girders and transverses don't intersect with the shell.

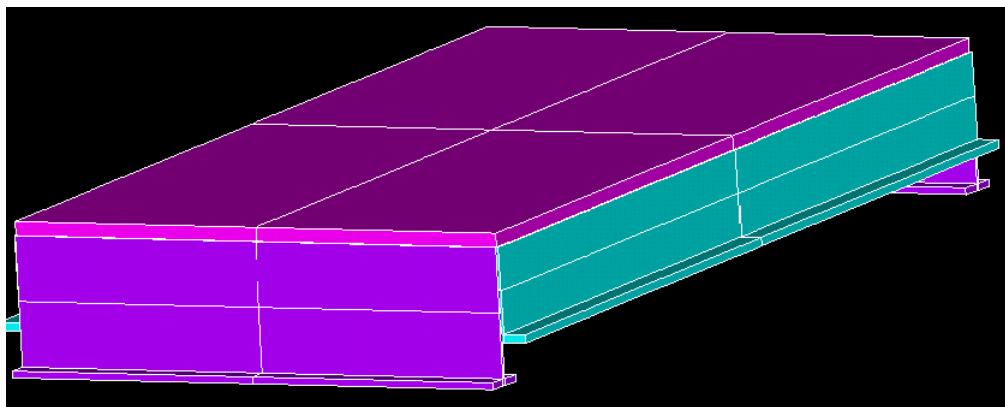


Figure 6.5 : Panel section assembly detail

6.1.3 Details of the Flight Deck

In this section the helideck geometry is presented. Flight deck consisted of 7 different cross-sectional areas for beams and 1 thickness parameter for the top shell. A small part of the deck is illustrated in Figure 6.6 for the sake of simplicity of the analysis. Views from other angles will be presented in Appendix A1 to A6.

Static equilibrium of the structure is fulfilled with columns because they are connecting the flight deck to main deck of the vessel. In the next session buckling analysis of the columns will be also performed. In order to explain the geometry better, a real helideck structure of “Commandante Toro” frigate belongs to Spanish Naval Forces is illustrated below in Figure 6.7:

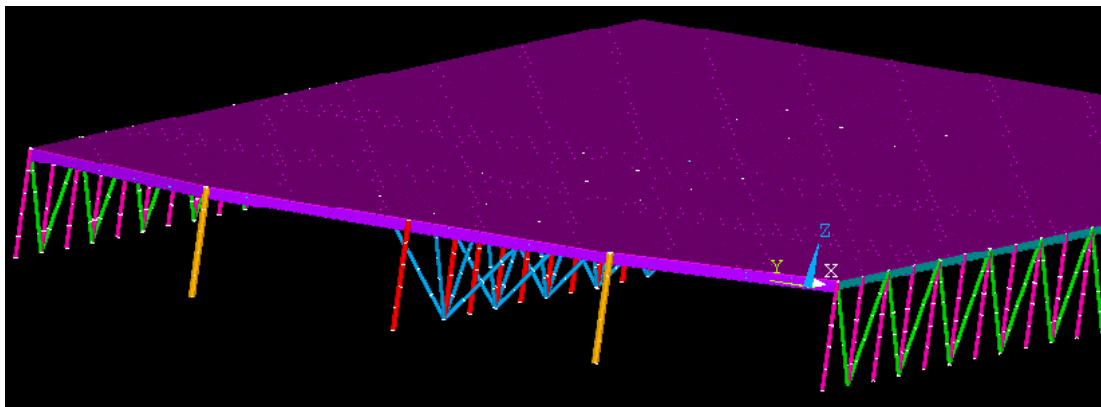


Figure 6.6 : Helideck design geometry



Figure 6.7 : Helideck example from a real frigate

6.1.4 Mathematical Modelling of the Geometry

In this section the mathematical model of the geometry is presented. Mathematical model is defined as MESH in ANSYS. In order to perform analysis, all structure must be defined in mathematical model, in other words, it must be meshed. It is important to remember that barely the geometry consists of only keypoints, lines, areas and volumes. Therefore, solid model does not participate in the finite element solution. In order to achieve mathematical model, geometry must be meshed. After performing meshing, these geometrical definitions are changed into nodes and elements. Adjacent elements which are working together in the physical geometry must use the same nodes.

Therefore, after constructing the geometry, merging all of the keypoints, lines, areas and volumes is compulsory before the meshing process.

In addition, meshing options are the most important factors that affects the response of the structure. It affects the computational cost and the accuracy of the solutions. Moreover, when the number of elements (mesh density) is increased, the solution gets closer and closer to the true solution. However, performing finer mesh does not mean always the results are accurate. The objectives of the analysis always decide fine or coarse mesh is required for the analysis. If the objective is to perform a nominal stress and deflection analysis, relatively coarse mesh will be enough and also some of the structural details may be omitted from the FE model.

Moreover, the shapes of the elements must be regular. In most cases, the model geometry is such that the areas have more than 4 sides, and volumes have more than 6 sides. To convert these to regular shapes, you may need to do one or both of these operations:

- Slice the areas (or volumes) into smaller, simpler shapes.
- Concatenate two or more lines (or areas) to reduce the total number of sides.

In helideck model, meshing is performed accurately by dividing the lines which forms the geometry. In order to achieve regular meshing, the process is performed by free quadrilateral meshing without receiving any warning messages from the programme. Span lengths of girders and transverses are specified as 750 mm and 1500 mm in order. Girders are divided into 2 parts regularly and around the landing area they are divided into 5 to ensure 300mm length for tyre pressure area. In

addition, transverses are divided into 2 parts regularly and they are divided into 5 parts around the landing area to ensure 150mm width for tyre pressure area. Formerly, it was stated that, the tyre print areas must be 300mm x 300mm areas each. Hence, each tyre pressure area uses 2x150mm lateral length and 300mm longitudinal length to achieve the accurate tyre print pressure area. Line divisions and meshing illustrations are presented in detail in Appendix section.

Moreover, the FE model of a part of the whole the structure is shown in Figure 6.8. Due to the sake of simplicity of the figure, only one small part of the structure is shown. Other views of the meshed structre are available in the appendix section.

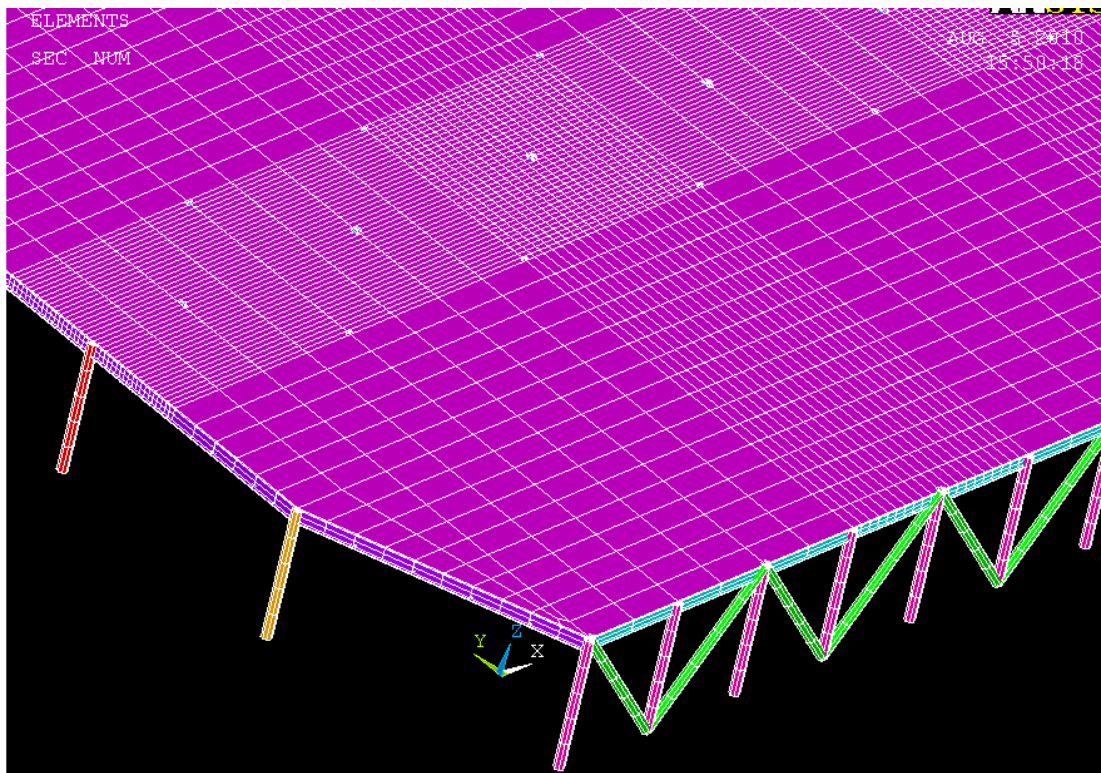


Figure 6.8 : A part of the helideck geometry FE model

6.1.5 Loading Conditions

In this section flight deck loading conditions are presented as presented in Chapter 5, helideck will have three main loads applied on it: helicopter crash landing load, static deck load and hangar load. All of the calculations were performed in the Chapter 5. Moreover, units of all calculated loads applied to flight deck must be turned into pressures in terms of N/mm^2 for consistency of the results. It must be kept in mind that, static deck loads must be at least 2 kN/m^2 on the helideck and hangar loads

must be at least 3 kN/m² in the hangar for any fastening requirements, stated in GL rules (2006).

In addition, the tyre print pressures must be applied on 300mm x 300mm area for each tire. The selected helicopter has three tyres, one is situated in rear and other two are in the front part. They are sharing the maximum take-off weight of the helicopter in 50% in rear and 25% in front for each tire as it was shown in Figure 5.7. Moreover, wheel-base tread distance in longitudinal and lateral directions must be calculated. Therefore, lateral distance of tyres is taken as 2.7m and longitudinal distance is taken as 7.5m from the helicopter manufacturer. Tyre print pressures must be calculated via the following equations shown below:

For rear tyre:

$$P_r = \frac{146 \text{ kN}}{300\text{mm} \times 300\text{mm}} = \frac{146000 \text{ N}}{90000\text{mm}^2} = 1.623 \text{ N/mm}^2 \quad (6.2)$$

For one of the front tyres:

$$P_f = \frac{73 \text{ kN}}{300\text{mm} \times 300\text{mm}} = \frac{73000 \text{ N}}{90000\text{mm}^2} = 0.812 \frac{\text{N}}{\text{mm}^2} \quad (6.3)$$

Tyre print pressure areas and static deck loads are shown in Figure 6.9. In this figure blue pressure area represents the rear tyre pressure, green pressure areas represent each of the fore tyre print pressures. Moreover, not only helicopter crash landing force is applied to the flight deck, but also static deck load is applied in the normal direction to all deck from aft of the helideck to the hangar entrance and shown in red contour. As it was stated before, static hangar load is higher than the static deck load (3 kN/m²), which starts from the hangar entrance to the end of the helideck, and applied on an area of 13.5m x 15 m in longitudinal and lateral dimensions in order. Hangar has to cover adequate area for the folded dimensions of the helicopter, stated by GL rules (2006).

Static deck load comprises of snow, ice, cargo etc. and hangar deck load comprises of fastening equipment and maintenance loads. Hangar deck static loads are illustrated in Figure 6.10. Blue pressure area defines the exact hangar area, while the red pressure area defines the boundary of the hangar structure.

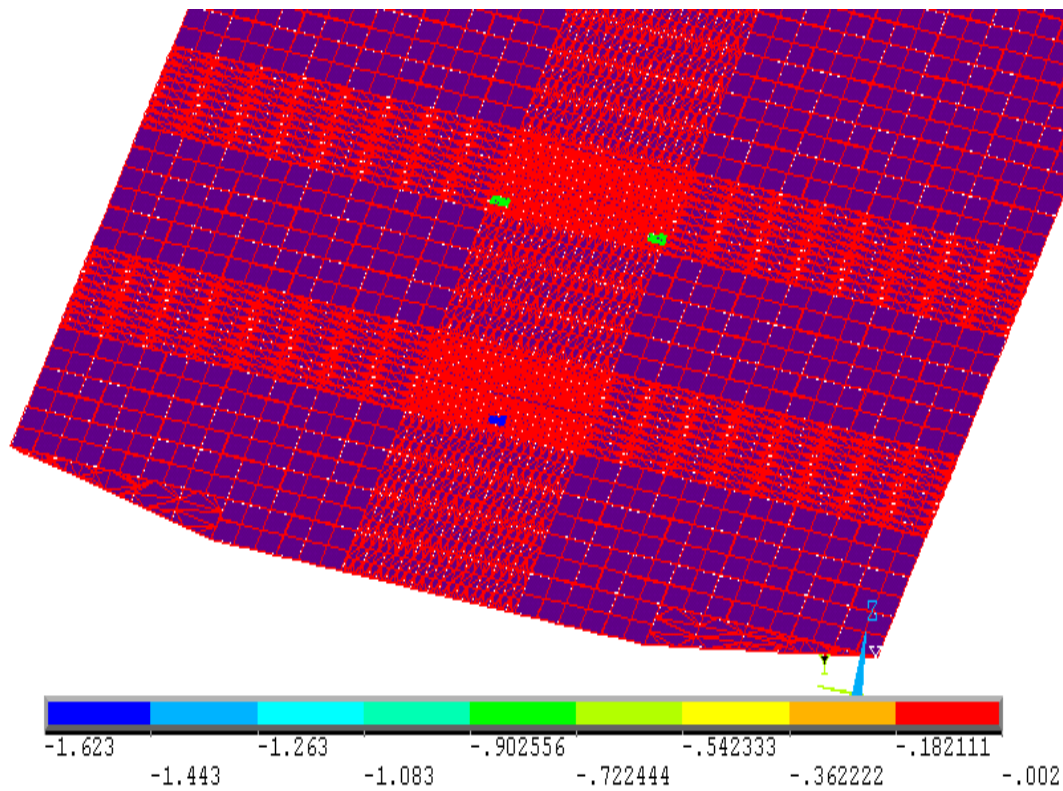


Figure 6.9 : Helicopter landing pressure and static deck pressure definition

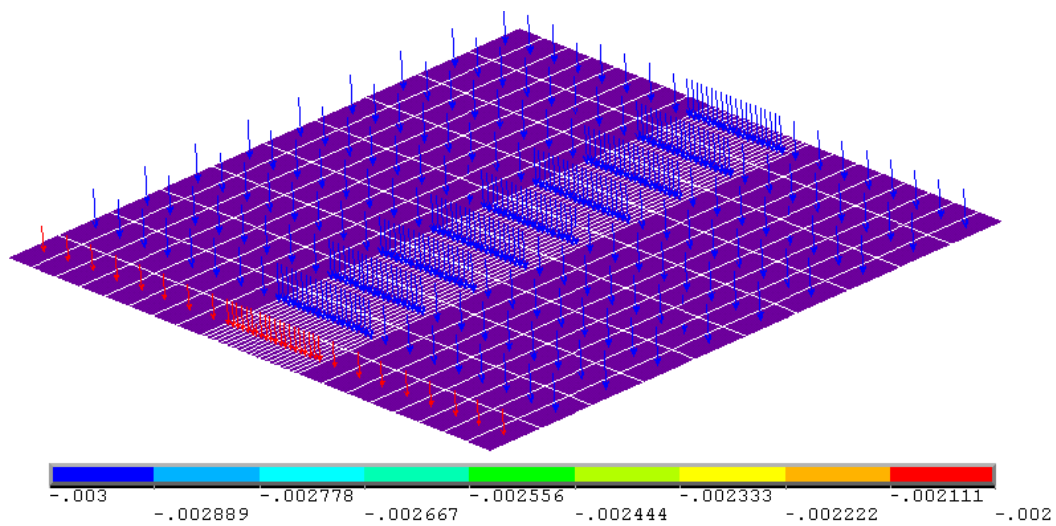


Figure 6.10 : Hangar deck static pressure definition

6.1.6 Boundary Conditions

In this section flight deck boundary conditions are presented. Flight deck is constrained around the circumference of the hangar. In addition, under the hangar a

bulkhead exists; hence it is also constrained. Circumference of the hangar is fully constrained due to the side walls and the superstructure of the vessel. Bulk head constrains translation of the hangar deck only in global z direction. Hence, bulkhead does not have a contribution to the structure to resist moments. It is just acting like simple support under the hangar. Moreover, as it was stated before, flight deck is carried by vertical and inclined columns positioned in the centre and at the sides of the helideck. All columns are fully constrained at their contact point to the main deck. There are not any supports at the conjunction points between the columns and grillage structure. Boundary conditions of the flight deck are illustrated in Figure 6.11. Yellow signs represent rotational constraints while green ones are representing translational constraints. Red ACEL sign stands for gravity acceleration.

