STRUCTURAL COST OPTIMISATION OF WARSHIPS

A Thesis submitted for the Degree of Master of Science in Engineering at the University of Glasgow.

BY

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ABSTRACT

This thesis describes the development of a structural optimisation model for warships designed to the MoD (N) NES 110 structural design code based on total relative fabrication cost. Total relative fabrication cost is evaluated for a representative portion of the midship section of a typical Royal Navy frigate and attempts to take into account the costs associated with material purchase, subassembly, assembly and erection of ship's structural components.

The inherent work content associated with modern day warship-building techniques are estimated by generating construction task algorithms. Each construction task algorithm can be regarded as a sequential activity list of elemental tasks which must be undertaken to effect the completion of the overall task. Every individual elemental task has an associated manhour value, this value having been derived by work study methods. Thus incorporated in the program **SHIPCOST** is an appropriate database of cost elements representing warship-building fabrication techniques, for the subassembly and assembly of the major structural components, namely orthogonally stiffened flat and curved panels.

The formulations used for longitudinal structural design embody the current MoD (N) structural design code for surface steel ships while those for the transverse structure are based on DnV Classification Society Rules. These "first principles" and "Rules based" design methods are combined within the program **FRIGATE** to offer the designer an opportunity to investigate the possibilities of optimising both longitudinal and transverse warship structure with respect to total steel relative fabrication cost.

Three individual studies were undertaken to investigate a basis model structure for least relative fabrication costs. Two of these studies investigated orthogonally stiffened flat panels deck structures while the third dealt with a typical frigate's double bottom structure. The results of the flat panel studies, constrained to have constant transverse panel section area together with either constant or varying transverse structure and spacing, indicate that labour costs generally increase with a corresponding

increase in longitudinal stiffener numbers and decrease with transverse spacing. In addition, when the Tee bar stiffeners of the basis model flat deck panel are replaced by commercially available OBP and flat bar sections, savings of 9.0% and 10.2 % respectively, are predicted.

The results from the double bottom study, when also constrained by constant sectional area, indicate that savings can be made on the total relative fabrication cost of the basis model by varying the plate thicknesses in relation to both section type and numbers. It is also demonstrated that the fabrication sequence of elemental tasks adopted in the construction of a double bottom has an important bearing on the manhours needed to complete this particular structural component. These results further demonstrate that labour cost dominates in the total relative fabrication cost relationship. This is highlighted by one option that indicates a 40% saving in material cost but only achieves a 14% saving in total relative fabrication cost. As with the flat deck panel studies, savings on the relative fabrication cost can be achieved by replacing the basis model Tee bar stiffeners by OBP and flat bar sections.

This thesis describes a basic working package of two independent computer programs developed for the evaluation of alternative structural variants to a general frigate arrangement. A limiting factor applying to the studies described has been the fixed position of midship section neutral axis by virtue of a simplifying constant sectional area constraint. It is reasonable to assume, that on removal of this constraint, different structural optima would be obtained. Further investigation is required both to demonstrate this and explore the full range of possible structural cost savings resulting from variations in the vertical position of the neutral axis of the midship section even though the neutral axis is not usually a free variable in structural design.

A present limitation of **SHIPCOST** is an inability to allow variations in the construction task algorithms applied to the fabrication of any of the structural components. Complete flexibility in this area would render **SHIPCOST** unwieldy, cumbersome and time consuming - unwanted attributes of a preliminary design tool.

The basis of a useful preliminary design evaluation tool has been developed and demonstrated. However, further effort is required to fully generalise the models to suit any warship structural configuration.

CONTENTS

CHAPTER 1
INTRODUCTION

A good ship designer, whether in the employ of a national government or a commercial enterprise, attempts to achieve a design that has been optimised to some pre-determined criterion. This criterion may represent the cost of construction and maintenance, least weight or a combination of these. In relation to the subject matter of this thesis, the criterion for optimisation is the relative fabrication cost of a typical warship structure.

In recent years the financing of Royal Navy vessels has become acute as successive governments have resorted to every means at their disposal to reduce defence costs, while the basic price of of many engineering commodities, including the warship, have greatly outstripped the rate of inflation. As the operational requirements of a naval vessel are a function of its intended capabilities in relation to the threat posed by hostile nations while also satisfying the relevant government's maritime strategy, the final product is a compromise between achieving these goals and the cost of the package. The concept and the processes involved with the design of a structure that is intended to be sent into "harms way" are very well described for Royal Navy ships by Bryson [1] and for U.S. Navy vessels by Palermo [2].

In both these papers, it is made clear that the costs of the weapon platform (i.e. the hull structure) and the weapon packages themselves are important and the need to take cost into account at an early stage of the design is emphasised. In other words, a structure that can be sent into "harms way", should the need arise, cannot be achieved at any cost. Therefore, a preliminary design tool that enables the merits of alternative structural configurations to be assessed in relation to initial fabrication cost criterion would be of benefit to the structural designer.

Historically the structural configuration of a warship has almost invariably been optimised to achieve minimum steelweight with little or no regard to fabrication cost. This rationale may have been encouraged, and indeed may have been expected, if the fabrication cost of the proposed structures was proportionally related to cost per tonne rates in the ship designer's mind. This notional association of cost and weight of structure has been shown [29, 30] to be an ill-advised and inaccurate method of estimating the true build cost of ship and offshore structures. Consequently, a more appropriate and accurate cost estimation method is required if fabrication costs are to be reflected realistically.

1.1 Aim of the Thesis.

The objectives of the project to which this thesis relates were to develop computer based methods, that would enable the structural designer to explore the possibilities of optimising a warship structure with respect to steel fabrication cost. In order that this could be achieved effectively, an appropriate database of cost elements, representing warship-building fabrication techniques, had to be compiled.

The purpose of this thesis is to describe a computer based procedure that will accurately predict the inherent work content of a defined structural topography, that can be regarded as a typical midship section of a modern warship, and demonstrate that this procedure is capable of being used as a design tool at the early stages of the design process. For simplicity the structural models have been restricted to the mid-third length of a vessel and the effects of fixed transverse structure, such as major transverse bulkheads, have been assumed constant.

1.2 Layout of the Thesis.

The contents of the thesis explain how the two main areas of interest within the context of the project were undertaken and indicates how the final computer based package can be used at the preliminary design stage. To achieve the primary objective outline in 1.1 above a secondary objective was identified, namely second objective was the development of a structural design package that could interface with the relative fabrication cost estimation package and would be capable of generating suitable longitudinal structural alternatives while coping with design variation in the transverse structure. It should be noted that these two requirements were developed concurrently and that the two computer programs which have resulted can therefore operate either individually or as a package.

In Chapter 2 a literature review on optimisation of ship's structure is presented along with a review of the published material concerned with the estimation of fabrication costs for steel structures, of both ship and offshore platform types.

In Chapter 3 a brief resume of the derivation of the existing database of elemental task times is presented along with one of the construction task algorithms generated to represent a build sequence of typical warship primary structure. The times associated with each elemental task were derived using work study methods. Also included in Chapter 3 is the rationale used in the development of these construction cost task algorithms and a complete set of the construction task algorithms used in this study are contained in Appendix 1. Furthermore, Chapter 3 explains the methods used and assumptions incorporated within the program **SHIPCOST** by which the relative work content inherent in the fabrication of typical warship structures is evaluated. For this purpose, a typical frigate midship section is regarded as a combination of flat and curved orthogonally stiffened panels. Work content is assessed for alternative predetermined fabrication sequences in terms of manhours and this can be converted to cost through the use of globally assumed labour rates. Material costs are assessed for both plate and section materials and an explanation of the methods used is given.

In Chapter 4 the formulations used in both longitudinal and transverse structural design of a typical midship section of a Royal Navy Frigate which are contained in the Fortran 77 source code of the program **FRIGATE** are presented. The design philosophy reflected in the longitudinal structural design is that of "first principles" expressed in the current NES 110, design code [43] of MoD(N) for surface steel hulled ships. In the absence of a suitable alternative, the design method for the transverse structure uses the "rules based" approach of DnV [44], more generally associated with commercial ship design.

In Chapter 5, the details and operational modes of the computer programs developed throughout the course of this study are presented. Program **FRIGATE** incorporates the strength formulations discussed in Chapter 4 for analyzing the strength of both longitudinal and transverse structure. Program **SHIPCOST** contains all the construction task algorithms generated to calculate the inherent workcontent of any structure, an example of which is discussed in Chapter 3.

Chapter 6 presents the results of relative fabrication cost studies on individual structural assemblies. The structural assemblies isolated for rigorous study were those that could modelled as flat panels, the component of ships structure that was the principal focus of attention during the earliest studies on structural optimisation of marine structures. Variations on basis model deck panels and double bottom structures were achieved by replacing the Admiralty preferred Tee bars by OBP and Flat bar sections in conjunction with varying plating thicknesses.

In Chapter 7 the conclusions from these studies are presented and areas for future work are indicated. It is concluded that savings on the relative fabrication cost of the basis model structures studied can be achieved when the Admiralty preferred long stalk tee bar longitudinals are replaced by commercially available rolled sections. A further general conclusion that can be made from the studies undertaken is that their exists a direct relationship between the relative fabrication costs of a structure and the number of it's constituent piece parts.

CHAPTER 2
LITERATURE REVIEW

The rationale of optimised structural design, particularly that of British naval ships has been, to date, based on the last best design. This approach, combined with iterative judicial changes to the design founded on the combination of experience and sound engineering judgement, was the normal pre-computer age optimisation technique. As detailed structural cost consideration is time consuming and relies on extensive rational databases, structural cost optimisation is therefore a relatively recent area of investigation. Consequently, early technical papers on the optimisation of ship structures were concerned only with achieving minimum structural weight.

The idea of optimising the component that can be considered as the bulk of ship's structure, i.e. the gross panel, for minimum weight but still be capable of withstanding various types of loading was tackled by Harlander [3]. The requirements for minimum structural steelweight, in both merchant and naval ships, are numerous and include greater deadweight for merchant ships and greater weapons fit and fuel capacity for naval ships. However, Harlander was aware of the conflict between weight of structure and the practicalities of it's fabrication, i.e. the structures that have minimum associated steelweight are those with thinner plating in conjunction with closely spaced stiffeners while minimum fabrication costs are associated with widely spaced stiffeners. Despite this conflict, Harlander maintained that such considerations of producibility do not invalidate the design trends that a designer should take advantage of to obtain a stiffened panel optimised for steelweight while satisfying other structural requirements.

The increasing availability of powerful computing facilities has led investigators to turn their attention to automating the discipline of ship structural design by adapting the design spiral to computer application through the development and integration of optimisation routines.

Evans and Khoushy [4] dealt with a midship section structure designed to American Bureau of Shipping (ABS) Classification Rules. By defining an "equivalent area", as the net weight of plating and sections divided by average thickness of plating, a weight optimum solution was sought. However it was recognised that consideration should be given to maintenance and repair costs and the compounded effects material weight has on the material cost actually incurred and on through life costs and payload. The resulting wide flat bottomed curve of the steelweight plotted against frame spacing indicated the lack of a sharply defined optimum between the two, an effect termed "flat laxity" by the authors. A significant conclusion from Evans and Khoushy is that the true optimum structure lies somewhere between the structure with weight as the optimisation criterion and that with construction cost as the optimisation criterion.

Mandel and Leopold [5] considered various optimisation techniques and suggested that ship structural design would be best served by an exponential random search technique. By applying such a technique to the following five design variables of a cargo ship optimisation of annual running costs was attempted:

i) Displacement
ii) Prismatic Coefficient
iii) Speed/Length Ratio
iv) Beam/Draft Ratio
v) Length/Depth Ratio

They concluded that as the optimal structural disposition is approached, the principal dimensions of the vessel could vary greatly resulting in an insignificant effect on the cost.

Moe and his collaborators [6,7] applied the concept of defining a mathematical design function and subsequently used a Sequential Unconstrained Minimization Technique (SUMT) to optimise in respect of specified parameters. The results contained in [6] are the forerunners of similar results from other independent studies. The general conclusion that thicker plating and large widely spaced stiffeners lead to least fabrication costs but do not generally offer a least weight optimum solution is also indicated by

Summers [8], Caldwell and Hewitt [9] and Chalmers [10]. The cost estimation methods employed in [6] and [7] include material costs and the labour costs associated with many of the essential tasks involved in ship construction but exclude the fundamental task of plate butt welding - thus rendering the results of limited use. However, despite this reservation, it is recognised that these early studies provided a significant contribution to the discipline of Ship Structural Cost Optimisation.

The value of the work of Moe and his contemporaries at Trondheim was appreciated by Nowacki, Brusis and Swift [11]. They enhanced and generalised Moe's technique for tanker preliminary design into a more general ship design technique. These authors favoured the Direct Search technique of Hooke and Jeeves [12] to find a specified optimum or optima in contrast to Powell's Direct Search method [13] favoured by Moe et al. By adapting this direct search to the constrained problem, these authors produced the Adapted Direct Search (ADS) technique. In common with the earlier studies, the models considered were of tanker structure and the ADS technique was able to demonstrate the sensitivity of these designs to a draft restriction. Furthermore, this method was flexible enough to permit the studies of the sensitivity of the design to other variations in technical requirements and economic conditions.

Further credence was given to the significance of the work at Trondheim by Kitamura [14] when he extended it to cater for the detailed components of flat grillages. This study involved the application of a SUMT to even smaller sub-divisions of the flat grillage fabrication process while optimising for minimum cost. The total material and fabrication costs were each calculated on a work station basis. This was to be commended in principle but unfortunately the labour costs used were based on historical data and therefore subject to the inclusion of inefficient practices and were also yard dependent - these points will be discussed further in Chapter 3.

The earlier work discussed above has proved to be the stepping stone to more sophisticated and integrated packages. Moe [15] with co-authors Muira and Kavlie, developed a design - redesign package, affectionately known as BOSS, which incorporated the extensive database and management system used in Norwegian shipyards. A comparable systematic method is described by Lin, Hughes and

Mahowald [16] incorporating the ABS design criteria and known as SHIPOPT. Hughes continuing in this field has devised MAESTRO [17] which is a rationally based design and optimisation package for large complex thin-walled structures. Within MAESTRO it is possible to define a measure of merit as any function of the design variables. In the case of the fabrication cost associated with stiffeners welded to plating the expression becomes a polynomial in terms of weld length and stiffener thickness. A term is included in this expression to cater for the sharp increase in fabrication cost associated with multiple pass welding and special edge preparation which in turn are functions of the stiffener thickness [18].

The aforementioned optimisation suites generally deal with commercial merchant ship design rules and criteria and a package to incorporate naval design criteria and indicate areas of high fabrication cost in new ship construction would be of benefit to the naval designer. This was provided by Furio [19] for the U.S. Navy in the form of the Ship Structural Cost Program (SSCP) which has been used by Wiernicki et al [20] and Nappi et al [21] to produce some interesting results when used in conjunction with the U.S Navy's Ship Structural Design Program (SSDP). The SSCP can therefore be described as a cost/weight trade off tool that can be used in conjunction with SSDP. The U.K. Government Defence Design System for Ships (GODDESS), is described by Pattison et al [22] and the computer package described by Holmes [23], are used for the design of Royal Navy ships in a similar way to SSDP. GODDESS currently incorporates a cost estimation procedure based only on weld length. Although better than weight as a criterion, weld length is not necessarily suitable when predicting build costs of modern warships using alternative structural materials and configurations.

The first traceable attempt at fabrication cost estimation at the University of Glasgow was carried out by Lee [24]. He attempted to evaluate the fabrication cost of structurally optimised grillages by applying a series of curve fitted coefficients to the elemental tasks of the construction sequence as well as the welding rates. The effect of curve fitting these values is to smooth out any step change in costs associated with particular elemental tasks, more particularly with the welding rates. The elimination of these technically justifiable step changes can have significant effect on fabrication cost calculations as welding is the major fabrication cost element. The total cost figure used by Lee included overheads, materials, labour and welding consumables.

A paper by Carryette [25] which outlines the approach traditionally used by shipyard estimators for predicting fabrication costs is worthy of mention. In this paper the labour cost is directly related to design parameters such as C_b and L_{pp}. The equations published were derived from historical returns of previous ships built within a specific shipyard. This data, as with Kitamura's [14], has all previous inefficient practices of the construction sequences included in the equation. However, in addition, the equations in this paper neglect a very important aspect needed to accurately estimate the fabrication cost of any given structure as duly noted by Buxton [26] and Chalmers [10]. This flaw is that the labour cost used by Carryette is related to the hull envelope of any structure and totally ignores the internal configuration. This may not be so important in large longitudinally or transversely framed commercial vessels but in the case of naval ships with their high degree of lattice type grillages it would appear to be somewhat inappropriate to implement this approach to predict fabrication costs of ship structures.

In the majority of the studies discussed above priority in the design optimisation procedure has been given to strength and/or weight criteria with fabrication cost being the secondary consideration. To give a fresh impetus to the problem several research establishments have more recently turned their attention to designing structures that would satisfy all the strength pre-requisites with optimum fabrication costs, most notably in the U.K. at the Universities of Glasgow and Strathclyde.

Flat grillage structure predominates as the component of a ship which has attracted most attention when optimisation procedures have been carried out with strength and/or weight as the criterion. It would therefore seem a natural progression that this structural component should feature when the emphasis of the optimisation changed from strength and/or weight of structure to fabrication cost of structure. This has been the case in recent papers by Kuo, MacCallum and Shenoi [27], MacCallum [28] and Winkle and Baird [29]. The essence of these studies has been to provide a tool which, in utilising method study derived elemental task times, is then able to assess the merits of various designs on a basis of realistic fabrication cost criteria. The methodology described in [29] is the one which has been subsequently developed and expanded to provide the subject matter of this thesis.

In particular, Winkle and Baird [29] investigated several grillage designs proposed by a U.K. warship builder as being structurally equivalent with the view of evaluating the influence of the structural arrangement on relative fabrication cost. The five grillage designs considered represented a range of extreme structural configurations, from fully transversely framed to completely longitudinally stiffened. One conclusion from these studies was that neither relative cost of fabrication or work content is proportional to weight of structure, they both varied inversely to weight. In these studies relative cost was normalised to a Cost Equivalent Relative Weight (CERW) factor in a manner similar to that proposed by Moe and Lund [7]. This factor is a useful device for representing the variability in labour rate and overhead cost and how these factors affect the final relative fabrication cost of the structure but is difficult to employ where component material costs vary widely.

A companion paper by Frieze et al [30] demonstrated an application of the general methodology of the work content estimation procedure described in [29]. By investigating several design codes and proposing a new formulation for the design of large stiffened tubulars, optimisation was achieved with weight and safety as the criterion. As a further means of comparison between each proposed design the work content of each structure was estimated. The results from these studies indicated which structures were least labour intensive and incurred least fabrication costs while also identifying the weight penalties which arose from achieving minimum time or cost of construction.

As is common when a subject progresses from initiation to a broader spectrum there will be parallel and independent research carried out. This is indicated by the paper by Shenoi and Emmerson [31] who have produced a computer based fabrication cost assessment tool, which has similarities to the work presented in this thesis but has concentrated more on production control and producibility applications related to merchant ships.

CHAPTER 3
STRUCTURAL FABRICATION COST ESTIMATION

In the current environment of keenly competitive independent shipyards vying for a decreasing number of contracts there is ever increasing pressure that a yard's contract tendered price must be correct. In this context, correct means low enough to be attractive to the customer while still covering the costs that are likely to be incurred by the shipyard during build and also being less than the price tendered by competitors. This requires that the tendered contract price of a commercial or naval vessel must be based on, amongst other things, an accurate and reliable procedure for estimating the fabrication cost.

One application of such a procedure would be at the preliminary design stage, where evaluation of the production kindliness, in terms of manhours required for fabrication, of alternative structures could be performed. This would be consistent with attempting to achieve the following ISSC design for production objectives :

> "Design to reduce production costs to a minimum compatible with requirements of the structure to fulfill it's operational functions with acceptable reliability and efficiency."

3.1 Historical Structural Fabrication Cost Estimation

The function of putting a price on a contract has traditionally been performed by the shipyard's estimating department. The basis of most estimating procedures is historically recorded manhours of similar vessels built within the yard which are usually analysed to give figures relating to cost per tonne of steelwork erected. Examination of this type of data can lead to a degree of useful information in the form of empirical relationships which will allow cost estimates to be made for vessels of a similar type and structural arrangement. These empirical relationships relate manhours expended during construction to some of the principal dimensions or design variables of the structure being built.

The best recent examples of these types of empirical relationships are published by Carryette [25] in the form of equations relating cost of structure to some of the principal design parameters of the vessel, such as C_b and L_{pp}. The equation given for steelwork manhours is :-

$$Mhrs_s = 227 \frac{\sqrt[3]{W_s^2 L_{pp}}}{C_b} \qquad (1)$$

where :

$Mhrs_s$ = Steelwork manhours

W_s = Steel weight

L_{pp} = Length between perpendiculars

C_b = Block coefficient

However, despite the convenience of equations in this form there are several factors that negate the usefulness of this approach when interest is centred on the influence of the structural design details on the cost of fabrication;

i) Empirical derivations are based on historical data collated from previous ships built within a given shipyard and should therefore be regarded as unique to that shipyard and its working practices.

ii) Empirical derivations usually relate to a series of similar vessels being built in a particular fashion within a given shipyard and are therefore "rigid", i.e. there is no mechanism to allow for changes in build method or indeed to cater for different types of vessels with differing structural configurations.

iii) The historical nature of the data and the methods used in recording such data mean that they implicitly incorporate any bad working practices and inefficiencies encountered during the construction. Therefore any forecasts of inherent cost resulting from such derivations will be inaccurate and tend to lock ineffective working practices into future contracts.

iv) The level of detail that can be catered for in this type of derivation is insufficient to indicate what effect variations of structural scantlings and stiffener type and arrangement will have on the final cost of the structure.

v) There is no reflection of the complexity of structure involved in any of these empirical formulations and therefore there is no consideration of either the influence of number and degree of integration of parts, or the effect that curved surfaces have on the final cost of fabrication.

vi) There is no means of quantifying the difficulties of working with the lighter scantlings generally associated with warship structures and the corresponding difficulties encountered in assembling such structures that frequently require rework.

vii) There is no means ot quantifying the disadvantages of fabricating orthogonal structures in which the use of automatic continuous fillet welding is greatly reduced.

For these reasons it is necessary to forego the convenience of using historical work records and investigate other more direct means of estimating the fabrication costs that are likely to be incurred by a shipyard throughout the ship building cycle.

3.2 The Development of more Accurate Methods of Structural Fabrication Cost Estimation.

The probable labour requirement for the fabrication of any structural configuration would be best estimated by a method that is capable of accurately predicting the inherent work content (aggregated manhours) involved with it's construction. Such a prediction can be utilized in two ways. Firstly the total costs, being the sum of labour, overhead and material costs, likely to be incurred are estimated. Secondly accuracy permits the use of such methods for production scheduling if the necessary manning levels for each stage of the build cycle are known. Therefore, if this approach is to be used for estimating the relative fabrication cost of ship structures, a database of standard times for given activities and related shipbuilding tasks is required.

Such a database exists at the University of Glasgow and has been used to date to estimate the relative fabrication costs of various structures including a range of representative warship grillages [29] and ring and stringer stiffened cylinder options of a North Sea Tension Leg Platform (TLP) [30]. While the main sources of these work study derived task times were Govan Shipbuilders and Sunderland Shipbuilders there has been some augmentation of the original database as other sources of similar data became available throughout the course of this study.

The database consists of standard elemental task times related to steel assembly and an extensive range of welding process times. The standard time of an elemental task is the summation of a basic time and allowances. The basic time element was recorded under controlled work study conditions by experienced work study practitioners and subsequently factored by an efficiency rating to give the calculated basic time. The allowances include time for normal recovery periods between subsequent tasks, taking into consideration fatigue, posture, the use of force, temperature and humidity and allow the worker a period of recovery from any physiological or psychological effects of having performed the task. Thus, the standard time of a task is the time taken by an experienced, properly motivated worker if he follows an accepted method of carrying out the defined task.

Welding process time consists of two components. One is a job constant associated with receiving instructions, clearing the work area, moving the welding equipment, setting the electrical current and joint preparation. The other component is a rate per metre which includes an allowance for inspection of the weld, the actual welding, changing of rods and finally cleaning the weld. Of the two sets of data that make up the complete database of standard times, that associated with the welding processes is the larger.

The main factors that influence the deposition rate of weld metal and consequently the time taken to complete a weld are the type of process, the type of rod, the edge preparation of the components to be welded, the physical orientation of the joint and the access the operative has to complete the joint. The range of each of these factors that can be catered for in the existing database is listed below :-

a) Type of Welding Process

   i) Manual Fillet - various applications such as section to plating, connection between transverse and longitudinal members etc.

   ii) Automatic Minideck - main application being flat panel seam welds

   iii) Manual Butt - applied when automatic plate butt welding is not feasible, e.g. unit link ups in sub-assembly areas or on building berth

b) Type of Welding Rod.

   i) Rutile - generally used when thickness of the material to be welded is not greater than 12mm

   ii) Low Hydrogen - generally used when thickness of the material to be welded is greater than or equal to 12mm or where higher tensile steel is being welded

   iii) Iron Powder - generally when fillet welding is the weld process involved

c) Assumed Positional Mode of the Joint.

i) Downhand - many applications in sub assembly areas and on the building berth

ii) Vertical - numerous applications in sub assembly areas and on the building berth

iii) Overhead - mainly used when welding takes place on the building berth when there is no practical alternative

iv) Horizontal - many applications in sub assembly areas and on the building berth

d) Edge Preparation of Material

The range of preparations contained in the database is shown in Fig.3.1

e) Access to the Weld Area

i) Unrestricted - easily accessible and ventilated

ii) Restricted - when the operator is having to perform the tasks in a confined space where movement and ventilation are difficult e.g. in a ship's double bottom.

Although the elemental task standard times for plating activities and material handling were derived using work study methods in commercial shipyards, the activities involved are generally independent of scantlings and can therefore be applied in relative terms at least to the lighter warship structures. Based on this assumption the relative fabrication costs of typical warship structures could be investigated using this database.

3.3 The Relative Fabrication Costs and Work Content of Typical Warship Structures

The total fabrication cost of any steelwork structure fabricated in any shipyard can be regarded as the summation of three cost components:-

$$\text{Total Cost} = \text{Material Costs} + \text{Labour Costs} + \text{Overhead Costs} \quad (2)$$

3.3.1 Material Costs.

When the British Steel Price Schedule [32] is studied it becomes apparent that the most convenient method of calculating prices of steel plates would be to use a flat rate per tonne for a specified grade of standard sized plate. This allows reasonably accurate cost estimation of plate related costs without having to deal with the intricacies relating to "extras" connected with order basing points and non standard plate sizes. As the main object under consideration within the scope of this study is a typical warship, the information used in pricing the plate material relates only to those grades of steel that are prepared for naval application. These grades are DGS 257A, DGS 207A and DGS 322BX. The plate cost output from **SHIPCOST** is the nett cost of plate, i.e. the cost of the plate material used in the construction of the structure only with no consideration of the cost of green material or gross tonnage of plate ordered to accommodate some element of scrap. If it is desired to investigate the use of other steel grades, minor modifications to the existing package would be required and could be easily dealt with.

As plate costs are only part of the total material costs, the costs of Long Stalk Tees (LST), [33], Offset Bulb Plates (OBP) [34] and Flat Bars (Flat) [35] British rolled sections are also calculated where appropriate. In the case of the LST's, currently used by the Ministry of Defence (N) as the preferred type of rolled section for longitudinal stiffeners and transverse members, it will be shown in Chapter 6 that the cost of sections can have a significant influence on the total fabrication cost of a structure.

The cost of sections output from **SHIPCOST** relates to the length welded to any particular plate at the panel sub-assembly stage. This length of section is generally taken as being 1 metre less than the length of the plate to which it is attached. This relates to the fabrication practise witnessed by the author and as such permits more accurate modelling of the overall fabrication technique employed in a modern day warship-building yard and is discussed in greater detail in Section 3.3.2.5

When the design criteria stipulates that a structural member requires a section modulus value greater than can be offered by any of the standard rolled sections then a fabricated section must be used. There can be several combinations of flange and web components used in the construction of a fabricated section :

i) Both the web and flange elememts consist of standard flat bar section.

ii) The web being made up of a plate material and the flange being a standard flat bar section or vice versa.

iii) Both the web and flange elements consisting of plate material.

In those instances where the web and flange or one of these is a standard flat bar the material cost can be easily calculated with due reference to the price list. However, in those instances where plate material is used for either element of the fabricated section material costs are not as easily calculated. The instinctive method of calculating material cost in these instances would be to price the material as it would be carried out for plates for use in panel construction and hence arrive at a plate material cost value. However, due to British Steel's pricing policy with regard to plates, this could lead to an inflated material cost for these types of fabricated sections because in effect the material would be costed as a series of non-standard plates which incur "extras" i.e a cost per tonne additional to the basis rate per tonne, resulting in the price per tonne of fabricated section material being abnormally high. Therefore the method adopted to calculate fabricated section material costs is simply to apply the steelweight of the plate material used for the fabricated section multiplied by the base rate per tonne of steel.

3.3.2 Labour Costs.

As shipyards are being compelled by the scarcity of new orders to submit more competitive contract prices, the question "How accurate is the labour cost estimation method?" is raised. In recent years it has been suggested in open literature [10, 29, 30] that existing methods are not of the accuracy now demanded by market conditions and as such other more accurate methods should be used, developed and implemented.

The method developed to estimate the inherent workcontent of warship structures throughout the course of this study had it's genesis in a project concerned with offshore platform tubular structures [30] and was shown to be flexible enough to estimate the relative fabrication costs of representative warship grillages [29]. The method used for these comparatively simple grillages, has been extended and enhanced in order that the total relative fabrication costs of a typical midship section of a Royal Navy Frigate can now be estimated. In the context of this thesis, the total relative fabrication costs of a midship section include the material cost in pounds sterling and a fabrication cost in manhours which can be converted to cost by the use of globally assumed labour rates. Throughout the duration of this project, a set of construction task algorithms have been developed which are embedded in the Fortran source code of the program **SHIPCOST**. These algorithms, the methods used and the assumptions incorporated are transparent to the user of **SHIPCOST** but full a definition of each construction task algorithm is contained in Appendix 1.

The scope of these construction task algorithms is such that the following list of shipyard fabrication activities can be modelled and their related inherent work content estimated :

1) Fabrication and assembly of structural blocks in a shop environment.
2) Installation of each assembly on the building berth.
3) Integration and link up of adjacent assemblies on the building berth in the vertical sense.

4) Shop fabrication of a second set of assemblies, identical to the first.

5) Installation of each assembly of the second set on the building berth.

6) Integration and link up of adjacent first and second set assemblies on the building berth in the longitudinal sense.

7) Integration and link up of adjacent second set assemblies on the building berth in the vertical sense.

Using the database of standard and basic times, derived from method study analysis of the elemental tasks used in ship construction, it was possible to develop a set of algorithms that could genuinely reflect the inherent work content of typical warship structures. With the unit of measurement of the work content being in manhours, it is simply multiplied by the appropriate labour rate to yield a figure in pounds sterling for the cost of the labour involved in the fabrication of a particular ship component. The results of the studies discussed in Chapter 6 employed a fixed labour rate of £15 per manhour. This was thought suitable to reflect currently charged shipyard labour rates (reflecting overheads). The following sections detail those activities involved with ship construction that are modelled by **SHIPCOST**, and explain why one method is preferred to another.

3.3.2.1 Flat panel fabrication

One specific component that predominates in a parallel sided midship section of a typical frigate is the orthogonally stiffened flat panel. A flat panel comprises three constituent parts, namely plates, longitudinal stiffeners and transverse frames. The manner in which these individual items are collectively integrated is very much dependent on the facilities available within any one shipyard. However, as one of the prime objectives of this study was to model current fabrication techniques in a modern warship-building yard, the treatment of flat panel fabrication assumes panel line assembly procedures.