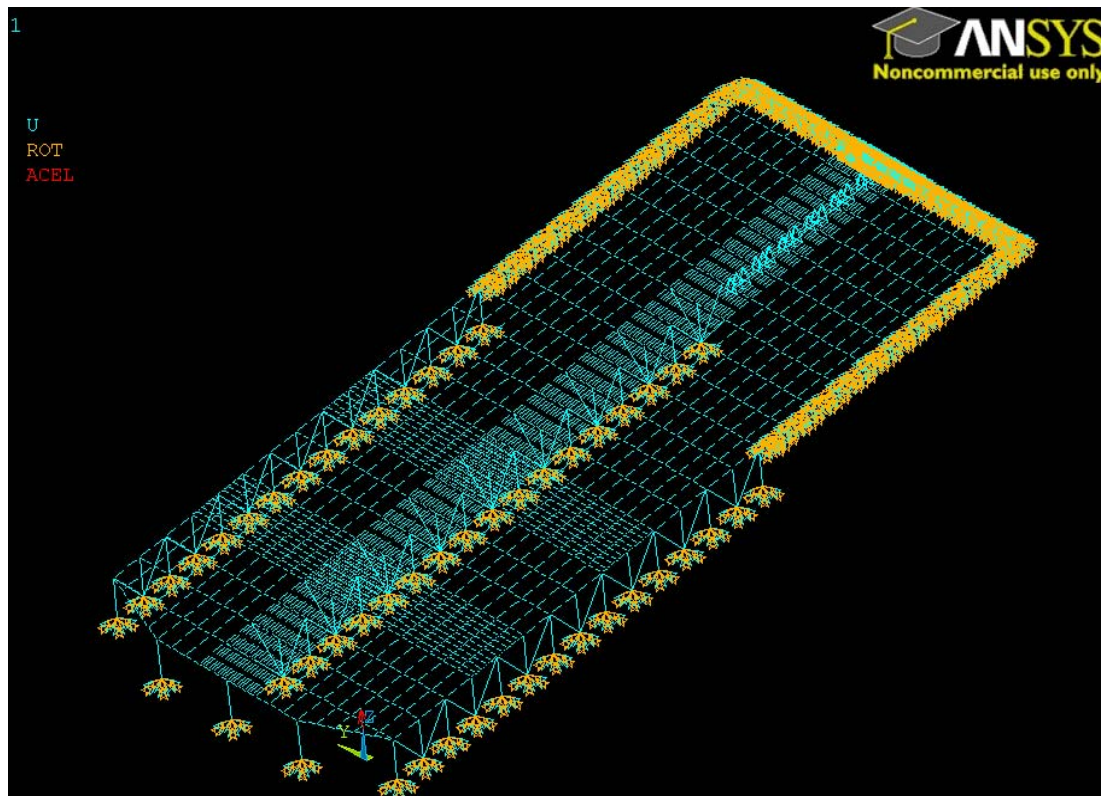


Figure 6.11 : Helideck boundary conditions

6.2 Static Structural Analysis

In this section helideck static structural analysis is presented. Static structural analysis is compulsory before the optimization process because, displacements and von-misses stresses are retrieved from the database in this section. ANSYS optimizer loops through the database file several times and performs this static analysis in each

loop with new parameter values assigned. Analysis is performed with the assigned first set values of the parameters. Hence, this process ensures whether the first parameter values provide enough strength and the responses are in the elastic region. In this analysis the threshold for displacements are determined as 5mm and von-misses stresses are determined as 160 N/mm². In the Figure 6.12 plot of nodal solution is illustrated. In addition, in the Figure 6.13 & 6.14 rear and front tyres detailed nodal solution plots are illustrated in order to avoid any incoherence.

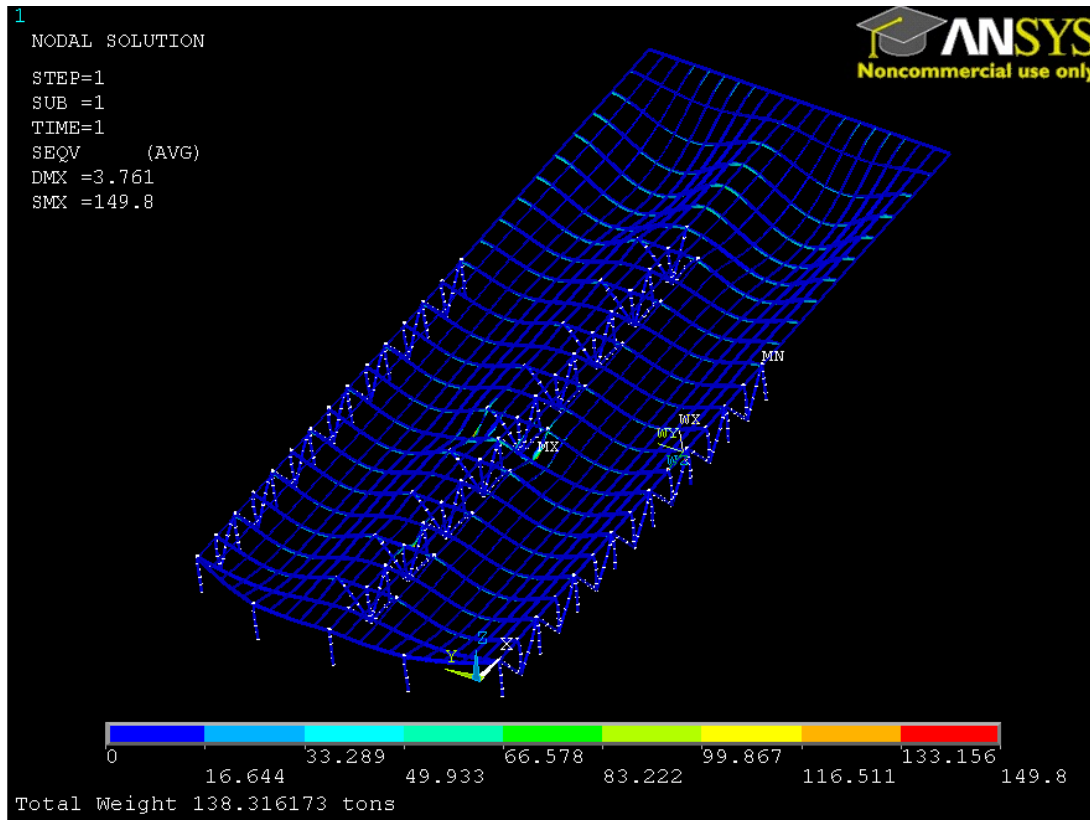


Figure 6.12 : Nodal solution

After the static solution, maximum deflection of the structure is observed as 3.761mm and maximum von-misses stress is observed as 149.8 N/mm². Response of the structure shows that the analysis was performed in the elastic region so former element approaches were accurate. Maximum stress is observed near the girders under the front tyres. However, rear tyre, which has also 50% of the total helicopter load, contributed to a high stress value of 125 N/mm². Maximum deflection is observed under the hangar deck which is 3.761mm. In addition weight of the structure while the first set parameters values assigned of is found as 138.316 tons.

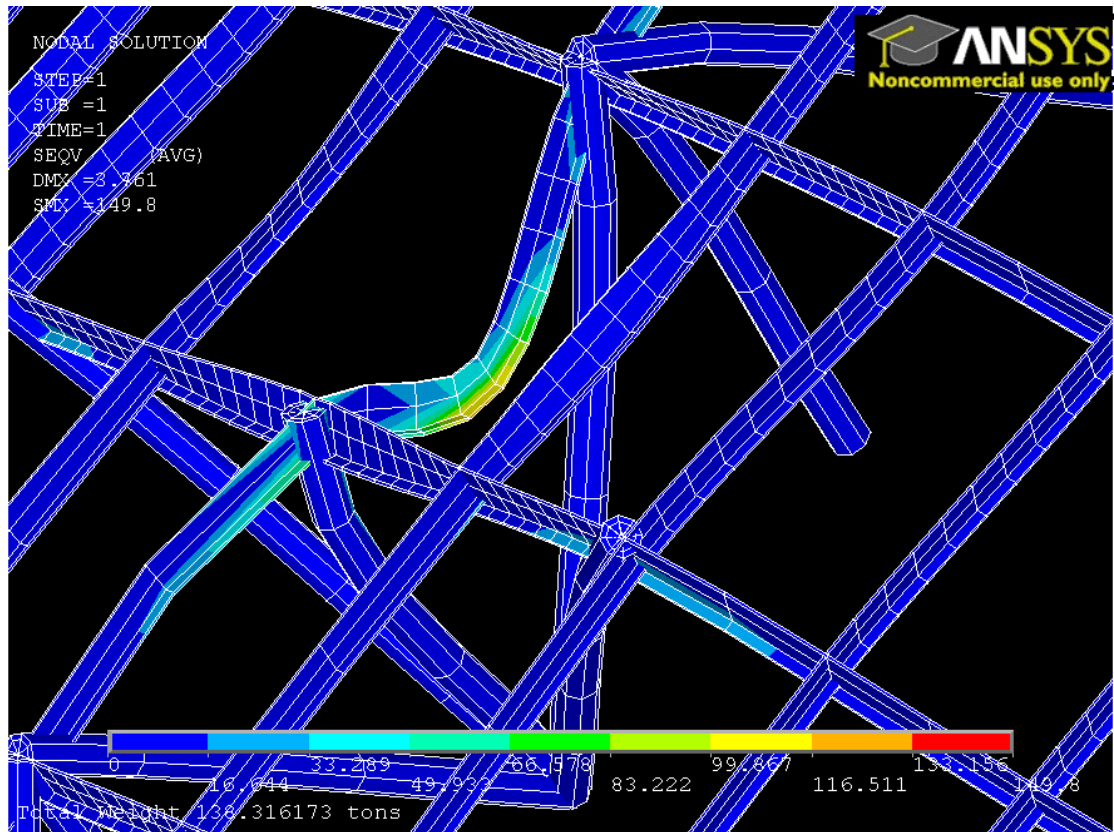


Figure 6.13 : Rear tyre print area nodal solution in detail

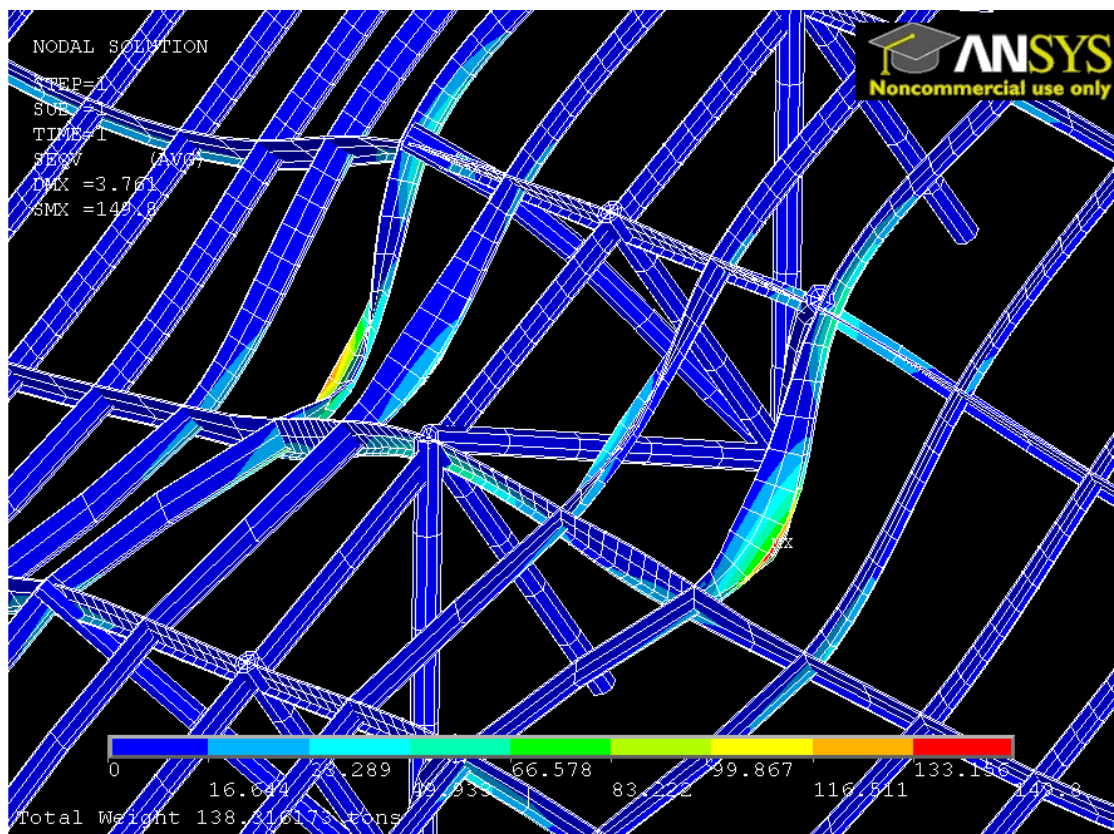


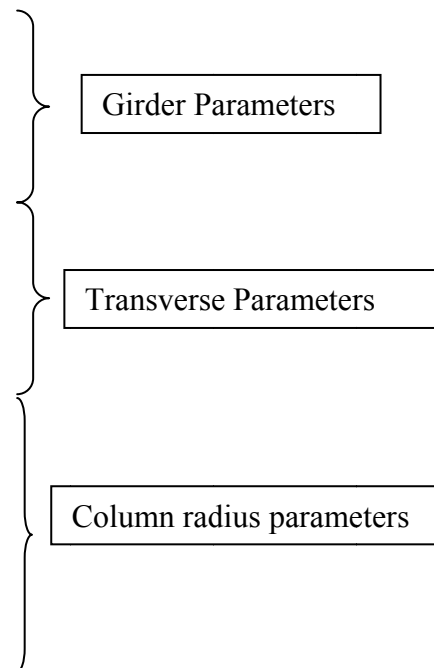
Figure 6.14 : Front tyres print area nodal solution in detail

6.3 Optimization of the helideck

In this section optimization of the helideck is performed. Optimization problems have DV's, SV's and OBJ function to perform the iteration.

6.3.1 Definition of the variables and objective function

In addition, all parameters with their upper and lower bound constraints are summarised below:



Moreover, tolerances of the design variables are calculated as stated before, in the formulae $TOLER = (MAX - MIN) / 100$. In figure 6.15 boundaries, tolerances and initial values of the DV's are summarised:

Design Variables				
Currently Defined Design Variables:				
Parameter	Minimum	Maximum	Tolerance	Value
CNTRINC	40.000	80.000	0.40000	40.000
CNTRVRT	40.000	80.000	0.40000	53.230
L_H	50.000	200.00	1.5000	136.61
L_T_1	5.0000	20.000	0.15000	12.138
L_T_2	5.0000	20.000	0.15000	5.0000
L_W	30.000	150.00	1.2000	69.631
RCLMNS	40.000	80.000	0.40000	67.799
SDINC	40.000	80.000	0.40000	40.000
SDVRT	40.000	80.000	0.40000	42.672
T_H	120.00	250.00	1.3000	197.34
T_T_1	5.0000	20.000	0.15000	9.8541
T_T_2	5.0000	20.000	0.15000	5.0000
T_W	50.000	180.00	1.3000	70.227

Figure 6.15 : Boundaries, tolerances and initial values of DV's

State variables comprises of the constraints on the design problem. Helideck optimization problem has 2 SV's. They are, maximum von-misses stress and maximum vertical deflection parameters summarized below:

$$S_{max} \leq 160 \text{ N/mm}^2$$

$$U_{max} \leq 5 \text{ mm}$$

Objective function of the optimization process is determined as total volume (VTOT) of the structure.

∴ Reasons to select total volume as an objective function are summarised below:

- It is a time saver strategy compared to calculating mass matrix in each loop.
- Results are more precise due to small tolerance values in mm^3 unit.
- Same material properties are used all in the structure so there is no need to calculate mass matrix in each loop. Achieving VTOT data and multiplying it by density just in the parameter section is enough.

6.3.2 Sub-problem method optimization

Sub-problem optimization is a zero order algorithm which requires only the response variables (SV's and OBJ). It is generally recommended for most applications because of its generality of approach and speed of execution.

Helideck structural optimization is first performed via this method. In the next section first-order method will be executed. Sub-problem method generally needs restart mechanism and approaching the global optimum generally takes time and lots of iterations.

Firstly, optimization process is performed under default objective tolerance value which is $174\text{e}^6 \text{ mm}^3$. The best design is found at the 6th iteration which is 134.46 tons of displacement. The optimization curve is illustrated in Figure 6.16. However, this result denotes a local optimum. In order to find the global optimum, objective function tolerance is altered to 1000 mm^3 , which will lead to more precise results. Moreover, generally, tightening the OBJ tolerance forces convergence based on DV tolerances. Secondly, latter sub-problem iteration process is illustrated in Figure 6.17. This time, the optimizer found the global optimum due to the change in the process direction in the data base. This change is made by tightening the OBJ

tolerance value. The best design is found at the 32nd set which is 118.28 tons of displacement. Thirdly, database sweep process is performed by sweep tool in ANSYS in order to ensure that the global optimum has been achieved. The database sweep curve is illustrated in Figure 6.18. The best design is achieved at the 45th set which is 117.95 tons of displacement. In addition, sweep tool is used for global sensitivity studies.

Finally, local sensitivity analysis is performed via gradient tool. This tool explains how a given design responds to small perturbations in DVs. Global optimum of the problem is found as 117.95 tons at the 45th set. Curve of the gradient tool is illustrated in the Figure 6.19.