In order that a flexible but manageable relative fabrication cost algorithm for orthogonally stiffened flat panel construction was developed, not all the parameters involved are variable. Also as a result of the recent abandonment of systematic work study job duration recording within British Shipbuilding, no assessment is available of some more recent fabrication techniques. Consequently some of the elemental tasks assumed and presented in the Construction Task Algorithms may not be strictly applicable in the absolute sense as reflecting current fabrication techniques. To illustrate this point, consider the following examples :

Example 1 - Plate Marking.

With the introduction of C.N.C plate cutting equipment to shipyards, it is now possible to automatically mark on the plate the longitudinal stiffener and transverse frame positions by powder marking, punch marking or simply inking techniques. Within the set of construction task algorithms developed this activity is modelled by assuming manual paint marking techniques.

Example 2 - Panel Plate Seam Welding.

As presented in the construction task algorithm for flat panel production, a panel seam weld operation is performed using a semi-automatic mini-deck welding machine. After the primary run of weld is completed the panel is reversed and a second run of weld is put down on the seam. Today this same panel seam weld could be completed using single sided welding techniques employing glass or ceramic backing strips. However, there is no information available to the same level of detail and recorded under the same controlled conditions as those times already existing in the welding database, on the completion time of single sided welding techniques. Therefore, single sided welding techniques cannot be modelled at the present time.

The inclusion of these traditional fabrication techniques in the construction task algorithms does not invalidate the information yielded on the inherent work content of a structure by such algorithms. By using more traditional fabrication processes the final figure given for the estimated work content of a structure may exceed that would be achieved using state of the art techniques, but as the emphasis of these studies is on ***relative*** fabrication time (and cost) these minor variations in absolute work content have little bearing on the search for cost minima among alternate structural designs of broadly similar grillage configurations.

The welding method assumed for longitudinal stiffener and transverse frame attachment to the plating is manual fillet welding. Although information exists in the welding database for the process times of semi-automatic welding techniques such as Gravimax, the thickness of the material (section web thicknesses) used in warship structures is generally too thin to be dealt with efficiently and effectively by this method. Thus with these assumptions applied, attention can now be paid to those facets of flat panel fabrication that can be considered variable.

The activity that allows the major degree of variability in the fabrication of orthogonally stiffened flat panels of fixed dimensions is the sequence in which the structural sections are attached to the plating. Are the longitudinal stiffeners attached before the transverse frames or vice versa ? Both these options are equally possible and the reasons for the preferred method, as used in **SHIPCOST**, are given below.

In **SHIPCOST**, precedence in the attachment of sections to plating is given to whichever member (longitudinals or frames) has the smaller overall height dimension. Adopting this procedure allows the maximum opportunity for extended runs of continuous, uninterrupted fillet welds to be used. This implies that the full length of section can be welded to the plate without discontinuities in the weld run in way of nothes cut in the section web which accommodate the passage of the smaller penetrating member.

3.3.2.2 Grillage connections

It is often said that warship grillages incur greater fabrication costs than those occasioned by the flat panel structure of a commercial ship to withstand the same environmental loading. This is partly attributable to the large amount of lattice type structure that exists in the warship grillage and the connections necessary to ensure structural integrity between intersecting members. These connections, although necessary, are expensive to complete on any grillage. In order that the costs associated with grillage inter-connections can be identified and quantified, recommendations for use in naval structures [45], were studied and the synthesis of the time taken to complete ***standard*** connections between orthogonal members is incorporated within **SHIPCOST**. Although the dimensions of a standard connection piece are derived on the premise that two Tees sections are intersecting, the methodology for this derivation is thought suitable for application when sections other than Tees are intersecting for the purposes of this study. The range of grillage connections that can be modelled by **SHIPCOST** is shown in Fig. 3.2. The dimensions which allow the associated work content of these connections to be estimated are contained in Table 3.1. Other structural connections that can be modelled are shown in Figs. 3.3 and 3.4 along with their associated dimensions.

3.3.2.3 Curved panel fabrication

When a sub-assembly cannot be adequately modelled as an orthogonally stiffened flat panel, such as in the case of the bilge structure, then a different construction task algorithm is requireu. In the case of an orthogonally stiffened curved panel, the same rationale applies to it's fabrication as was applied to the flat panel, i.e. manual paint marking-off and the order in which the orthogonal members are attached to the plating. However a significant change in the method of plate seam welding is necessary due to the curvature of the individual plates. As a result of the plate contours it is no longer suitable employ mini-deck welding to carry out the plate seam weld and consequently this is done by a manual butt welding process. The number of weld runs required to complete a satisfactory seam is a function of the plate edge preparation and the plate thickness and is dealt with automatically in **SHIPCOST**. Grillage connections are dealt with in the same manner as for the flat panel.

3.3.2.4 Building Berth Installation and Integration

Once each of the assemblies has been individually fabricated in the workshop, they must subsequently be installed on the building berth. There may again be conflicting working practises in different shipyards at this stage of the build cycle depending on the facilities available. For example, one shipyard may link up two or more of these individual assemblies to form another structural unit in the work shop, whereas the link up of the same sub-assembly types may be performed outwith the work shop in another ship yard. This link up process is highly dependent upon the nature and capacity of the mechanical handling equipment which govern the upper limit of the number of assemblies that can be linked at this stage, the availability of fabrication shop floor space and the overall construction method employed. All of these factors will be unique to each shipyard and therefore in the context of **SHIPCOST** the size and extent of assemblies are based on judicious judgement of what might be generally acceptable in most shipyards.

In **SHIPCOST**, this area of the build cycle is modelled by assuming the following method of assembly unit link up based on a bottom up build philosophy :

1) Shop fabrication of orthogonally stiffened outer bottom structure.
2) Shop fabrication of orthogonally stiffened tank top panel.
3) Workshop link up of the tank top to the outer bottom.
4) Installation of the double bottom unit on the building berth.
5) Shop fabrication of orthogonally stiffened plating of the bilge structure (port and starboard).
6) Installation of the bilge structures on the building berth and it's integration with the double bottom unit.

7) Shop fabrication of orthogonally stiffened side shell structure (port and starboard).
8) Installation of the parallel sided shell panels on the building berth and their integration with the bilge structure.
9) Shop fabrication of Nº 2 Deck panel assembly.
10) Installation of Nº 2 Deck panel assembly on the building berth and link up with the side shell structure.
11) Shop fabrication of Nº 1 Deck panel assembly.
12) Installation of Nº 1 Deck panel assembly on the building berth and link up with the side shell structure.
13) Shop fabrication of Nº 01 Deck panel assembly.
14) Installation of Nº 01 Deck panel assembly on the building berth and link up with the side shell structure.

Installation of the assemblies on the building berth includes activities such as the use of building berth cranes, temporary shoring and overall securing of these assemblies prior to the link welding. The term "link up" includes all those activities associated with the :

a) fairing of adjacent structures, plates and sections
b) completion of plate butt welding
c) fitting and welding grillage marrying pieces
d) fitting and welding transverse frame web doubler plates and/or knee brackets at deck/side shell transverse intersections
e) manual fillet welding of deck plating to the side shell plating
f) fitting and welding of collar plates where side shell transverse frames penetrate the deck plating.

The butt welding of adjacent erection joints in plating is performed manually using a standard plate edge preparation imposed on the plate within the Fortran source code. This method, although it may be slightly dated, is assumed to apply at this stage of the fabrication process, because no information is available on more modern techniques such as orbital welding, at the level of detail required for compatibility with the existing welding data-base.

3.3.2.5 Grillage link up techniques.

As was mentioned briefly in Section 3.3.1, there is a deficit of 1 metre between the length of the plate and the length of the attached longitudinal stiffener. Similarily, there is a shortfall of 1 metre between the width of the panel and the length of the section that is the transverse frame. This descrepancy in lengths is by design and is necessary if true emulation of the fabrication techniques used in grillage link up procedures is to be achieved. There are basically two methods used for grillage link ups that are favoured in shipbuilding today and a brief descrition of each is given below.

One method is to allow a shortfall of 0.5 metres at each end of the section in relation to the plate length or width. This permits the fitting of a 1 metre long section "marrying piece" when two adjacent grillages are being linked up to integrate their collinear structural members particularly in the longitudinal direction, thereby ensuring continuity. The other fabrication process that is employed is one where the rolled sections of the grillage are allowed to overhang at one edge of the plate and fall short at the opposite edge. If this overhang is taken as 0.5 metre (with a similar length left unwelded to the plate), the weld length is the same in each of the fabrication procedures and a similar section cost will result. However, this fabrication technique then requires a different grillage link up procedure from that described above. In this case, the structural sections of one grillage are "cut back" from their original overhang length until they are sufficiently short to be butt welded to the shortfall edge of the adjacent section. This results in only one butt welded connection between sections instead of the two required when fitting a "marrying piece". Examples of each grillage join up procedure are shown in Fig. 3.5.

However within **SHIPCOST** only the "marrying piece" method is dealt with. This results not from any personal choice but rather from a lack of elemental task details with regard to the "cut back" method, specifically the burning times required to achieve necessary cut back length. Thus as standard and basic times for fairing the flanges and webs of sections are available within the work content database and the subsequent welding times can be extracted from the welding database, an accurate estimation of the manhours required to fit and complete the welding of a grillage marrying piece is possible, although superficially this would appear to be the method likely to incur the greater labour cost.

Within the context of **SHIPCOST**, the link up of adjacent grillages occur mainly on the building berth and as such a variety of different joint orientations have to be catered for. As a consequence of the orientation and nature of the erection joints (vertical or longitudinal) different subroutines are required to model the major alternative erection procedures for adjacent grillage members. In broad terms there is a range of three grillage joint orientations - vertical, horizontal and longitudinal. Vertical applies to joints such as that between bilge and side shell grillages, longitudinal to the joint between linear adjacent structures in the horizontal plane while horizontal applies to the joints between grillage members of deck panel assemblies and the side shell, i.e. connections between perpendicular sections. The cases of vertical and longitudinal grillage joints involve fairing and tacking a 1 metre length marrying piece and butt welding at either end of the marrying piece. However, in the case of the grillage joint between deck structure and side shell structure (horizontal) the procedure is not as straightforward as described above. The treatment of such a horizontal grillage joint involves the following events :

1) A section marrying piece, **0.5 metres** in length, is faired and tacked at either side of the deck panel assembly (1 metre in total per transverse frame).
2) Overhead manual fillet welding of marrying piece web to the underside of the deck plating.
3) Manual overhead butt welding of the inboard end of the marrying piece to the end of the deck panel transverse frame.
4) Manual overhead fillet welding of the outboard web and flange of the marrying piece to the side shell transverse frame flange face.

Steps (2) to(4) are repeated for the other 0.5 metre length of marrying piece and steps (1) to (4) are repeated for each deck panel to transverse frame link up. Figs. 3.6 and 3.7 highlight the three orientations of grillage link up are be modelled in **SHIPCOST**.

3.3.3 Overhead Costs.

Although fixed overhead costs must be included in the contract price, their omission can be justified in relative design studies when the sources of such costs are identified. As in similar relative fabrication cost estimation studies [29, 30], at the University of Glasgow these fixed overhead costs are taken to include plate preparation along with operation and maintenance of means of transport within the shipyard all of which are assumed to maintain a constant labour resource.

Direct variable overhead costs are related to national insurance payments, provisions of holidays and pension scheme payments and can be included for our purposes within the labour rate used in these studies. Overheads not directly related to direct labour manhours include supervisory staff and power supplies but are assumed to vary as the variable overhead cost and treated in the same way. Indirect overhead costs are those which are independent of the level of production and can be attributed to repair and maintenance of plant and machinery along with their running costs, rates and staff related costs and for the purposes of this study are ignored on the same basis as the fixed overhead.

With overhead costs dealt with as outlined above the ***relative*** fabrication cost of a structure can now be estimated in terms of the the total variable cost, defined as:-

$$\text{Total Variable Cost} = \text{Material Costs} + \text{Labour Costs}$$

$$= \Sigma\text{Weight x Material Rate} + \Sigma\text{Manhours x Labour Rate} \qquad (3)$$

3.4 The Relative Fabrication Cost of a Typical Warship's Double Bottom Unit.

As an example, to illustrate how the relative fabrication costs of a steel structure are calculated, a typical warship's double bottom unit is highlighted and a construction task algorithm is presented.

The structural nature of a double bottom unit leads to readily identifiable structural assemblies. These assemblies being tank top plating and the outer bottom plating and their respective attachments. It is a logical progression that, depending on what are regarded as tank top attachments and what are considered as outer bottom attachments, different construction sequences can be identified. In total four different construction sequences have been identified for a typical double bottom unit. Construction Sequence 1 is described below and all the construction task algorithms are detailed in Appendix 1.

3.4.1 Typical Double Bottom Unit of a Modern Warship.

From structural drawings a typical warship double bottom can be considered to consist of the following two structural assemblies :

i) Tank top plating with longitudinal stiffeners, plate longitudinals, vertical keel, vertical floors and transverse frames.

ii) Outer bottom plating and orthogonal stiffening.

With these two individual structures defined, Construction Sequence 1 is described below and it's construction task algorithm developed in Appendix 1.

A major assumption applied to all the sub-assembly fabrication in this study is that they are performed in a workshop environment.

3.4.2 Double Bottom Unit Construction Sequence 1

The activity sequence shown in Fig. 3.8 indicates the order in which the double bottom unit is fabricated when using Construction Sequence 1. Other activity sequences developed using Construction Sequences 2 - 4 are shown in Figs. 3.9 - 11 respectively.

The first sub-assembly to be fabricated is the tank top flat panel. The construction sequence is synthesised from elemental tasks taken from the workcontent database. These elemental tasks are chosen as those that most closely emulated flat panel assembly procedure in a present day warship building yard.

Having fabricated a fundamental flat panel, other sub-assemblies are attached which subsequently identifies this flat panel as belonging to the tank top. Typical of such sub-assemblies are the plate longitudinals. However, before a plate longitudinal can be connected to the tank top it must first be fabricated. In reality, plate longitudinals are fabricated from a series of small individual plate parts all connected together to form a long plate girder. The size and number of these individual parts is multi-variable and as such the following assumptions apply to plate longitudinal fabrication within the context of this study.

1) Each plate longitudinal is regarded as one piece of continuous plating, equal in length to the tank top plate to which it is attached.
2) There are no lightening holes cut in the continuous plate.
3) In the absence of lightening holes there is no consideration of the time required to fit flat bar riders as they exist on warship structures.
4) The plate longitudinal is stiffened asymmetrically with the number of stiffeners equalling the number of transverse frames of the tank top flat panel.
5) The material cost of the plate longitudinal is ignored.

After their fabrication, the plate longitudinals are fitted and welded to the tank top flat panel.

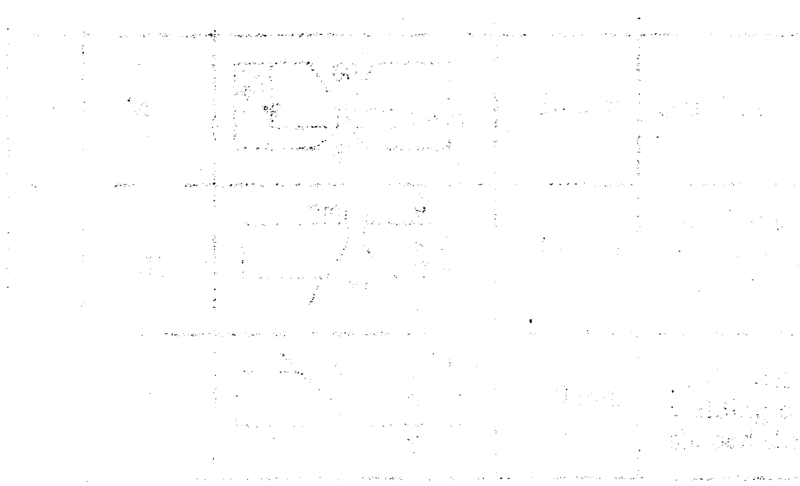
As warships are generally considered to be longitudinally stiffened, it is necessary that the vertical floors are intercostal in relation to the continuous longitudinal structure, primarily the plate longitudinals. This necessitates that each vertical floor comprises individual piece parts, the number of which is dependent upon the number of plate longitudinals. As with the plate longitudinals no consideration is given to the effect of lightening holes, the fitting of flat bar riders on the fabrication cost or the material cost. Once all the vertical floor piece parts are completely welded to the tank top structure i.e. the tank top plating and plate longitudinals, then in terms of Construction Sequence 1, the tank top sub-assembly is complete.

The next stage of the double bottom fabrication process is to construct the orthogonally stiffened outer bottom sub-assembly. This sub-assembly may be regarded as a curved panel or two adjacent flat panels butt welded at the ship's centre line. Construction Sequence 1 treats the outer bottom as an orthogonally stiffened flat panel.

The subsequent step in the double bottom unit assembly is to rotate the the outer bottom structure 180° about it's centreline and drop it onto the tank top structure. Alignment of the respective sub-assembly components is then carried out. The final join up activities include all welding activities to effect the completion of the double bottom unit. It is worth noting here that these welding operations are carried out in what can only be described as unfavourable conditions, i.e. overhead in confined spaces where access is restricted, and where heat and fumes are likely to build up.

By reading the previous paragraphs of this section the reader may be lead to believe that fabrication of the outer bottom is commenced once the tank top sub-assembly is completed. This is not intended to be the case as more likely than not, these two sub-assemblies will be fabricated in parallel or staggered production and not in series as described. The amount of overlap in production depends on the relative workcontent of each, the availability of shop floor space the the disposition of the steelwork labour force within the yard at any particular time in the build cycle.

The labour cost inherent to a steel structure is taken as the accumulation of standard times relating to the elemental tasks used in its fabrication multiplied by a labour rate. The labour costs calculated in this study relate to those activities that are carried out by steel trades only. That is to say no attempt is made to estimate the labour cost associated with the installation of equipment and electrical circuitry or pipework systems.



[illegible]

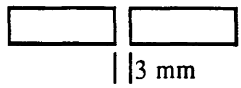
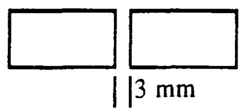
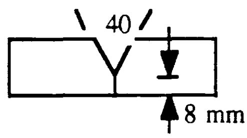
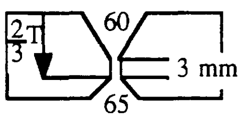
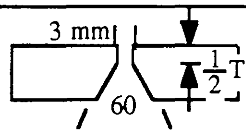
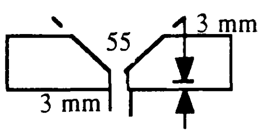
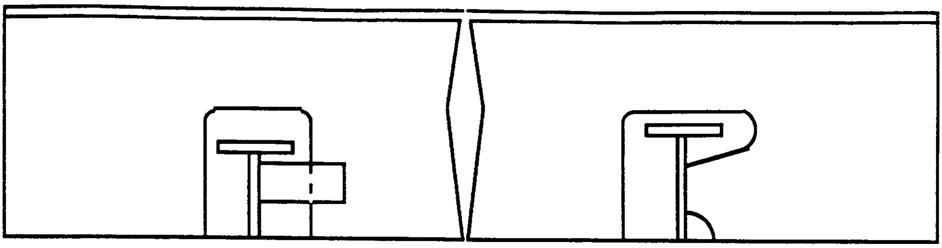
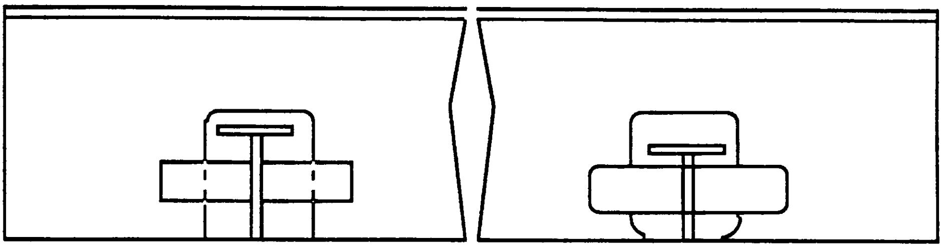
No	Symbol	Edge Preparation	Max Thick	Tasks
1	J		13 mm	Minor decks and b/heads
1	J		19 mm	Decks, tank tops, flat panels and b/heads
2	KM		26 mm	Decks, tank tops, flat panels and b/heads
4	M		38 mm	Unit Butts
5	SK		19 mm	Unit Butts decks and tank tops
6	K		19 mm	Positional welding e.g. shaped shells

Fig. 3.1

Material Edge Preparations used in the Welding Database

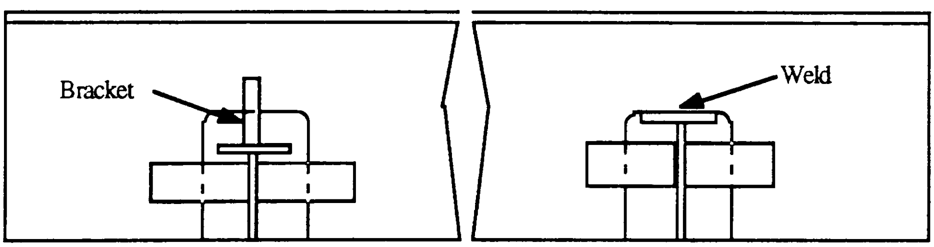


One-lug Connections

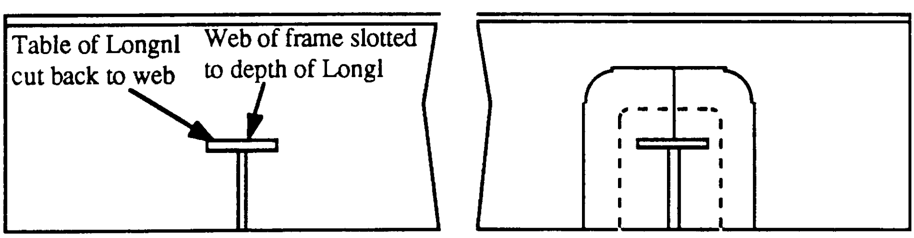


Lip or Tongue

Two-lug Connections



Rigid Connections



Egg Box

Lapped Collar

Rigid Connections

Fig. 3.2

Typical Grillage Connections used in Warship Structres

Type of Connection	Vertical cross sectional Area	Depth of piercing member / Depth of main member > 0.65	0.65 - 0.40	< 0.40
No lug plus bracket or direct weld	A_b =	1.5 * A_w	1.2 * A_w	0.9 * A_w
One Lug	A_l =	Not recommended	2.0 * A_w	1.5 * A_w
One lug plus bracket or direct weld	A_b = A_l =	0.8 * A_w 1.3 * A_w	0.65 * A_w 1.0 * A_w	0.5 * A_w 0.7 * A_w
Two lug	A_l =	1.0 * A_w	0.8 * A_w	0.6 * A_w
Two lug plus bracket or direct weld	A_b = A_l =	0.8 * A_w 0.5 * A_w	0.65 * A_w 0.4 * A_w	0.5 * A_w 0.3 * A_w
Two piece lapped collar	Collar plate thickness = Web thickness of main member			

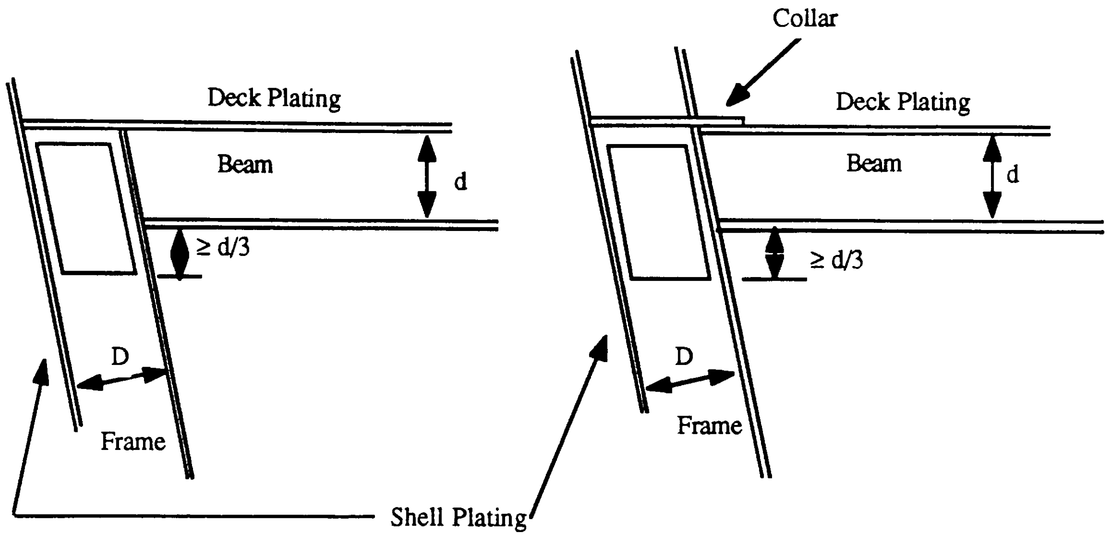
A_b = Vertical cross section area of bracket in way of weld to the main member web

A_l = Vertical cross section area of EACH lug

A_w = Web area of piercing member

Table 3.1

Dimensions of Brackets and Compensation Pieces used in Warship Grillages



Frame web doubler plate used at upper decks

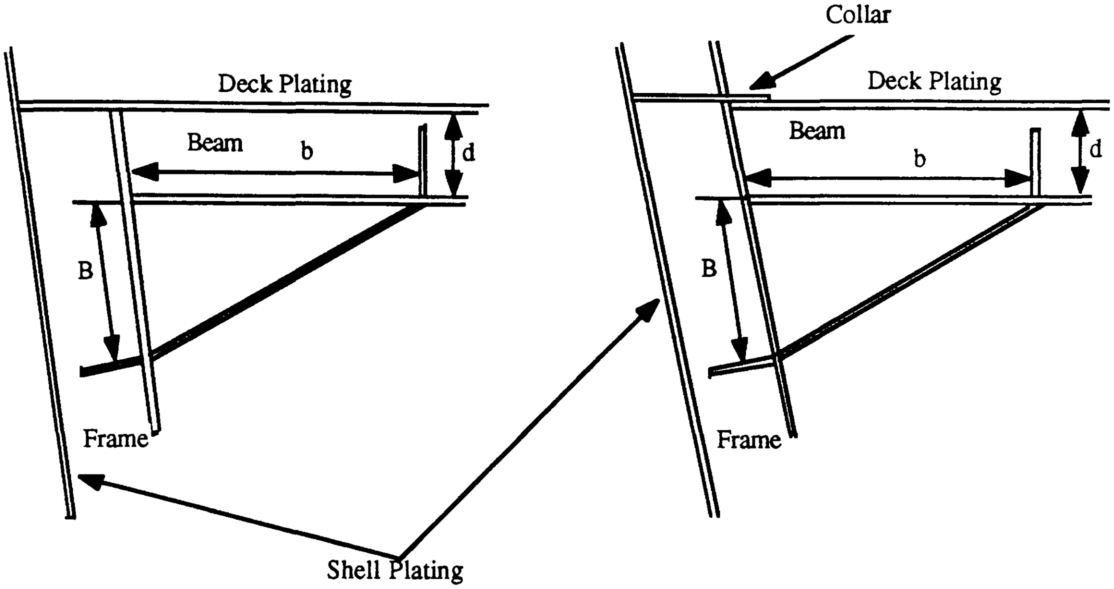
Frame web doubler plate used at lower decks

Fig. 3.3
Typical Frame web Doubler Plate Connections

D \ d	11.43	12.7	15.24	17.78	20.32	25.4
11.43	0.533					
12.7	0.317	0.635				
15.24	0.317	0.457	0.762			
17.78	*	0.317	0.635	0.889		
20.32	*	*	0.381	0.635	1.016	
25.4	*	*	*	0.381	0.635	1.143

Thickness of web doubler plate
All dimensions in centimetres
* No doubler plate required

Table 3.2
Doubler Plate dimensions

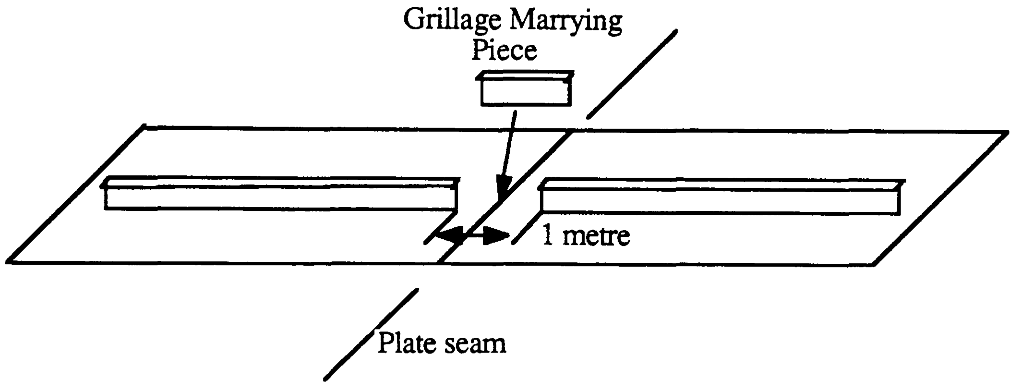


Standard bracket used at upper decks

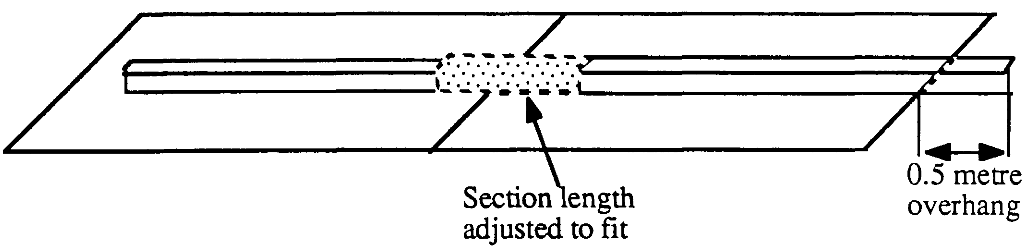
Standard bracket used at lower decks

B	=	Bracket web thickness * 60
Bracket flange area	=	Beam flange area
Bracket web thickness	=	Thickness of beam web
Bracket flange breadth	=	b/30
Bracket flange thickness	=	Bracket flange breadth/30

Fig. 3.4
Typical Bracket Connections used in Warship Structures



Grillage structural section link up using section "marrying piece" - requires two butt welds.



Grillage structural section link up using "cut back" method - requires one butt weld

Fig 3.5

Alternative link up methods for grillage structural section link up

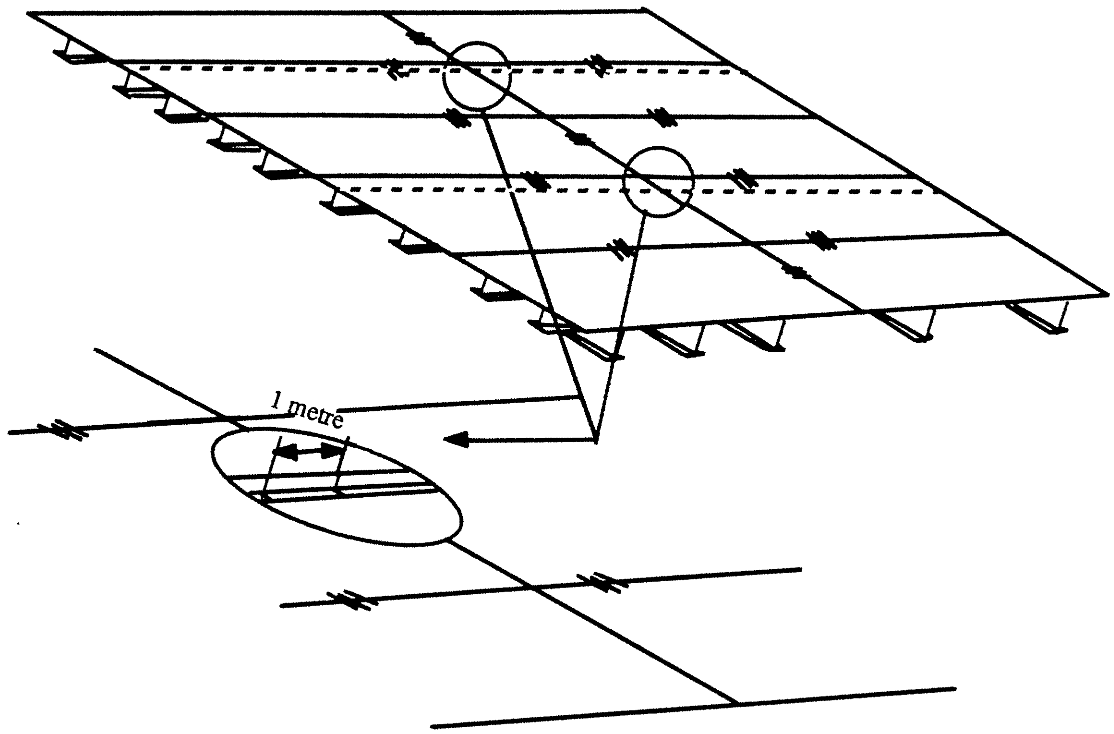


Fig. 3.6
Longitudinal Grillage Link-up on the Building Berth

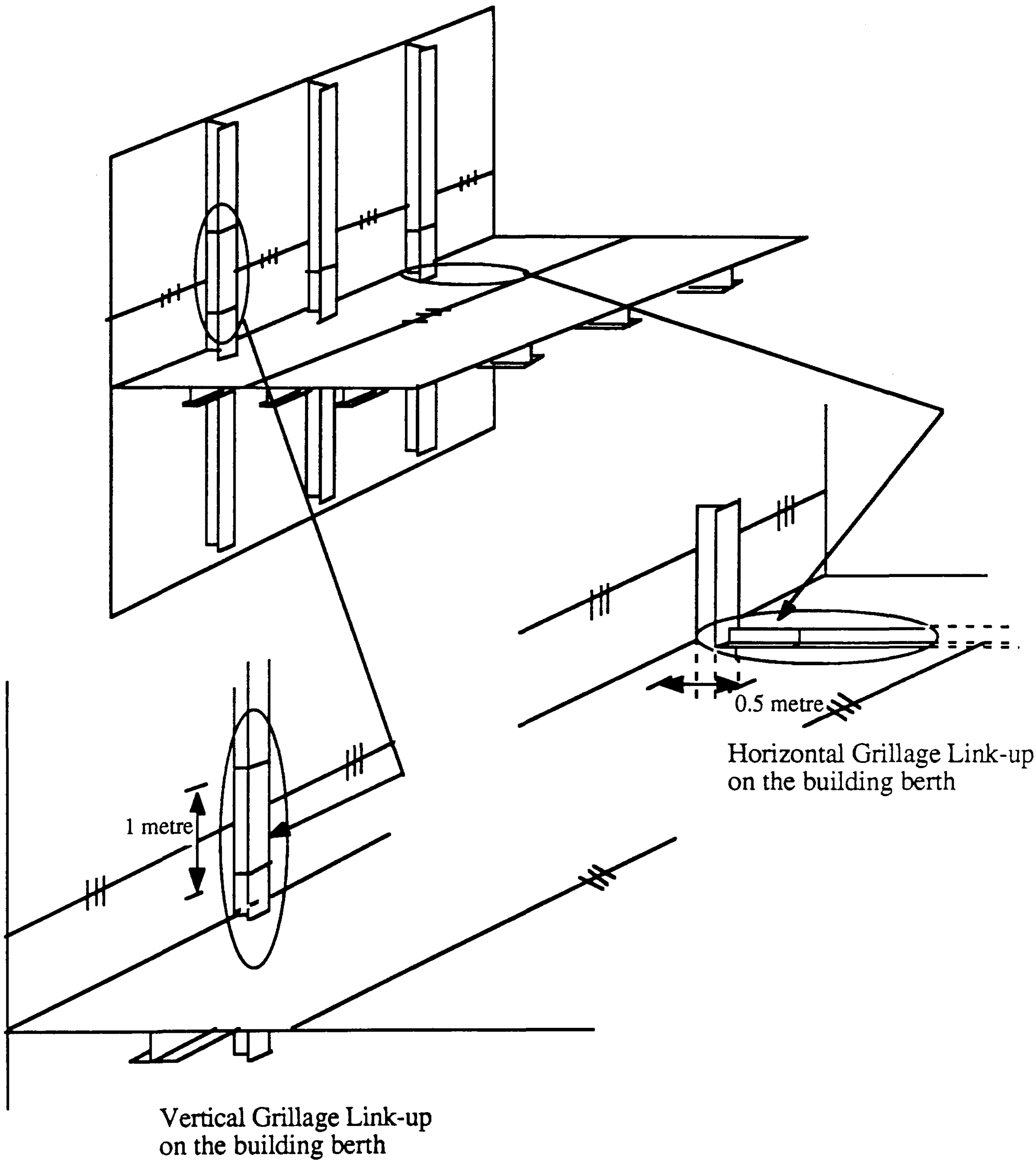


Fig. 3.7

**Horizontal and Vertical Grillage Link-ups
on the Building Berth**

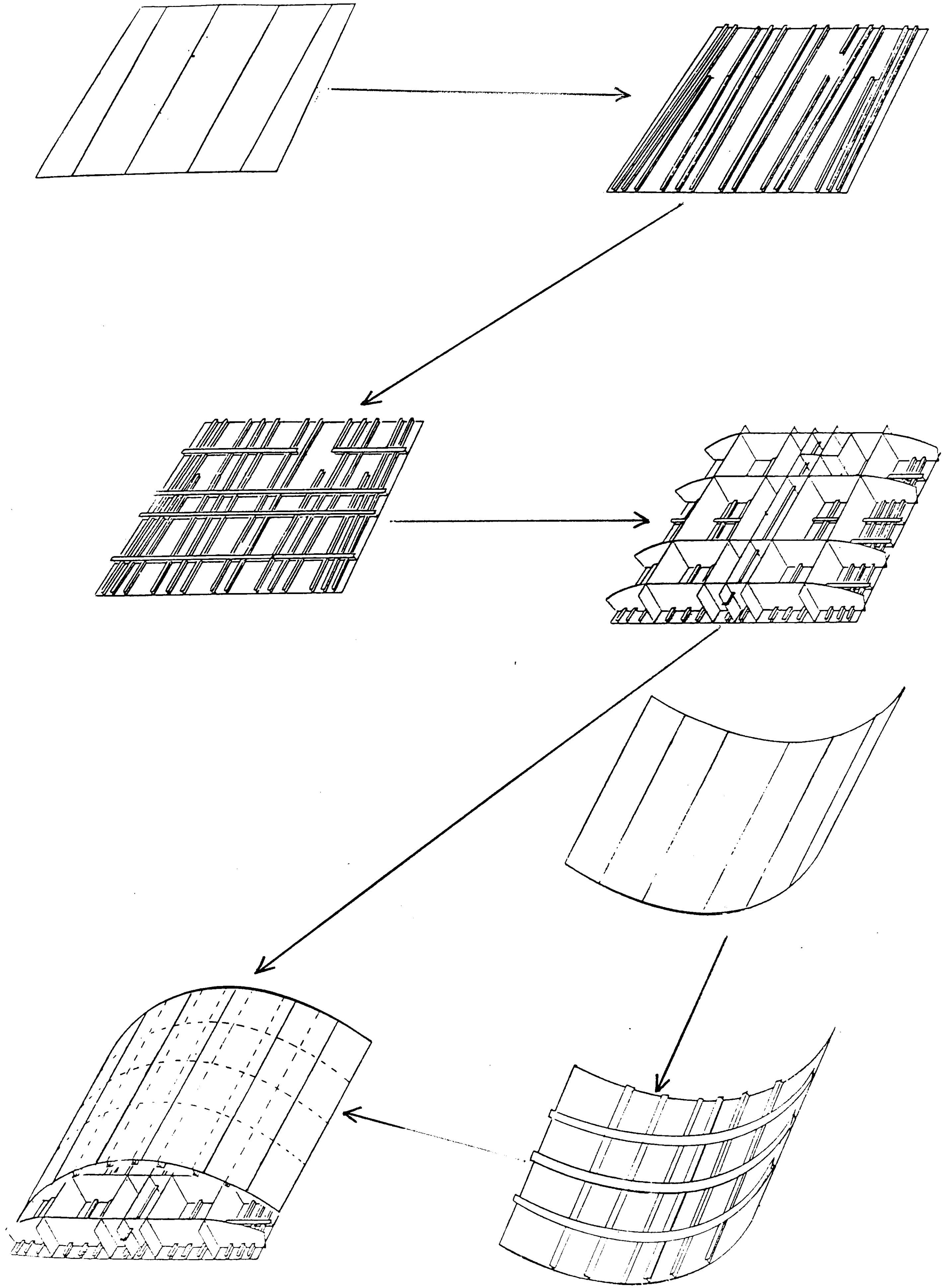


Fig. 3.8 - Double Bottom Construction Sequence 1

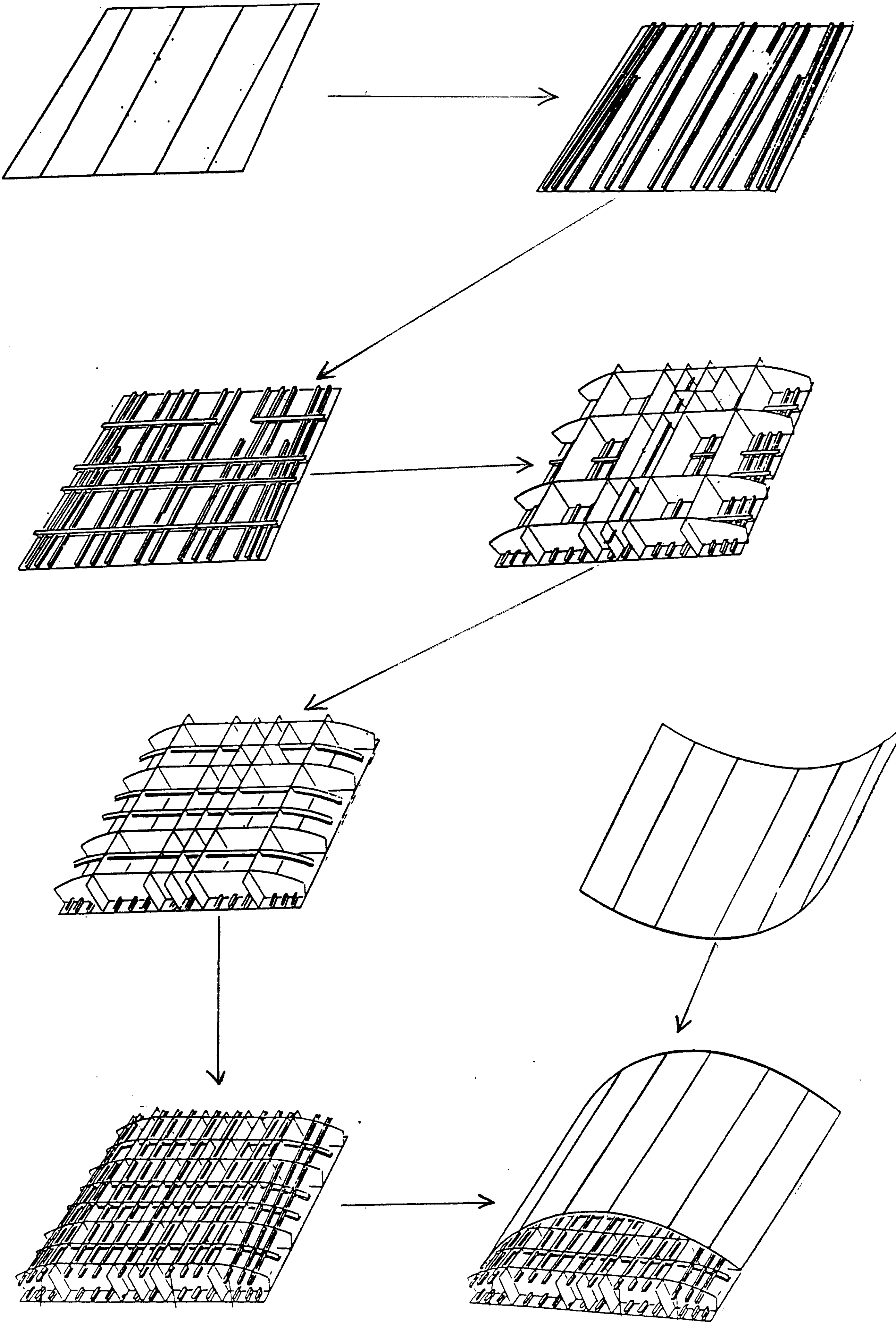


Fig. 3.9 - Double Bottom Construction Sequence 2

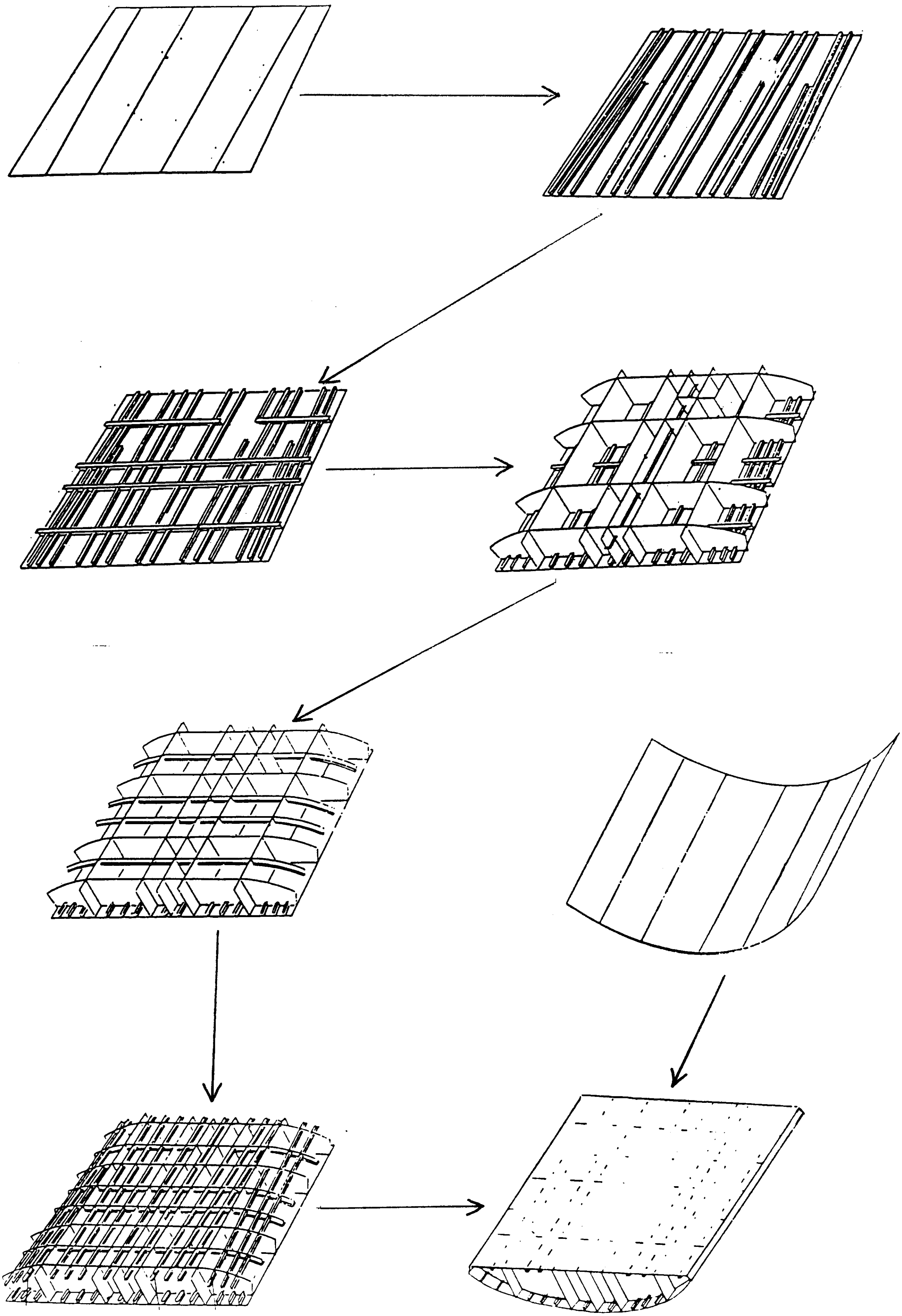


Fig. 3.10 - Double Bottom Construction Sequence 3

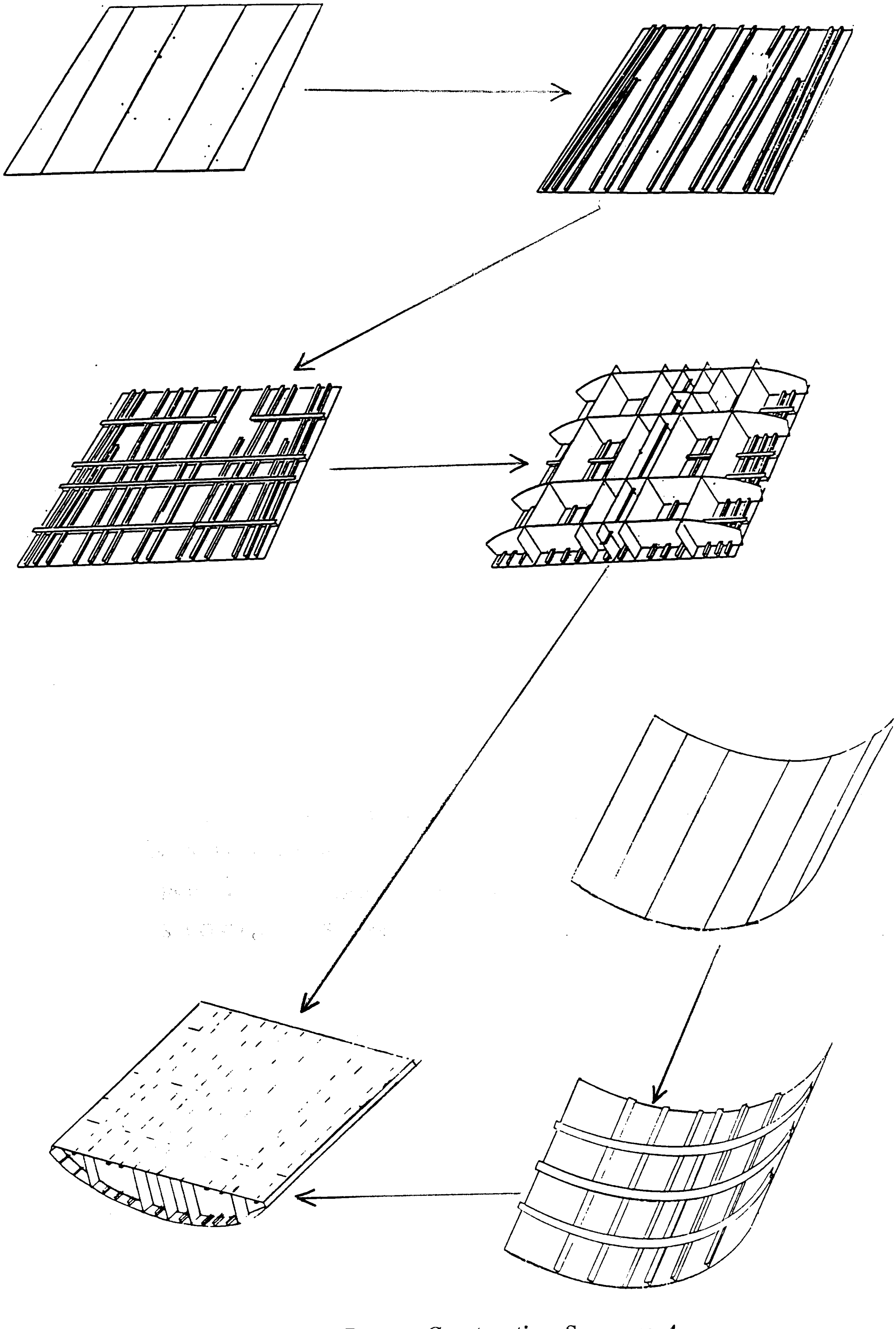


Fig. 3.11 - Double Bottom Construction Sequence 4

CHAPTER 4

STRUCTURAL DESIGN OF FRIGATE MIDSHIP SECTION

In order to give the structural designer maximum flexibility to propose alternative structural arrangements, a large number of design parameters must be considered as variables. These parameters include plating thicknesses, types of section (rolled and fabricated) used as structural members, their scantling sizes, and the spacings of longitudinal and transverse members. As these design parameters also have a direct bearing on the ultimate strength of the structure, there must be some means of assessing the global effect on the load carrying capacity of the structure resulting from any localised changes to them. This requires design criteria to determine the strength of the ship in response to both longitudinal and transverse loading

The longitudinal strength criteria incorporated in the overall strength formulations are taken from the current Royal Navy Design Manual - NES 110 [43]. Transverse structural design is assessed according to Det Norske Veritas (DnV.) Classification Society Rules for the design of flat plate grillages [44].

It is convenient to divide overall ship's structure into the three types as first suggested by St. Denis [36] :

PRIMARY - The hull when it is considered in its totality.

SECONDARY - Stiffened gross panels of plating bounded by side-shell, transverse and longitudinal bulkheads or other means of vertical support

TERTIARY - Unstiffened plate elements supported by transverse and longitudinal stiffeners.

This allows design assessment to be considered at the various levels corresponding to the above breakdown of structural elements.

As a further convenience, secondary structure is defined as a GRILLAGE when stiffened orthogonally and as a PANEL when stiffened in only one direction. In turn these are made up of tertiary PLATE elements (bounded by neighbouring transverse members and longitudinal stiffeners) as illustrated in Fig. 4.1.

N_{BH}, N_{BS} = Loads per unit width applied to bottom structure by design hogging and sagging bending moments.

D = Moulded depth

B_D = Load bearing width of upper deck allowing for the presence of large holes.

B_B = Load bearing width of bottom structure (turn of bilge to turn of bilge).

c = Design coefficient related to size and type of ship

The calculation of these line loads at the upper and lower flanges of the hull girder shown in Fig. 4.2 allows the detailed design of these structures to begin.

4.2. Design of Secondary Structure.

The use of Long Stalk Tee (LST) rolled sections as longitudinal stiffeners is standard practise in current Royal Navy ships. This is understandable as these sections were designed to yield a better distribution of weight for a high moment of inertia compared to other standard rolled steel sections. The use of LSTs thus allows the design of lightweight stiffened panels with high collapse loads. However, when weight is no longer the only constraint in structural optimisation other standard rolled steel sections can be considered for structural members. In this study the use of Offset Bulb Plate (OBPs) and Flats have been investigated as longitudinal and transverse members as alternatives to the LSTs.

Various load actions must be taken into account when checking the strength of deck structures, however during the design of structural sections it is generally adequate to consider the following :-

i) compressive in-plane loads that are a result of applied bending moments (sagging)

ii) the tensile in-plane loads that are a result of applied bending moments (hogging)

iii) lateral loads imposed by normal environmental conditions.

4.2.1 Designing Against Interframe Panel Collapse Failure Mode.

To ensure that deck structures can carry the loads calculated in equations (5) and (6), the interframe flexural compressive collapse stresses for longitudinals and their associated plating must be predicted. These predicted compressive collapse stresses must be at least an appropriate factor of safety greater than the actual applied compressive stresses induced by hull bending.

In longitudinally stiffened structures where the transverse frame spacing is greater than the longitudinal stiffener spacing (i.e.in Fig. 4.1, a > b,), the plating loses effectiveness immediately on application of in-plane loads because of initial imperfections. However, for slender plate elements, (b/plating thickness > 60 for mild steel), which have their unloaded edges constrained to remain straight there is significant post buckling strength. This can be interpreted as elastic buckling, though not in the critical sense, with the out-of-plane deformations increasing proportional to compressive load. The stress distribution in the plate for any given load and an illustration of the "effective width" concept b_e are shown in Fig. 4.3.

Von Karman postulated that the maximum post buckling load such a plate can sustain occurs when the edge stress σ_e, reaches the yield stress σ_y. Based on this and the further assumption that the unloaded edges of a long "pinned" plate remain straight, he derived an engineering solution for minimum effective width at failure -:

$$\frac{b_{em}}{b} = \frac{\sigma_m}{\sigma_y} = \frac{1.9\,t}{b}\sqrt{\frac{E}{\sigma_y}} = \frac{1.9}{\beta} \qquad (7)$$

where :

b = longitudinal spacing

b_{em} = minimum effective width of plating

σ_m = maximum average stress at plate failure

σ_y = plate yield stress

t = plate thickness

E = Young's Modulus of Elasticity

$$\beta = \frac{b}{t}\sqrt{\frac{\sigma_y}{E}} = \text{plate slenderness parameter} \tag{7a}$$

However, the effective width of plating said to be acting with an attached stiffener must be calculated at compressive stresses other than the yield stress σ_y. Faulkner in his comprehensive review of the treatment of this concept [37] proposed an alternative formulation :-

$$\frac{\sigma_m}{\sigma_y} = \frac{2}{\beta} - \frac{1}{\beta^2} \tag{8}$$

This relationship, corrected for a residual stress factor $\eta = 3$ is used within the design formulations of this study. These residual stresses result from the forming operations the section undergoes to acquire its final shape or as a result of the heat input from the welding operations during fabrication of sections and their attachment to the plate.

In order that the design of deck and side shell longitudinals can get underway a "first shot" value of the ratio of Ru, the stress in the longitudinal at collapse to the material yield stress must be assumed. Assuming Ru = 0.95, allows the effective plate slenderness ratio to be calculated from :

$$\beta_{eff} = \frac{b}{t}\sqrt{Ru}\sqrt{\frac{\sigma_y}{E}} \tag{9}$$

The effective width of plating said to be acting with the stiffener can now be calculated from equation (8)

$$\frac{b_e}{b} = \left(\frac{2}{\beta_{eff}} - \frac{1}{\beta_{eff}^2}\right)_{\eta = 3} \tag{10}$$

which allows the calculation of the effective longitudinal sectional properties for the combination of stiffeners and effective plate as outlined below.

$$I_s = I_{sect} + \frac{1}{12} b_e t^3 + A_{sect}(\bar{y} - \bar{y}_{sect})^2 + b_e t(\bar{y} - \bar{y}_{plate})^2 \qquad (11)$$

$$k = \sqrt{\frac{I_s}{A_{tot}}}$$

where :

I_s = second moment of area of stiffener and effective width of plating[1]

I_{sect} = second moment of area of stiffener only

b_e = effective width of plating

A_{sect} = cross sectional area of stiffener only

$\bar{y}_{sect}$ = height above datum of stiffener neutral axis

$\bar{y}_{plate}$ = height above datum of plate neutral axis

$\bar{y}$ = height above datum of neutral axis of stiffener and effective width of plating

$$= \frac{A_{sect}\bar{y}_{sect} + b_e t \bar{y}_{plate}}{A_{sect} + b_e t}$$

$$= \frac{A_{sect}\bar{y}_{sect} + b_e t \bar{y}_{plate}}{A_{tot}}$$

A_{tot} = $A_{sect} + b_e t$

k = radius of gyration of effective section

t = plate thickness = nominal thickness - corrosion allowance.

---

1 Note that I_s corresponds to effective width, b_e, rather than the reduced effective width b_e' from which I_s' is calculated.

The column slenderness ratio, λ, is defined as :-

$$\lambda = \frac{a}{k\pi}\sqrt{\frac{\sigma_y}{E}} \tag{12}$$

where :

a = length of column, normally the transverse frame spacing

σ_y = material yield stress

E = Youngs Modulus of Elasticity.

In the absence of residual stresses, the critical stress σ_c of a column with pinned ends, (i.e. the axial stress at which it first shows signs of out-of-plane deformation) is given by Euler's Theory for long perfectly elastic struts :-

$$\sigma_c = \frac{\pi^2 E}{\left(\frac{L}{k}\right)^2} \tag{13}$$

However, in columns made of rolled steel sections or a combination of plates and sections fabricated by welding, residual stresses will be present, as noted above. These residual stresses can be relieved by annealing after fabrication but this is generally both costly and impracticable. Therefore, in the calculation of the critical buckling stress of columns the effect of residual stresses must also be taken into account. As the load on such a column increases, some of the material begins to yield where the sum of the applied stress and the residual stress reach yield stress. As the applied stress is increased greater amounts of material reach the yield stress, thus leading to the failure of the column at a stress lower than calculated from equation (13). This results in a loss of effectiveness of the column as the applied stress reaches the yield stress. The possible effects of residual stresses on the crippling loads of columns have been examined both experimentally and theoretically in Refs. 38 and 39. Ref. 40 suggests that for practical ship structural systems the critical stress can be calculated using Johnson's empirical formula :-

$$\sigma_c = \sigma_y - \frac{\sigma_y^2}{4\pi^2 E}\left(\frac{L}{k}\right)^2 \quad \text{when} \quad \frac{1}{2} < \frac{\sigma_c}{\sigma_y} < 1 \tag{14}$$

or

$$\sigma_c = \frac{\pi^2 E}{\left(\frac{L}{k}\right)^2} \quad \text{when} \quad \frac{\sigma_c}{\sigma_y} \leq \frac{1}{2} \tag{15}$$

When equations (14) and (15) are plotted non-dimensionally there is a common point of tangency at which they merge, see Fig. 4.4 These relationships are suitable for use in the design of practical steel beam-column structures used in ships construction.

Using values of λ calculated from equation (12) in conjunction with Fig. 4.4 the ratio of collapse stress to yield stress, Ru, can be found. If this value of Ru is more than 5% different from the "first shot" value of Ru used in equation (9) then re-iteration of the design procedure is required, starting from equation (9) through to the stage just described, until the difference between the value of Ru used in equation (9) and that obtained from Fig. 4.4 is less than 5%.

Once this condition has been achieved the average compressive collapse stress σ_{ave} for the longitudinal stiffener and effective plating, in the absence of lateral loads (assuming pinned connections to the frames), is then given by :-

$$\sigma_{ave} = \frac{Ru\, A_{tot}\, \sigma_y}{A_{sect} + bt} \tag{16}$$

This value σ_{ave} should be at least 20% greater than the maximum axial compressive stress applied to the longitudinals of the strength deck, and 25% greater than the maximum axial compressive stress applied to other longitudinals in deck, tank top or outer bottom structures. If these safety factors are achieved, then this combination of longitudinal type, scantlings, spacing and plating thickness is potentially suitable for use in the design of deck and side shell structures.

4.2.2 Design of Bottom Longitudinals

In practise, when bottom longitudinals buckle under the application of combined end and lateral pressure loads, their deformed shape is similar to that of a series of connected beams, having encastre ends at their points of connection. This differs from the alternating half wave buckles of the deformed deck and side shell longitudinals with no lateral loading, which maybe considered to be pinned at their connections to the frames. Fig. 4.5 illustrates the deformed shapes of each type of longitudinal.

The design procedure for bottom longitudinals is carried out in two stages. Firstly, the method described in Section 4.2.1 is used to calculate pinned end compressive collapse stress of a rolled section acting with an effective width of plating. Secondly the procedure calculates the collapse stress when the ends of the longitudinal are considered clamped at their connection to the frames. This is achieved by reducing the slenderness ratio of the column, λ_{clamp} to the value for encastre columns given by :

$$\lambda_{clamp} = \frac{a}{2k\pi}\sqrt{\frac{\sigma_y}{E}} \qquad (17)$$

Because of the combination of axial and pressure load systems that exists for the bottom longitudinals, a means of describing their elastic behaviour and ultimate failure loads is required. Exact theories exist for these phenomena but lead to complicated and unweildly expressions. Hence an engineering approximation is required. This assumes the form of a "reduction factor" which allows the easily calculated effects of normal loads to be influenced by the end loads. This reduction factor is defined as :-

$$1 - \frac{P_h}{P_c} \qquad (18)$$

where :

P_h = lateral pressure acting on the longitudinal

P_c = three hinge plastic collapse pressure of the longitudinals assuming they are clamped at the frames.