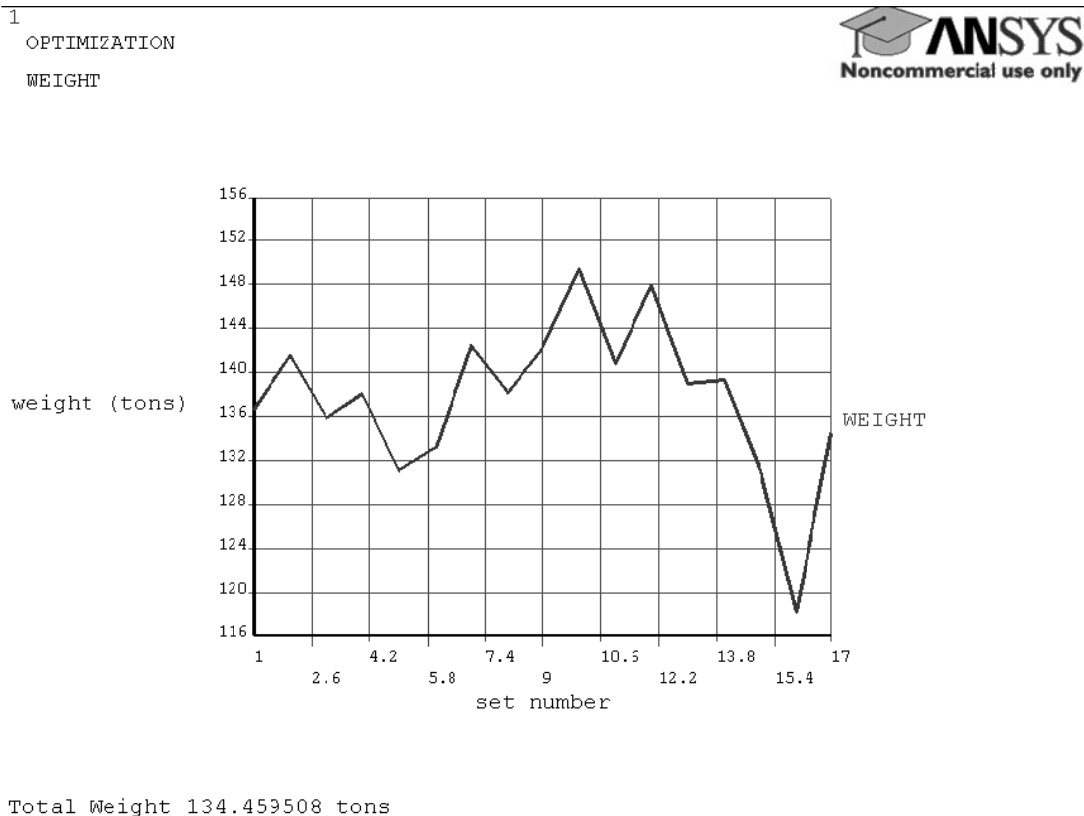
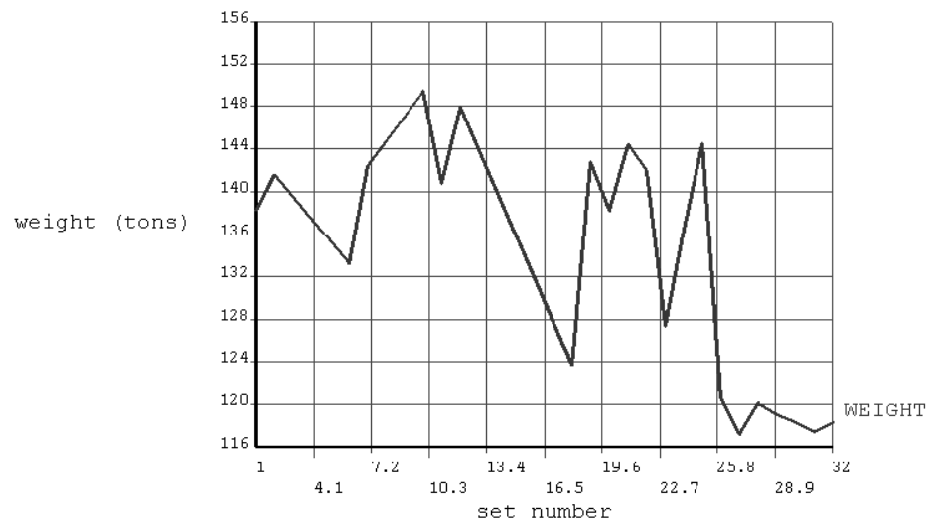
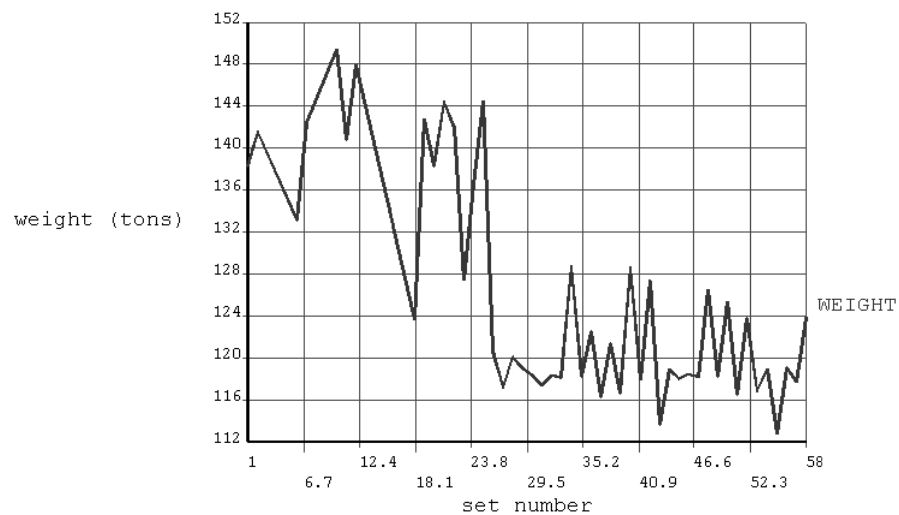


Figure 6.16 : First sub-problem iteration



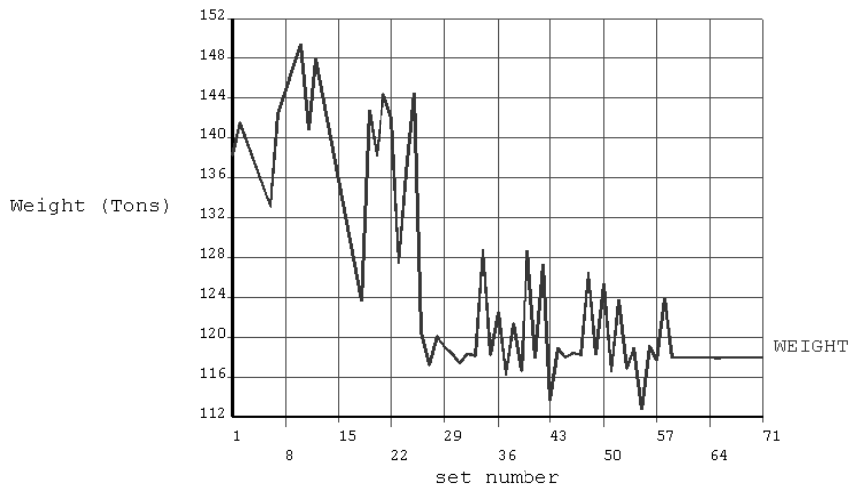
Total Weight 118.27913 tons

Figure 6.17 : Second sub-problem iteration



Total Weight 123.825514 tons

Figure 6.18 : Database sweep curve



Total Weight 117.950553 tons

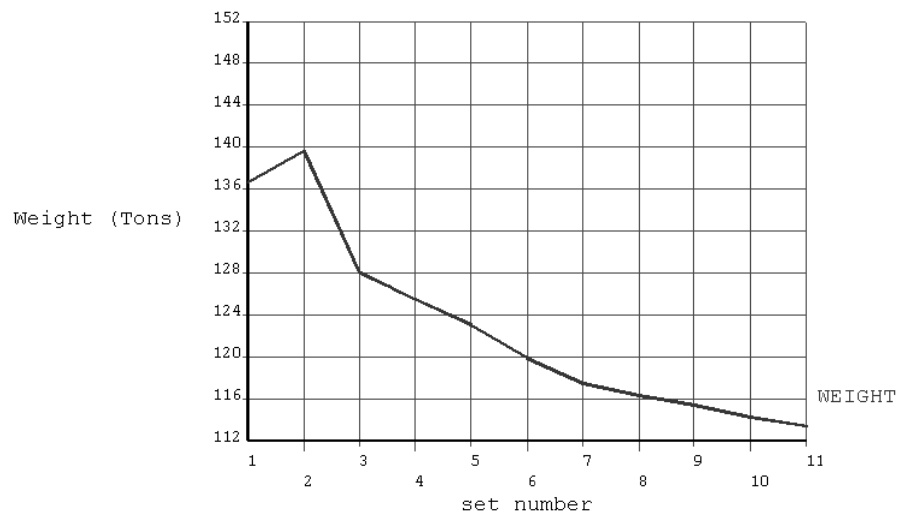
Figure 6.19 : Gradient curve

6.3.3 First Order Method

In this section optimization via first-order method is presented. Formerly, it was stated that, first order method uses derivatives of the response variables - OBJ and SV's - to determine search direction and arrive at an optimum. The method is more accurate because no approximations are used. In Figure 6.20 helideck optimization problem via first order method is illustrated. OBJ tolerance is assigned as 1000 mm^3 for the total volume (TOTVOL) objective function. Hence, the results are precise and accurate. It can be observed from the Figure 6.20 that, the global optimum is reached at the 13th set with a displacement of 113.34 tons.

First order method is very precise thus; there is no need to perform data sweep process again to find global sensitivity. Gradient tool is applied to the 13th set of the iteration process in order to investigate whether the best result is perched on a hillside or not. In Figure 6.21 it is illustrated that, after performing the gradient tool the curve is stabilized at the global optimum while the final displacement is observed as 113.34 tons.

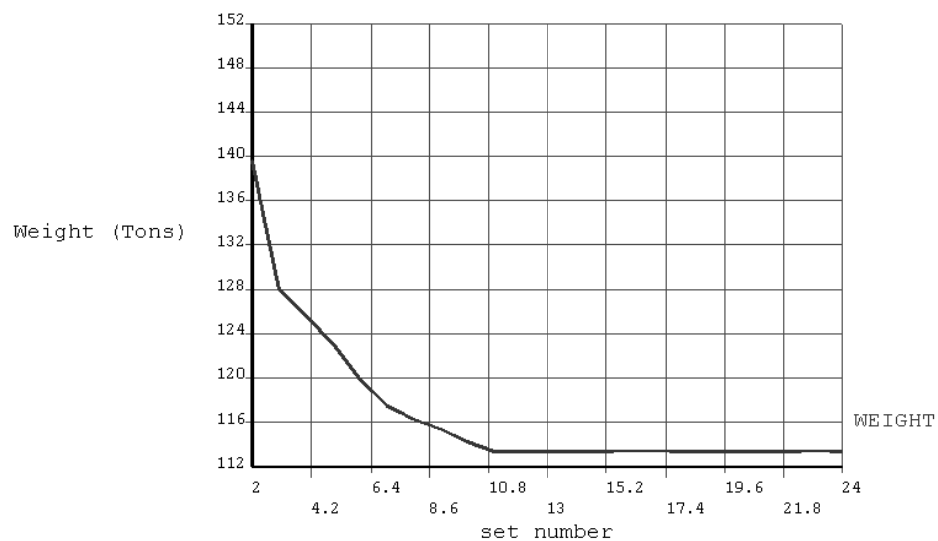
1
OPTIMIZATION
WEIGHT



Total Weight 113.34143 tons

Figure 6.20 : First order method

1
OPTIMIZATION
WEIGHT



Total Weight 113.361068 tons

Figure 6.21 : Gradient curve

6.4 Conclusions

In chapter 6 the reader has been presented about helideck geometry with a specific emphasis on the parametrically designed cross-sectional areas. Also the adopted approaches to perform the optimization process have been described. Using the validated optimization tools responses of the helideck design has been showed in detail. Finally summary of this section is given below:

- Fundamentals of the structural analysis were explained in detail. Element selection, element properties and dimensions of the helideck including supporting column numbers were defined.
- Parameters, their definitions and cross-sectional properties were issued. One of the flight deck panels was illustrated to ensure readers understand the geometry. Moreover, translations of the girders and transverses, which are moving up or down to work with the top shell together, were explained in detail.
- Mathematical model of the geometry, namely meshing, was defined in detail and illustrated in figures.
- Loading conditions and all of the required calculations were defined.
- Boundary conditions and their reasons were discussed.
- Static structural analysis, its requirements and results were discussed.
- Design variables, state variables and objective function boundaries tolerances and initial set of values were defined.
- Structural optimization was performed via sub-problem and first-order methods. Database sweep tool and gradient tool results and aims were discussed.

7. RESULTS & COLUMN BUCKLING ASSESSMENT

Upon optimization of the helideck structure via sub-problem optimization method and first-order method, it is required to compare the optimization results. In order to meet this requirement; Chapter 7 presents the comparison of two different algorithms via their computational costs and accuracy. Moreover, global and local sensitivity of the design parameters are also executed with database sweep tool and gradient tool in order.

A review of the former optimization process is given in section 7.1; section 7.2 describes the comparison of two algorithms via table; section 7.3 presents global and local sensitivity analysis of the parameters and their ranks to affect the design weight; section 7.4 describes the best design point (global optimum) parameter values and the weight concerns; section 7.5 describes the buckling assessment of the supporting columns under the helideck ABS buckling formulae. Finally section 7.6 gives the conclusions of the chapter.

7.1 Review of the optimization process

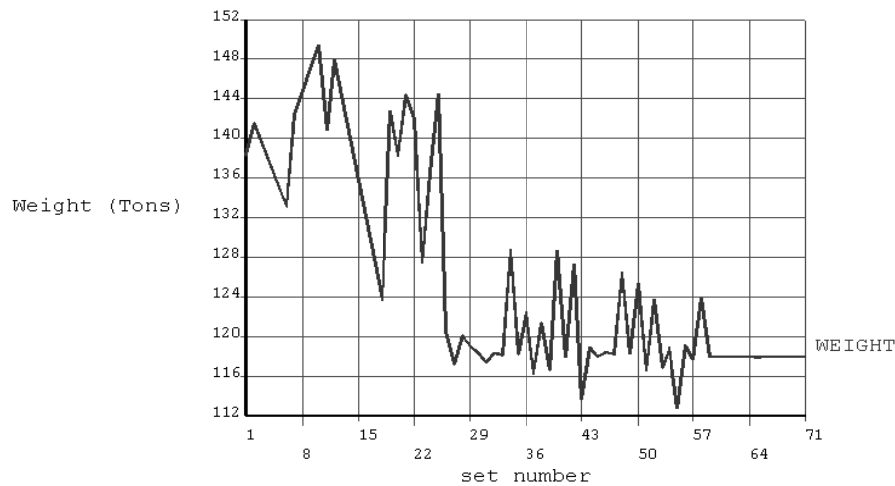
In order to optimize the structure in ANSYS, two different algorithms are used. Firstly, sub-problem optimization method is used and the global optimum solution of the problem is found at the 45th iteration and after the 59th set optimization curve is stabilized. In sub-problem method, restart mechanism is used via tightening the OBJ value to 1000mm³. Briefly, in order to achieve the global solution and stabilize the optimization curve totally 71 iterations are performed. Moreover, to ensure that the global optimum is achieved, database sweep performed and for local sensitivity analysis gradient tool is used. It can be observed from Figure 7.1.

Secondly, first-order method is used without performing database sweep operation because the global optimum is achieved after 13 iterations and the result is accurate. OBJ value tolerance is given 1000mm³, which is the same value with sub-problem method, to compare the optimization iterations. Gradient tool is used after

iteration to find whether the global optimum point is stable after small perturbations in the parameters. It can be observed from Figure 7.2.

1

OPTIMIZATION
WEIGHT

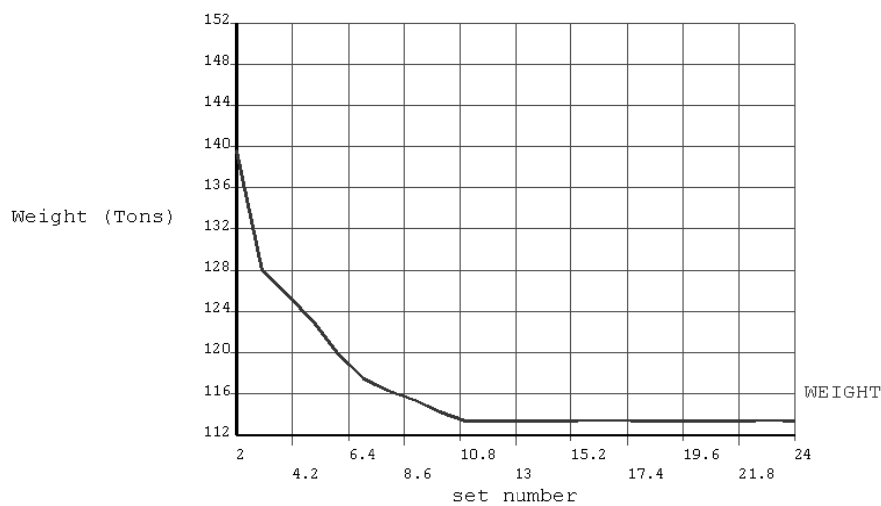


Total Weight 117.950553 tons

Figure 7.1 : Sub-problem iteration

1

OPTIMIZATION
WEIGHT



Total Weight 113.361068 tons

Figure 7.2 : First-order iteration

7.2 Comparison of the algorithms

Aim of this section is to compare sub-problem method with first-order method, via their computational costs and accuracy. Computational cost means the Central Processor Unit (CPU) usage so the time consumed to achieve the global optimum. All design sets of these two methods will be available in a list in Appendix section. The methods are compared in Table 7.1 via their computational costs and accuracies:

Table 7.1 : Comparison of the algorithms

	Sub-problem method	First order method
Time consumed to find global optimum	1.5 hrs	4.5 hrs
Achieved global optimum value	117.94 tons	113.34 tons

It can be observed from the Table 7.1 that, first order method is more accurate than the sub-problem method because; it is using the derivatives of the response variables (SV's and OBJ) without any approximations. Sub-problem method uses least squares fit approximation to find an optimum solution. However, accuracy of the first order method causes a disadvantage of time consumption. It is nearly three times more than the sub-problem method. Briefly, selection of these methods depends on the engineer and the problem specifications.

7.3 Global and local sensitivity analysis

Aim of this section is to perform global and local sensitivity analysis of the parameters with both of the methods. Sub-problem method requires data sweep operation and gradient tools to find sensitivities. Results from the sweep tool indicate how each DV affects the design - global sensitivity. Starting from the best design it increments each DV separately from MIN to MAX to investigate the effect of each DV on design. Parameters are grouped into four for the sake of simplicity of the figures. In Figure 7.3 effects of the column radius parameter on the design is shown below:

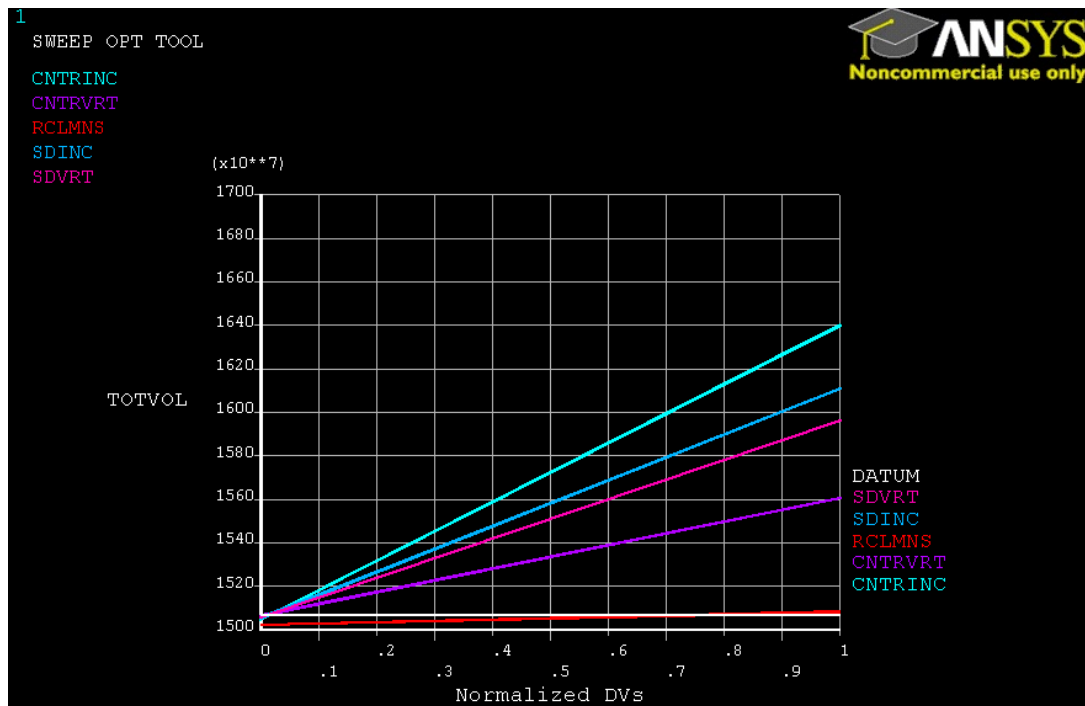


Figure 7.3 : Global sensitivity of column parameters (sub-optimization method)

It can be observed from the above figure that, central inclined (CNTRINC) column radius has contributed to weight of the structure the most within the column parameters. In the x and y axis, the x axis shows normalized DV's while the y axis shows the total volume of the structure. Incline of the lines represents the global sensitivity of the parameters. It can be ranked from the highest sensitivity to the lowest for column radius parameters below:

$$\text{CNTRINC} > \text{SDINC} > \text{SDVRT} > \text{CNTRVRT} > \text{RCLMNS}$$

It can be observed from Figure 7.4 that, girder profile thickness (L_T_1) has contributed the most within the girder parameters. Ranked of the girder parameters from the highest sensitivity to the lowest sensitivity are stated below:

$$\text{L_T_1} > \text{L_T_2} > \text{L_H} > \text{L_W}$$

It can be observed from the below Figure 7.5 that, transverse flange width (T_W) has contributed the most within the transverse parameters. Ranked of the transverse parameters can be stated below from the highest sensitivity to the lowest:

$$\text{T_W} > \text{T_H} > \text{T_T_1} > \text{T_T_2}$$

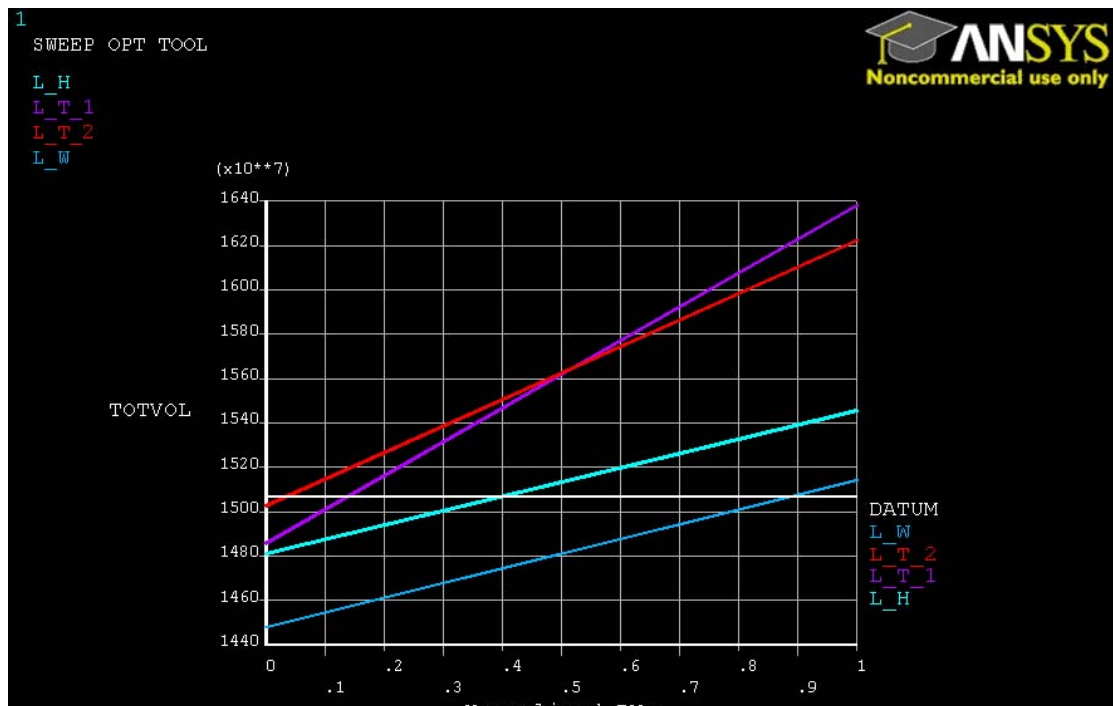


Figure 7.4 : Global sensitivity of girder parameters (sub-optimization method)

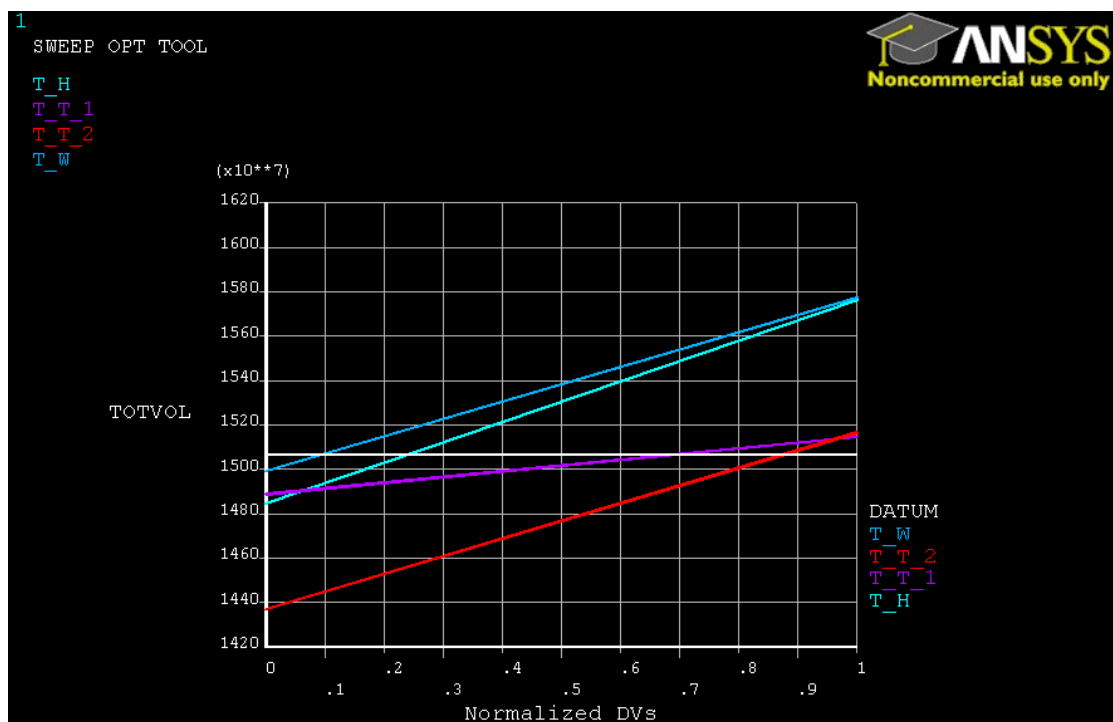


Figure 7.5 : Global sensitivity of transverse parameters (sub-optimization method)

In order to perform the local sensitivity analysis, gradient tool is used. Results from the gradient tool indicate how a small change in a DV affects the design - local sensitivity. For example, what happens to TOTVOL if DSINC is perturbed by $\pm 1\%$ Figure 7.6 shows small perturbations performed on the column radius parameters:

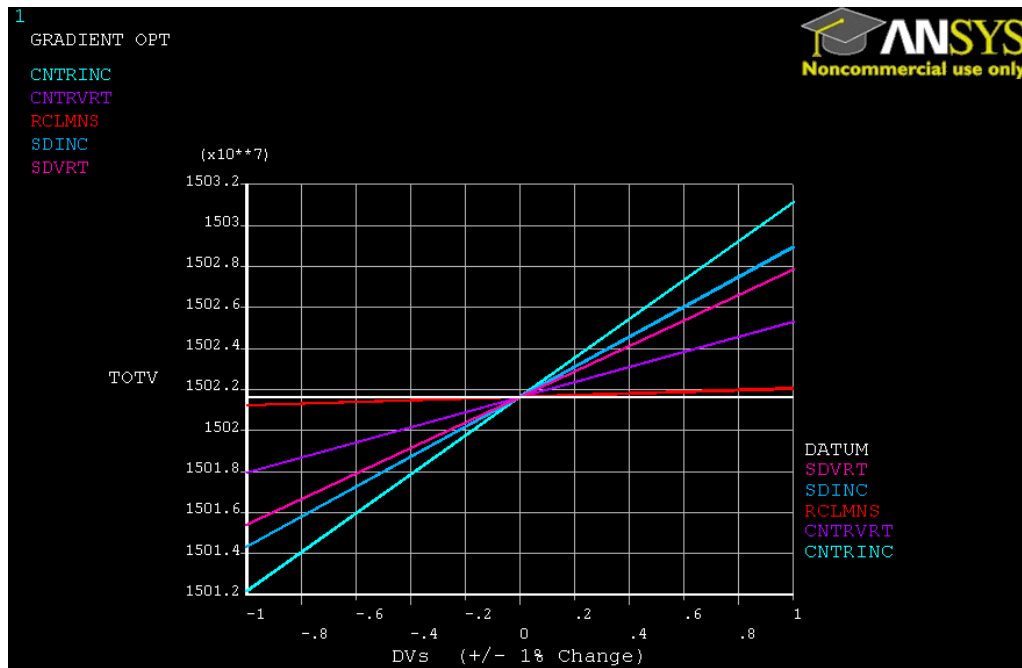


Figure 7.6 : Local sensitivity of column parameters (sub-optimization method)

X and y axis in the local sensitivity figures show the percentage of perturbation and the total volume in order. It can be observed from the Figure 7.6 that CNTRINC has the biggest change within the column radius parameters. However, perturbation of the CNTRINC leads to only 157 kg of displacement change in the structure. Change of the column parameters can be ranked from the biggest to the smallest stated below:

$$\text{CNTRINC} > \text{SDINC} > \text{SDVVRT} > \text{CNTRVRT} > \text{RCLMNS}$$

It can be observed from the Figure 7.7 that L_W has the biggest change within the girder parameters. However, perturbation of the L_W leads to only 118 kg of displacement change in the structure. It can be ranked as stated below from the biggest change to the smallest one for girder parameters:

$$\text{L_W} > \text{L_T_1} > \text{L_H} > \text{L_T_2}$$

Finally, it can be observed from the Figure 7.8 that T_H has the biggest alternation within the transverse parameters. However, perturbation of the L_W leads to only 165 kg of displacement change in the structure. It can be ranked as stated below from the biggest change to the smallest one for transverse parameters:

$$\text{T_H} > \text{T_T_2} > \text{T_W} > \text{T_T_1}$$

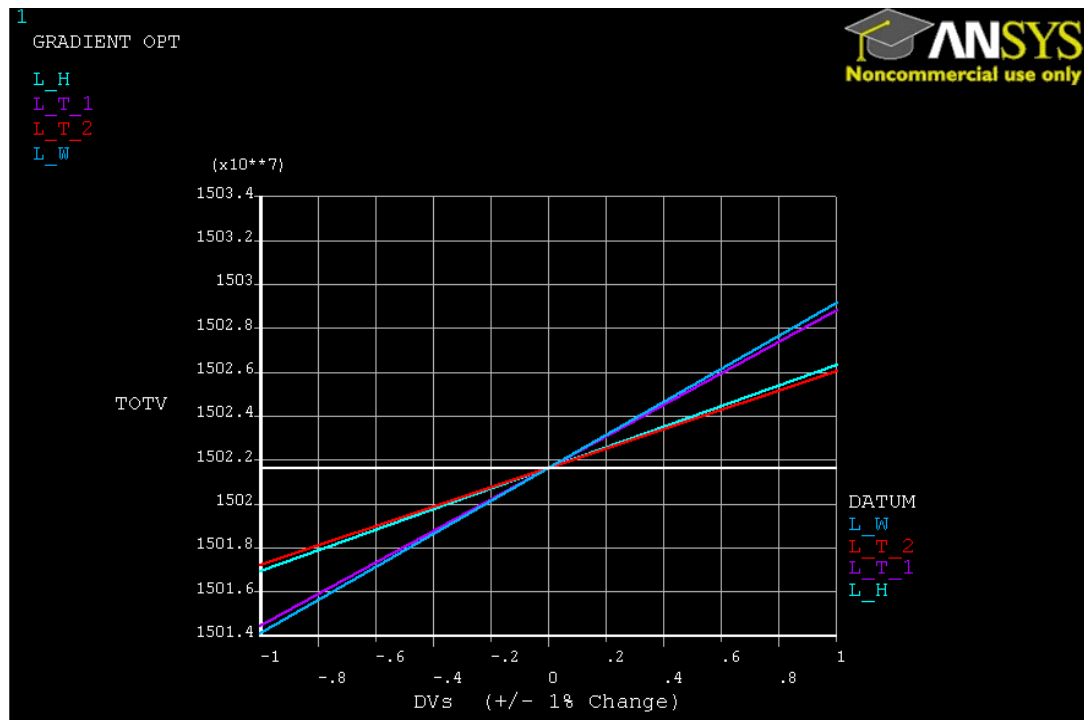


Figure 7.7 : Local sensitivity of girder parameters (sub-optimization method)

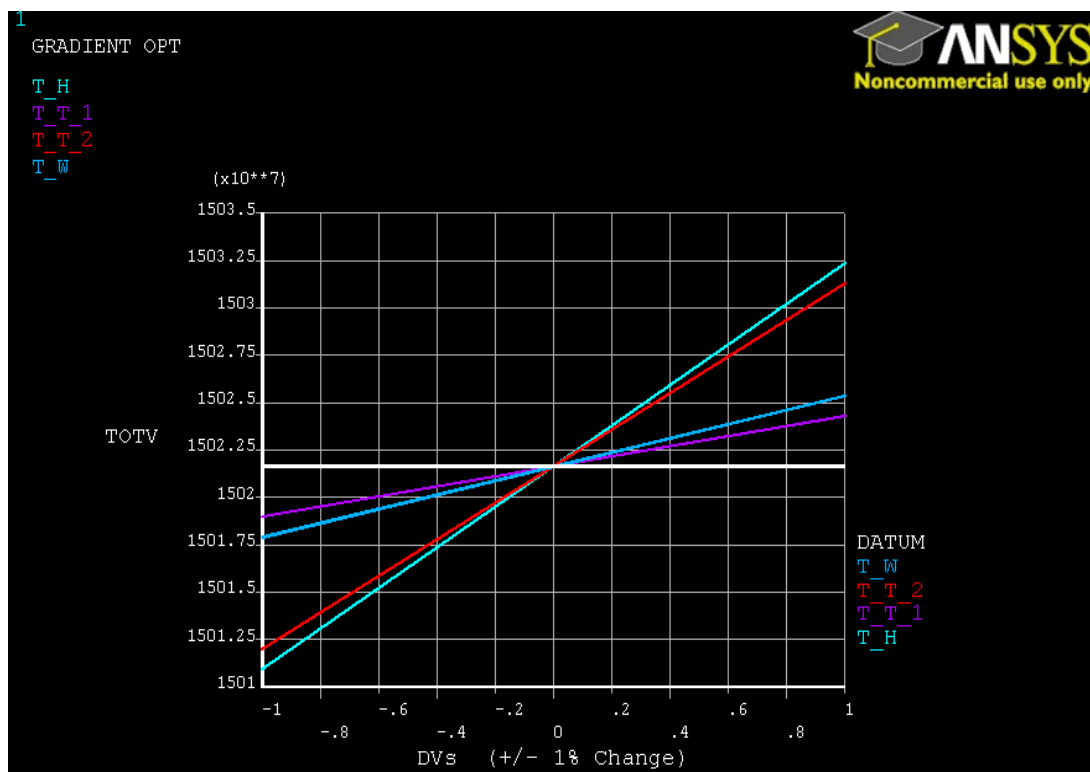


Figure 7.8 : Local sensitivity of transverse parameters (sub-optimization method)

Moreover, while performing the first-degree method there is no need to perform database sweep. Hence, after achieving the best design, gradient tool is used to investigate the local sensitivities.