Using the value λ_{clamp} in conjunction with Fig. 4.4, the average compressive stress for a column clamped at its frame connections is given by :-

$$\sigma_{clamp} = \left(\frac{Ru\ A_{tot}\ \sigma_y}{A_{sect} + bt} \right)_{clamp} \qquad (19)$$

By multiplying σ_{clamp} by the reduction factor given in equation (18), the average collapse stress for a column with clamped ends under the actions of axial and lateral loads is given by :-

$$\sigma_{lateral} = \sigma_{clamp} \left(1 - \frac{P_h}{P_c} \right) \qquad (20)$$

The stress that the bottom longitudinals must be designed to withstand is the lower of the values calculated from equations (16) and (20) and this should be at least 25% greater than the compressive stress applied to the bottom longitudinal in question.

The factor of safety stated in the previous paragraph only applies to longitudinal stiffeners if they are of tee section. When OBP longitudinals are being considered an increased safety factor is required. A supplementary partial safety factor of 1.1 (or a reduction in permissible stress of 10%) is employed as suggested in Ref. 41. This supplementary safety factor allows the OBP stiffeners to be designed on the basis of simple beam theory ignoring the effects of asymmetry. If flat bars are being considered then limiting the depth/thickness ratio to less than 10 is necessary to ensure avoidance of tripping under conditions of elasto-plastic bending compression as recommended in Ref. 42.

4.3 Design of Tertiary Structure.

In the instances where the stiffener disposition is such that relatively large unstiffened plate elements exist in the structure, there must be a design criterion by which these tertiary elements are assessed. In this study these elements are designed such that the minimum in-plane edge stress to initiate plate buckling is at least a factor of safety (assumed 1.1, Ref. 46) greater than the actual in-plane edge stress that is distributed along the edge of the plate element. The critical buckling stress for a long plate element (i.e. one in which the in-plane edge stress is applied along the shorter sides of the plate element) is given by :

$$\sigma_{cr} = \frac{4 E \pi^2}{12(1 - \upsilon^2)} \left(\frac{t}{b} \right)^2 \qquad (21)$$

and for a wide plate element (i.e. one in which the in-plane edge stress is applied along the longer sides) the expression for the critical buckling stress becomes :

$$\sigma_{cr} = \frac{\pi^2 E}{12(1 - \upsilon^2)} \left(\frac{t}{b} \right)^2 \left[1 + \left(\frac{b^2}{a^2} \right) \right]^2 \qquad (22)$$

4.4 Design of Transverse Structural Members.

To allow a greater range of structural alternatives to be proposed by the designer, there has to be an element of the design procedure where it is possible to propose and assess changes in the transverse structure. The transverse structural design procedure has to be capable of taking account of variations in plating thickness, longitudinal stiffener spacing, transverse frame spacing and the type and scantlings of the sections used as transverse frames and longitudinal stiffeners as well as their influence on the global structural behaviour of the complete midship section structure.

Several studies throughout the course of the project have concentrated on constant area, fixed transverse frame spacing structural alternatives of major elements of the midship section structure, namely strength deck and double bottom. The results of these studies are discussed in Chapter 6. Consequently by maintaining a fixed transverse frame member type, size and spacing, a severe limitation was imposed on the range of possible structural alternatives that could be investigated. In order that a wider range of structural possibilities could be investigated with a view to the ultimate optimisation of relative fabrication cost, the design of the transverse structure had to become an integral part of the overall structural design package - thus removing the fixed transverse frame spacing constraint.

The need for a "Rules based" approach for the design of the transverse structure became apparent after various attempts at establishing a "ready reckoner" type algorithm, relating longitudinal material and stresses with their transverse counterparts proved fruitless and the algorithm remained elusive, despite using a finite element method of analysis. From a study of the applicability and ease of manipulation of several Classification Societies' Rules to frigate transverse design. As a result, largely through their well developed theoretical base, DnV Rules for the Design of Mobile Offshore Units, Ref. 44, were found most suitable and have been incorporated as program subroutines into a simple transverse structural design model.

Chapter 3 of these DnV Rules relates to Stiffened Flat Plates and is concerned with the design of such structures to avoid failure by various buckling modes. These failure modes include :-

Plate buckling	- local plate buckling between stiffeners
Stiffener buckling	- buckling of stiffeners and attached plating between girders (plate or stiffener induced failure)
Local buckling	- of stiffeners and girders
Girder buckling	- overall buckling involving bending of stiffeners and girders with attached plating (plate induced or flange induced failure)

It is this last failure mode that has been applied to the design of warship transverse structure. The design criteria and formulations relating to girder buckling have a tangible relationship to the longitudinal structure and can readily incorporate the design loads as specified in NES 110, [43]. These formulations are presented below as the basis for the design of warship transverse structures adopted in this project.

The primary function of transverse structure is to offer the means of support to the longitudinal structure and also to resist lateral pressure loads. Therefore it is necessary to design a transverse girder that supports longitudinally stiffened plating to resist a lateral pressure load p_d, which is equal to :-

$$p_d = p + p_o \tag{23}$$

where:

$$p_o = \frac{0.4(t + \frac{A}{s})}{H(1 - \frac{s}{S})} \left(\frac{\sigma_y}{E}\right)\left(\frac{S}{l}\right)^2 \sigma_x \tag{24}$$

but:

$$p_o \geq 0.02 \left(\frac{t + \left(\frac{A}{s}\right)}{l}\right) \sigma_x \tag{25}$$

and :

p = design pressure head as defined in NES 110, Annexe 8A

t = plate thickness = nominal thickness - corrosion allowance

A = stiffener cross sectional area excluding effective flange of plating

s = longitudinal stiffener spacing

H = web height of transverse member

S = Transverse member span

E = Young's Modulus of Elasticity

σ_y = material yield stress

σ_x = Axial compressive stress of longitudinal stiffeners (induced by hull bending)

l = length of longitudinal stiffener = transverse frame spacing

The effective bending stress during buckling of an encastre beam is taken as :-

$$\sigma_b = \frac{p_d\, S^2\, l}{12\, Z_e} \qquad (26)$$

where :

Z_e = effective section modulus of the transverse member calculated with an effective flange of plating l_e

The effective plating flange width, l_e, is taken as the value required for flange induced failure :-

$$l_e = \frac{S}{\sqrt{4 + \left(\frac{S}{l}\right)^2}} \qquad (27)$$

Re-arranging (26) results in an expression which allows the calculation of a rule determined minimum value for the transverse member section modulus:-

$$Z_e = \frac{p_d\, S^2\, l}{12\, \sigma_b} \qquad (28)$$

By allowing the maximum bending stress to reach σ_y, the final expression for minimum section modulus of the transverse frame is given by:-

$$Z_e = \frac{p_d\, S^2\, l}{12\, \sigma_y} \qquad (29)$$

or if a safety factor (SF) is to be employed then the expression becomes:-

$$Z_e = \frac{p_d\, S^2\, l}{12\, \sigma_y (SF)} \qquad (30)$$

The above formulations have been incorporated in Fortran subroutines contained in the structural design program **FRIGATE** to be used in a number of ways to assess the transverse strength of warship structures.

Basically, two approaches are used within the context of this project when dealing with the structural design of a typical midship section of a Royal Navy Frigate. Firstly, the longitudinal and transverse structures are defined and the design package proceeds to re-design the midship section in the longitudinal sense while the transverse structure remains unchanged. Alternatively, by varying the transverse structure while maintaining the longitudinal structure as defined initially, this gives a second means of designing alternative midship section structures.

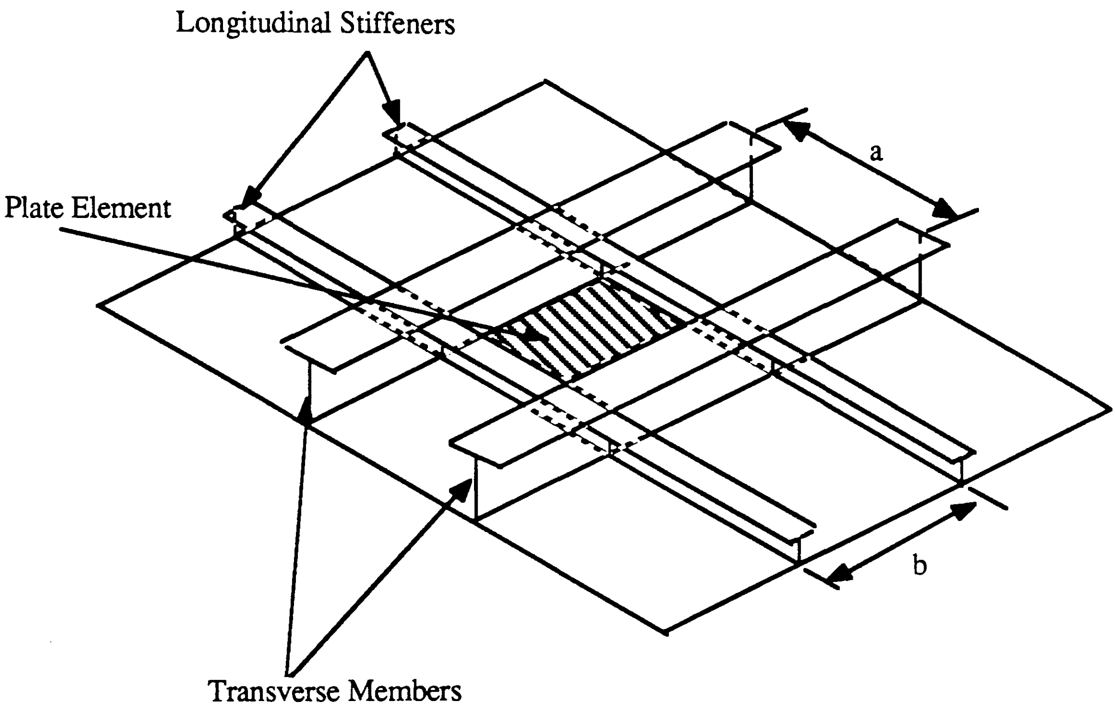


Fig. 4.1
Idealised Secondary structure

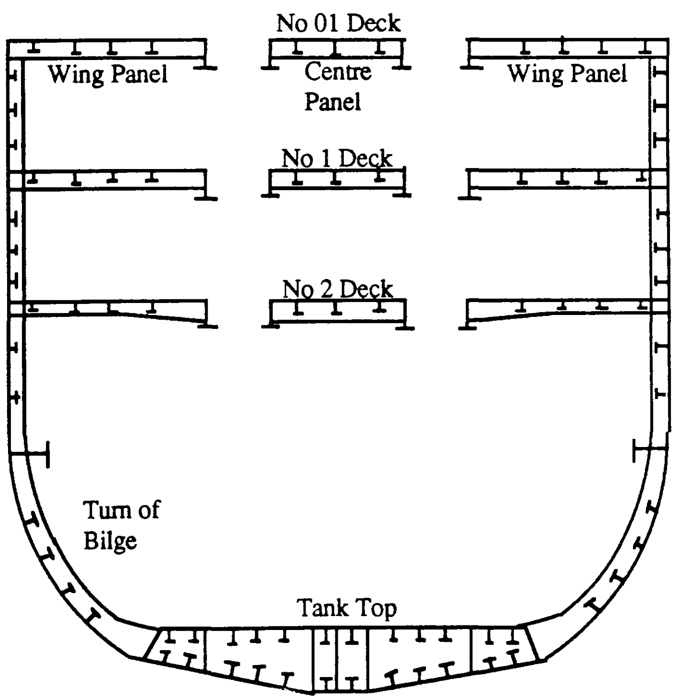
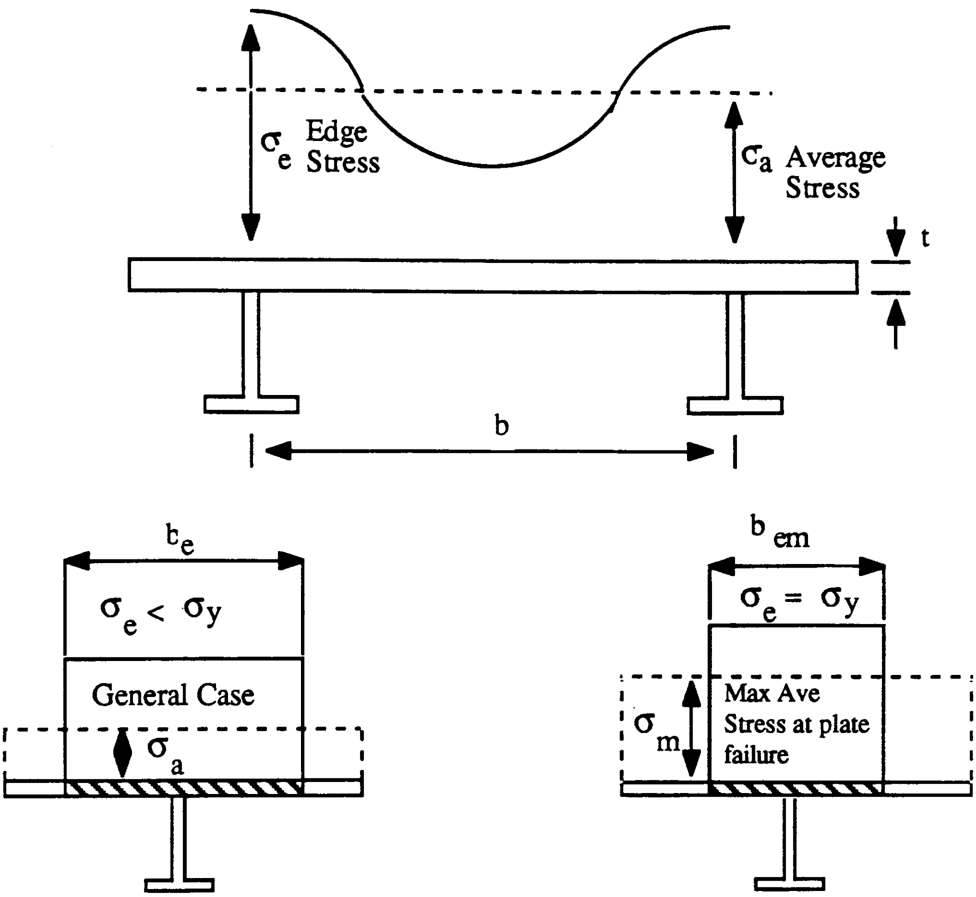


Fig. 4.2
Primary Effective Longitudinal Structure



b_e = Effective Width of Plating

$$= \frac{\sigma_a}{\sigma_e} . b \quad \text{in General Case when} \quad \sigma_e < \sigma_y$$

$$= \frac{\sigma_m}{\sigma_y} . b \quad \text{at plate failure when} \quad \sigma_e = \sigma_y$$

σ_b = Elastic Buckling Stress

Fig. 4.3
Effective Width of Plating Concept

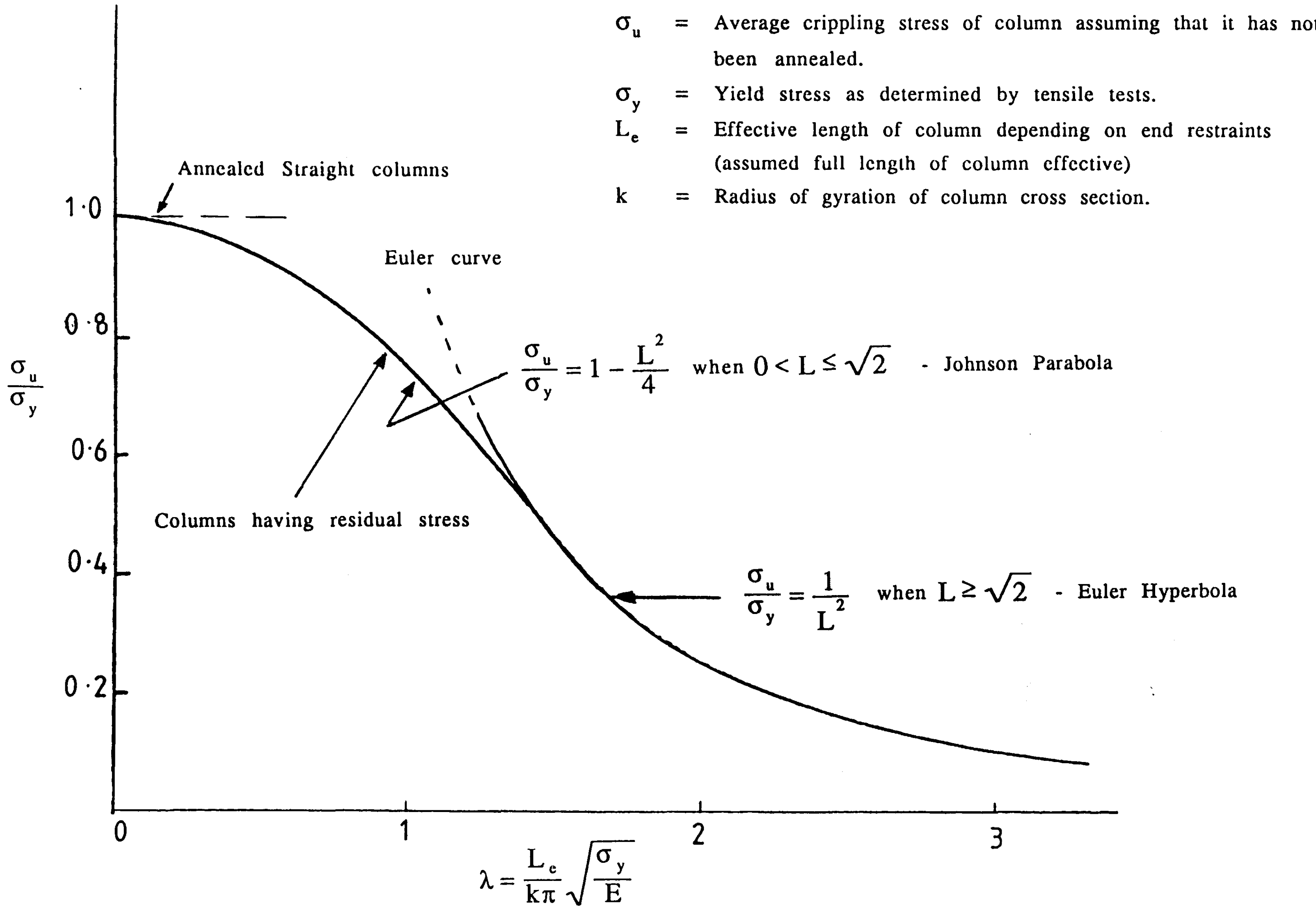
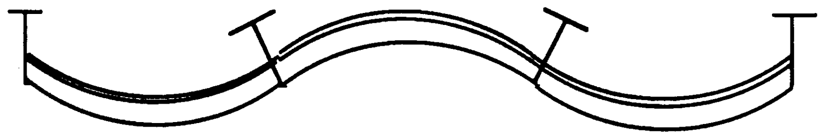


Fig. 4.4
Basic Column Curve for Structural Steels



Deck Longitudinal Deformation -
Axial Compressive Load Only

Bottom Longitudinal Deformation -
Combined Lateral and Axial Loads

Fig. 4.5
Typical Longitudinal Stiffener Deformations

CHAPTER 5
COMPUTER SUBROUTINE SUITES

In order for parallel development in both the structural design and relative fabrication cost aspects of the project to be possible, two independent programs were compiled in the Fortran 77 programming language. One program **FRIGATE** deals with the structural design of a typical Royal Navy Frigate midship section and the other program **SHIPCOST** deals with the algorithms and mechanisms necessary for estimating the relative fabrication cost of a such a vessel.

5.1. Structural Design of Typical Frigate Midship Section.

To maximize the benefits that can be gained by using a computer at the preliminary structural design stage, the software must be written in a manner that enables iteration of the design variables to be included, thus automating the design procedure (spiral). Iterative re-calculation is needed to assess the effect of local changes in the design parameters on the global acceptability of a structure in relation to the design criteria that are applied in it's design.

The design criteria incorporated within the Fortran coding relates to two different design philosophies. For the design of longitudinal structure, the design method is a "first principles" approach and employs the design criteria that is currently applied to the design of Royal Navy steel surface ships while for the transverse structure a Classification Society Rules approach is used. The conclusions from an assessment of the applicability of several Classification Society's Rules to the design of a frigate's transverse structure indicated that the most suitable set of rules appeared to be DnV for Mobile Offshore Units, Part 3, [44].

From the beginning, it was found that the design of a complete midship cross section from first principles without some initial constraints was outwith the scope of the work. Consequently, in order that the design procedure can get underway, several of the design parameters must be selected as constants. By studying the details of Ref. 48, a basis model of a typical frigate midship section was built up of the following structure as shown in Fig. 4.2.

1) All plating is taken as mild steel.

2) Nº. 01 deck structure :

   2.1 10 mm plating

   2.2 10 off 114 * 44 mm Tee bar longitudinals

   2.3 2 off 152 * 76 mm Tee bar longitudinals

   2.4 2 off 205 * 101 mm Tee bar longitudinals

   2.5 2 off 254 * 127 mm Tee bar longitudinals

   2.6 Transverse frames spaced at 1 metre intervals consisting of 152 * 76 mm Tee bar

3) Nº 1 deck structure :

   3.1 10 mm plating

   3.2 10 off 114 * 44 mm Tee bar longitudinals

   3.3 2 off 152 * 76 mm Tee bar longitudinals

   3.4 2 off 205 * 101 mm Tee bar longitudinals

   3.5 2 off 254 * 127 mm Tee bar longitudinals

   3.6 Transverse frames spaced at 1 metre intervals consisting of 152 * 76 mm Tee bar

4) Nº 2 deck structure :

   4.1 10 mm plating

   4.2 5 off 76 * 25 mm Tee bar longitudinals

   4.3 2 off 127 * 53 mm Tee bar longitudinals

   4.4 2 off 295 * 101 mm Tee bar longitudinals

   4.5 2 off 254 * 127 Tee bar longitudinals

   4.6 Transverse frames spaced at 1 metre intervals consisting of 127 * 53 mm Tee bar

5) Tank top structure :

5.1 10 mm plating

5.2 12 off 114 * 44 mm Tee bar longitudinals

5.3 Transverse frames consisting of 152 * 76 mm Tee bar

6) Outer bottom structure :

6.1 10 mm plating

6.2 12 off 114 * 44 mm Tee bar longitudinals

6.3 5 positionally fixed plate longitudinals with dimensions :

3 off 2.0 * 0.01 m

2 off 1.15 * 0.01 m

6.4 Plate floors existing between alternate transverse frame members consisting of 152 * 76 Tee bar bracket floors.

6.5 Rise of floor taken as 10.2° from the horizontal

7) Bilge structure structure :

7.1 10 mm plating

7.2 8 off 114 * 44 mm Tee bar longitudinals

7.3 Fabricated transverse frames spaced at intervals of 1 metre

7.4 Bilge radius taken as 3.275 metres

8) Parallel side shell structure :

8.1 10 mm plating

8.2 9 off 114 * 44 mm Tee bar longitudinals

8.3 Transverse frames between No 01 deck height and No 2 deck height taken as 152 * 76 mm Tee bar and spaced at 1 metre intervals

8.4 Transverse frames between No 2 deck height and the beginning of the bilge radius taken as 127 * 53 mm Tee bar

9) The total width of deck plating considered to be longitudinally continuous is 8.6 metres except for the tank top where width is 9.6 metres.

10) All decks are considered horizontal and parallel to the base line i.e. no camber

11) Parallel side shell structure is considered vertical and perpendicular to the base line.

12) The superstructure is regarded as ineffective material providing no resistance to longitudinal bending of the hull girder.

With this level of detail forming the basis structural model, the design bending moments for the hull girder in the hogging and sagging conditions are required as further pre-requisites for the design process to proceed. The data input sequence for **FRIGATE** is shown in Fig. 5.1

5.1.1 Design Methods used for a Midship Section of a Typical Royal Navy Frigate.

The program **FRIGATE** is designed to generate midship sections which are structurally equivalent to the basis model midship section. The means by which **FRIGATE** does this, is to develop structural components which have total area values equivalent to those of the basis model area values but with the make-up of that total area is altered by varying plating thicknesses, stiffener types and scantlings. These structurally equivalent alternatives are required to satisfy the design criteria that govern the longitudinal and transverse structural design and can be generated by maintaining a fixed transverse structural arrangement while allowing the longitudinal structure to vary. Alternatively, equivalent structures can be generated if the longitudinal structural arrangement remains fixed while the transverse structure varies. Both of these methods are used to develop structural alternatives to the basis model of a typical frigate's midship section. As a further convenience in relation to data handling within the subroutines the midship section is divided into the following seven identifiable structural components, using a bottom up philosophy :

1) outer bottom
2) tank top
3) bilge
4) 2 Deck

5) side shell

6) 1 deck

7) 01 Deck.

5.1.2 Design Method 1 - Constant Transverse Structure with Variable Longitudinal Structure.

In this design method the longitudinal material of each structural component is optimised in terms of the minimum number of longitudinal stiffeners of any particular type while the transverse structure remains unaltered.

As can can be seen from Fig. 4.2, there are three deck structures considered in the basis structural model of a typical frigate midship section. In order that **FRIGATE** operates with maximum flexibility, each deck structure is allowed to have a unique structural arrangement of longitudinal stiffeners and transverse frames associated with it so that a particular arrangement on one deck need not be repeated on either of the other two. Through the diversity of structural components and different set of loading conditions on each deck, it is unlikely that the optimum deck frame spacings will be the same. Such a structure is impractical to fabricate and the minimum spacing within the group will determine the most satisfactory frame spacing for the deck structures taken as a group. This transverse frame spacing is then applied throughout the remainder of the midship section.

With the basis model defined it is now possible to calculate various properties of this particular structural definition of a midship section. These properties include the position of the neutral axis for the midship section as a whole, the position of the local neutral axis of each structural component, the second moment of area for the whole midship section and the area contributions of plating and longitudinal stiffeners to the area total of each structural component . Using these values and applying simple beam theory to the hull girder, the compressive stresses induced by hull bending can be calculated for each structural component. If these environmentally imposed loads do not exceed the limit loads, adjusted for safety factors, in each structural component, then the design procedure can continue. The principal limit loads are those applied to the strength deck with the hull girder in the sagging condition and the outer bottom by the hogging condition. Conversely if the limit loads in any of the structural components are exceeded, then the midship section must be re-defined before the design procedure can continue.

Using a structurally acceptable longitudinal midship section structural definition the procedure advances to checking the transverse structure in terms of scantlings and spacings within each structural component. The assumed loadings on the transverse members are those detailed in Appendices 8,9 and 10 of Ref. 43 in which the transverse members are considered to be resisting bending loads only while offering structural support to the longitudinal material.

The method employed in determining the transverse frame spacing for a particular midship section is described below and is shown in Fig. 5.2: -

1) calculate the DnV Rule required minimum section modulus, REQMOD, for Nº 01 deck transverse member, under the specified loading and an assumed transverse frame spacing of 1 metre.

2) calculate the actual effective section modulus, ACTULZ, of the transverse member acting with the Rule-determined effective breadth of plating.

3) if the section modulus value calculated in step (2), ACTULZ, is greater than or equal to REQMOD, calculated in step (1), then this transverse member may be used in the strength deck structure at the assumed transverse spacing.

4) maintaining these transverse member scantlings, increase the transverse frame spacing incrementally until the actual section modulus is still just greater than the required

minimum allowed by DnV for this particular transverse member under the specified loading conditions.

5) by increasing the frame spacing, the column length of the longitudinals is increased, hence interframe panel buckling must be reconsidered.

6) if the increased transverse frame spacing results in failure of the longitudinal structure it is then necessary to calculate the maximum column length of the smallest longitudinal of the strength deck that can withstand the applied loading conditions with the specified safety margin.

7) the frame spacing (= longitudinal column length) calculated in step (6) is the upper bound limit on the frame spacing that satisfies the criteria for both the transverse member and the longitudinal structure.

By following the procedure described in steps (1) to (7), above, for each deck structure a maximum transverse frame spacing for each deck can be calculated. Only the smallest of these frame spacings, applied to all three deck structures, will ensure that both fabrication and structural design criteria are not being violated. Therefore, the transverse frame spacing for the midship section is subsequently taken as the minimum transverse frame spacing value calculated by following the procedure outlined in steps (1) to (7) above after application to each of the deck structures in turn.

Once a transverse frame spacing has been rationally calculated and accepted in accordance with the design criteria, the remaining transverse structural members must be designed such that they can withstand the environmental lateral loading to which they are subjected at this predetermined frame spacing.

5.1.3 Design of Side Shell Transverse Members.

For those members that form the transverses at the side shell other simplifying assumptions have been made. The first assumption is that one uniform member extends from the height of Nº. 01 deck to the start of the bilge radius. This deviates from normal ship structure where different sized sections are used to form the transverse member between decks. In such cases, transition pieces are required to ensure continuity of the structure. The second assumption is that each intermediate length of the side shell transverse frame member between decks is considered to be pinned to it's adjacent section at the intersection of the deck and side shell transverse members. As the height between decks can be variable, the critical length of section governing the design of side shell transverse frame members to the predetermined frame spacing, is therefore taken as the maximum length between these pinned joints (i.e.the maximum 'tween deck height).

5.1.4 Design of Bilge Structure and Outer Bottom Transverse Members.

The design of the members forming transverse frames in the bilge and the outer bottom structures is not as straightforward as for the other structural components. The design load on these members takes into account the static head of seawater as well as the contribution made by the dynamic head of seawater as the vessel moves through the water. This implies a linearly varying lateral load which is directly proportional to the draught of the vessel. This raises the problem of how best to deal with a linearly varying lateral load on the transverse members of a particular structural component. The method adopted in **FRIGATE** is to design the whole member so that it will not fail if the peak load is applied uniformly over the total length of the member. This will result in a degree of redundancy at those parts of the member close to the waterline.

5.1.5 Design of Fabricated Sections.

Due to the intensity of the applied load and the predetermined spacing of the transverse members of the bilge and outer bottom structures, it may transpire that standard rolled sections, of a type specified by the user, cannot provide sufficient scantling dimensions or section modulus to satisfy the design criteria. When situations of this nature arise it is necessary to design a suitable fabricated section which for the purposes of this study is assumed to be a tee. The scantlings of the web and flange of these fabricated tees are determined by a procedure that stems from a subjective study of the LST's currently used in Royal Navy design. By considering the dimensions of the web and flange of the larger LSTs it was found that both the web depth to flange width and the flange to web thickness ratios are approximately two. Maintaining these ratios for the fabricated section, a section can be designed that when acting with the effective breadth of plating will have at least the required section modulus value. To initiate this design procedure, the web depth is taken as 250 mm (approximately the same as the largest LST) and increased incrementally, together with the flange width, until the design section modulus is attained. Checks on the geometry of the section are carried out in accordance with the guidelines of NES 110, Vol 1, [43] for the design of large fabricated sections, to ensure that web or flange buckling does not occur.

The subsequent steps in the design procedure involve altering the longitudinal structure of the originally defined midship section. An effective means by which this can be done is by maintaining a constant area value for each structural component in turn, but vary the components that make up this constant area value. By evaluating the area of longitudinally continuous material required in each structural component of the basis model midship section and varying the contributions made to these areas by the plating and stiffeners, different structural arrangements can be produced.

5.1.6 Longitudinal Stiffener Disposition.

From the details shown in Fig. 4.2 of the basis model midship section, it can be seen that two panel types exist for each deck consisting of two identical wing panels and a centre panel separated by engine uptake/downtake trunking. Varying dispositions of plating and stiffener material must satisfy the total area constraint as well as the longitudinal design criteria for each panel. Several previous studies, [8, 9, 10], investigating the fabrication costs of ship structures, conclude that minimal fabrication costs are incurred when the maximum longitudinal stiffener spacing is achieved across the width of a panel. Bearing this in mind, the sectional material is disposed across both deck panel types such that a maximum longitudinal stiffener spacing is achieved in each panel type. The wider of these spacing is taken as the critical spacing of the complete deck structure in question for the calculation of the interframe panel collapse load of the longitudinal stiffener and effective width of plating. If this interframe panel collapse load is at least the specified margin of safety greater than the axially compressive, hull bending induced load, the structural arrangement is considered as a structurally acceptable alternative to the basis model longitudinal structure. Furthermore, when dealing with these deck panel types, there are six positionally fixed longitudinals. This arises from studying the details of Ref. 47 where these fixed girder positions are at the hatch sides on the three panels (4 stiffeners) and at 0.5m distance inboard from the port and starboard side shell.