It can be observed from the Figure 7.9 that, CNTRINC has the biggest alternation within the column parameters. However, the small perturbation of the CNTRINC leads to only 141 kg of displacement change in the structure. It can be ranked as stated below from the biggest change to the smallest one for column parameters:

CNTRINC > SDINC > CNTRVRT > SDVRT > RCLMNS

It can be observed from the Figure 7.10 that, L_W has the biggest change within the girder parameters. Nevertheless, perturbation of the L_W leads to only 141 kg of displacement change in the structure. Ranked of the weight change can as stated below from the biggest change to the smallest one for girder parameters:

L_W > L_T_1 > L_H > L_T_2

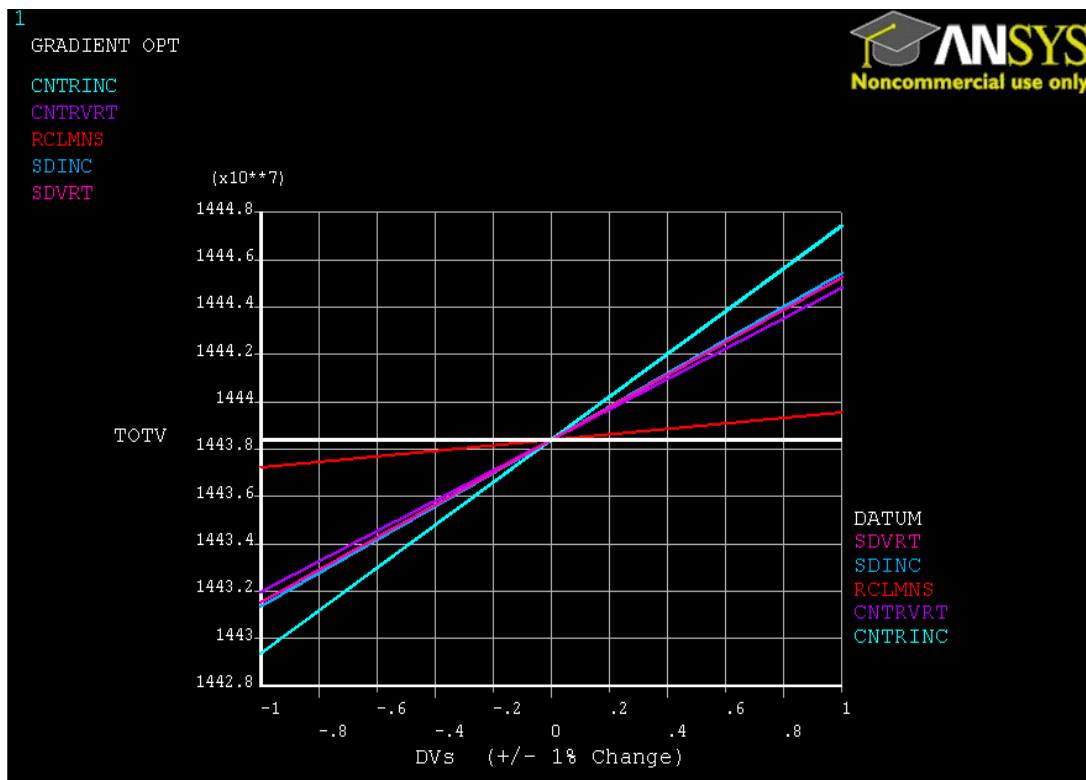


Figure 7.9 : Local sensitivity of column parameters (first-order method)

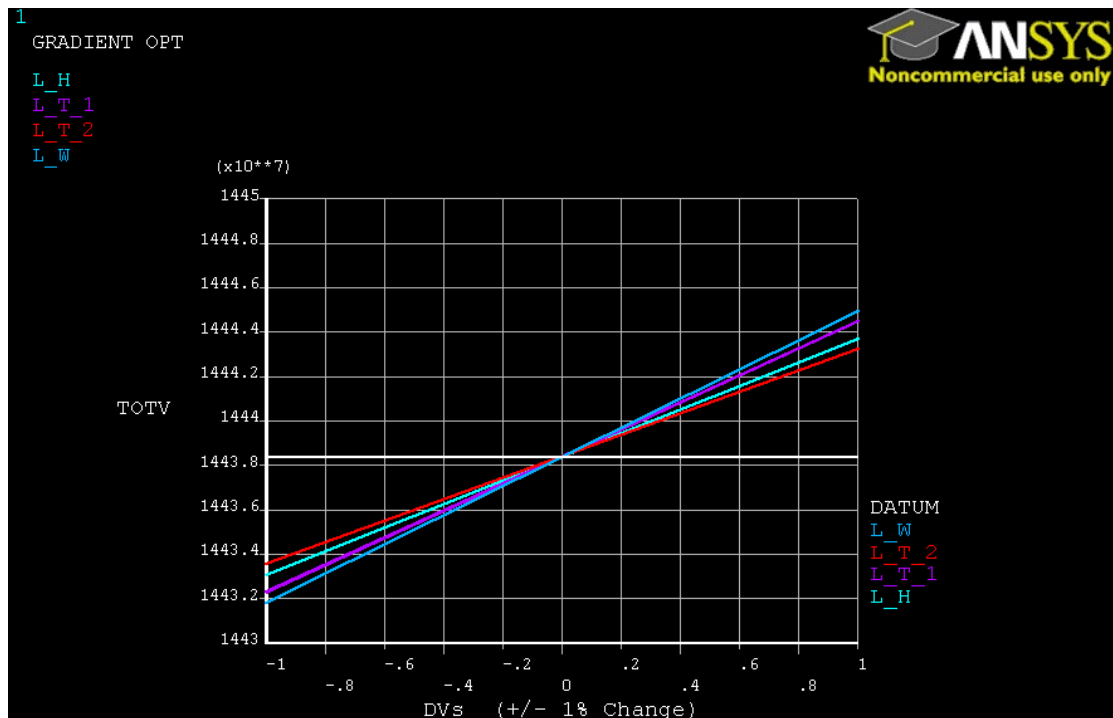


Figure 7.10 : Local sensitivity of girder parameters (first-order method)

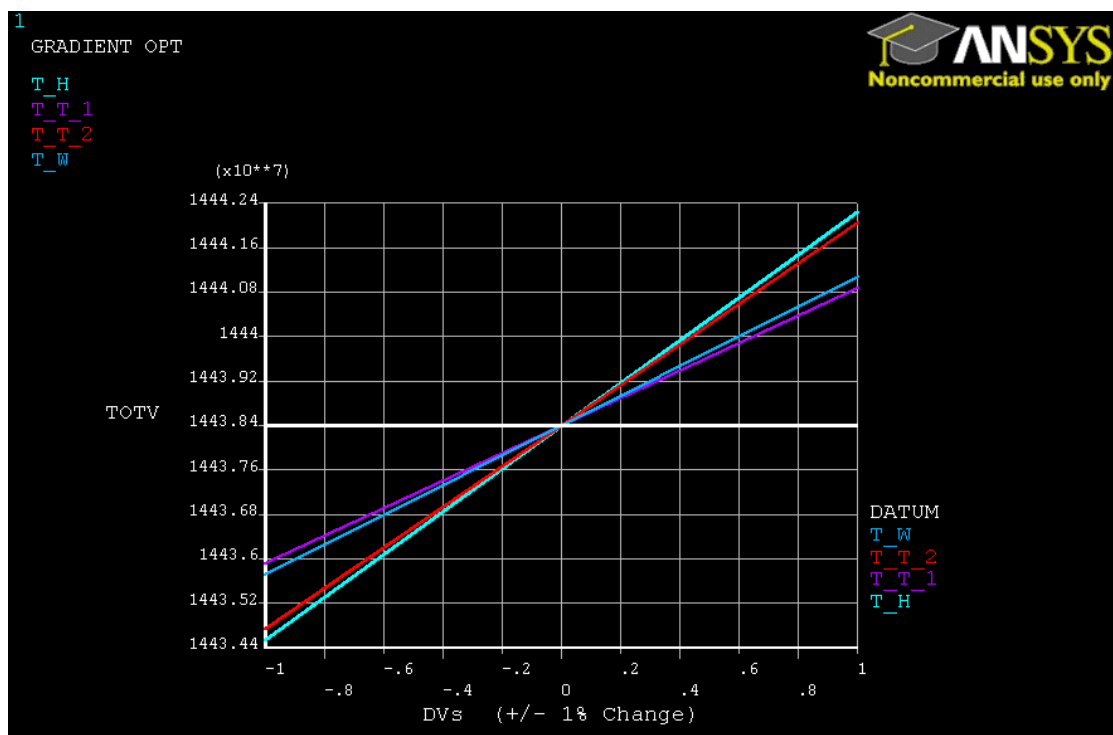


Figure 7.11 : Local sensitivity of girder parameters (first-order method)

It can be observed from the Figure 7.11 that, T_H has the biggest change within girder parameters. Nevertheless, perturbation of the T_H leads to only 63 kg of

displacement change in the structure. Rank of change can be stated below from the biggest change to the smallest one for transverse parameters:

$$T_H > T_T_2 > T_W > T_T_1$$

7.4 Global optimum parameter values

Global optimum is executed via the first order method after 11 iterations. As it was mentioned before, first-order method has more accurate results than the sub-problem method because; it doesn't use any approximations. Best design parameters are summarized in the Table 7.2 below:

Table 7.2 : Global optimum parameter values

Parameters	Values
SMAX (SV)	157.34 N/mm ²
UMAX (SV)	4.5774 mm
CNTRINC (DV)	40.000 mm
CNTRVRT (DV)	53.230 mm
L_H (DV)	136.61 mm
L_T_1 (DV)	12.138 mm
L_T_2 (DV)	5.0000 mm
L_W (DV)	69.631 mm
RCLMNS (DV)	67.799 mm
SDINC (DV)	40.000 mm
SDVRT (DV)	42.672 mm
T_H (DV)	197.34 mm
T_T_1 (DV)	9.8541 mm
T_T_2 (DV)	5.0000 mm
T_W (DV)	69.577 mm
TOTVOL (OBJ)	0.14438E+11 mm ³
Weight	113.34 tons
First set weight	138.32 tons
Weight Reduction	24.98 tons
Reduction percentage	18 %

Moreover, after performing the first-degree optimization, global optimum weight of the structure is found as 113.34 tons and weight reduction is calculated as 24.98 tons which gives the structure an advantage of 18 % less weight.

7.5 Column buckling assessment

Buckling is one of the most important phenomena which affect columns in a negative way and make them fail before bending stresses. Ship structures consist of beam and plates and sometimes compressive loads are applied to them. Hence, it is important to consider buckling.

In this section Euler buckling forms the basis of the assessment. In literature there are some buckling formulas to calculate critical buckling loads and critical buckling stress. Critical buckling stress of a pillar or strut of mild steel material is specified by American Bureau of Shipping (ABS) in the following equation:

$$\sigma_{cr} = 1.232 - 0.00452 \left(\frac{l}{k} \right) \quad \text{tonf/cm}^2 \quad (7.1)$$

This ABS formula is theoretically based on Tetmayers's experimental result which is specified in the following equation:

$$\sigma_{cr} = a - b \left(\frac{l}{k} \right) \quad \text{tonf/cm}^2 \quad (7.2)$$

In these equations a , b are buckling coefficients, I is the moment of inertia of the cross section, A is the cross-sectional area, l is the length of the column and k is the radius of gyration which is specified in the following equation:

$$k = \sqrt{\frac{I}{A}} \quad (7.3)$$

Columns under the helideck structure have full circular cross-sectional area so radius of gyration can be calculated as specified in the following equation:

$$k = \sqrt{\frac{I}{A}} = \sqrt{\frac{\frac{\pi r^4}{4}}{\pi r^2}} = \sqrt{\frac{r^2}{4}} = \frac{r}{2} \quad (7.4)$$

Radius of gyration of columns can be calculated by using global optimum column radius values and putting them into the above equation:

$$k = \frac{40}{2} = 20 \quad (7.5)$$

Length of the central inclined columns is the longest in our design the length is specified in the following equation:

$$l = \sqrt{1500^2 + 2000^2} = 2500 \text{ mm} \quad (7.6)$$

Finally, ABS column critical stress value is calculated as:

$$\sigma_{cr} = 1.232 - 0.00452 \left(\frac{2500}{20} \right) = 667e^{-3} \frac{\text{tonf}}{\text{cm}^2} = 65.41 \text{ MPa} \quad (7.7)$$

ANSYS is capable to execute axial direct stress (SDIR) on selected BEAM 189 element. Calculations are performed in the element table and axial direct stress is found maximum -18 MPa shown in the Figure 7.12. Minus sign refers to the compressive stress in the results. Therefore, maximum compressive axial stress is found as -18.63 MPa.

In order to double-check the buckling stress, axial direct forces are calculated in ANSYS. The maximum axial compressive force is found as -100286 N. However, maximum axial stress was under the front tyre print area because; the radius of the CNTRINC columns is smaller than the CNTRVRT ones. Therefore, axial force at the maximum axial stress column is found as -93645 N. Finally, axial pressure can be simply calculated by the following equation:

$$\sigma_{cr} = \frac{F}{A} = \frac{-93645 \text{ N}}{\pi \cdot 40^2} = -18.63 \text{ MPa} \quad (7.8)$$

Finally, structure passed the column buckling test. Hence, it is safe and reliable.

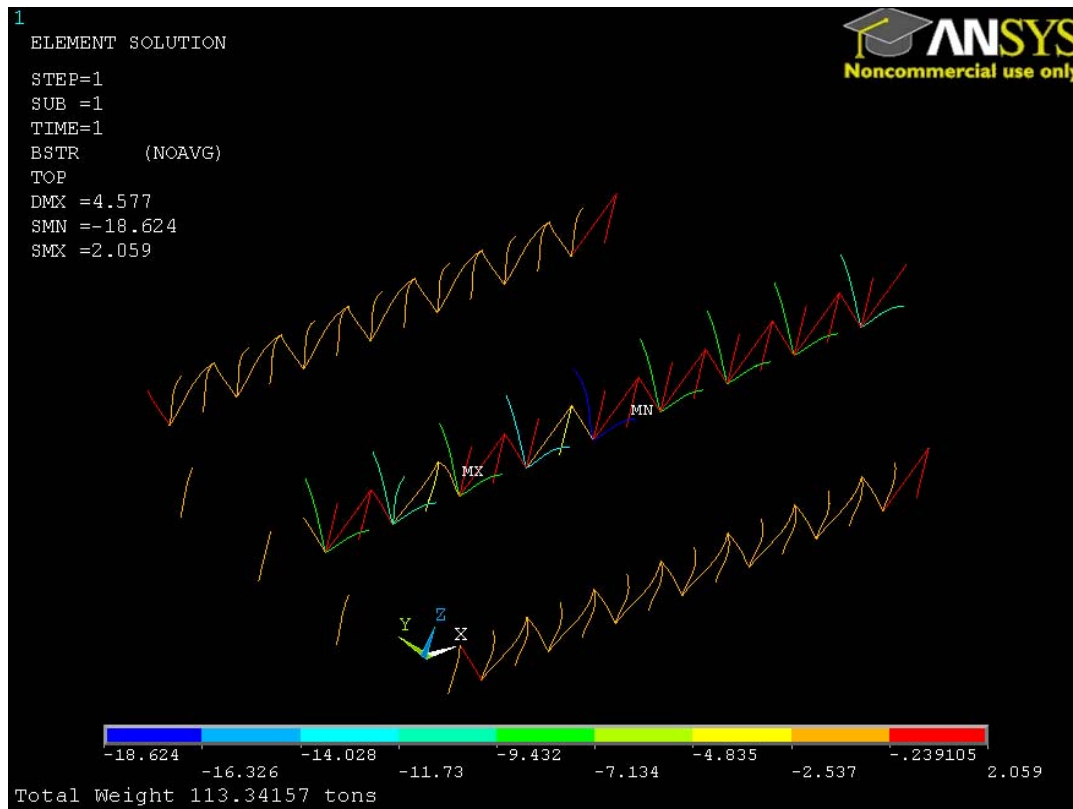


Figure 7.12 : Axial stress of columns

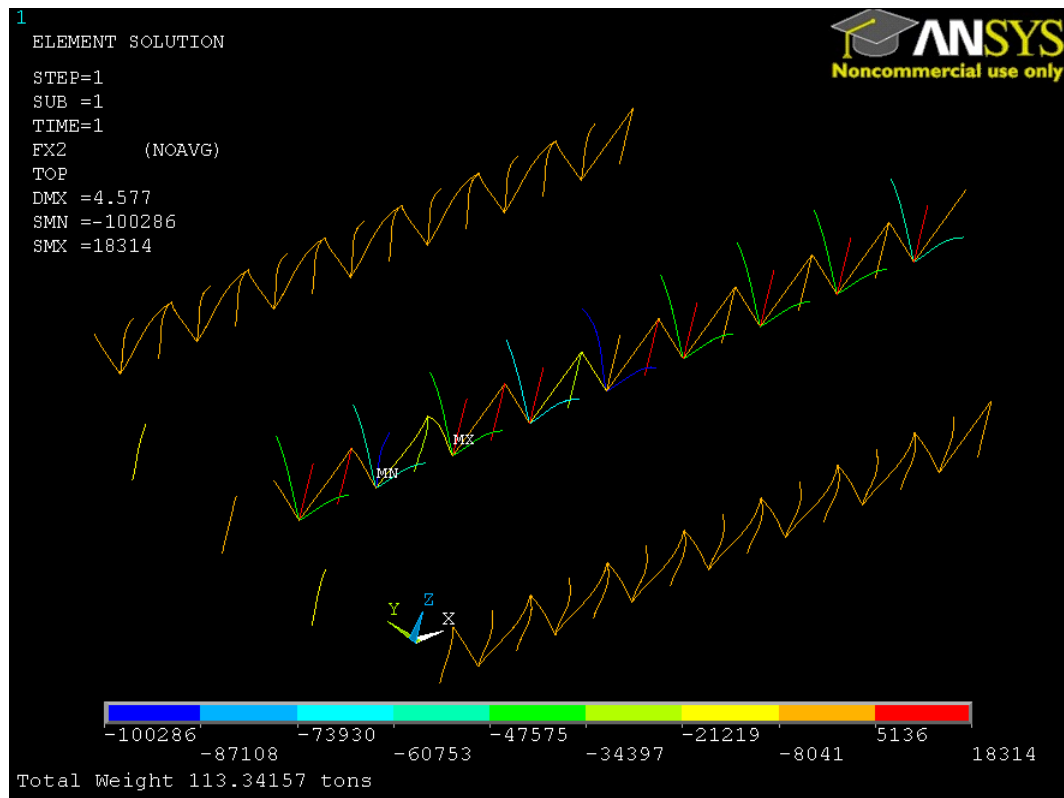


Figure 7.13 : Axial forces applied to columns

7.6 Conclusions

In chapter 7 the reader has been presented about optimization results with a specific emphasis on the global and local sensitivity of the parameters. In addition, the adopted approaches to perform the optimization process have been described. Using the validated optimization tools responses of the helideck design has been showed in detail. Finally summary of this section is given below:

- Review of the optimization process was performed. Each of the methods was concerned and their iteration process was defined in advance to develop the appropriate conditions to perform the sensitivity of the parameters.
- Comparison of the two algorithms was performed via their computational cost and accuracies. First-order method performed the most accurate optimization results while sub-problem optimization method's time consumption was better.
- Global and local sensitivity analysis of the parameter was executed. In sub-optimization method database sweep and gradient tool were used. These

methods were applied to the best design of the iteration process to find out global and local sensitivities. In addition, column, girder and transverse parameters rank of sensitivities were stated.

- Global optimum point's parameter values were stated in detail with the stress, displacement, initial and the final weight, weight reduction and reduction percentage.
- Buckling assessment of the columns was executed via ABS standards. In order to ensure the results are accurate, axial stress and axial forces were calculated separately and double-checked whether the structure is safe or not.

8. CONCLUSIONS

Chapter 8 presents an overall summary of the helideck optimization performed in this study, comprising of the main conclusions and recommendations for further research.

In Section 8.1 the basis of the helideck optimization study is given. Based upon this rationale, an overall summary of the work carried out in each chapter is presented including a final re-evaluation of the aims and specific objectives of the work in Section 8.2. In Section 8.3, the main conclusions derived from the thesis are presented while recommendations are proposed for future work in Section 8.4.

8.1 Basis of the thesis

The basis of the current study combines the unique research area of naval ship design and structural optimization. Nowadays, structural optimization is a very common issue in naval vessel design due to the construction of naval ships with less material. In other words, naval ships are displacement critique ships that must satisfy a specific displacement value for speed, manoeuvring and operational concerns. However, naval vessels must be designed with respect to rules and regulations. The rules and regulations comprises of the constraints of the optimization process. Helideck structural optimization is an important design area because; generally helidecks are situated at the stern of the ship and not only affect the weight of the ship tremendously, but also affects the vibration on board and manoeuvring characteristics of the vessel. Therefore structural optimization of existing naval ship helideck structural displacement and stress concerns was an excellent starting point for the research.

The candidate helideck design scantlings were taken from Bremen Class Frigates of German Naval Forces. A new helideck was designed with respect to the scantlings of this Bremen Class Frigates. Therefore, it provides a comparison between the former designs and the new design. Formerly, helideck design was subject to some previous

undergraduate research within the school. However, none of these studies concerned structural optimization; only design regulations and rule development studies were concerned. Moreover, lack of the structural optimization studies related to naval ship helidecks in the open literature made this study to be performed in this reputational area of optimization. Results also proved that structural optimization of helidecks was an important process to reduce the weight of the vessel tremendously.

In the context of the above motivations, the current research charged itself with providing a useful and implementable optimization process, which can be beneficial for future development of naval ship helideck designs. The optimization was performed via different algorithms with respect to GL design rules and regulations. Optimization of the structural design of helideck provides new insights for future developments in the naval ship design area.

8.2 Overall summary

To implement the above thesis basis, the research was categorised into specific objectives, outlined previously in Chapter 1. These objectives are now re-concerned for the integrity of the work has been done.

The first objective of the thesis was to perform a literature review, to assess the former optimization studies in naval ship structural design subject and to show relevance and importance of the current research. The second objective was to define fundamental search direction decision maker algorithms and penalty functions which constitute of the foundation of optimization process in ANSYS.

The third objective was to define the optimization methodology in ANSYS. The methodology section constitutes of building parametric design, creating the optimization log file and making some changes on it to perform loops, utilization of two different optimization algorithms, their properties and flow diagrams. The fourth objective was to define calculations and regulations of the helideck from GL rules. The fifth objective was to perform the optimization of the new design of helideck with the denoted methods in the fourth section. The sixth objective was to assess the results for global and local sensitivity studies of the optimization parameters and to assess buckling characteristics of the columns supporting the helideck structure.

Moreover, sixth objective includes the comparison of the two optimization algorithms in ANSYS.

The author's motivation aims and specific objectives of the thesis were outlined in Chapter 1 together with an outline of the thesis. Chapter 2 met the first objective of the thesis with a critical review of naval ship structural optimization and also design weight comparison with respect to classification societies. Fundamental methods for optimization in ANSYS were presented in Chapter 3 to provide enough knowledge about the programme's search direction decision maker modules. Chapter 4 presents the third objective of the thesis with a special interest on how to perform an optimization process in ANSYS and when and how to use sub-optimization method and first-order method in optimization process. Moreover, optimization tools were explained in this chapter. Chapter 5 addressed the calculations and regulations regarding to GL rules which is the fourth objective of this dissertation. The helideck optimization process was performed in Chapter 6 addresses the fifth objective of the thesis. First helideck structural analysis was performed and then optimization took place. Chapter 7 addresses the sixth objective of the study, which aimed to perform sensitivity analysis of the parameters. Finally Chapter 8 presents the main conclusions and future recommendations.

8.3 Main conclusions

Based upon the work carried out in this dissertation study, the following main conclusions are obtained:

- Helideck structure weight was reduced more than 23.32 tons which corresponded to 17% of weight decrease with the final design.
- First order method was found more accurate and in this study it had found an optimum which was 4 tons less than the sub-optimization method's solution. However, computational cost of first order method was nearly 3 times more than its opponent.
- Buckling assessment was performed via ABS rules. Depending on ANSYS axial direction stress and force calculations, it was proven that the columns had enough stress to withstand buckling. Moreover, safety coefficient of the columns was found as 3.

- Flight deck thickness was not been involved as a parameter into the optimization process because, it leads to arrive local optimum after several iterations. Therefore, its thickness was calculated via GL rules and assigned to design.

8.4 Recommendations for future work

Due to the lack of time and resources allocated to the research enforced practical boundaries to perform this optimization study. However, ship design is an iterative and comprehensive process that following recommendation can be applied to the future naval ship optimization studies.

- Vibration in naval ships is one of the most important main concerns in design. Therefore, vibration can be included into the optimization process. This means that, optimization will be performed in different physical environments.
- Different boundary conditions can be applied so better results may be achieved.
- Number of supporting girders and transverses can also be included in the optimization via nearest integer (NINT) module in ANSYS. However, the more assigned parameter means that, the more chance to find a local optimum.
- Helideck may be divided into sub-models and every model has its own stress values. All these stresses will be integrated to find global stress in the structure. This process can lead to more accurate stress distributions all over the structure.

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APPENDIX

This section presents the helideck design figures and optimization sets.