When structural components other than the multi-panel deck structures are investigated, the most convenient means of determining the critical longitudinal stiffener spacing is simply to divide the total panel width by the number of stiffeners plus one.

It should be noted here that each alternative structural arrangement consists of plating and the relevant number of uniform stiffeners. This may be regarded as an additional design constraint in view of the fact that the basis model midship section definition may have varied longitudinal sizes on each deck panel type. However, various methods of allowing combinations of different sized longitudinals in any structural component proved cumbersome and unwieldy and are therefore not implemented.

During the search for the optimal structure for any of the structural components (i.e. the alternative structure that has the least number of components) various checks are performed to ensure that the fabrication of such a structure is not unnecessarily complicated by the fact that the welder has limited accessibility to a particular joint. Using an expression published in Ref. 20 the minimum spacing allowed between symmetrical stiffeners can be calculated. By adapting this expression, this minimum spacing check can also be extended to asymmetrical sections. Therefore, as long as any alternative design spacing calculated for each structural component is not less than the minimum spacing, this ensures that proper fabrication techniques are possible and a wholly acceptable structural alternative has been generated for that particular structural component .

Another important geometrical check performed is to guarantee a minimum flange clearance between intersecting grillage members. This minimum flange clearance is taken as 40mm in accordance with section 6 of Ref. 43 in the case of OBPs and Flats. However, in keeping with the basis model, using LSTs, this flange clearance is not always attainable and therefore when using LSTs 35mm is taken as adequate. As the longitudinals are regarded as being continuous, the transverses have a slot cut in their webs. In order to retain structural strength of these penetrated members it is assumed that all cutouts are bridged by compensation pieces.

5.1.7 The use of "curve fit" data .

In many design procedures reference is sometimes made to graphical information. This aspect has been eliminated in **FRIGATE** by using polynomial equations, fitted by a "least squares" approach, to the graphical in the design codes.

The first instance where such a polynomial expression is needed is in the calculation of the effective width of plating that is considered to be acting with the attached stiffener. In order to evaluate the effective width ratio b_e/b it is necessary to estimate the plate slenderness ratio β (defined in Eqn. 7a) using Faulkner's plate strength relationship, Eqn. 10, for a residual stress factor $\eta = 3$ (see Fig. 5.3). A 14^{th} order polynomial expression is used in this instance to provide the same accuracy as the manual interpolation. A limitation on this expression is the necessity to keep it within the same data range as the graph and therefore any plate thickness and stiffener spacing ratio that causes β to exceed the value 5 is ignored.

A further occasion where the use of such curve fit data is useful is during the calculation of the critical buckling stress of steel columns. In this calculation it is necessary to determine the the ratio of the average crippling stress of un-annealed steel columns (stiffener acting with an effective width of plating) to the material yield stress for various values of the column slenderness parameter λ. In Fig. 4.4 the abscissa λ is related to the ordinates of the ratio σ_u/σ_y, a combination of the Euler hyperbola and Johnson parabola merged at a point of common tangency. In this case, there is an upper bound value to the data range $\lambda = 3.0$. Therefore, if the column slenderness is greater than 3.0 the design procedure is terminated and re-started using a new section.

5.2. Design Method 2 - Variations in the Transverse Structure.

In this design method, the transverse structure is considered variable in terms of transverse frame member types, scantlings and spacing within each structural component. Following a successful run of **FRIGATE** operating in this secondary mode, to establish a satisfactory transverse structural design, the program automatically enters the design procedure outlined as Design Method 1 in Section 5.1.1.

Both means of data input, i.e. from datafile or keyboard, are suitable in this particular design method. Design Method 2 is flexible enough to allow different section types to be used as transverse frames in each of the different structural components. This may or may not be practicable from a fabrication viewpoint but it is a facility that is available to the user which allows comprehensive exploration of the complete range of available options.

Some features of Design Method 1 are repeated in Design Method 2, primarily the need to define a complete midship section structural arrangement of longitudinal material. The same basis model as described in paragraph 5.1.2 can be used to initiate the design procedure or an alternative structural arrangement can be detailed by the user. Progressing from the need to define a complete midship section, the user is asked to input the following design parameters in order that the design of the transverse structure can proceed :-

1) the nature of the hull bending moment, sagging or hogging.
2) the type of rolled section to be used as the transverse frame member within each particular structural component .
3) the length and spacing, in metres, of the transverse frame.

4) the design head of seawater considered to be acting on the transverse frame.

5) the scantlings of a "first shot" transverse frame member.

After determining these input factors the design process continues by stepping through the following procedure shown diagrammatically in Fig. 5.4..

1 calculate the DnV Rule-required minimum section modulus , REQMOD, for Nº 01 deck transverse member under the user specified loading and frame spacing.

2 calculate the actual effective section modulus, ACTULZ, of the transverse member acting with the Rule-determined effective breadth of plating.

3 if the section modulus value calculated in step (2), ACTULZ, is greater then or equal to REQMOD, calculated in step (1), then this transverse member may be used in Nº 01 deck structure at the user specified transverse frame spacing.

4 if the section modulus value calculated in step (2), ACTULZ, is less than REQMOD, calculated in step (1), then **FRIGATE** asks the user to decide on one of the options for the particular structural component under investigation :

a) search out the next suitable available size of the section type chosen ?

b) for the particular transverse frame member specified, determine the transverse frame spacing that satisfies the criteria being used for the design of the transverse structure ?

5 if after searching through all the available section sizes and ACTULZ is still less than REQMOD, **FRIGATE** will automatically calculate the maximum transverse frame spacing allowed by DnV Rules, for the largest section of the type specified by the user.

If step (4a) is answered in the affirmative, then a search is commenced for the first section from the database that provides a combined section modulus value, greater than that required by Dnv rules.

If the response to step (4a) is negative, **FRIGATE** will ask if the design procedure should seek out a transverse spacing that, when used in conjunction with the specified section type and size, will provide a suitable section modulus value for the specified loading conditions. If at the end of this design loop, the section modulus value still does not satisfy the design criteria then the program will suggest that the use of a bigger section should be investigated. If after rejecting option (4a) and then (4b) is not accepted, **FRIGATE** will stop and the complete design procedure has to be re-entered from the very beginning.

Irrespective of which design method is used, **FRIGATE** will always search out an alternative structure which has fewer fundamental components than the basis model described by the user. The search sequence employed by **FRIGATE** is shown in Fig. 5.5.

5.3. Relative Fabrication Cost Subroutines

In broad terms, the fabrication of a complete midship section twin unit assembly can be regarded as three distinct groups of related activities, from the initial stages of sub-assembly through to the final stages of erection on the building berth. The program **SHIPCOST** gives the structural designer a means of rapidly assessing the relative fabrication costs associated with these three stages of the build cycle in the progressive sequence they would form in reality. These three stages are :

1) primary components and their fabrication into the structural components detailed in section 5.1.1.

2) installation of each structural component unit on the building berth and the link up and integration with adjacent structures in their vertical sense to form a complete transverse structural ring, e.g. side shell to bilge structure.

3) installation of a second transverse structural ring, identical to the first, including the link up and integration to each structural component counterpart on the building berth in the longitudinal sense, e.g. double bottom unit to double bottom unit; bilge structure to bilge structure; etc.

The input data required for **SHIPCOST** can be generated in two ways. Firstly, as output from the structural design program **FRIGATE** or secondly as user response to a menu driven structural topography definition procedure.

5.3.1 Data Input Requirements.

1) Using data from **FRIGATE**

The raw output from **FRIGATE** is only part of the data required as input to **SHIPCOST** and consequently additional data is required. In structural design it is not necessary to know how many panels and individual plates within panels go into the total width of plating that is considered longitudinally continuous in any one structural component. Similarily, it is not necessary to know the individual panel lengths or plate widths when dealing with the structural design of of a midship section. However, this additional data is required when dealing with the relative fabrication cost estimation of a structure. Therefore, as is the case with **FRIGATE**, reference is made to a detailed basis model midship section for **SHIPCOST** which is supplemented and updated as the optimisation of the structure is carried out by **FRIGATE.**

The basis model in this instance is sub-divided into the same structural components as previously discussed together with the additional details listed below, using the bottom up philosophy :

1) Outer bottom - 1 orthogonally stiffened flat panel with the following plating dimensions :

No off	Length	Width	Thickness.
2	7.22	1.75	0.010
2	7.22	2.50	0.010
1	7.22	2.00	0.010

2) Tank top - 1 orthogonally stiffened flat panel with the following plating dimensions :

No off	Length	Width	Thickness.
4	7.22	1.75	0.010
1	7.22	2.50	0.010

3) Bilge structure - 1 orthogonally stiffened curved panel with the following plating dimensions :

No off	Length	Width	Thickness.
1	7.22	2.75	0.010
1	7.22	2.00	0.010

4) Nº 2 Deck - 3 orthogonally stiffened flat panels with the following plating dimensions :

Wing Panel Plates :

No off	Length	Width	Thickness.
2	7.22	1.95	0.010
2	7.22	1.65	0.010

Centre Panel Plates

No off	Length	Width	Thickness.
1	7.22	1.50	0.010

5) Side shell - 1 orthogonally stiffened flat panel with the following plating dimensions

No off	Length	Width	Thickness.
1	7.22	2.50	0.010
1	7.22	2.15	0.010
1	7.22	1.90	0.010

6) Nº 1 Deck - 3 orthogonally stiffened flat panels with the following plating dimensions :

Wing Panel Plates :

No off	Length	Width	Thickness.
2	7.22	1.95	0.010
2	7.22	1.65	0.010

Centre Panel Plates

No off	Length	Width	Thickness.
1	7.22	1.50	0.010

7) Nº 01 Deck - 3 orthogonally stiffened flat panels with the following plating dimensions :

Wing Panel Plates :

No off	Length	Width	Thickness.
2	7.22	1.95	0.010
2	7.22	1.65	0.010

Centre Panel Plates

No off	Length	Width	Thickness.
1	7.22	1.50	0.010

Using this format to define panel and plate sizes in each structural component allows **FRIGATE** to post process it's datafile for input to **SHIPCOST** in terms of plating sub-division, thicknesses and number and type of structural sections used in both the longitudinal and transverse directions.

2) User Defined input to **SHIPCOST**

This means of data generation allows the relative fabrication cost of any mild steel midship section, defined by the user, to be estimated assuming that there are no radical changes to the construction method so that the relative fabrication cost algorithms contained in **SHIPCOST** are still applicable. The data input sequence for **SHIPCOST** is shown in Fig. 5.6

This method of data input to **SHIPCOST** is more flexible than that involving post processed output from **FRIGATE**. This flexibility, however is gained at the expense of speed in that the user defined input requires considerable time in preparation and entry and thereby prolongs the execution time of **SHIPCOST**. This type of input can be entered to **SHIPCOST** by two methods, either directly from a datafile previously prepared by the user or by prompting from a menu driven data generation procedure during the program execution. Listed below is a sample set of the prompts used in this method of a structural component structural detail definition.

Ship Area 2 - Tank Top (P > = Prompt , **R > = User Response**)

P > How many orthogonally stiffened panels are there in the tank top structure ?

R > 1

P > Input type of sections used as i) Longitudinal Stiffeners
ii) Transverse Members

R > TEES_FAB

P > Input number of plates in Tank top Panel number 1

R > 2

P > Input :

i) Length of Plate (m)
ii) Width of Plate (m)
iii) Thickness of Plate (m)
iv) Number of Transverse members
v) Number of Plate Longitudinals attached to this Plate

R > 10.0,5.0,0.010,9,1

P > Input PLate Longitudinal Dimensions :

i) Plate Longitudinal Length (m)
ii) Plate Longitudinal Height (m)
iii) Plate Longitudinal Thickness (m).

R > 10.0,2.0,0.010

P > Input :

i) Length of Plate (m)
ii) Width of Plate (m)
iii) Thickness of Plate (m)
iv) Number of Transverse members
v) Number of Plate Longitudinals attached to this Plate

R > **10.0,2.5,0.010,9,0**

P > How many different sizes of section are being used as longitudinal stiffeners.

R > **2**

P > Input longitudinal dimensions and number used.

i) Overall section height (m)

ii) Section stalk thickness (m)

iii) Number of this section being used on this panel.

R > **0.1143,0.0056,10.**

P > Input longitudinal dimensions and number used.

i) Overall section height (m)

ii) Section stalk thickness (m)

iii) Number of this section being used on this panel.

R > **0.1778,0.0076,2**

P > Input component dimensions of transverse fabricated section.

i) Web height (m)

ii) Web thickness (m)

iii) Flange width (m)

iv) Flange thickness (m)

R > **0.450,0.010,0.100,0.006**

P > Are there vertical floors to be considered as part of the tank top ?

R > **Yes**

P > Input :

i) Number of vertical floors

ii) Number of piece parts in each vertical floor.

R > **2,4**

P > Input length, height and thickness of each VF piece part.

R > **2.0,1.5,0.010**

P > Input length, height and thickness of each VF piece part.

R > **2.0,1.5,0.010**

P > Input length, height and thickness of each VF piece part.

R > **2.0,1.5,0.010**

P > Input length, height and thickness of each VF piece part.

R > **2.0,1.5,0.010**

Similar sets of prompts are repeated for each structural component in turn to supply the necessary details which enable **SHIPCOST** to estimate the relative fabrication cost of fabrication and erection and the material cost associated with each structural component structural block. However, this is not the limit of the detail input that **SHIPCOST** can cater for. At that part of **SHIPCOST** which models the link up and integration of structural component units on the building berth the program will prompt the user for information regarding the use of brackets, collar plates where structural sections penetrate plating, web doubler plates and whether one or two connection lugs are used at major transverse bulkhead penetrations. In these instances the user replies with a simple YES or NO. If the affirmative is entered, then all dimensions of the collar plates, web doubler plates, brackets or connections are automatically calculated in terms of the web depth, flange width and thickness of the structural component member to which they apply.

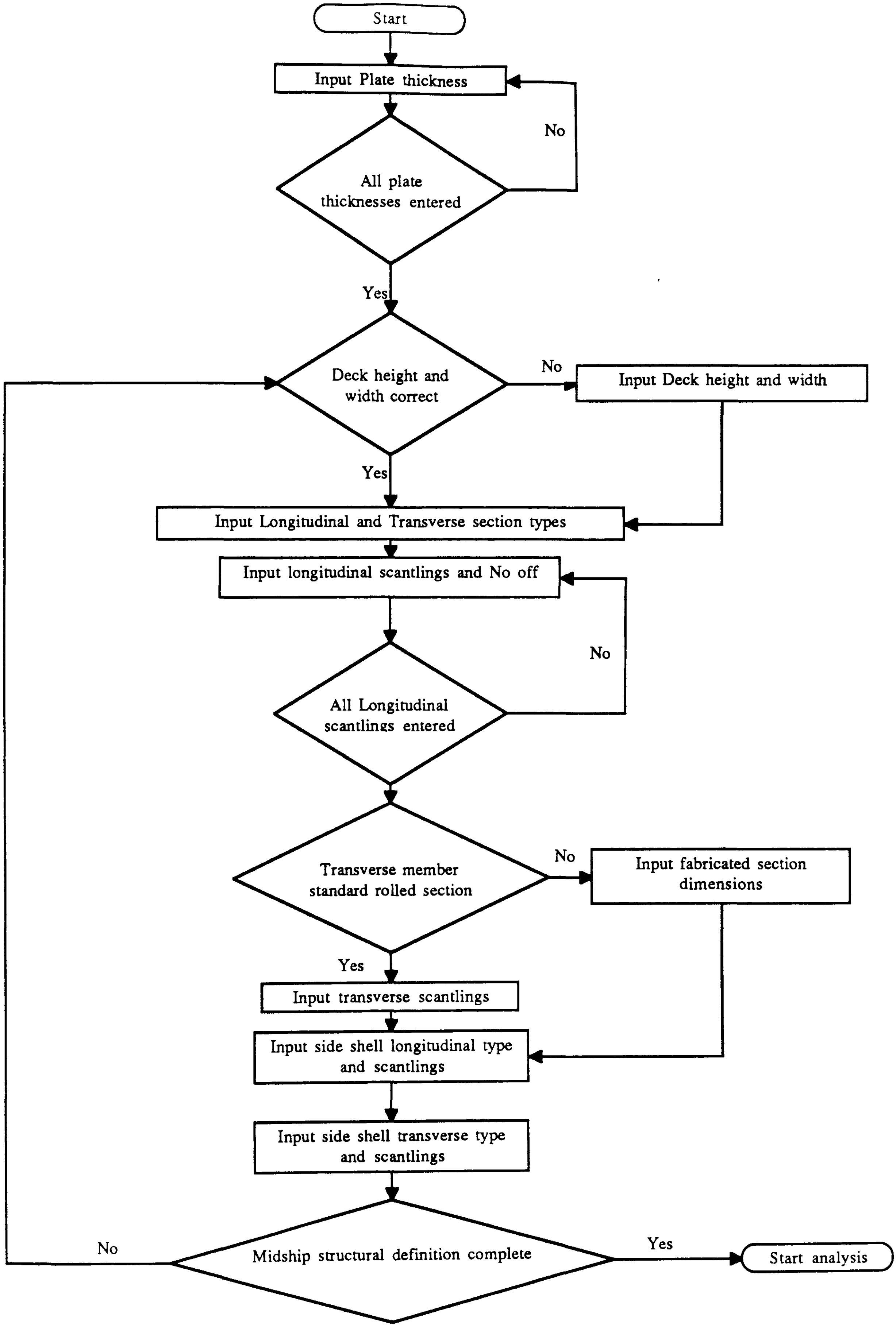


Fig. 5.1
Data Input Requirement for program FRIGATE

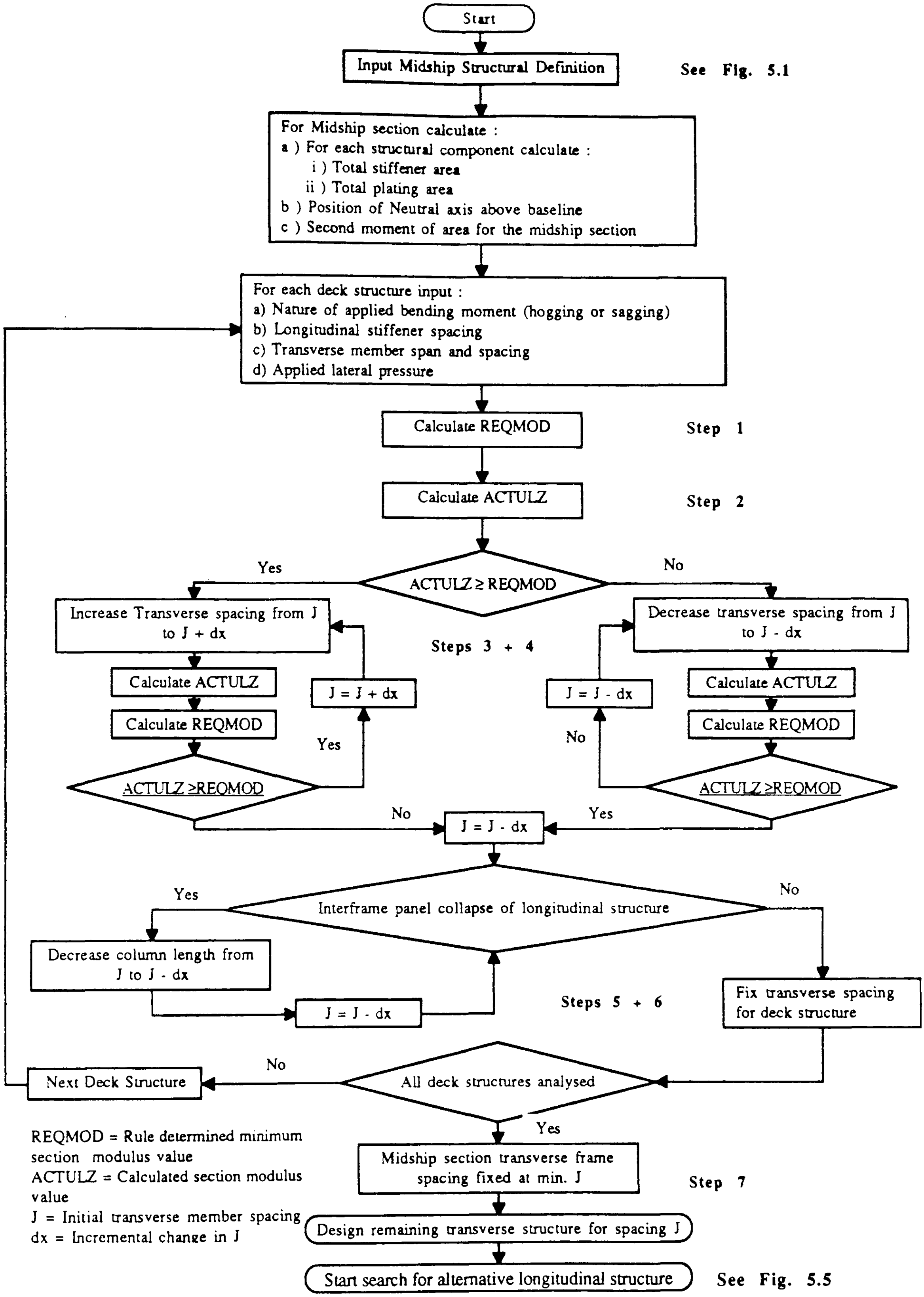


Fig. 5.2
Design Method 1 - Longitudinal Structural Variations to the Basis Model

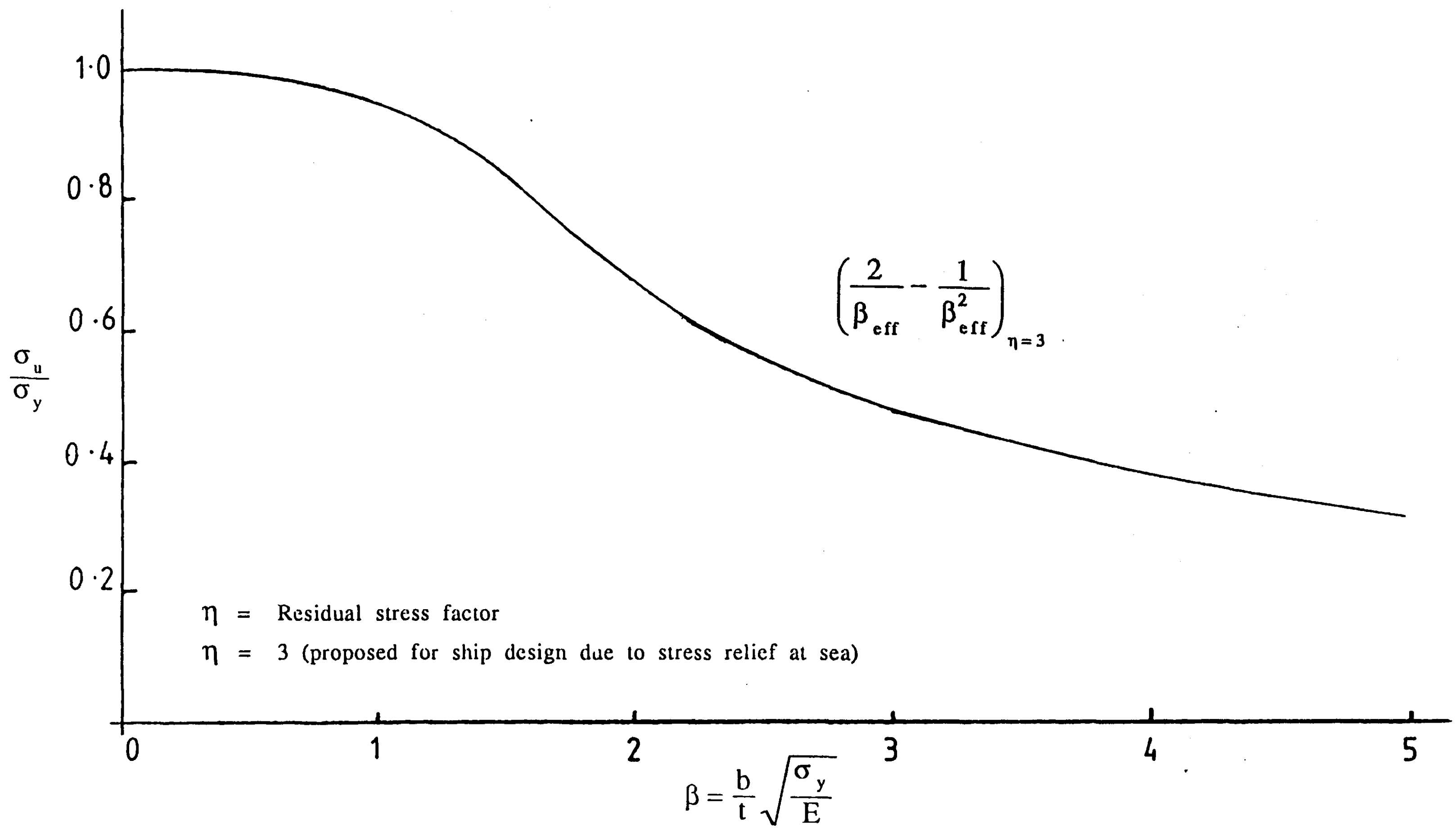


Fig. 5.3
Plate Strength - Pinned Edges

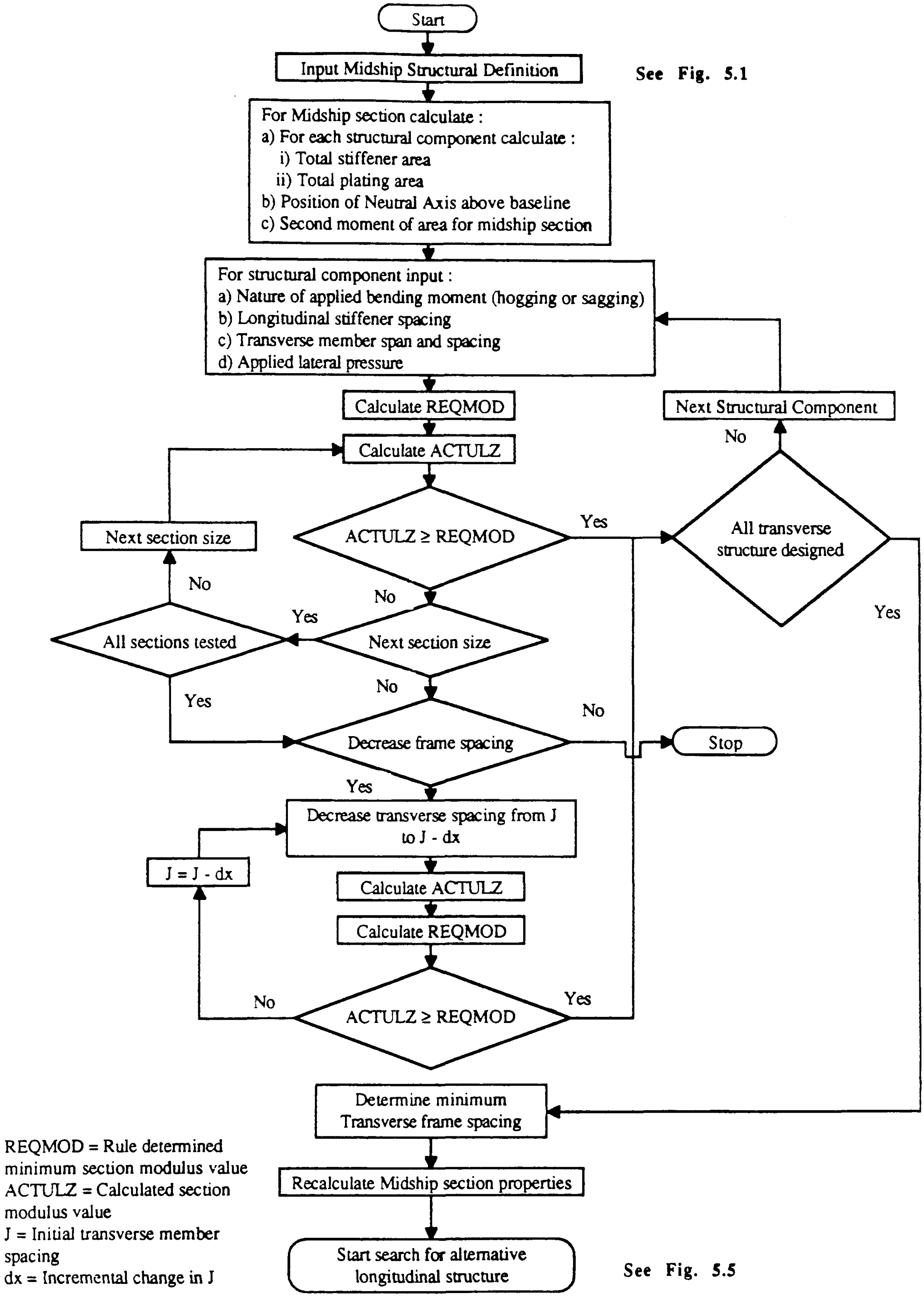


Fig.5.4
Design Method 2 - Transverse Structural Variations to the Basis Model

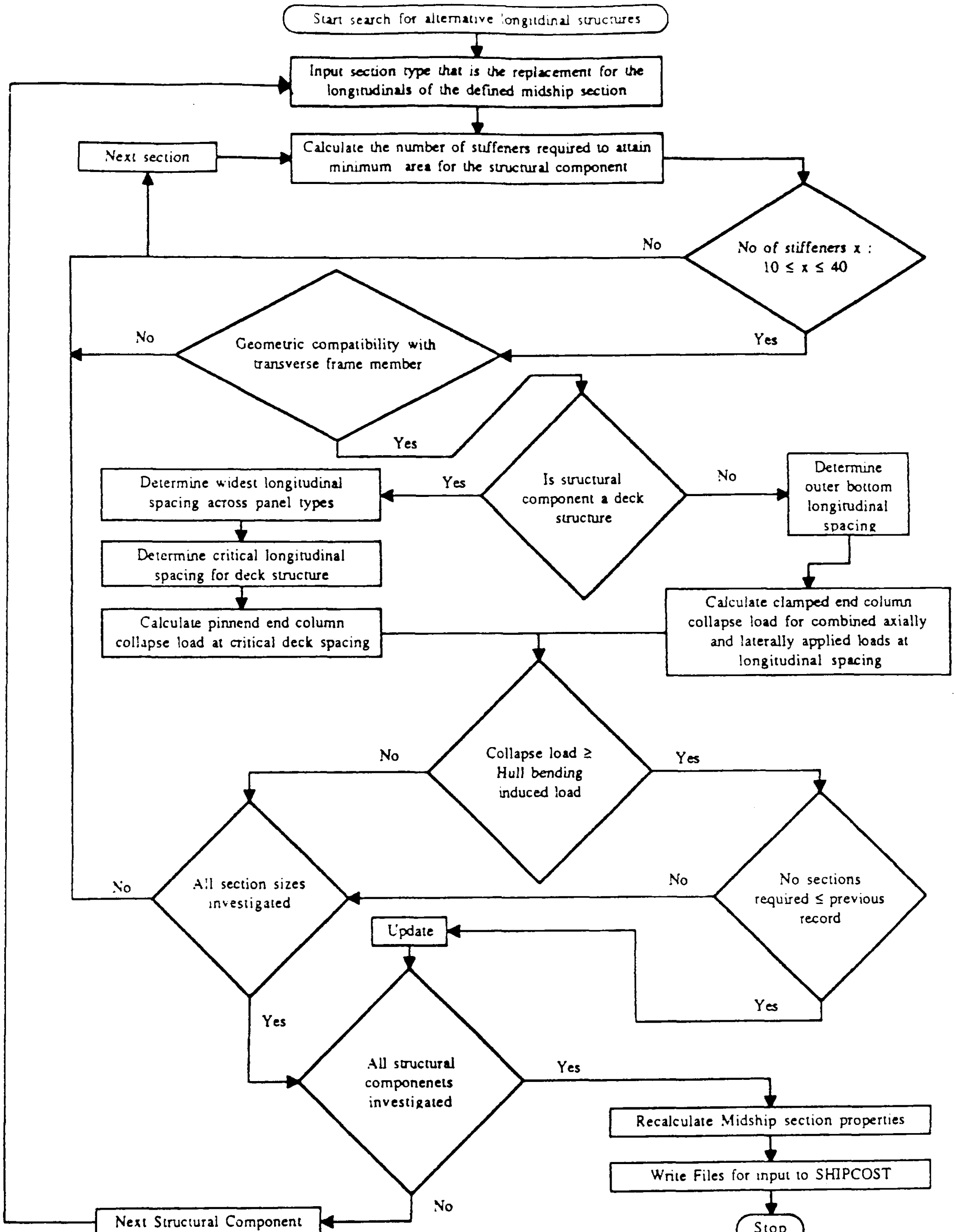


Fig. 5.5
Search Pattern for Alternative Structural Arrangements

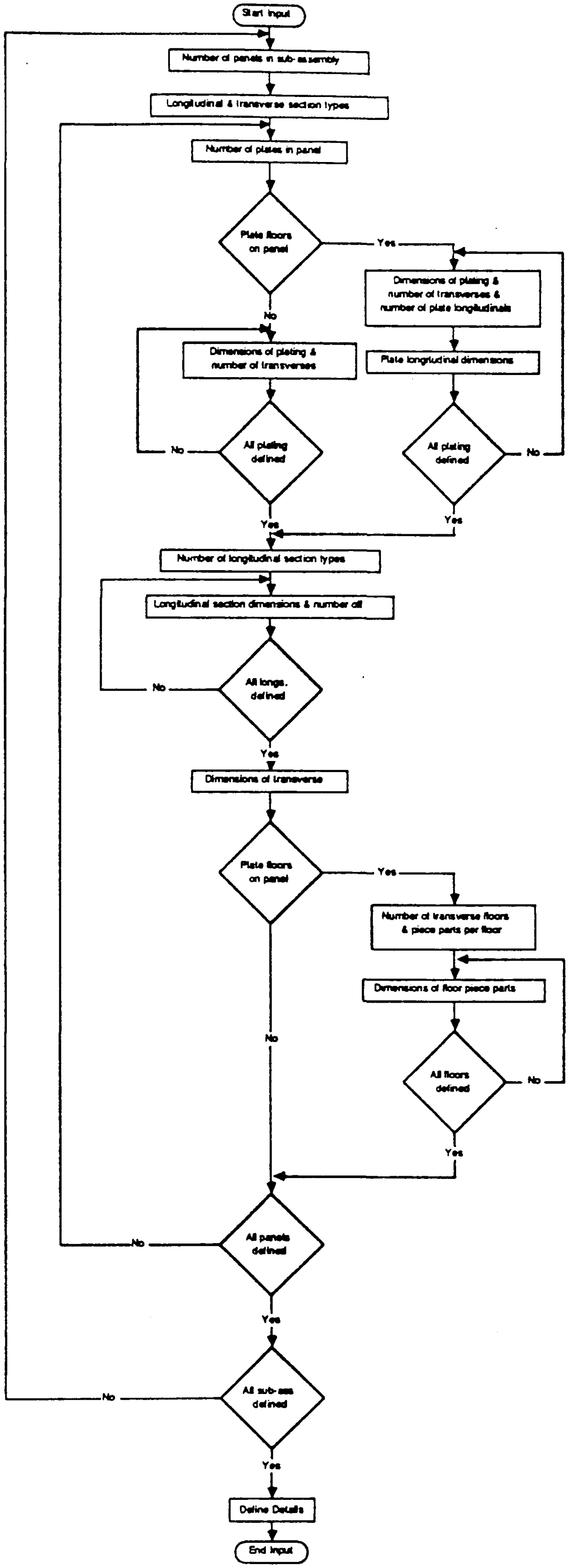


Fig. 5.6
Midship Panel Definition Flowchart

CHAPTER 6
DESIGN STUDIES AND DISCUSSION OF RESULTS

Using early versions of **FRIGATE** and **SHIPCOST**, initial studies were carried out on the structural design and relative fabrication cost of typical frigate structural components. Two types of structural component were principally involved, namely flat panel deck structure and double bottom structure. By isolating these two types of structure and generating structurally equivalent alternatives (by the method described in Chapter 5, section 5.1.7) it was intended to establish trends, indicating the direction a structural designer should take to achieve structures with optimum associated relative fabrication cost while still meeting their operational requirements. As these studies were undertaken prior to the development of the transverse design analysis scheme, the following constraints were applied to the structural model throughout :

a) fixed transverse member type (Tee)
b) fixed transverse member scantlings (76 * 127 mm)
c) transverse frame spacing fixed at 1 metre
d) six positionally fixed deck panel side girders with basis model scantlings
e) constant area value assumed equal to the basis model area for the structural component under investigation