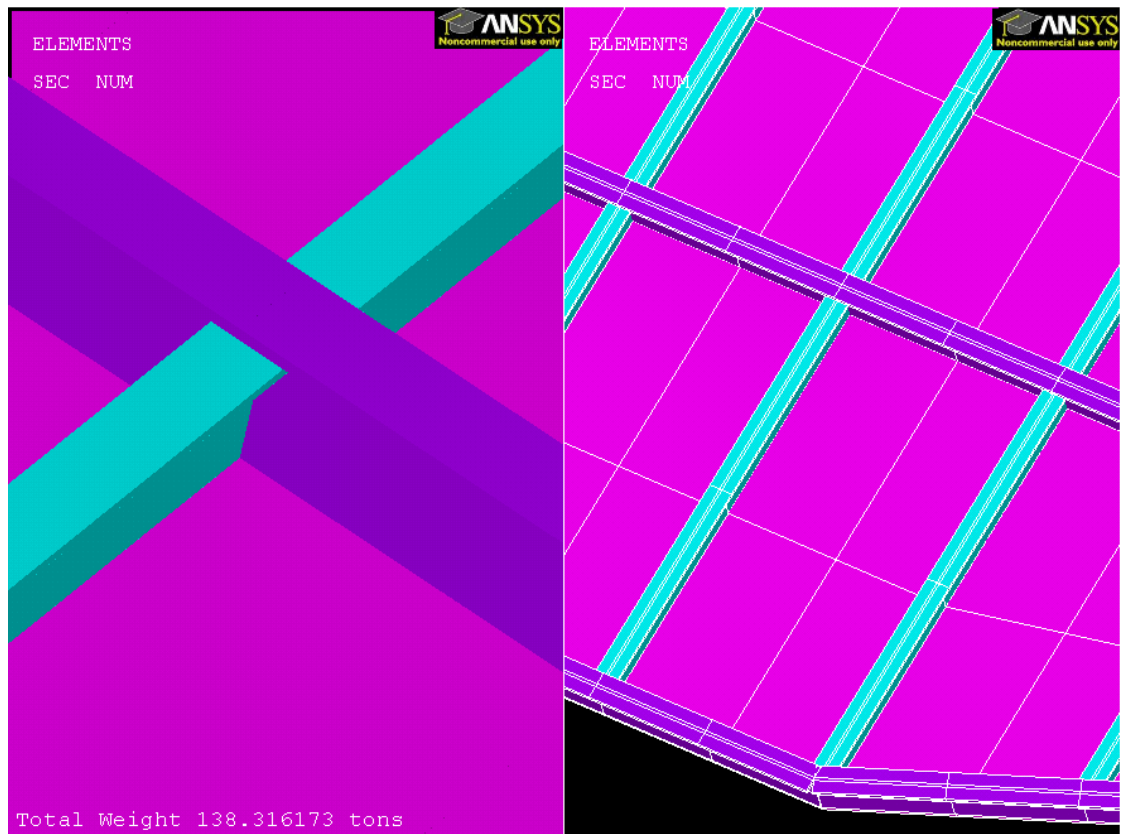


Figure A.1 : Joint details of the girders, transverses and flight deck

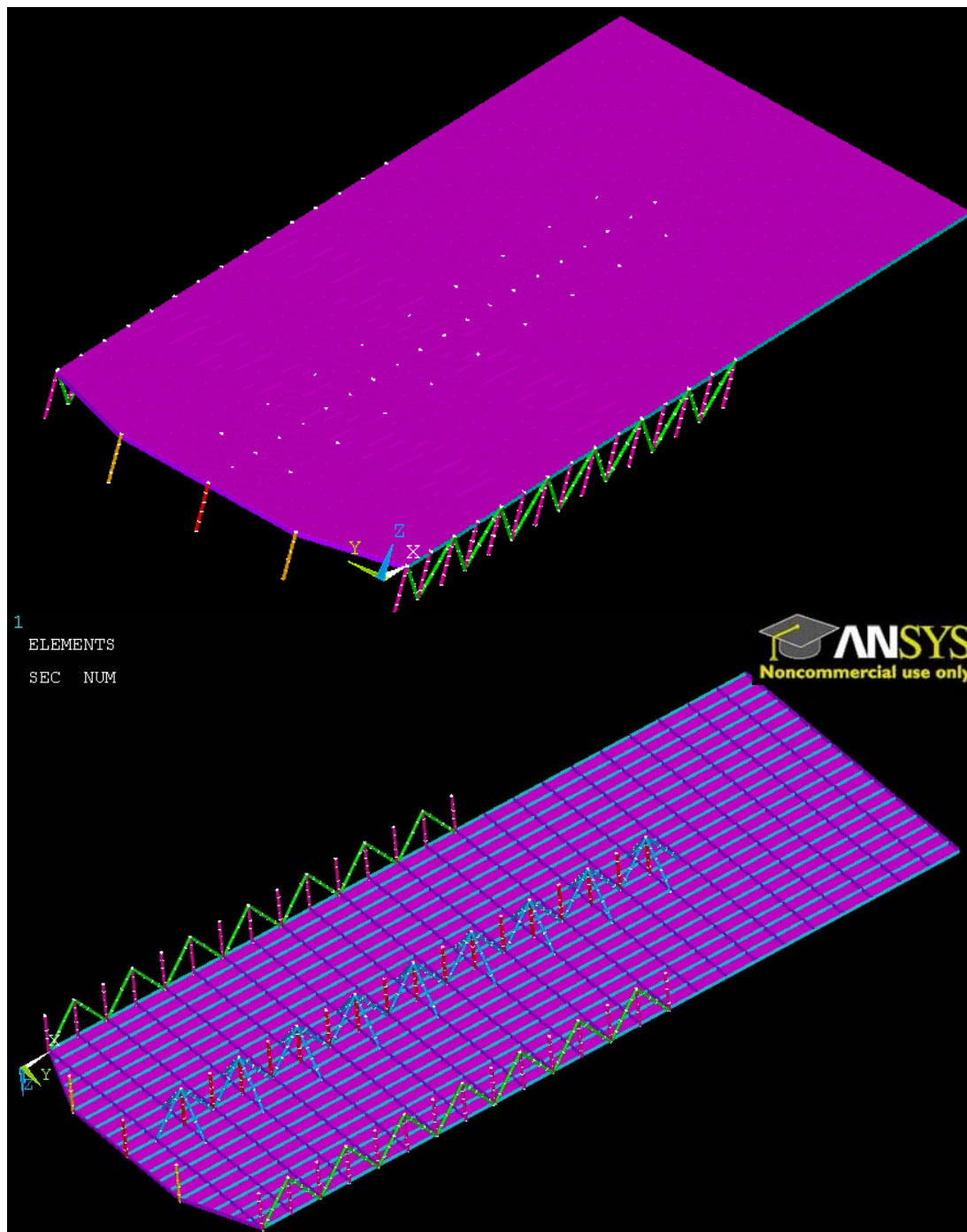


Figure A.2 : Helideck form different angles of view

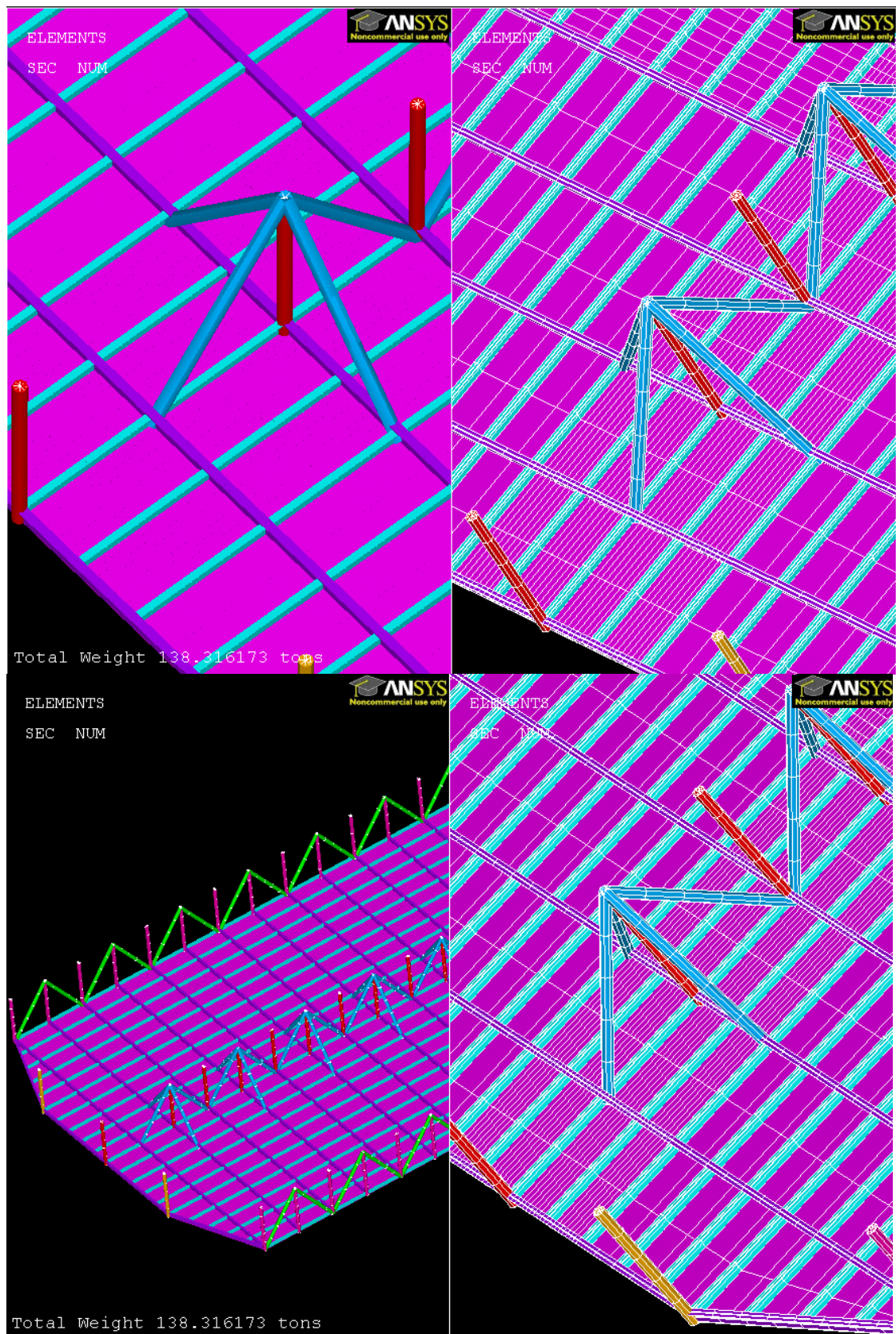


Figure A.3 : Column arrangements under helideck and mesh

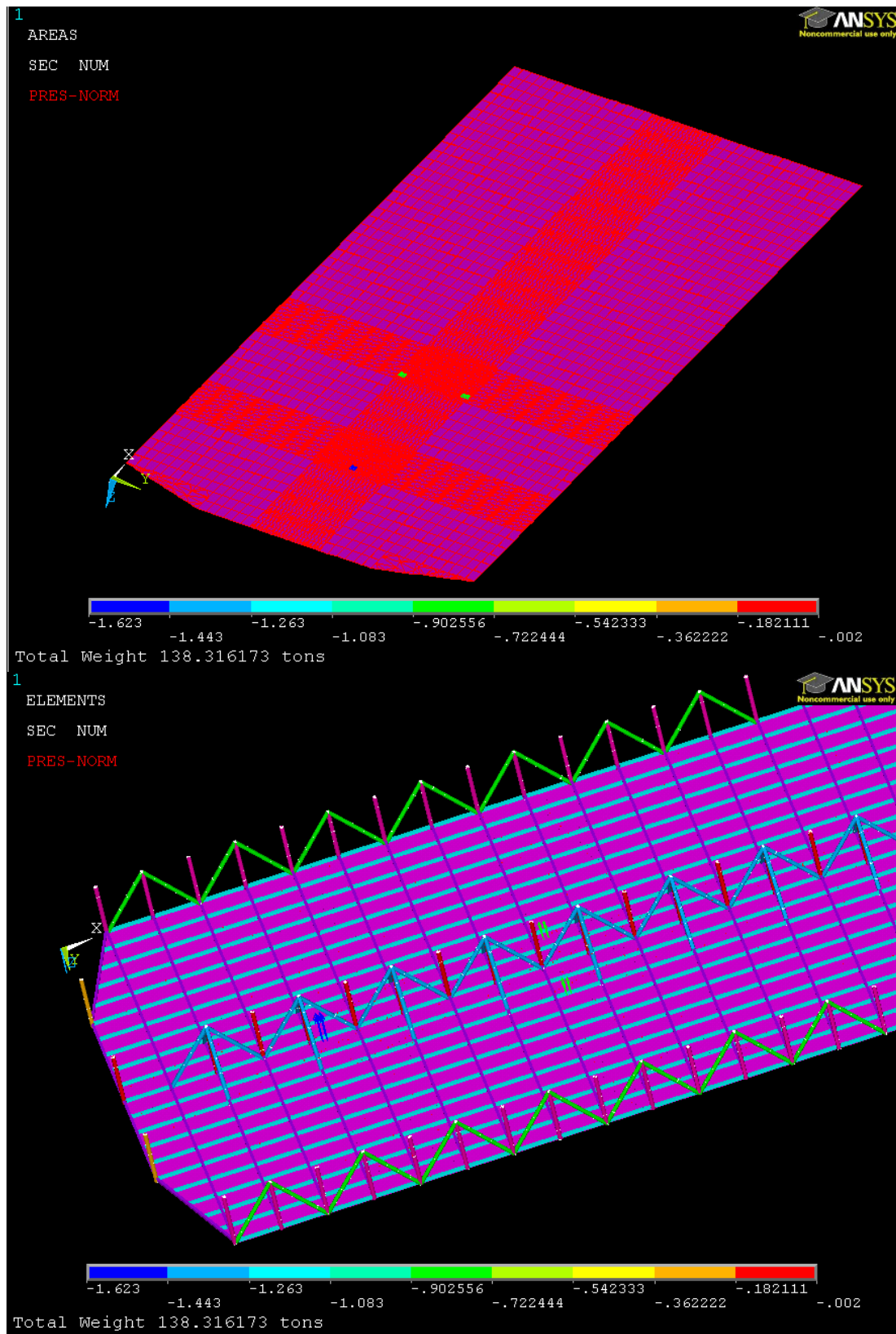


Figure A.4 : Static deck and hangar deck loadings with helicopter crash load

Below sets present the sub-problem optimization method solution sets. They were automatically defined whether they were feasible or not. Infeasible sets were explained why they out of were range by the signs < and >.

		SET 1 (FEASIBLE)	SET 2 (FEASIBLE)	SET 6 (FEASIBLE)	SET 7 (FEASIBLE)
SMAX	(SV)	149.80	117.08	136.46	148.41
UMAX	(SV)	3.7599	2.6672	2.9739	1.8045
CNTRINC	(DV)	70.000	73.887	40.480	67.629
CNTRVRT	(DV)	70.000	58.287	65.008	67.532
L_H	(DV)	145.00	108.20	125.28	121.37
L_T_1	(DV)	10.000	15.386	7.0860	17.822
L_T_2	(DV)	8.0000	13.063	8.9920	5.2841
L_W	(DV)	75.000	104.15	138.85	71.946
RCLMNS	(DV)	70.000	73.914	52.492	48.933
SDINC	(DV)	70.000	40.133	59.421	63.673
SDVRT	(DV)	70.000	58.764	68.196	46.589
T_H	(DV)	175.00	161.64	185.36	247.39
T_T_1	(DV)	12.000	16.891	15.398	16.047
T_T_2	(DV)	10.000	13.732	18.512	18.217
T_W	(DV)	90.000	140.37	62.576	127.67
TOTVOL	(OBJ)	0.17620E+11	0.18031E+11	0.16963E+11	0.18145E+11
		SET 10 (FEASIBLE)	SET 11 (FEASIBLE)	SET 12 (FEASIBLE)	SET 18 (FEASIBLE)
SMAX	(SV)	159.46	119.75	95.473	149.50
UMAX	(SV)	3.6911	3.5394	3.1114	4.1114
CNTRINC	(DV)	76.423	56.717	52.080	40.188
CNTRVRT	(DV)	78.873	42.068	76.351	48.666
L_H	(DV)	91.914	84.796	190.56	125.28
L_T_1	(DV)	7.4275	15.524	7.2175	7.0855
L_T_2	(DV)	11.197	19.780	19.905	5.6953
L_W	(DV)	132.53	140.27	39.427	136.40
RCLMNS	(DV)	57.174	64.232	48.802	43.444
SDINC	(DV)	67.873	60.400	51.691	58.603
SDVRT	(DV)	79.223	41.388	63.636	46.579
T_H	(DV)	133.88	139.57	133.42	160.74
T_T_1	(DV)	16.762	15.429	19.797	15.398
T_T_2	(DV)	18.072	18.207	15.209	18.512
T_W	(DV)	149.10	144.41	150.14	62.576
TOTVOL	(OBJ)	0.19032E+11	0.17937E+11	0.18841E+11	0.15752E+11
		SET 19 (FEASIBLE)	SET 20 (INFEASIBLE)	SET 21 (INFEASIBLE)	SET 22 (INFEASIBLE)
SMAX	(SV)	117.19	> 169.12	118.53	> 189.23
UMAX	(SV)	4.0538	> 5.4178	> 5.4135	> 2.2270
CNTRINC	(DV)	75.268	59.836	53.331	71.598
CNTRVRT	(DV)	69.394	67.218	79.742	55.742
L_H	(DV)	156.57	84.411	136.96	81.986
L_T_1	(DV)	9.9049	11.086	18.599	10.951
L_T_2	(DV)	16.584	9.7345	12.198	5.0531
L_W	(DV)	127.17	144.10	145.95	103.62
RCLMNS	(DV)	76.363	66.889	54.110	40.553
SDINC	(DV)	59.646	77.547	71.956	65.236
SDVRT	(DV)	48.399	62.468	44.716	50.331
T_H	(DV)	199.33	142.44	155.04	237.39
T_T_1	(DV)	9.6699	15.095	7.7954	16.883
T_T_2	(DV)	6.9726	11.110	13.607	19.303
T_W	(DV)	56.896	82.881	53.868	134.34
TOTVOL	(OBJ)	0.18184E+11	0.17613E+11	0.18395E+11	0.18081E+11

		SET 23 (INFEASIBLE)	SET 24 (FEASIBLE)	SET 25 (FEASIBLE)	SET 26 (FEASIBLE)
SMAX	(SV)	> 234.34	145.59	75.312	152.75
UMAX	(SV)	> 8.5123	2.8238	3.7198	3.6576
CNTRINC	(DV)	55.781	78.809	47.208	40.103
CNTRVRT	(DV)	79.873	61.948	73.537	41.942
L_H	(DV)	56.017	134.29	164.89	115.45
L_T_1	(DV)	11.472	6.2136	16.769	7.0820
L_T_2	(DV)	12.026	7.8737	10.835	5.6942
L_W	(DV)	142.79	130.14	142.74	136.41
RCLMNS	(DV)	73.592	44.279	44.525	69.142
SDINC	(DV)	49.925	45.321	57.666	45.377
SDVRT	(DV)	41.114	42.979	59.773	41.832
T_H	(DV)	135.05	160.88	126.38	170.15
T_T_1	(DV)	10.877	12.829	19.776	15.393
T_T_2	(DV)	13.032	18.664	12.928	18.512
T_W	(DV)	55.592	147.15	123.15	62.581
TOTVOL	(OBJ)	0.16232E+11	0.17381E+11	0.18409E+11	0.15360E+11
		SET 27 (INFEASIBLE)	SET 28 (FEASIBLE)	SET 29 (FEASIBLE)	SET 30 (FEASIBLE)
SMAX	(SV)	> 167.11	155.47	160.48	160.64
UMAX	(SV)	> 6.6790	3.8387	4.6479	4.7571
CNTRINC	(DV)	40.086	40.098	40.085	40.750
CNTRVRT	(DV)	40.504	41.304	40.446	40.309
L_H	(DV)	109.93	112.88	109.58	109.62
L_T_1	(DV)	7.0772	7.0810	7.0768	7.0762
L_T_2	(DV)	5.6936	5.6940	5.5341	5.5224
L_W	(DV)	136.41	136.41	136.41	136.41
RCLMNS	(DV)	69.137	69.140	69.137	72.417
SDINC	(DV)	41.518	43.903	43.896	41.034
SDVRT	(DV)	41.289	42.192	42.190	40.709
T_H	(DV)	130.72	166.74	153.18	152.19
T_T_1	(DV)	14.043	15.357	15.357	15.353
T_T_2	(DV)	18.512	18.512	18.512	18.149
T_W	(DV)	62.576	62.581	62.567	62.310
TOTVOL	(OBJ)	0.14931E+11	0.15294E+11	0.15160E+11	0.15074E+11
		SET 31 (INFEASIBLE)	SET 32 (FEASIBLE)	SET 33 (FEASIBLE)	SET 34 (FEASIBLE)
SMAX	(SV)	> 163.43	160.81	160.85	157.45
UMAX	(SV)	> 5.2849	4.8042	4.8044	4.8006
CNTRINC	(DV)	40.543	40.932	40.000	80.000
CNTRVRT	(DV)	40.310	40.307	40.307	40.307
L_H	(DV)	109.61	109.62	109.62	109.62
L_T_1	(DV)	7.0768	7.0762	7.0762	7.0762
L_T_2	(DV)	5.2125	5.5224	5.5224	5.5224
L_W	(DV)	136.41	136.41	136.41	136.41
RCLMNS	(DV)	72.416	72.417	72.417	72.417
SDINC	(DV)	40.321	40.758	40.758	40.758
SDVRT	(DV)	40.258	40.621	40.621	40.621
T_H	(DV)	149.83	151.49	151.49	151.49
T_T_1	(DV)	15.435	15.371	15.371	15.371
T_T_2	(DV)	18.149	18.149	18.149	18.149
T_W	(DV)	53.094	62.309	62.309	62.309
TOTVOL	(OBJ)	0.14954E+11	0.15067E+11	0.15046E+11	0.16402E+11

		SET 35 (FEASIBLE)		SET 36 (INFEASIBLE)		SET 37 (INFEASIBLE)		SET 38 (FEASIBLE)
SMAX	(SV)	160.81	>	163.30	>	270.27		124.71
UMAX	(SV)	4.8042		4.8040		4.9427		4.1687
CNTRINC	(DV)	40.932		40.932		40.932		40.932
CNTRVRT	(DV)	40.000		80.000		40.307		40.307
L_H	(DV)	109.62		109.62		50.000		200.00
L_T_1	(DV)	7.0762		7.0762		7.0762		7.0762
L_T_2	(DV)	5.5224		5.5224		5.5224		5.5224
L_W	(DV)	136.41		136.41		136.41		136.41
RCLMNS	(DV)	72.417		72.417		72.417		72.417
SDINC	(DV)	40.758		40.758		40.758		40.758
SDVRT	(DV)	40.621		40.621		40.621		40.621
T_H	(DV)	151.49		151.49		151.49		151.49
T_T_1	(DV)	15.371		15.371		15.371		15.371
T_T_2	(DV)	18.149		18.149		18.149		18.149
T_W	(DV)	62.309		62.309		62.309		62.309
TOTVOL	(OBJ)	0.15065E+11		0.15607E+11		0.14811E+11		0.15456E+11
		SET 39 (INFEASIBLE)		SET 40 (FEASIBLE)		SET 41 (INFEASIBLE)		SET 42 (FEASIBLE)
SMAX	(SV)	> 198.99		147.93	>	162.31		135.23
UMAX	(SV)	4.8652		4.5001		4.8080		4.6953
CNTRINC	(DV)	40.932		40.932		40.932		40.932
CNTRVRT	(DV)	40.307		40.307		40.307		40.307
L_H	(DV)	109.62		109.62		109.62		109.62
L_T_1	(DV)	5.0000		20.000		7.0762		7.0762
L_T_2	(DV)	5.5224		5.5224		5.0000		20.000
L_W	(DV)	136.41		136.41		136.41		136.41
RCLMNS	(DV)	72.417		72.417		72.417		72.417
SDINC	(DV)	40.758		40.758		40.758		40.758
SDVRT	(DV)	40.621		40.621		40.621		40.621
T_H	(DV)	151.49		151.49		151.49		151.49
T_T_1	(DV)	15.371		15.371		15.371		15.371
T_T_2	(DV)	18.149		18.149		18.149		18.149
T_W	(DV)	62.309		62.309		62.309		62.309
TOTVOL	(OBJ)	0.14856E+11		0.16384E+11		0.15026E+11		0.16223E+11
		SET 43 (INFEASIBLE)		SET 44 (FEASIBLE)		*SET 45* (FEASIBLE)		SET 46 (FEASIBLE)
SMAX	(SV)	> 384.87		152.73		160.82		160.81
UMAX	(SV)	4.9352		4.7827		4.8042		4.8042
CNTRINC	(DV)	40.932		40.932		40.932		40.932
CNTRVRT	(DV)	40.307		40.307		40.307		40.307
L_H	(DV)	109.62		109.62		109.62		109.62
L_T_1	(DV)	7.0762		7.0762		7.0762		7.0762
L_T_2	(DV)	5.5224		5.5224		5.5224		5.5224
L_W	(DV)	30.000		150.00		136.41		136.41
RCLMNS	(DV)	72.417		72.417		40.000		80.000
SDINC	(DV)	40.758		40.758		40.758		40.758
SDVRT	(DV)	40.621		40.621		40.621		40.621
T_H	(DV)	151.49		151.49		151.49		151.49
T_T_1	(DV)	15.371		15.371		15.371		15.371
T_T_2	(DV)	18.149		18.149		18.149		18.149
T_W	(DV)	62.309		62.309		62.309		62.309
TOTVOL	(OBJ)	0.14481E+11		0.15142E+11		0.15022E+11		0.15082E+11

		SET 47 (FEASIBLE)	SET 48 (FEASIBLE)	SET 49 (FEASIBLE)	SET 50 (FEASIBLE)
SMAX	(SV)	160.82	160.56	160.83	160.63
UMAX	(SV)	4.8042	4.8035	4.8042	4.8035
CNTRINC	(DV)	40.932	40.932	40.932	40.932
CNTRVRT	(DV)	40.307	40.307	40.307	40.307
L_H	(DV)	109.62	109.62	109.62	109.62
L_T_1	(DV)	7.0762	7.0762	7.0762	7.0762
L_T_2	(DV)	5.5224	5.5224	5.5224	5.5224
L_W	(DV)	136.41	136.41	136.41	136.41
RCLMNS	(DV)	72.417	72.417	72.417	72.417
SDINC	(DV)	40.000	80.000	40.758	40.758
SDVRT	(DV)	40.621	40.621	40.000	80.000
T_H	(DV)	151.49	151.49	151.49	151.49
T_T_1	(DV)	15.371	15.371	15.371	15.371
T_T_2	(DV)	18.149	18.149	18.149	18.149
T_W	(DV)	62.309	62.309	62.309	62.309
TOTVOL	(OBJ)	0.15054E+11	0.16109E+11	0.15058E+11	0.15962E+11

		SET 51 (INFEASIBLE)	SET 52 (FEASIBLE)	SET 53 (INFEASIBLE)	SET 54 (FEASIBLE)
SMAX	(SV)	> 171.26	159.28	> 166.09	160.30
UMAX	(SV)	> 7.7974	2.1589	> 6.1401	4.4277
CNTRINC	(DV)	40.932	40.932	40.932	40.932
CNTRVRT	(DV)	40.307	40.307	40.307	40.307
L_H	(DV)	109.62	109.62	109.62	109.62
L_T_1	(DV)	7.0762	7.0762	7.0762	7.0762
L_T_2	(DV)	5.5224	5.5224	5.5224	5.5224
L_W	(DV)	136.41	136.41	136.41	136.41
RCLMNS	(DV)	72.417	72.417	72.417	72.417
SDINC	(DV)	40.758	40.758	40.758	40.758
SDVRT	(DV)	40.621	40.621	40.621	40.621
T_H	(DV)	120.00	250.00	151.49	151.49
T_T_1	(DV)	15.371	15.371	5.0000	20.000
T_T_2	(DV)	18.149	18.149	18.149	18.149
T_W	(DV)	62.309	62.309	62.309	62.309
TOTVOL	(OBJ)	0.14844E+11	0.15766E+11	0.14889E+11	0.15147E+11

		SET 55 (INFEASIBLE)	SET 56 (FEASIBLE)	SET 57 (INFEASIBLE)	SET 58 (FEASIBLE)
SMAX	(SV)	> 166.63	160.40	> 162.85	157.00
UMAX	(SV)	> 6.5588	4.6377	> 5.2943	2.6306
CNTRINC	(DV)	40.932	40.932	40.932	40.932
CNTRVRT	(DV)	40.307	40.307	40.307	40.307
L_H	(DV)	109.62	109.62	109.62	109.62
L_T_1	(DV)	7.0762	7.0762	7.0762	7.0762
L_T_2	(DV)	5.5224	5.5224	5.5224	5.5224
L_W	(DV)	136.41	136.41	136.41	136.41
RCLMNS	(DV)	72.417	72.417	72.417	72.417
SDINC	(DV)	40.758	40.758	40.758	40.758
SDVRT	(DV)	40.621	40.621	40.621	40.621
T_H	(DV)	151.49	151.49	151.49	151.49
T_T_1	(DV)	15.371	15.371	15.371	15.371
T_T_2	(DV)	5.0000	20.000	18.149	18.149
T_W	(DV)	62.309	62.309	50.000	180.00
TOTVOL	(OBJ)	0.14368E+11	0.15166E+11	0.14994E+11	0.15774E+11

		SET 59 (FEASIBLE)	SET 60 (FEASIBLE)	SET 61 (FEASIBLE)	SET 62 (FEASIBLE)
SMAX	(SV)	160.81	160.82	160.39	159.94
UMAX	(SV)	4.8042	4.8042	4.8006	4.8022
CNTRINC	(DV)	41.132	40.932	40.932	40.932
CNTRVRT	(DV)	40.307	40.507	40.307	40.307
L_H	(DV)	109.62	109.62	110.37	109.62
L_T_1	(DV)	7.0762	7.0762	7.0762	7.1512
L_T_2	(DV)	5.5224	5.5224	5.5224	5.5224
L_W	(DV)	136.41	136.41	136.41	136.41
RCLMNS	(DV)	40.000	40.000	40.000	40.000
SDINC	(DV)	40.758	40.758	40.758	40.758
SDVRT	(DV)	40.621	40.621	40.621	40.621
T_H	(DV)	151.49	151.49	151.49	151.49
T_T_1	(DV)	15.371	15.371	15.371	15.371
T_T_2	(DV)	18.149	18.149	18.149	18.149
T_W	(DV)	62.309	62.309	62.309	62.309
TOTVOL	(OBJ)	0.15026E+11	0.15023E+11	0.15025E+11	0.15029E+11

		SET 63 (FEASIBLE)	SET 64 (FEASIBLE)	SET 65 (FEASIBLE)	SET 66 (FEASIBLE)
SMAX	(SV)	160.66	160.45	160.82	160.82
UMAX	(SV)	4.8036	4.8033	4.8042	4.8042
CNTRINC	(DV)	40.932	40.932	40.932	40.932
CNTRVRT	(DV)	40.307	40.307	40.307	40.307
L_H	(DV)	109.62	109.62	109.62	109.62
L_T_1	(DV)	7.0762	7.0762	7.0762	7.0762
L_T_2	(DV)	5.5974	5.5224	5.5224	5.5224
L_W	(DV)	136.41	137.01	136.41	136.41
RCLMNS	(DV)	40.000	40.000	40.200	40.000
SDINC	(DV)	40.758	40.758	40.758	40.958
SDVRT	(DV)	40.621	40.621	40.621	40.621
T_H	(DV)	151.49	151.49	151.49	151.49
T_T_1	(DV)	15.371	15.371	15.371	15.371
T_T_2	(DV)	18.149	18.149	18.149	18.149
T_W	(DV)	62.309	62.309	62.309	62.309
TOTVOL	(OBJ)	0.15028E+11	0.15025E+11	0.15022E+11	0.15025E+11

		SET 67 (FEASIBLE)	SET 68 (FEASIBLE)	SET 69 (FEASIBLE)	SET 70 (FEASIBLE)
SMAX	(SV)	160.81	160.66	160.79	160.79
UMAX	(SV)	4.8042	4.7594	4.7973	4.7972
CNTRINC	(DV)	40.932	40.932	40.932	40.932
CNTRVRT	(DV)	40.307	40.307	40.307	40.307
L_H	(DV)	109.62	109.62	109.62	109.62
L_T_1	(DV)	7.0762	7.0762	7.0762	7.0762
L_T_2	(DV)	5.5224	5.5224	5.5224	5.5224
L_W	(DV)	136.41	136.41	136.41	136.41
RCLMNS	(DV)	40.000	40.000	40.000	40.000
SDINC	(DV)	40.758	40.758	40.758	40.758
SDVRT	(DV)	40.821	40.621	40.621	40.621
T_H	(DV)	151.49	152.14	151.49	151.49
T_T_1	(DV)	15.371	15.371	15.446	15.371
T_T_2	(DV)	18.149	18.149	18.149	18.224
T_W	(DV)	62.309	62.309	62.309	62.309
TOTVOL	(OBJ)	0.15025E+11	0.15026E+11	0.15023E+11	0.15026E+11

		SET 71
		(FEASIBLE)
SMAX	(SV)	160.72
UMAX	(SV)	4.7810
CNTRINC	(DV)	40.932
CNTRVRT	(DV)	40.307
L_H	(DV)	109.62
L_T_1	(DV)	7.0762
L_T_2	(DV)	5.5224
L_W	(DV)	136.41
RCLMNS	(DV)	40.000
SDINC	(DV)	40.758
SDVRT	(DV)	40.621
T_H	(DV)	151.49
T_T_1	(DV)	15.371
T_T_2	(DV)	18.149
T_W	(DV)	62.959
TOTVOL	(OBJ)	0.15026E+11

Below sets present the first-order method solution sets. They were automatically defined whether they were feasible or not. Infeasible sets were explained why they out of were range by the signs < and >.

		SET 2	SET 3	SET 4	SET 5
		(FEASIBLE)	(FEASIBLE)	(FEASIBLE)	(FEASIBLE)
SMAX	(SV)	140.25	136.96	144.04	153.28
UMAX	(SV)	3.5012	4.4694	4.0094	4.3656
CNTRINC	(DV)	70.129	56.984	54.696	52.483
CNTRVRT	(DV)	70.004	64.624	63.581	62.550
L_H	(DV)	135.89	132.10	129.91	126.94
L_T_1	(DV)	11.567	13.215	12.738	12.306
L_T_2	(DV)	8.8057	5.8741	5.0000	5.0000
L_W	(DV)	76.464	84.815	79.705	74.802
RCLMNS	(DV)	70.000	69.401	69.276	69.151
SDINC	(DV)	70.014	59.575	57.706	55.886
SDVRT	(DV)	70.041	61.159	59.516	57.911
T_H	(DV)	179.32	175.76	184.08	182.43
T_T_1	(DV)	12.178	11.077	11.341	11.060
T_T_2	(DV)	10.116	7.2760	7.0450	6.3801
T_W	(DV)	92.254	80.514	83.955	80.864
TOTVOL	(OBJ)	0.17783E+11	0.16304E+11	0.15992E+11	0.15675E+11

		SET 6	SET 7	SET 8	SET 9
		(FEASIBLE)	(FEASIBLE)	(FEASIBLE)	(FEASIBLE)
SMAX	(SV)	148.40	158.57	149.35	156.68
UMAX	(SV)	4.7542	4.1533	3.6004	3.7458
CNTRINC	(DV)	47.344	44.061	40.000	40.000
CNTRVRT	(DV)	60.108	58.435	56.345	55.735
L_H	(DV)	129.35	125.90	128.89	126.65
L_T_1	(DV)	12.843	12.129	12.621	12.329
L_T_2	(DV)	5.0000	5.0000	5.0000	5.0000
L_W	(DV)	78.067	69.849	72.901	69.302
RCLMNS	(DV)	68.853	68.640	68.370	68.288
SDINC	(DV)	51.620	48.828	45.385	44.430
SDVRT	(DV)	54.181	51.675	48.615	47.739
T_H	(DV)	183.62	193.25	203.33	202.50
T_T_1	(DV)	10.663	10.965	11.184	10.987
T_T_2	(DV)	5.0000	5.0000	5.0000	5.0000
T_W	(DV)	76.753	80.686	83.761	81.668
TOTVOL	(OBJ)	0.15269E+11	0.14962E+11	0.14815E+11	0.14697E+11

		SET 10 (FEASIBLE)	*SET 11* (FEASIBLE)	SET 12 (FEASIBLE)	SET 13 (FEASIBLE)
SMAX	(SV)	149.29	157.34	157.34	157.34
UMAX	(SV)	4.3661	4.5774	4.5773	4.5774
CNTRINC	(DV)	40.000	40.000	40.200	40.000
CNTRVRT	(DV)	53.966	53.230	53.230	53.430
L_H	(DV)	139.42	136.61	136.61	136.61
L_T_1	(DV)	12.513	12.138	12.138	12.138
L_T_2	(DV)	5.0000	5.0000	5.0000	5.0000
L_W	(DV)	74.113	69.631	69.631	69.631
RCLMNS	(DV)	67.902	67.799	67.799	67.799
SDINC	(DV)	40.000	40.000	40.000	40.000
SDVRT	(DV)	43.662	42.672	42.672	42.672
T_H	(DV)	198.26	197.34	197.34	197.34
T_T_1	(DV)	10.055	9.8541	9.8541	9.8541
T_T_2	(DV)	5.0000	5.0000	5.0000	5.0000
T_W	(DV)	71.836	69.577	69.577	69.577
TOTVOL	(OBJ)	0.14553E+11	0.14438E+11	0.14443E+11	0.14441E+11
		SET 14 (FEASIBLE)	SET 15 (FEASIBLE)	SET 16 (FEASIBLE)	SET 17 (FEASIBLE)
SMAX	(SV)	157.07	156.89	157.14	156.78
UMAX	(SV)	4.5733	4.5760	4.5765	4.5750
CNTRINC	(DV)	40.000	40.000	40.000	40.000
CNTRVRT	(DV)	53.230	53.230	53.230	53.230
L_H	(DV)	137.36	136.61	136.61	136.61
L_T_1	(DV)	12.138	12.213	12.138	12.138
L_T_2	(DV)	5.0000	5.0000	5.0750	5.0000
L_W	(DV)	69.631	69.631	69.631	70.231
RCLMNS	(DV)	67.799	67.799	67.799	67.799
SDINC	(DV)	40.000	40.000	40.000	40.000
SDVRT	(DV)	42.672	42.672	42.672	42.672
T_H	(DV)	197.34	197.34	197.34	197.34
T_T_1	(DV)	9.8541	9.8541	9.8541	9.8541
T_T_2	(DV)	5.0000	5.0000	5.0000	5.0000
T_W	(DV)	69.577	69.577	69.577	69.577
TOTVOL	(OBJ)	0.14441E+11	0.14442E+11	0.14446E+11	0.14444E+11
		SET 18 (FEASIBLE)	SET 19 (FEASIBLE)	SET 20 (FEASIBLE)	SET 21 (FEASIBLE)
SMAX	(SV)	157.34	157.33	157.33	157.20
UMAX	(SV)	4.5774	4.5774	4.5774	4.5476
CNTRINC	(DV)	40.000	40.000	40.000	40.000
CNTRVRT	(DV)	53.230	53.230	53.230	53.230
L_H	(DV)	136.61	136.61	136.61	136.61
L_T_1	(DV)	12.138	12.138	12.138	12.138
L_T_2	(DV)	5.0000	5.0000	5.0000	5.0000
L_W	(DV)	69.631	69.631	69.631	69.631
RCLMNS	(DV)	67.999	67.799	67.799	67.799
SDINC	(DV)	40.000	40.200	40.000	40.000
SDVRT	(DV)	42.672	42.672	42.872	42.672
T_H	(DV)	197.34	197.34	197.34	197.99
T_T_1	(DV)	9.8541	9.8541	9.8541	9.8541
T_T_2	(DV)	5.0000	5.0000	5.0000	5.0000
T_W	(DV)	69.577	69.577	69.577	69.577
TOTVOL	(OBJ)	0.14439E+11	0.14442E+11	0.14442E+11	0.14440E+11

		SET 22	SET 23	SET 24
		(FEASIBLE)	(FEASIBLE)	(FEASIBLE)
SMAX	(SV)	157.26	157.27	157.24
UMAX	(SV)	4.5596	4.5600	4.5526
CNTRINC	(DV)	40.000	40.000	40.000
CNTRVRT	(DV)	53.230	53.230	53.230
L_H	(DV)	136.61	136.61	136.61
L_T_1	(DV)	12.138	12.138	12.138
L_T_2	(DV)	5.0000	5.0000	5.0000
L_W	(DV)	69.631	69.631	69.631
RCLMNS	(DV)	67.799	67.799	67.799
SDINC	(DV)	40.000	40.000	40.000
SDVRT	(DV)	42.672	42.672	42.672
T_H	(DV)	197.34	197.34	197.34
T_T_1	(DV)	9.9291	9.8541	9.8541
T_T_2	(DV)	5.0000	5.0750	5.0000
T_W	(DV)	69.577	69.577	70.227
TOTVOL	(OBJ)	0.14440E+11	0.14444E+11	0.14441E+11

CURRICULUM VITAE



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