The implication of constraint (b) is that it eliminated some of sizes of replacement sections due to minimum value of ABS(depth of transverse - depth of longitudinal) to permit good fabrication procedures in terms of access for the welding operator. The implications of constraint (e) are twofold, firstly the neutral axis position of the midship section longitudinal material remains virtually unchanged. Secondly, the weight of the midship section material also remains relatively unchanged. Minor variations to the basis model values were inevitable due to integer stiffener numbers required to attain the minimum area requirement of the structural component.

Limitations of the relative fabrication cost assessment model at this particular stage of the overall study were that additional work content associated with intercostal grillages and the fitting of tripping brackets were not considered.

As discussed in more detail in Chapter 3 of this thesis, all fabrication costs which can be considered as constant overheads are omitted from the final fabrication cost figures. Hence the figures are only meaningful in a *relative* and not in an absolute context. A basic labour rate of £15 per calculated manhour is assumed throughout these design studies.

6.1 Relative Fabrication Costs of Flat Panel Deck Structures

The study of flat panel deck structures was undertaken in two stages. The first attempts at generating alternative structural arrangements were restricted to using Tees as the longitudinal members with constraints (a) to (e) effective. After establishing the method of generating structurally equivalent deck structures, it was used to replace the longitudinal Tees of the basis model flat panel structure by either OBPs or Flats.

6.1.1 The Relative Fabrication Costs of a deck structure using Tee bar Longitudinals.

The results shown in Fig. 6.1 and 6.2 indicate that for a constant deck area, stiffener size has a major influence on the relative fabrication cost for any plate thickness. Such a result is not unexpected as the Tee scantlings increase from 25 * 76 mm to 127 * 254 mm, the sectional area available per stiffener increases and the number of longitudinals needed to meet the minimum area requirement decreases for a given plate thickness. This results in a reduced stiffener fillet weld length and reduced number of longitudinal to transverse connections. Hence, fewer manhours are required for the completion of the orthogonally stiffened flat panel.

Fig. 6.1 also shows that for each stiffener size, the local cost optima is associated with the thickest plating (i.e. minimum number of stiffeners). It can also be seen from Fig. 6.1, that for each stiffener size there is a minimum relative fabrication cost associated with the boundary of a feasible design space. Taking cognizance of constraint (b), the results shown in Fig 6.1 for the 76 * 127 mm Tee bar are optimistic as the influence of intercostal grillage connections on the inherent work content are not reflected in the aggregate relative fabrication cost figures presented. Similarily, the results for the 25 * 76 mm Tee bar are also optimistic if the recommendations of Ref. 49 for tripping brackets are adhered to.

Fig. 6.2 clearly shows the cost optimum to be associated with the minimum number of attached stiffeners regardless of plate thickness. Furthermore, near the optimum, as the contribution from the plating to the constant area value increases (i.e. as plating thickness increases) relative to the contribution made by the stiffeners, there is a slight reduction in the relative fabrication cost of the deck panel. This reflects the low material cost of the plating relative to that of Tee stiffeners. The reversal of this trend associated with larger number of stiffeners and 8mm and 9mm plating is directly related to the substantially lower cost per tonne of the two smallest sections used in these options. Following the trend line from top right to bottom left for the 8mm plating, each data point represents an increasing stiffener size. Thus as plating costs are constant on this trend line, the step increase is directly associated with the step increase in the cost per tonne of 5 largest Tee stiffener sizes. The close proximity of these trend lines indicates that the material cost has a minor bearing on the total relative fabrication cost of the structure in relation to the major influence of the number of component parts used in construction which should clearly be minimised.

Fig. 6.3 indicates that although some options of stiffener size and plate thickness show marked differences in the cost of each type of material, particularly in relation to plate thickness, Fig. 6.4 indicates total material cost variations are much smaller, the percentage variation between minimum and maximum being 15.2% while the the corresponding variation in total relative fabrication cost is 115.7%. This serves to further emphasise that the dominant influence on the relative fabrication costs of a structure is the associated work content related to the number of component parts.

6.1.2 Relative fabrication costs of Deck Structures using OBPs and Flats as longitudinals.

The trends shown in Fig. 6.2 indicate that a cost optimised structure is unlikely to be associated with structural alternatives requiring greater than 40 stiffeners. Furthermore, structures with less than 10 stiffeners are unlikely to satisfy the longitudinal design criteria applied to deck panels. By incorporating these two restrictions and releasing constraint (d) of the opening paragraph, flat panel deck structures were investigated for least relative fabrication cost using longitudinal stiffeners of either OBP or Flat Bar section. There is however one further point to consider at this juncture. When the computer model was used to investigate feasible structural alternatives to the basis model deck panel structure using both these section types as longitudinals, the initial results could not be used to substantiate the trends in Section 6.1.1 or indeed establish other different trends. This was because there were too few structural alternatives to the basis model deck panel generated by the computer model. The reason being simply, that the in-plane compressive stress loading (hull bending induced) applied to the deck structure was at a level that prohibited the use of OBPs and Flats, in the numbers required to maintain the constant area constraint, as longitudinal stiffeners. Therefore, the following discussion relates to a deck panel structure that is closer to the midship neutral axis and thus is subjected to less severe hull bending induced compressive stresses.

The results shown in Tables 6.1 and 6.2 indicate that a wide range of feasible designs for a constant area deck panel can be proposed using different types and sizes of stiffeners in conjunction with varying plating thicknesses. As evidenced in these Tables, the area per stiffener is inversely proportional to the number required for a fixed plating area contribution in order to achieve the constant total area constraint.

When these results are presented in a graphical format there is a clearly defined relationship between the number of stiffeners and the fabrication manhours and hence ultimately the relative fabrication cost. Fig. 6.5 indicates that the inherent work content related to flat panel construction is directly proportional to the number of flat bar stiffeners used in it's fabrication. This association of increased stiffener numbers and increased relative fabrication cost is shown to apply for different plate thicknesses. This phenomena is emphasised by the "flatness" of those trend lines representing the material cost element of the total relative fabrication cost figure. Similar trends to those of Fig. 6.5 are reflected in Fig. 6.6 for OBP stiffener types across a smaller range of stiffener numbers. The structures using the thicker plating material invariably incur greater material costs and this is reflected in slightly higher relative fabrication costs. This is a significant result. Referring to Tables 6.1 and 6.2, when the structures using 8mm and 9mm plating and similar number of stiffeners are compared, in terms of relative fabrication time, the deck panel using the lighter plating and the heavier stiffener requires more manhours for completion than the heavier plated lighter stiffener structure. Thus, when the heavier plated lighter stiffener structure incurs greater relative fabrication cost, this reveals that the effect of plate material cost dominates that of increased relative fabrication time when the labour rate of £15/manhour. This effect would be lessened and indeed reversed if an increased labour rate is assumed to apply.

A further measure of merit presented in Figs. 6.7 and 6.8 is the relative fabrication time against safety factor. In this instance , the safety factor is defined as the ratio of the critical collapse stress of the effective columns in the deck panel to the axially compressive hull bending induced in-plane deck stress. As described in Chapter 5, section 5.1.7, there are two individual panel types with independent stiffener dispositions considered to represent a deck panel structure, wing panels and a centre panel. The critical collapse load of the deck structure, is taken to be the collapse load associated with the wider longitudinal spacing across the wing and centre panel types. The general trends depicted in Figs. 6.7 and 6.8 is that as the factor of safety increases so too does the associated work content of the completed deck panel, in other words - increased safety levels incur fabrication cost penalties.

Fig. 6.9 is an overlay of Figs. 6.5 and 6.6 and includes data points indicating the relative fabrication cost of those structural alternatives to the basis model of this deck panel when Tee bars are used as the longitudinal stiffeners. Fig. 6.9 clearly highlights the directly proportional relationship that exists between the number of stiffeners and the relative fabrication costs, irrespective of stiffener type and plating thickness. It is also indicated, by the individual data points relating to the Tee bar Stiffeners, by inference of the number of stiffeners required to maintain the constant area constraint, that structures stiffened with the smaller Tee bar sizes incur comparable relative fabrication costs to the other two section types. Whereas, when the larger size of Tee bars are used, there is a distinct difference in the relative fabrication cost. Since, the number of component parts used in each alternative structure is equal and only minor differences in inherent work content can be expected due varying stiffener scantlings, then the major difference in relative fabrication costs must be attributable to the greater cost of large Tee bar sections when compared to the other two section types.

From Tables 6.1 and 6.2 it can be seen that there are several instances where the same number of stiffeners of varying scantlings, attached to the same thickness of plating result in different fabrication manhours and material cost. As the material pricing policy of British Steel. is the major cause of this effect, accurate modelling of material price structures must form part of any detailed optimisation although they are outwith the control of a designer. Differences in the relative fabrication manhours however needs further explanation. This is done separately for OBPs and Flat bars for clarity, although the principle outlined below generally applies to both section types.

Firstly, consider the case of using Flat bar section types for the replacement longitudinals of the basis model deck panel. When Flat bar sections, of the scantlings detailed in Table 6.1, are welded to plating thicknesses of 8 and 9 mm, it is the lesser of the material thicknesses that determines the fillet welding rate applicable for stiffener attachment to plating. Therefore, in those cases using 40 * 35 mm and 45 * 30 mm, where 28 in number are required, in addition with 9 mm plating, the welding rate applied to the welding activities on each panel are identical in every respect - but there is a difference in relative fabrication time. To explain this apparent paradox, the total relative fabrication manhour figures require to be broken down into their constituent values. The information presented in Tables 6.3 and 6.4 indicate where the differences occur for two deck panel structures, identical in every respect other than the scantlings of the longitudinal stiffeners.

If the deck panel to which the results presented in Tables 6.3 relate, is referred to as Deck Panel No 1 and it's component panels referred to as Panels 1(a), 1(b) and 1(c) it can be seen that the flat bar stiffeners used as longitudinals have the dimensions 40 * 35mm. Using a similar notation, Panels 2(a), 2(b) and 2(c) have longitudinal flat bar stiffeners with dimensions 45 * 30mm, as shown in Tables 6.4. On closer inspection it can be seen that the manhours expended on plating activities on Panels 1(a), 1(b) and 1(c) and on Panels 2(a), 2(b) and 2(c) are the same. Similarily, the welding times expended on plate seams, longitudinal and transverse member attachment to plating are the same across corresponding panels of Deck Panels No 1 and No 2. However, there is a difference in the time it takes to complete the connections between the orthogonal members of the grillage across these two Deck Panels. This can be attributed to the fact that the dimensions of the lug used in connecting the orthogonal members is a function of the ratio of the depth of the main member (transverse Tee bar) to the depth of the piercing member (longitudinal flat bar) and the web thickness of the main member. As on both Deck Panel No 1 and Deck Panel No 2, the transverse member has the same dimensions then the difference in "connection time" can be regarded as a function of the difference in depth (overall section height) between the two flat bar stiffeners used. This result highlights the factors of the design detail that ultimately have a bearing on the relative fabrication cost of the structure. Furthermore, it emphasises the level of detail that needs to be examined, if the true optimum, in terms of relative fabrication costs, is to be found.

Minor differences in relative fabrication time and ultimately in connection time are shown in the situation where the same number of OBP stiffeners of different sizes are attached to the same plating thickness. However, the magnitude of these differences is somewhat less than in the Flat bar case. As explained above, the dimensions of the lug used for connections between orthogonal members of the grillage are primarily a function of the depth of the piercing members (in this particular design study these are constant, i.e. the Tee bar transverses of the size stated in constraint (b)) and the thickness of the main member. Therefore, the minor variations in connection time in this instance are attributable to the minor variations in the web thickness of the main member.

6.1.3 Relative Fabrication Costs of Flat Panel Deck Structures of varying Transverse Arrangement.

Having investigated and discussed the heavily constrained basis model flat deck panel structure (Section 6.1.1) and proceeded with a less constrained model (Section 6.1.2) the next study undertaken was to investigate a further model which was the least constrained of the structures discussed thus far. To this end the transverse member was no longer regarded as having fixed scantlings, the frame spacing was no longer maintained at 1 metre and the deck girders, previously regarded as fixed, were allowed to vary in terms of scantlings but not in their positions.

Using DnV Classification Society Rules [44], the scantlings of the transverse member were determined, while the applied load cases they were being designed to resist were dictated by NES 110 [43]. Firstly, the basis model frame spacing was maintained at 1 metre and alternative structures, both transverse and longitudinal, were proposed by using different sizes of Tee section in conjunction with varying plating thicknesses. This process was then repeated for 1.3m and 0.7m transverse frame spacing and the relative fabrication costs compared.

The trends indicated in the earlier studies (Sections 6.1.1 and 6.1.2) suggest that a direct relationship exists between the number of longitudinal stiffeners and the relative fabrication cost, this relationship being independent of stiffener type. By harnessing this fact, only Tee sections were considered in producing alternatives to the basis model in this particular study. This limited the number of structures considered, in relation to the possible number of feasible alternative designs, when constraints (b), (c) and (d) of the opening paragraph were no longer applicable.

Fig. 6.10 shows the results of varying a basis model flat deck panel in terms of transverse member scantlings, spacing and plating thickness. Fig. 6.10 re-emphasises the trend apparent in the earlier studies that relative fabrication costs are directly proportional to the number of longitudinal stiffeners. The other clear trend, is that for any discrete number of longitudinal stiffeners, the relative fabrication cost is inversely proportional to the transverse frame spacing. Fig. 6.11 indicates that although the basis deck panel was probably optimised in terms of both weight and strength initially, it also is the optimum in terms of relative fabrication cost. This is the influence of the high material cost of the larger sizes of tee bars which dominates that of the work content of structures using more component parts but smaller tee bar sizes.

Furthermore, Fig. 6.10 shows that for a selected frame spacing and chosen longitudinal arrangement (i.e. fixed number of longitudinal stiffeners), the relative fabrication cost is directly related to the size of the transverse member. The vertical increases in the relative fabrication cost correspond to discrete increases in the size of the Tee section being used for the transverse member. Such an increase in relative fabrication costs is the outcome of a combination of influences relating to both labour cost and material cost. As the scantlings of the transverse member increase, the labour costs associated with fillet welding the section to the plating and intersecting longitudinal structure vary proportionally. Further, as the Tee section web and flange dimensions increase, there is a corresponding increase in the material cost. Thus, this combination of factors dictate that as the transverse member scantlings increase, for a constant longitudinal structure, so does the relative fabrication cost for an orthogonal flat panel grillage.

6.2 Design Study of a Typical Double Bottom Unit of a Royal Navy Frigate

Suitable structural alternatives to the basis model double bottom unit as described in Chapter 5, Section 5.1, were generated using the method described in Chapter 5 with due reference to Ref. 48. As the structural elements in the transverse sense were considered non-variable, restrictions were forced on the Tee bar sections that could be considered as suitable longitudinals on the tank top and outer bottom.

Paragraph 0618, Clause d of Ref. 43 relating to flange clearance, eliminates Tee bar longitudinals with dimensions 127 * 53 mm, 152 * 76 mm, 205 * 102 mm when the transverse frame is a Tee bar with 205 * 102 mm dimensions. The cost implications indicated in the study of deck panel structures of using Tee bars of dimensions of 76 * 25 mm (tripping bracket requirement) and 178 * 89 mm (fully intercostal grillage), also render these two options unsuitable for consideration as longitudinal members for the tank top and outer bottom orthogonal panel structures of the double bottom unit. For these reasons, the dimensions of the Tee bars that are considered as suitable longitudinal members for the double bottom unit in this study are 114 * 44 mm and 254 * 127 mm.

Paragraph 2301 of Ref. 50, does not permit the position of the longitudinal plate girders to vary without incurring major design changes. Therefore, in this study, the longitudinal plate girders are positionally fixed, and consequently their height is fixed, thus only allowing their thickness to be considered as a variable.

With all the above factors taken into consideration, three variable parameters could be established for the double bottom unit, namely thicknesses of tank top, outer bottom and longitudinal plate girders. This provided the means of obtaining a range of suitable Tee bar sections to maintain a constant double bottom area while using each of the options listed below :

OPTION A : The outer bottom plating and the tank top plating varys from nominal thickness of 13mm to 8mm simultaneously. Within each step change of outer bottom and tank top plating thickness the longitudinal plate girders' thickness varys from 13mm to 8mm.

OPTION B : The outer bottom plating and the longitudinal plate girders varys from nominal thickness of 13mm to 8mm simultaneously. Within each step change of outer bottom and longitudinal plate girder thickness the tank top thickness varys from 13mm to 8mm.

OPTION C : The tank top plating and longitudinal plate girders varys from nominal thickness of 13mm to 8mm simultaneously. Within each step change of tank top plating and the longitudinal plate girders the outer bottom plating thickness varys from 13mm to 8mm.

The structural nature of the double bottom unit leads to two easily identifiable structural assemblies. Namely, the tank top plating and attachments and the outer bottom plating and attachments. It follows that depending what are referred to as tank top attachments and what are referred to outer bottom attachments in conjunction with the sequencing of the tasks involved in the construction of the double bottom unit, different construction sequences can be identified. The following four construction sequences were identified in this project :

DOUBLE BOTTOM CONSTRUCTION SEQUENCE 1 -Fig. 3.8

In this case the tank top includes the sub-assembly of rolled sections being used as longitudinals and transverses, plate longitudinals and vertical floors. The outer bottom structure includes the rolled sections that are the longitudinal stiffeners and the transverse members. This construction sequence involves "dropping" the orthogonal outer bottom grillage onto the tank top assembly.

DOUBLE BOTTOM CONSTRUCTION SEQUENCE 2 - Fig. 3.9

In this case the tank top sub-assembly includes the attachments of rolled sections being used as the longitudinals and transverse, plate longitudinals, vertical floors and the rolled sections of the outer hull. This construction sequence involves "wrapping" the tank top assembly with the outer bottom plating.

DOUBLE BOTTOM CONSTRUCTION SEQUENCE 3 - Fig. 3.10

In this case the tank top and outer bottom attachments are as described for Sequence 1, above. However this construction sequence involves "dropping" the tank top assembly into the orthogonal outer bottom grillage assembly

DOUBLE BOTTOM CONSTRUCTION SEQUENCE 4 - Fig. 3.11

In this case the tank top attachments and the outer bottom attachments are as described for Sequence 2, above. However this construction sequence involves "dropping" the tank top assembly into the unstiffened outer bottom plating sub assembly.

6.2.1 Double Bottom Relative Fabrication Costs.

The results of the double bottom fabrication costs study are plotted in Figs. 6.12 - 6.21.

When options A (as described above) were analysed, two very clear trends were identified, as shown in Fig. 6.12. Firstly, increasing thickness of tank top and outer bottom plating result in decreasing relative fabrication costs for a particular thickness of longitudinal plate girders. Secondly, as the the thickness of the longitudinal plate girders increases for given uniform thickness of tank top and outer bottom plating, decreasing relative fabrication cost result. A further trend that can be seen is that lower fabrication costs can be achieved if the heavier of the two allowable Tee bars is used. Fig. 6.12 also indicates that the local cost optimum for each combination of plating thickness and stiffener types fall within a narrow band of relative fabrication costs.

Fig. 6.15 shows identical trends to those in Fig. 6.12, but in this case Construction Sequence 1 (Construction Task Algorithm 7, Appendix 1) was used in the relative fabrication cost calculation.

Analysing options B, similar trends to those described above are evident (Fig. 3.8 - Construction Sequence 1, Fig. 3.9 - Construction Sequence 2). It can be seen from Figs. 6.13 and 6.16 that increasing thicknesses of outer bottom and longitudinal plate girders for a given thickness of tank top plating also produces a decreasing cost trend. Furthermore, increasing the tank top thickness will also result in lower relative fabrication costs for a given thickness of outer bottom plating and longitudinal plate girders. Again, with the heavier Tee bar, the relative fabrication costs are lower than when the lighter Tee bar is used, as might be expected. The local cost optima for each combination of plating thicknesses fall within a narrow band of relative fabrication costs, similar to those of options A.

Figs. 6.14 and 6.17 (Construction Sequences 1 and 2 respectively), show the same trends that are evident for options A and B of decreasing relative fabrication costs with increasing outer bottom plating thickness and uniform thickness of plate longitudinal girders and tank top.

Fig. 6.13 (Construction Sequence 1), also shows that there are minor cost savings that can be made for the same structure using the same construction sequence. The savings results from different stiffener dispositions. When the number of stiffeners required is such that different suitable dispositions can be formed, from a structural integrity viewpoint (i.e. different numbers of longitudinals on the tank top and outer bottom but the same total) the lower cost solution occurs when the majority of the stiffeners are attached to the outer bottom plating. Construction Sequence - 2, also indicates that similar savings associated with additional outer bottom stiffeners can be achieved.

Fig. 6.18 depicts the local optima for each of the options using the 114 * 44 mm Tee bar. The abscissa indicates the third thickness variable and the option prefix indicates the other two thicknesses. The general trend indicated is that as the third thickness increases, the other two become thinner and reduced relative fabrication costs result. It can be seen that all of the acceptable options pivot about the relative fabrication cost of the basis model double bottom. It is not surprising that the basis model has lower relative fabrication costs than some of the options, but as the options approach the structural design criteria limit, some further reduction in relative fabrication costs can be achieved. Fig. 6.19 shows the local optima for each of the options using the heavier Tee bar, using the same format as Fig. 6.18. However, due to the smaller range of suitable structural alternatives, general trends are not so easily identified.

Combining Figs. 6.18 and 6.19 results in Fig. 6.20, which illustrates the interaction of tee bar size and plating thicknesses. It can be seen that individual trends of local optima are associated with constant double thickness options which have significant steps associated with a reduction in this double thickness. The result is a "saw-toothed" trend line with the best results associated at the bottom of each step. To expand on this, consider the trend line for Options A and the 114 * 44 mm Tee. The two points on the left hand side of Fig. 6.20 indicate a double thickness of 10mm. As the third thickness increases fewer stiffeners are required for the constant area value to be maintained, resulting in a reduction of the relative fabrication cost of the double bottom unit. However, on reducing the double thickness, greater numbers of stiffeners are required, resulting in increased relative fabrication costs. Therefore this "saw-toothed" effect is the result of an increase in stiffener numbers required to meet the minimum area requirement which thereby increases the inherent work content.

The foregoing discussion of the results in this section have been related to Construction Sequence - 1 and largely with the smaller of the two allowable Tee bars, i.e. 114 * 44mm. Due to the scarcity of options when using the 254 * 127mm Tee bar trends are less obvious. However, the local optima shown in Figs. 6.12 - 6.20 indicate that by using these heavier sections, the relative fabrication cost of the structure compare favourably with the best local optima when using the lighter sections.

The range of relative fabrication costs, when using the lighter sections, in comparison to the basis model is +15.8% to -14.2%. The option which indicates the cost saving of 14.2% on the basis model is the one having 13mm tank top plating and the remaining two thicknesses as 9mm. The minimum area requirement is attained by 8 off 114 * 44mm stiffeners. Consequently, the crude structural analysis employed at the preliminary design stage and used in these double bottom studies should be checked by a more detailed structural analysis to ensure the validity of this particular arrangement. When the heavier stiffener is used, the relative fabrication cost range is between -3.4% and -12.7% of the basis model, i.e. **all** options using the heavier section incur less relative fabrication costs than the basis model double bottom unit. Again, before maximum savings can be realised, the option yielding them (all plating being 9mm) should progress from preliminary design analysis to the more thorough detail design stage to ensure the structural design criteria are not being violated.

6.2.2 The Effect Of Using Tee bars and Double Bottom Construction Sequences 3 and 4 on the Relative Fabrication Costs.

Using Construction Task Algorithms 9 and 10 that were generated to represent Double Bottom Construction Sequences 3 and 4, outlined in Figs. 3.10 and 3.11 respectively, the relative fabrication costs of the double bottom unit were calculated using Tee bars that were compatible with the double bottom transverse members (i.e. satisfied flange clearance requirements).

Using the same format for curves developed for Construction Sequences 1 and 2, shown in Figs. 6.12 - 6.20, cost profiles can be generated for each feasible structure and double bottom Construction Sequence. Fig. 6.21. indicates the general trends obtained for alternative structures being fabricated by Construction Sequences 1 and 3. Only values obtained by using two of the double bottom construction sequences are shown in order that the figure remains clear while still indicating the savings possible by using Construction Sequence 3 rather than using Construction Sequence 1. Invariably the relative fabrication costs incurred when using Construction Sequences 3 and 4 are less than those incurred using Construction Sequences 1 and 2. Construction Sequence 3 always incurs the least relative fabrication cost.

6.2.3 The Effect of Using OBPs as Longitudinal Stiffeners and Double Bottom Construction Sequences 1, 2, 3, and 4 on the Relative Fabrication Costs.

By adopting the same procedure for calculating the required number of longitudinals to maintain the double bottom constant area and while considering the full range of commercially available OBP sections, over 6000 structural configurations of the basis double bottom unit were generated. Structural assessment led to only 27 being considered acceptable from longitudinal strength considerations. As with the Tee bars, Construction Sequence 3 incurs the least relative fabrication cost. Table 6.5 shows the range of acceptable structural alternatives and the relative fabrication costs associated with each construction sequence.

6.2.4 The Effect of Using Rolled Flats as Longitudinal Stiffeners and Double Bottom Construction Sequences 1, 2, 3 and 4 on the Relative Fabrication Costs.

The number of possible structural configurations of the basis model double bottom unit using flat bars as longitudinal stiffeners was 22,000. Structural assessment of these led to 38 being considered as structurally acceptable. As in the cases of Tee bars and OBPs Double Bottom Construction Sequence 3 incurs the least relative fabrication cost. Table 6.6 shows the range of the structurally acceptable double bottom alternatives and associated relative fabrication costs of each Construction Sequence.

6.2.5 Comparative Relative Fabrication Costs of the Double Bottom Unit for Differing Section Types using Double Bottom Construction Sequence 3.

The relative fabrication cost of the basis double bottom unit with Tee bars as the longitudinal stiffeners and using Double Bottom Construction Sequence 3 is 4% less expensive than when using Construction Sequence 1. Replace the Tees with OBPs and the relative fabrication cost of the double unit is 14% less expensive. This is achieved with plate thicknesses of 8 mm for the outer bottom and tank top and 10mm for plate longitudinals using 280 * 12 mm OBP longitudinals. With Flat Bars as the stiffening members the relative fabrication cost of the double bottom unit is 14% less expensive than the basis model double bottom unit. This is achieved with 8mm tank top and plate longitudinals, 11mm outer bottom plating and 120 * 20 mm Flat Bars.

Summarising for the basis model double bottom unit and Construction Sequence 3, a saving of 10.5% can be achieved on the relative fabrication costs if the plating thickness are altered and OBPs are used. Similarly, a saving of 7.9% can be realised if the Tee bars are replaced with Flat bars in conjunction with altered plating thicknesses.

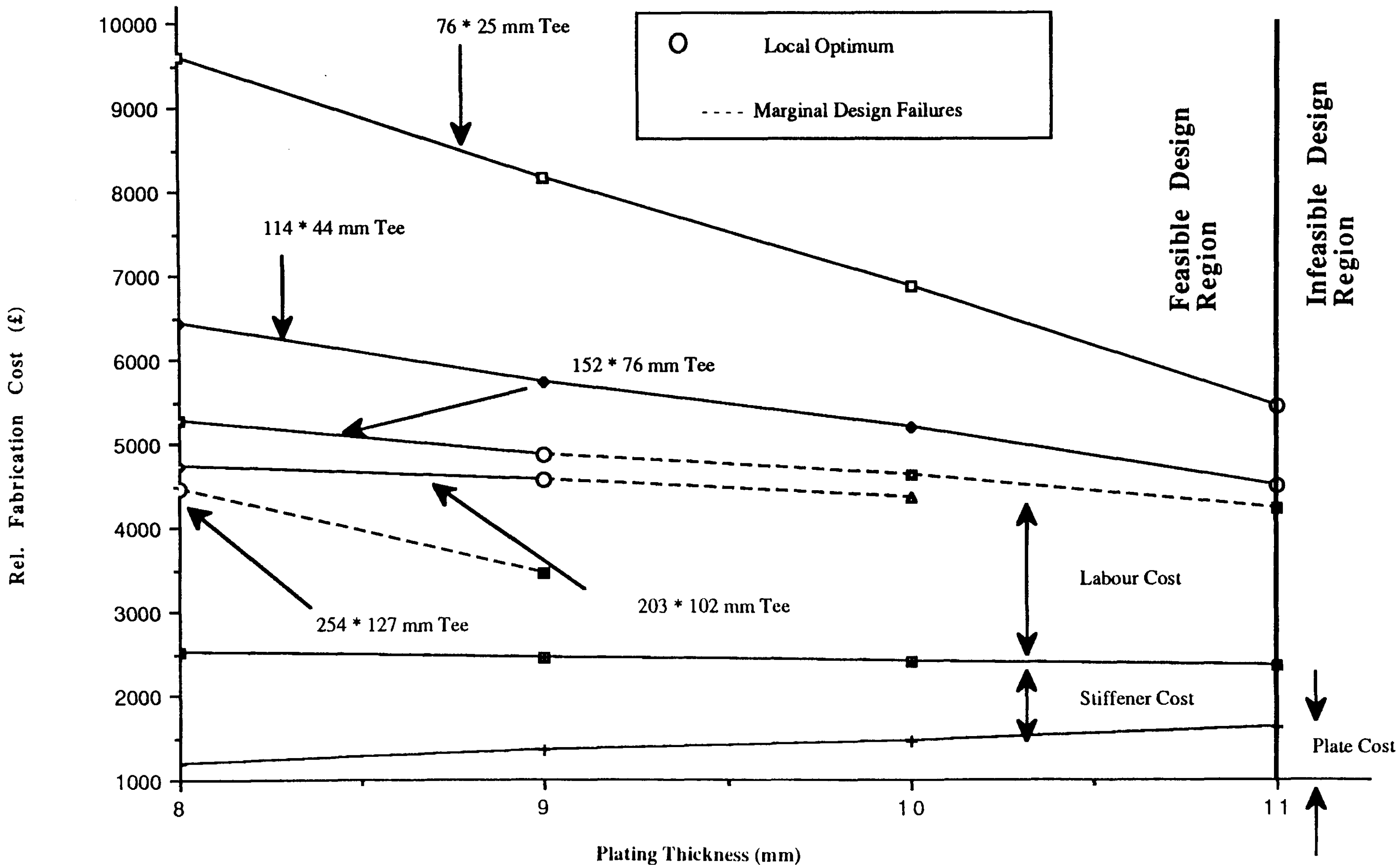


Fig. 6.1 - Flat Deck Panel - Constant Transverse Structure - T-bar longitudinals Breakdown of Panel Costs per T-bar size vs Plating Thickness

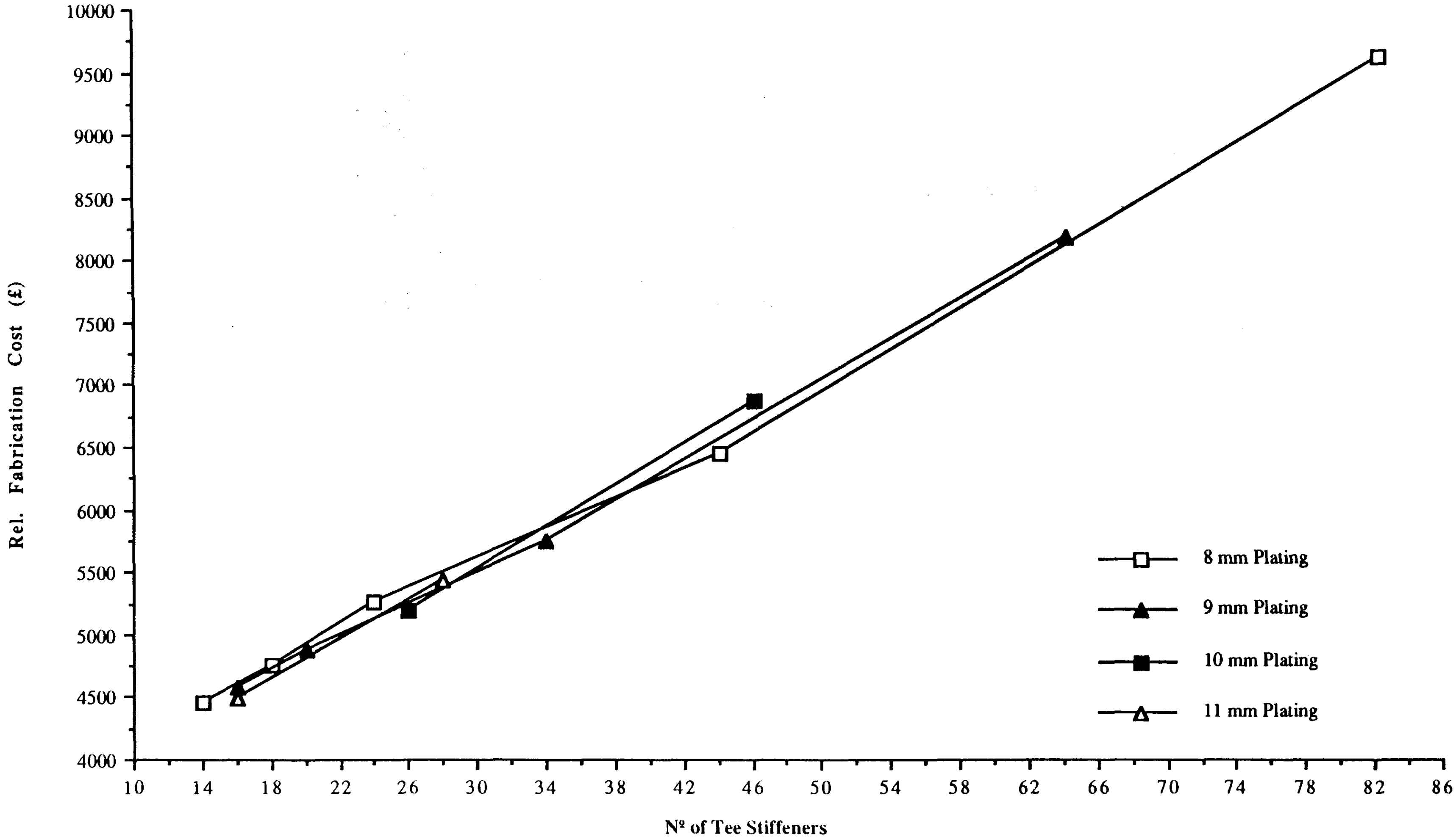


Fig. 6.2 - Flat Deck Panel - Constant Transverse Structure - T-bar longitudinals
Total Rel. Fabrication Cost vs No. of Stiffeners for varying Plate Thicknesses

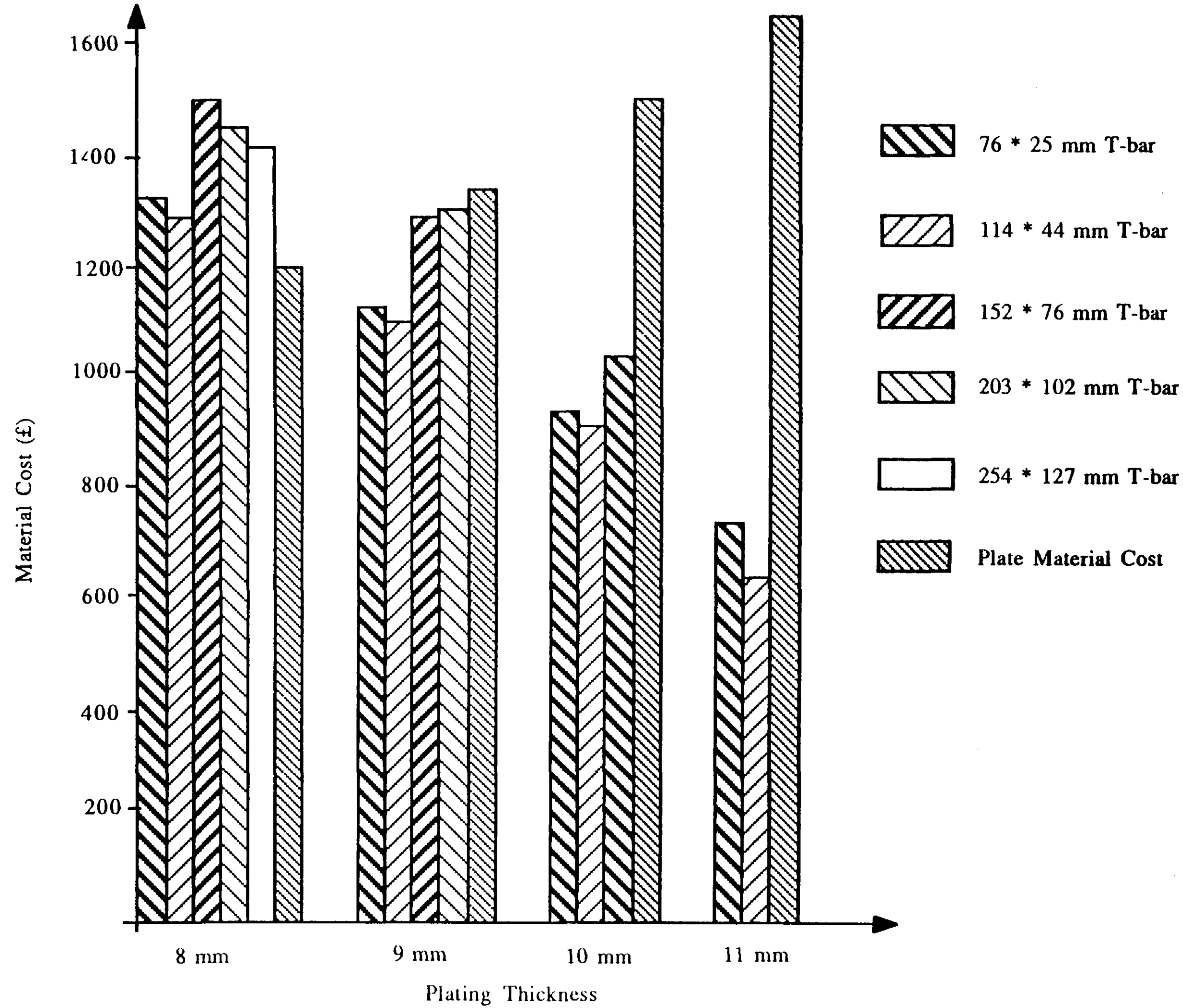


Fig. 6.3 - Flat Deck Panel - Constant Transverse Structure - T-bar Longitudinals Breakdown of Material Costs per T-bar size for each Plating Thickness

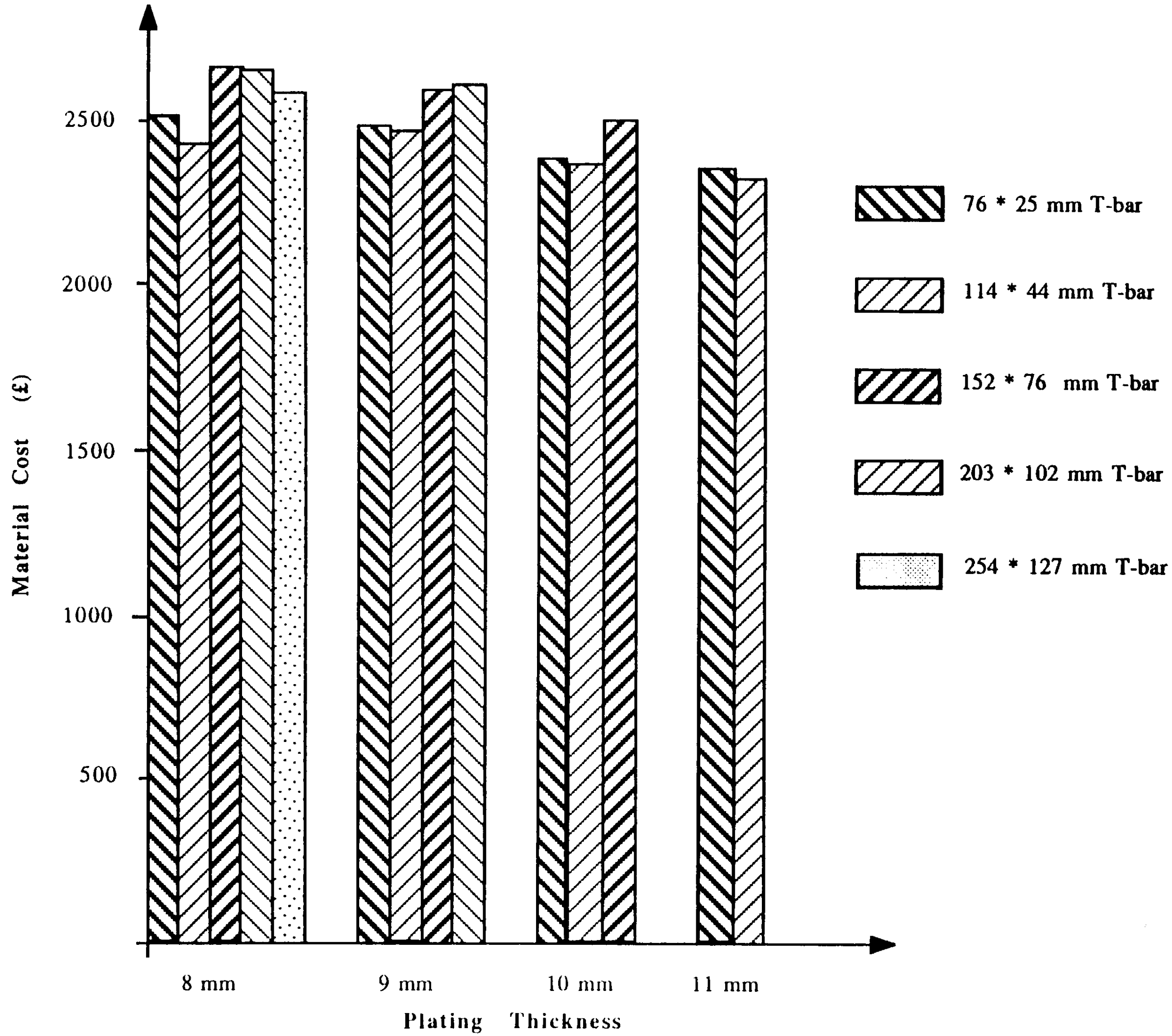


Fig. 6.4 - Flat Deck Panel - Constant Transverse Structure - T-bar Longitudinals Total Material Cost for each Alternative Panel Design

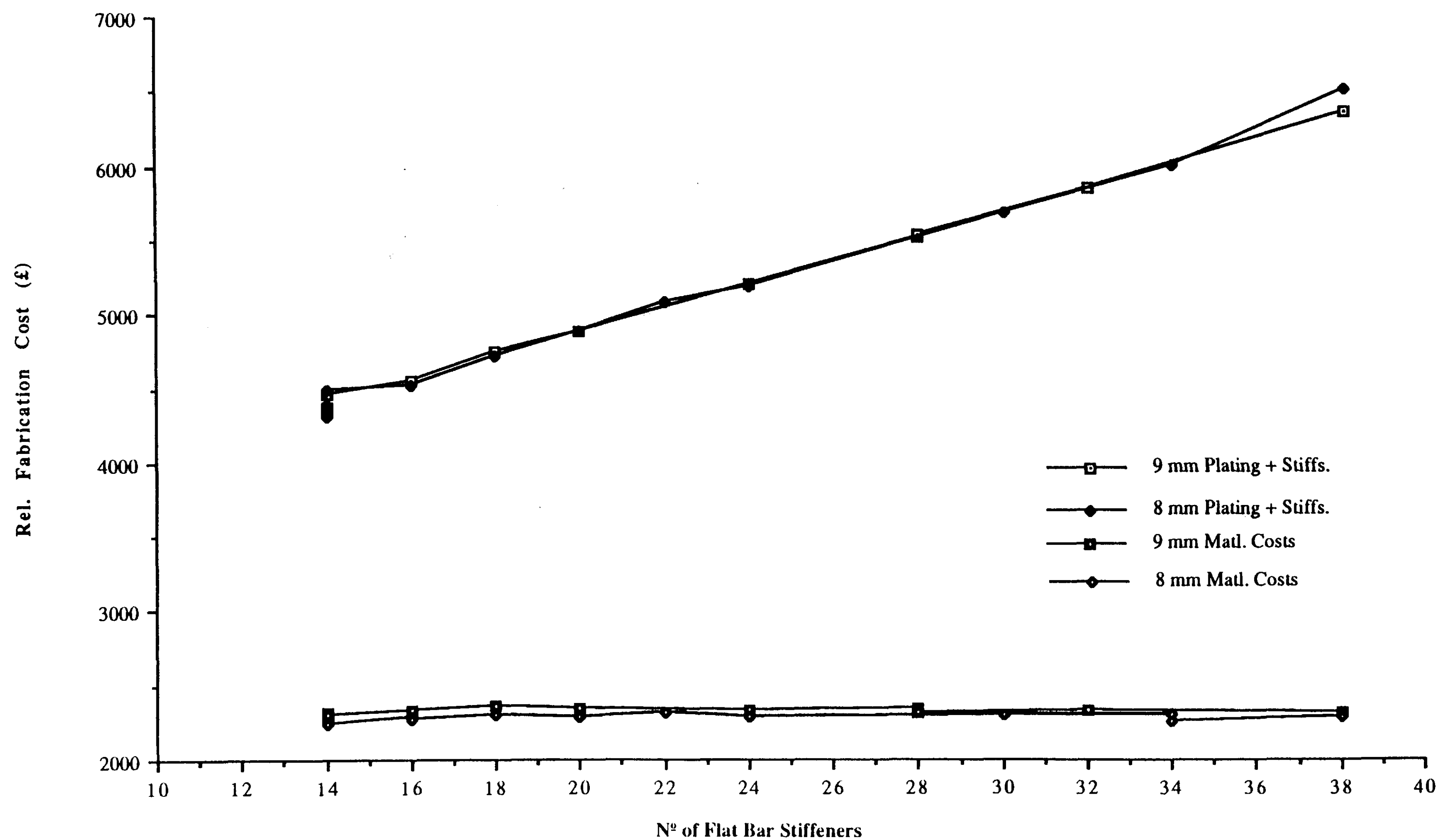


Fig. 6.5 - Flat Deck Panel - Constant Transverse Structure - Flat bar longitudinals Total Rel. Fabrication and Matl. Costs vs No. of Stiffeners for two Plate Thicknesses

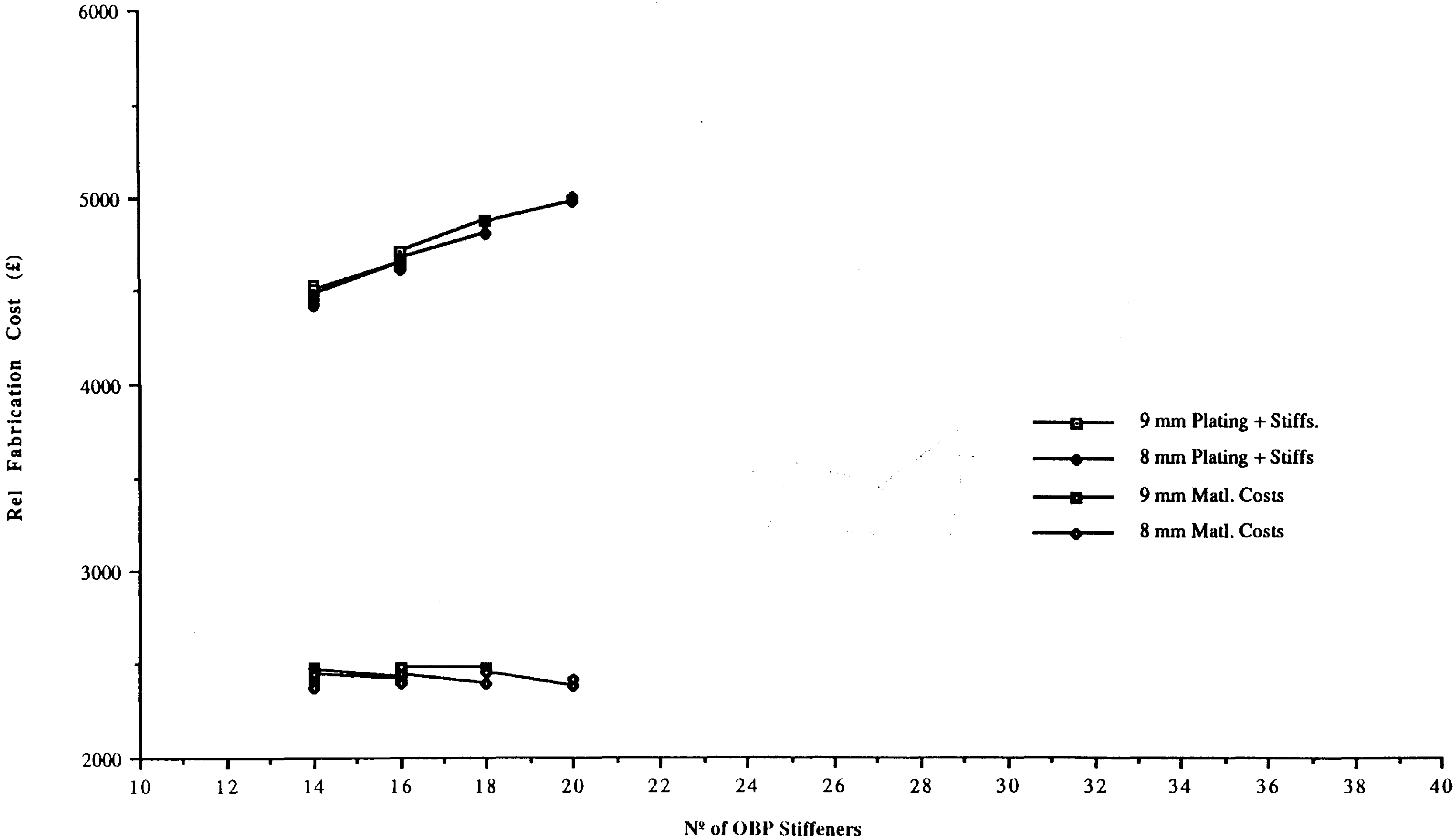


Fig. 6.6 - Flat Deck Panel - Constant Transverse Structure - OBP longitudinals
Total Rel. Fabrication and Matl. Costs vs No. of Stiffeners for two Plate Thicknesses

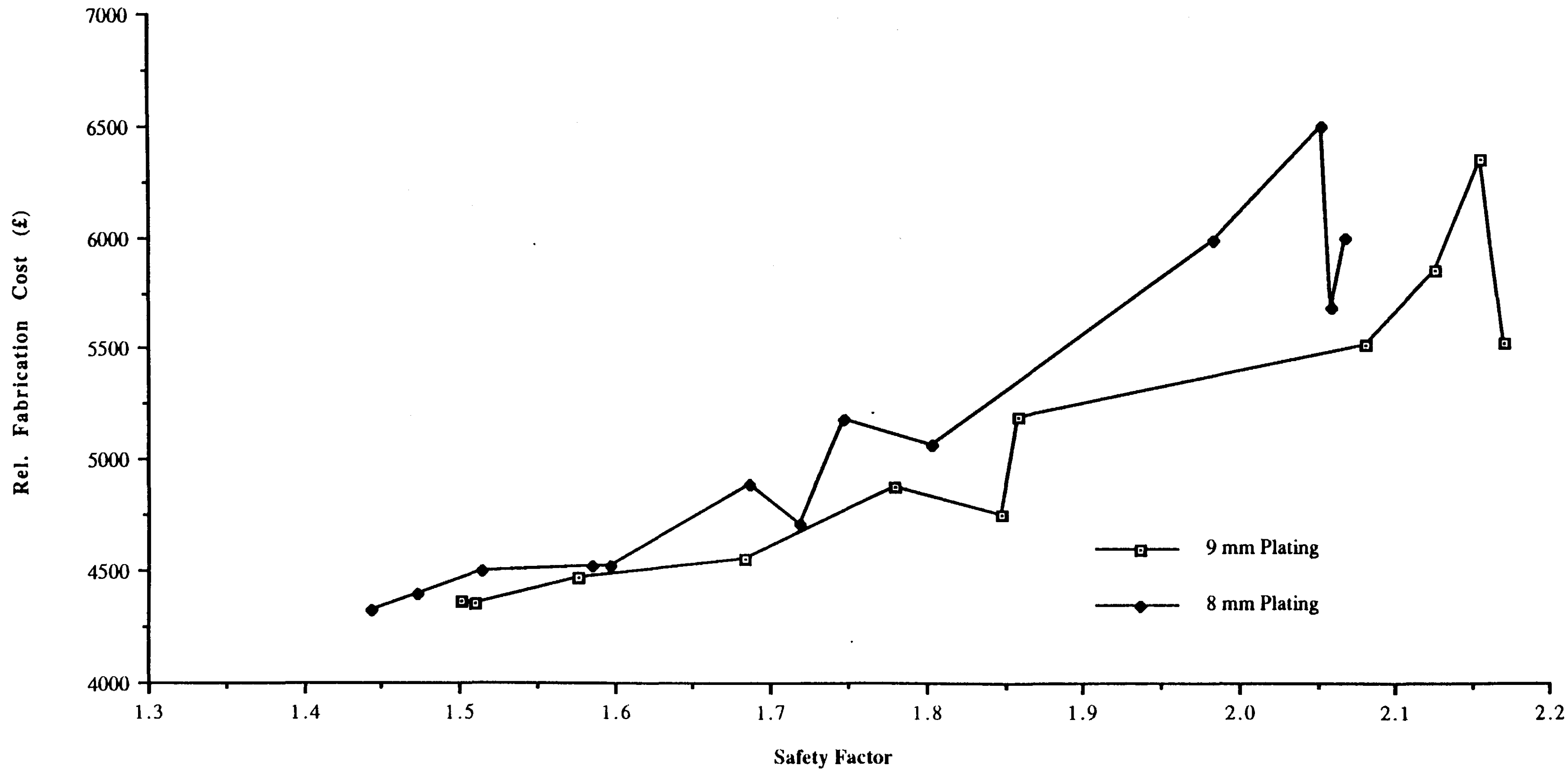


Fig. 6.7 - Flat Deck Panel - Constant Transverse structure - Flat bar longitudinals Safety Factor against Inter-frame Deck Panel Collapse vs Rel. Fabrication Cost (£)

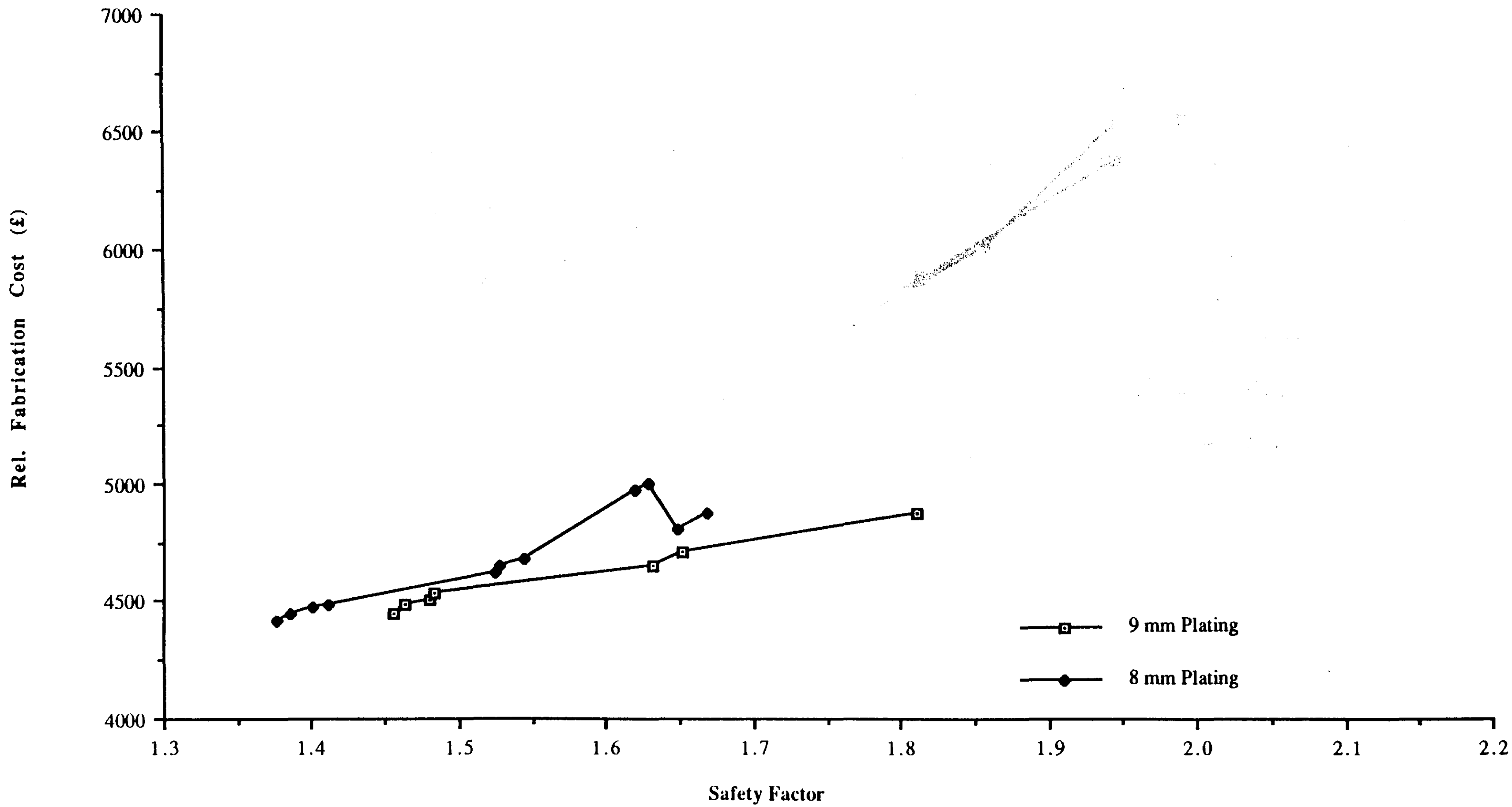


Fig. 6.8 - Flat Deck Panel - Constant Transverse Structure - OBP longitudinals
Safety Factor against Inter-frame Deck Panel Collapse vs Rel. Fabrication Cost (£)

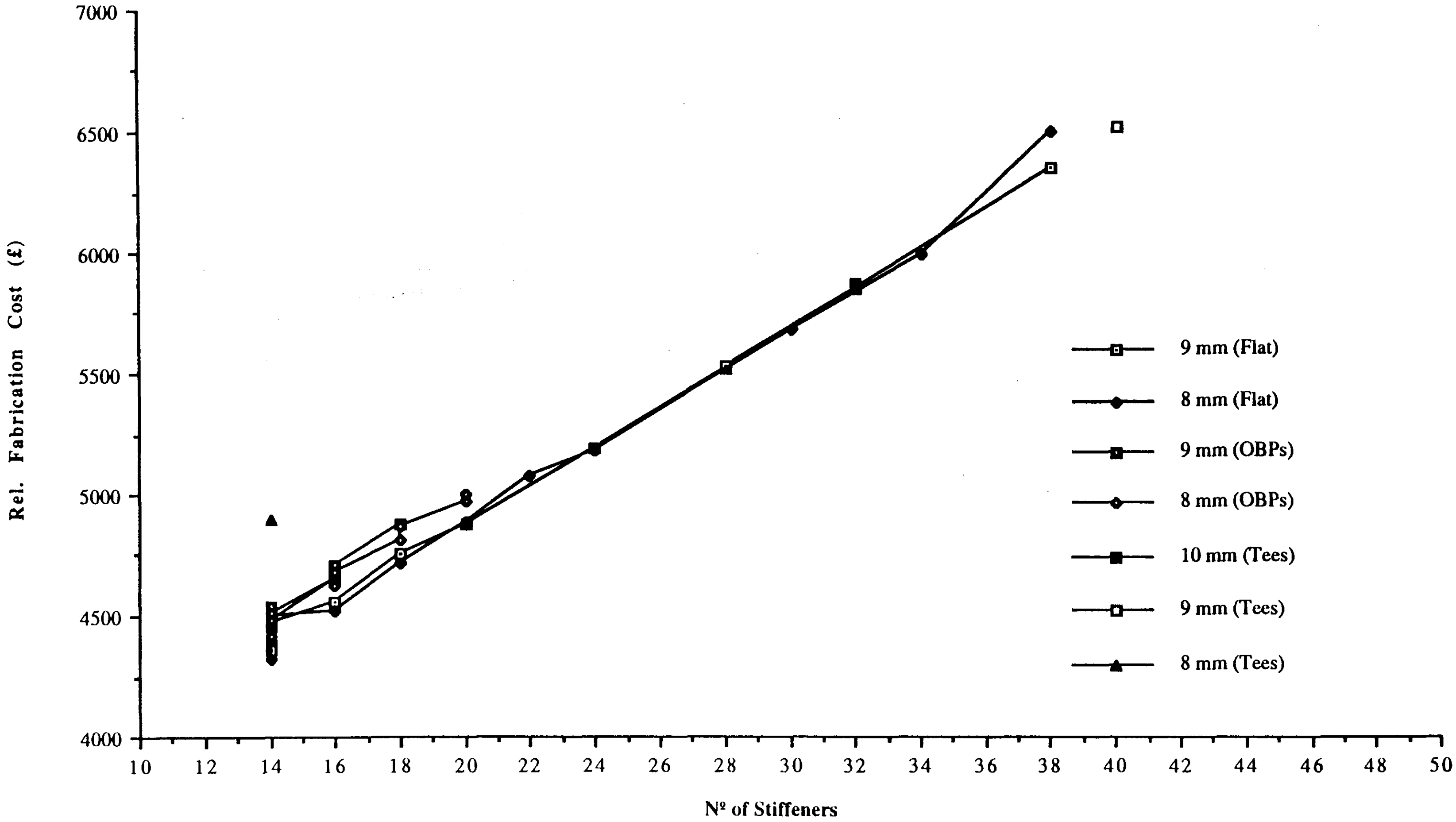


Fig. 6.9 - Flat Deck Panel - Constant Transverse Structure - Three longitudinal types
Total Rel. Fabrication Costs vs No. of Stiffeners for varying Plate Thicknesses

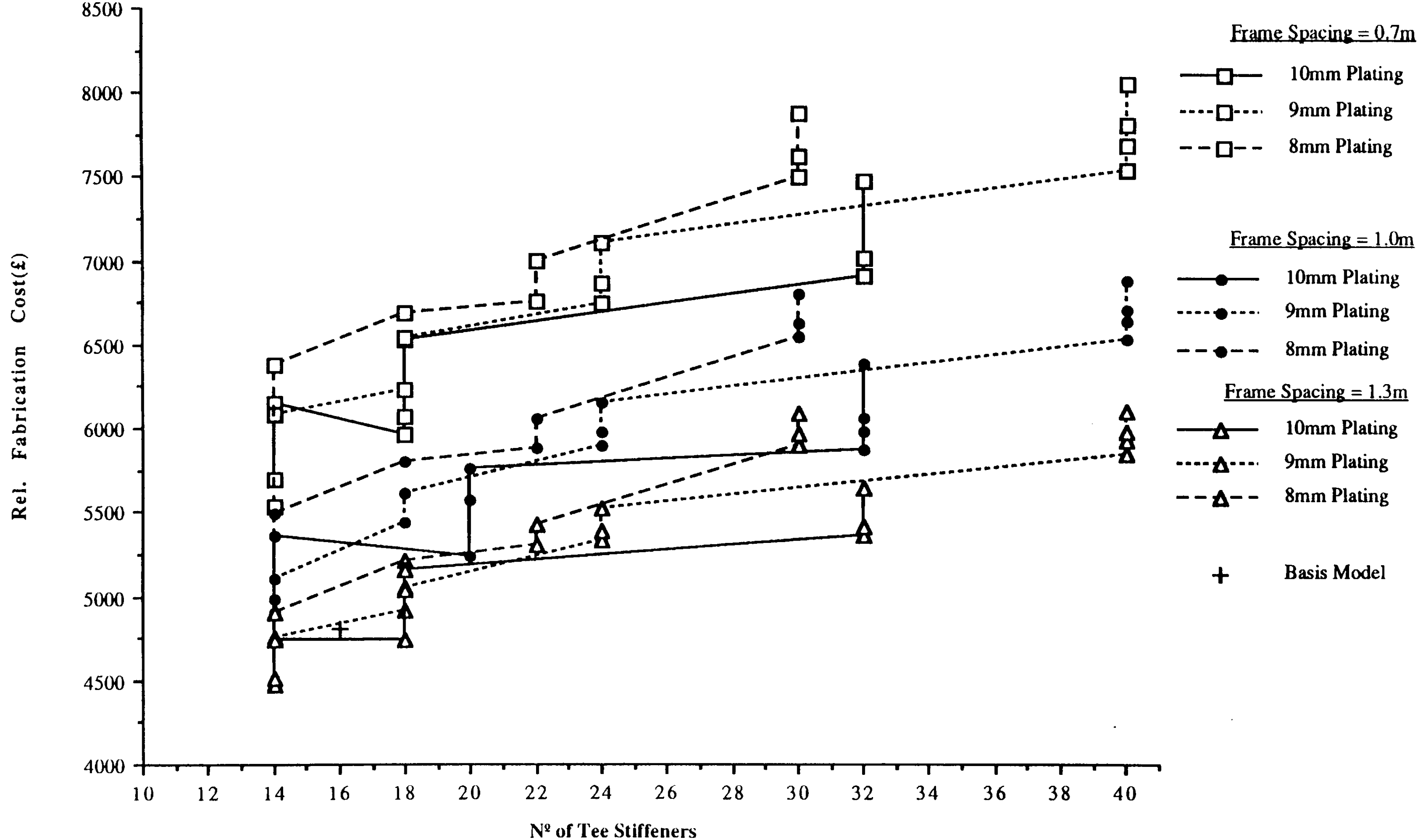


Fig. 6.10 - Flat Deck Panel - Varying Transverse Structure and Spacing - T-bar longitudinals Total Rel. Fabrication Cost vs No. of Stiffeners for Varying Plate Thicknesses

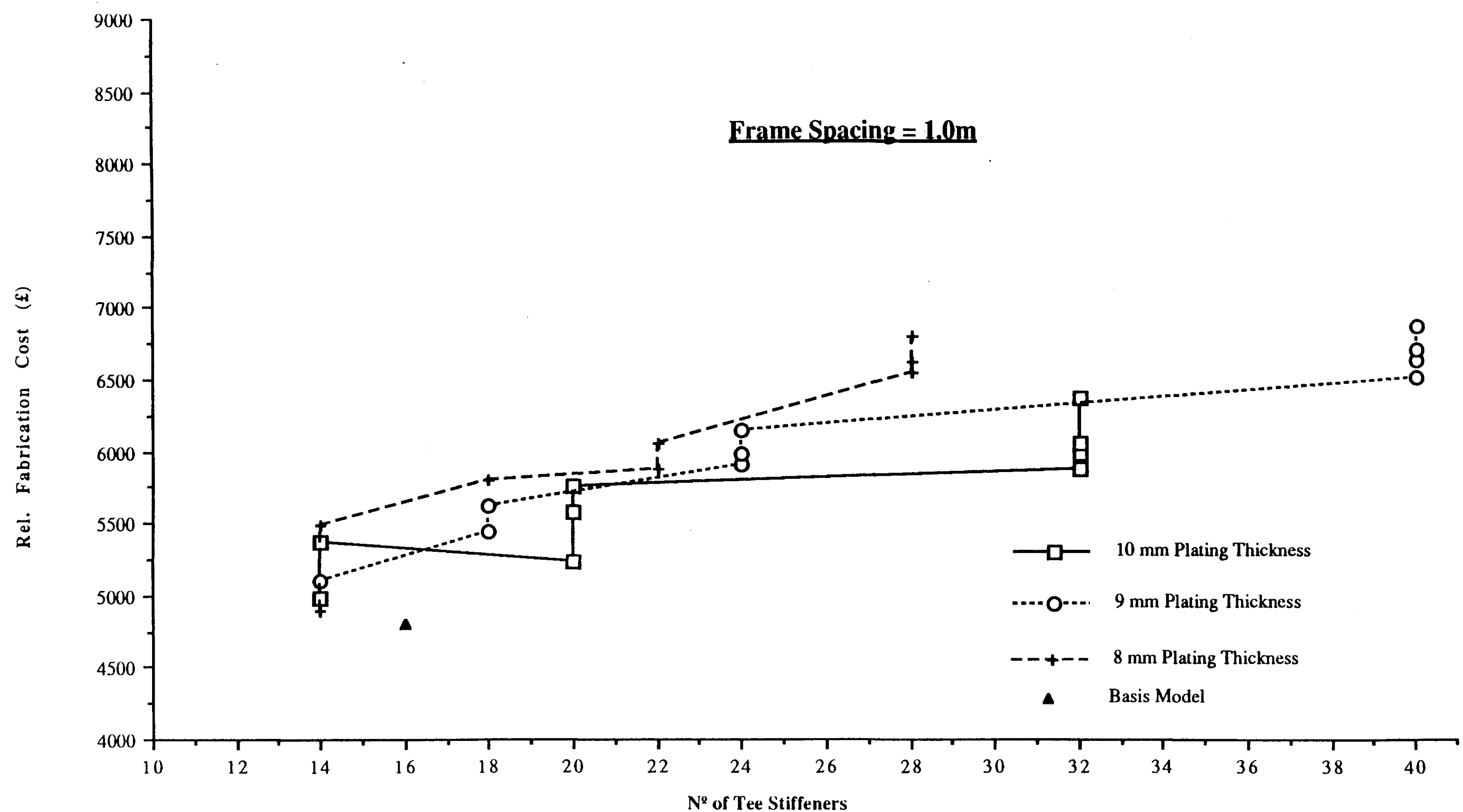


Fig. 6.11 - Flat Deck Panel - Varying Transverse Structure - T-bar longitudinals
Total Rel. Fabrication Costs vs No. of Stiffeners for varying Plate Thicknesses

Stiffener Type	Plate Thick (mm)	Stiffener size (mm)	Number of Stiffeners	Fabrication Manhours	Material Cost (£)	Panel Weight (T)	Safety Factor	Rel. Fab Cost (£)
OBP	9	200 * 8.5	18	160.1	2478	7.05	1.811	4878
		200 * 9	16	148.1	2428	6.91	1.632	4648
		200 * 10	16	148.3	2480	7.06	1.652	4706
		200 * 11	14	135.3	2444	6.95	1.463	4489
		200 * 12	14	135.2	2487	7.08	1.483	4536
		220 * 9	14	135.2	2415	6.89	1.456	4451
		220 * 10	14	135.1	2465	7.05	1.481	4505
OBP	8	200 * 8.5	20	172.2	2387	6.78	1.619	4971
		200 * 9	20	172.5	2416	6.87	1.629	5003
		200 * 10	18	160.6	2399	6.82	1.649	4808
		200 * 11	18	161.1	2457	7.01	1.668	4872
		200 * 12	16	148.1	2418	6.88	1.528	4653
		220 * 10	16	148.3	2394	6.84	1.524	4620
		220 * 11	16	148.7	2448	7.01	1.545	4678
		220 * 12	14	136.6	2398	6.85	1.386	4447
		240 * 10	14	136.1	2376	6.78	1.377	4416
		240 * 11	14	136.3	2431	6.96	1.401	4476
		260 * 10	14	136.1	2444	7.03	1.412	4484

Table 6.1
Flat Deck Panel Alternative Structural Designs using OBP Stiffeners

Stiffener Type	Plate Thick (mm)	Stiffener size (mm)	Number of Stiffeners	Fabrication Manhours	Material Cost (£)	Panel Weight (T)	Safety Factor	Rel. Fab Cost (£)
Flat bar	9	40 * 25	38	269.9	2312	6.915	2.153	6350
		40 * 30	32	234.6	2327	6.93	2.125	5846
		40 * 35	28	211.5	2347	6.974	2.08	5520
		45 * 30	28	214.3	2310	6.906	2.169	5525
		45 * 35	24	190.8	2330	6.906	1.858	5192
		50 * 40	20	169.4	2340	7.013	1.79	4881
		55 * 40	18	159.2	2362	6.993	1.848	4750
		60 * 40	16	143.7	2327	6.935	1.684	4558
		60 * 45	14	136.4	2321	6.906	1.502	4367
		65 * 40	14	137.8	2262	6.837	1.51	4359
		90 * 30	14	144.8	2297	6.906	1.577	4469
Flat bar	8	40 * 30	38	280.7	2289	6.914	2.051	6500
		40 * 35	34	246.1	2295	6.894	1.983	5987
		45 * 30	34	249.5	2250	6.811	2.067	5993
		45 * 35	30	226.1	2293	6.877	2.058	5683
		50 * 40	24	193.2	2280	6.914	1.747	5178
		55 * 40	22	193.2	2318	6.933	1.803	5071
		60 * 40	20	173.4	2289	6.914	1.686	4890
		60 * 45	18	161.1	2299	6.943	1.719	4716
		60 * 50	16	148.7	2291	6.914	1.585	4522
		65 * 45	16	150.3	2267	6.855	1.597	4522
		65 * 50	14	137.8	2252	6.792	1.443	4319
		80 * 40	14	142.1	2226	6.757	1.473	4392
		110 * 30	14	150.5	2241	6.826	1.514	4499

Table 6.2
Flat Deck Panel Alternative Structural Designs using Flat bar Stiffeners

Tables 6.3

ESTIMATED FABRICATION TIME, MATERIAL WEIGHT AND COSTS OF A TYPICAL MIDSHIP SECTION OF A ROYAL NAVY FRIGATE

Deck structure

DECK STRUCTURE CONSISTS OF 3 PANELS:

Table 6.3a	-	Wing Panel
Table 6.3b	-	Centre Panel
Table 6.3c	-	Wing Panel
Table 6.3d	-	Summary of Total Deck

Table 6.3a

THE DIMENSIONS OF EACH PLATE ON PANEL Nº 1 ARE :

LENGTH (m)	WIDTH (m)	THICKNESS (m)
7.22	1.9	0.009
7.22	1.65	0.009

SECTION	TYPE	DIMENSIONS (m)	Nº OFF
LONGITUDINALS	FLAT	0.040 * 0.035	11
TRANSVERSES	TEES	0.1520 * 0.073	7

	Nº OFF	WELDING METHOD	WELDING TIME
MILD STEEL PLATES	2	MINIDECK	4.181
FLAT LONGITUDINALS	11	FILLET	16.190
TEE TRANSVERSES	7	FILLET	6.845
CONNECTIONS BETWEEN ORTHOGONAL MEMBERS	77	FILLET	31.069

SUMMARY OF TIMES

TOTAL PLATING TIME FOR THIS FLAT PANEL	=	25.960
TOTAL WELDING TIME FOR THIS FLAT PANEL	=	58.286
TOTAL FABRICATION TIME FOR THIS FLAT PANEL	=	84.245

COMPONENT	% FAB. TIME
PLATING	35.78
LONGITUDINALS	16.22
TRANSVERSES	8.13
CONNECTIONS	36.88

	WEIGHT (Tonne)	COST (£)
SECTIONS	0.752	203.02
PLATES	1.825	601.98
TRANSVERSES	0.297	169.02
TOTAL	2.873	974.02

Table 6.3b

THE DIMENSIONS OF EACH PLATE ON PANEL Nº 2 ARE :

LENGTH (m)	WIDTH (m)	THICKNESS (m)
7.22	1.50	0.009

SECTION	TYPE	DIMENSIONS (m)	Nº OFF
LONGITUDINALS	FLAT	0.040 * 0.035	6
TRANSVERSES	TEES	0.1520 * 0.073	7

	Nº OFF	WELDING METHOD	WELDING TIME
MILD STEEL PLATES	1	MINIDECK	0.000
FLAT LONGITUDINALS	6	FILLET	8.950
TEE TRANSVERSES	7	FILLET	3.011
CONNECTIONS BETWEEN ORTHOGONAL MEMBERS	42	FILLET	16.947

SUMMARY OF TIMES

TOTAL PLATING TIME FOR THIS FLAT PANEL =
14.078
TOTAL WELDING TIME FOR THIS FLAT PANEL =
28.908

TOTAL FABRICATION TIME FOR THIS FLAT PANEL = 42.986

COMPONENT	% FAB. TIME
PLATING	32.75
LONGITUDINALS	20.82
TRANSVERSES	7.01
CONNECTIONS	39.42

	WEIGHT (Tonne)	COST (£)
SECTIONS	0.410	110.74
PLATES	0.760	255.45
TRANSVERSES	0.057	32.50
TOTAL	1.227	398.69

Table 6.3c

THE DIMENSIONS OF EACH PLATE ON PANEL Nº 1 ARE :

LENGTH (m)	WIDTH (m)	THICKNESS (m)
7.22	1.9	0.009
7.22	1.65	0.009

SECTION	TYPE	DIMENSIONS (m)	Nº OFF
LONGITUDINALS	FLAT	0.040 * 0.035	11
TRANSVERSES	TEES	0.1520 * 0.073	7

	Nº OFF	WELDING METHOD	WELDING TIME
MILD STEEL PLATES	2	MINIDECK	4.181
FLAT LONGITUDINALS	11	FILLET	16.190
TEE TRANSVERSES	7	FILLET	6.845
CONNECTIONS BETWEEN ORTHOGONAL MEMBERS	77	FILLET	31.069

SUMMARY OF TIMES

TOTAL PLATING TIME FOR THIS FLAT PANEL	=	25.960
TOTAL WELDING TIME FOR THIS FLAT PANEL	=	58.286
TOTAL FABRICATION TIME FOR THIS FLAT PANEL	=	84.245

COMPONENT	% FAB. TIME
PLATING	35.78
LONGITUDINALS	19.22
TRANSVERSES	8.13
CONNECTIONS	36.88

	WEIGHT (Tonne)	COST (£)
SECTIONS	0.752	203.02
PLATES	1.825	601.98
TRANSVERSES	0.297	169.02
TOTAL	2.873	974.02

Table 6.3d

SUMMARY FOR DECK PANEL

	WEIGHT (Tonne)	COST (£)
SECTIONS	1.914	516.78
PLATES	4.410	1459.41
TRANSVERSES	0.650	370.55
TOTAL	6.974	2346.74

TOTAL FABRICATION TIME FOR DECK PANEL = 211.477 MANHOURS

TOTAL MATERIAL COST FOR DECK PANEL = 2346.74 POUNDS

	% WEIGHT	%COST
PLATES	63.23	62.19
LONGITUDINALS	27.45	22.02
TRANSVERSES	9.33	15.79

Tables 6.4

ESTIMATED FABRICATION TIME, MATERIAL WEIGHT AND COSTS OF A TYPICAL MIDSHIP SECTION OF A ROYAL NAVY FRIGATE

Deck Panel structure

DECK STRUCTURE CONSISTS OF 3 PANELS:

Table 6.4a	-	Wing Panel
Table 6.4b	-	Centre Panel
Table 6.4c	-	Wing Panel
Table 6.4d	-	Summary of Total Deck

Table 6.4a

THE DIMENSIONS OF EACH PLATE ON PANEL Nº 1 ARE :

LENGTH (m)	WIDTH (m)	THICKNESS (m)
7.22	1.95	0.009
7.22	1.65	0.009

SECTION	TYPE	DIMENSIONS (m)	Nº OFF
LONGITUDINALS	FLAT	0.045 * 0.030	11
TRANSVERSES	TEES	0.1520 * 0.073	7

	Nº OFF	WELDING METHOD	WELDING TIME
MILD STEEL PLATES	2	MINIDECK	4.181
FLAT LONGITUDINALS	11	FILLET	16.190
TEE TRANSVERSES	7	FILLET	6.845
CONNECTIONS BETWEEN ORTHOGONAL MEMBERS	77	FILLET	32.178

SUMMARY OF TIMES

TOTAL PLATING TIME FOR THIS FLAT PANEL	=	25.960
TOTAL WELDING TIME FOR THIS FLAT PANEL	=	59.395
TOTAL FABRICATION TIME FOR THIS FLAT PANEL		85.354

COMPONENT	% FAB. TIME
PLATING	35.31
LONGITUDINALS	18.97
TRANSVERSES	8.02
CONNECTIONS	37.70

	WEIGHT (Tonne)	COST (£)
SECTIONS	0.725	188.52
PLATES	1.825	601.98
TRANSVERSES	0.297	169.02
TOTAL	2.846	959.52

TABLE 6.4b

THE DIMENSIONS OF EACH PLATE ON PANEL Nº 2 ARE :

LENGTH (m)	WIDTH (m)	THICKNESS (m)
7.22	1.50	0.009

SECTION	TYPE	DIMENSIONS (m)	Nº OFF
LONGITUDINALS	FLAT	0.045 * 0.030	6
TRANSVERSES	TEES	0.1520 * 0.073	7

	Nº OFF	WELDING METHOD	WELDING TIME
MILD STEEL PLATES	1	MINIDECK	0.000
FLAT LONGITUDINALS	6	FILLET	8.950
TEE TRANSVERSES	7	FILLET	3.011
CONNECTIONS BETWEEN ORTHOGONAL MEMBERS	42	FILLET	17.552

SUMMARY OF TIMES

TOTAL PLATING TIME FOR THIS FLAT PANEL	=	14.078
TOTAL WELDING TIME FOR THIS FLAT PANEL	=	29.513
TOTAL FABRICATION TIME FOR THIS FLAT PANEL		43.591

COMPONENT	% FAB. TIME
PLATING	32.30
LONGITUDINALS	20.53
TRANSVERSES	6.91
CONNECTIONS	40.26

	WEIGHT (Tonne)	COST (£)
SECTIONS	0.395	102.83
PLATES	0.760	255.45
TRANSVERSES	0.057	32.50
TOTAL	1.213	390.78

Table 6.4c

THE DIMENSIONS OF EACH PLATE ON PANEL Nº 3 ARE:

LENGTH (m)	WIDTH (m)	THICKNESS (m)
7.22	1.95	0.009
7.22	1.65	0.009

SECTION	TYPE	DIMENSIONS (m)	Nº OFF
LONGITUDINALS	FLAT	0.045 * 0.030	11
TRANSVERSES	TEES	0.1520 * 0.073	7

	Nº OFF	WELDING METHOD	WELDING TIME
MILD STEEL PLATES	2	MINIDECK	4.181
FLAT LONGITUDINALS	11	FILLET	16.190
TEE TRANSVERSES	7	FILLET	6.845
CONNECTIONS BETWEEN ORTHOGONAL MEMBERS	77	FILLET	32.178

SUMMARY OF TIMES

TOTAL PLATING TIME FOR THIS FLAT PANEL	=	25.960
TOTAL WELDING TIME FOR THIS FLAT PANEL	=	59.395
TOTAL FABRICATION TIME FOR THIS FLAT PANEL		85.354

COMPONENT	% FAB. TIME
PLATING	35.31
LONGITUDINALS	18.97
TRANSVERSES	8.02
CONNECTIONS	47.70

	WEIGHT (Tonne)	COST (£)
SECTIONS	0.725	188.52
PLATES	1.825	601.98
TRANSVERSES	0.297	169.02
TOTAL	2.846	959.52

Table 6.4d

SUMMARY FOR DECK PANEL

	WEIGHT (Tonne)	COST (£)
SECTIONS	1.846	479.87
PLATES	4.410	1459.41
TRANSVERSES	0.650	370.55
TOTAL	6.906	2309.83

TOTAL FABRICATION TIME FOR DECK PANEL = 214.299 MANHOURS

TOTAL MATERIAL COST FOR DECK PANEL = 2309.83 POUNDS

	% WEIGHT	%COST
PLATES	63.85	63.18
LONGITUDINALS	26.73	20.78
TRANSVERSES	9.42	16.04

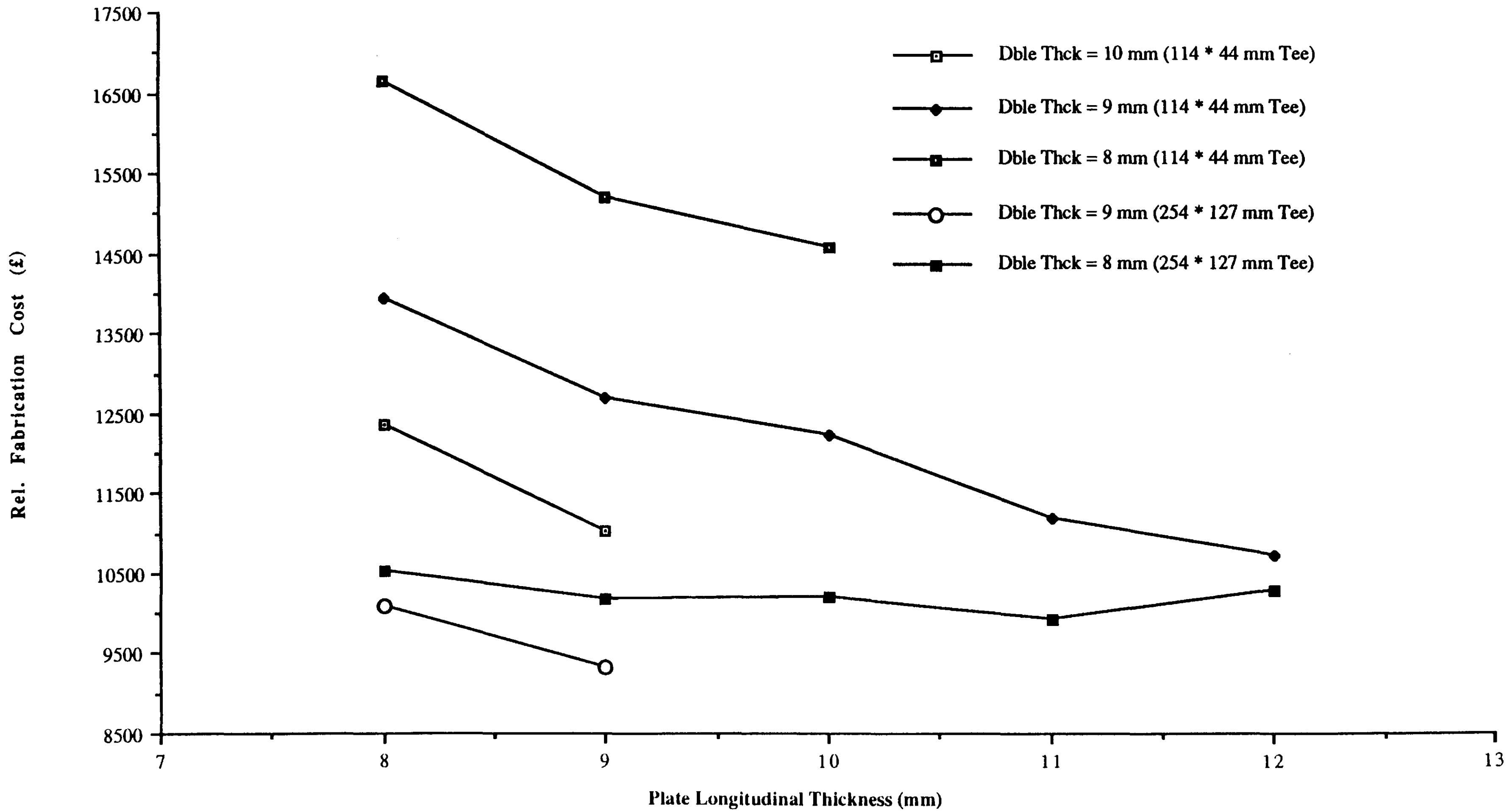


Fig. 6.12 - Double Bottom Construction Sequence 1 - Double thickness of Tank Top and Outer Bottom Plating Plate Longitudinal Thickness vs Total Rel. Fabrication Cost for varying Double Thicknesses and two stiffener sizes

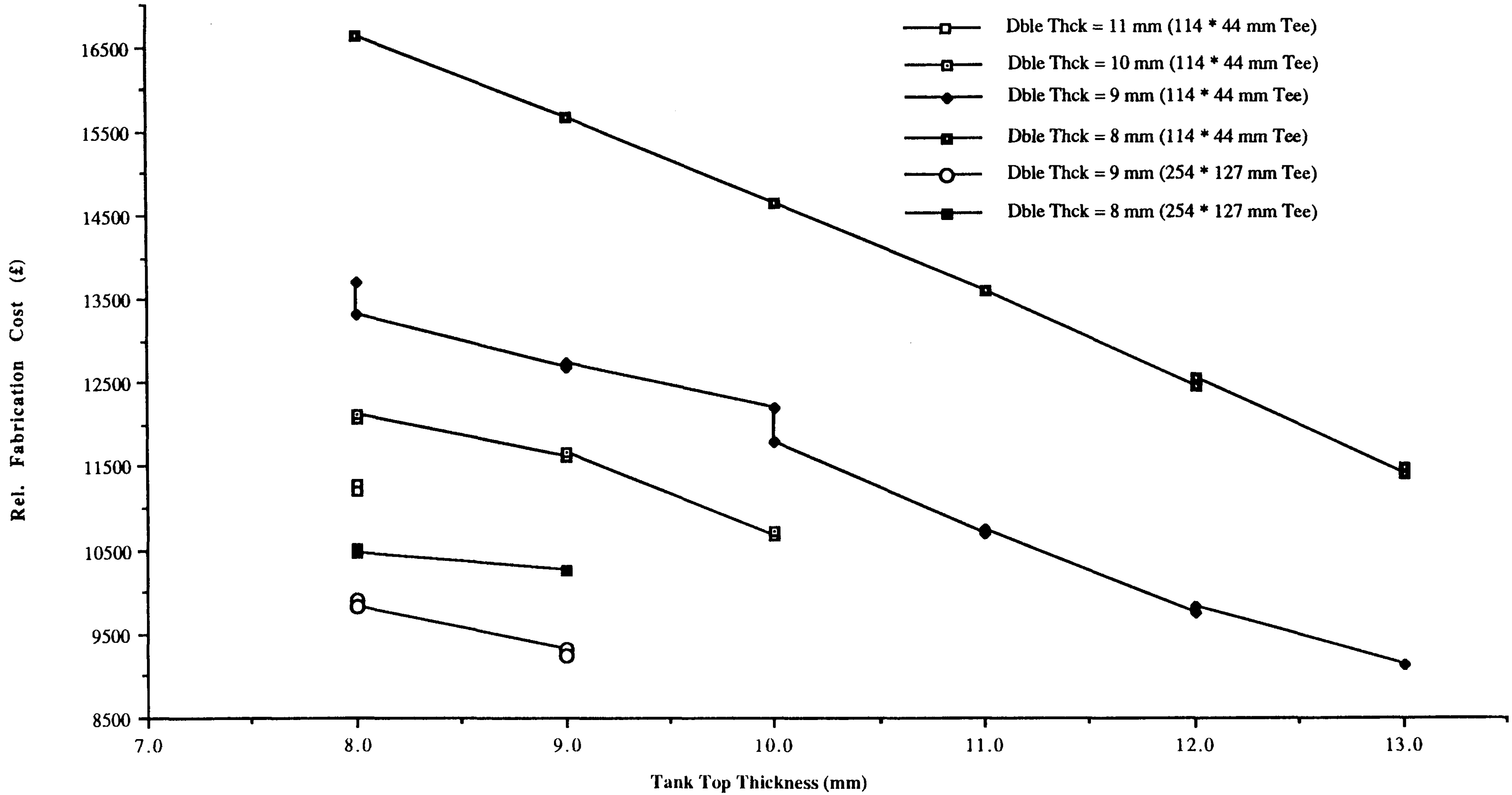


Fig. 6.13 - Double Bottom Construction Sequence 1 - Double Thickness of Plate Long. and Outer Bottom Plating Tank Top Thickness vs Total Rel. Fabrication Costs for varying Double Thicknesses and two stiffener sizes

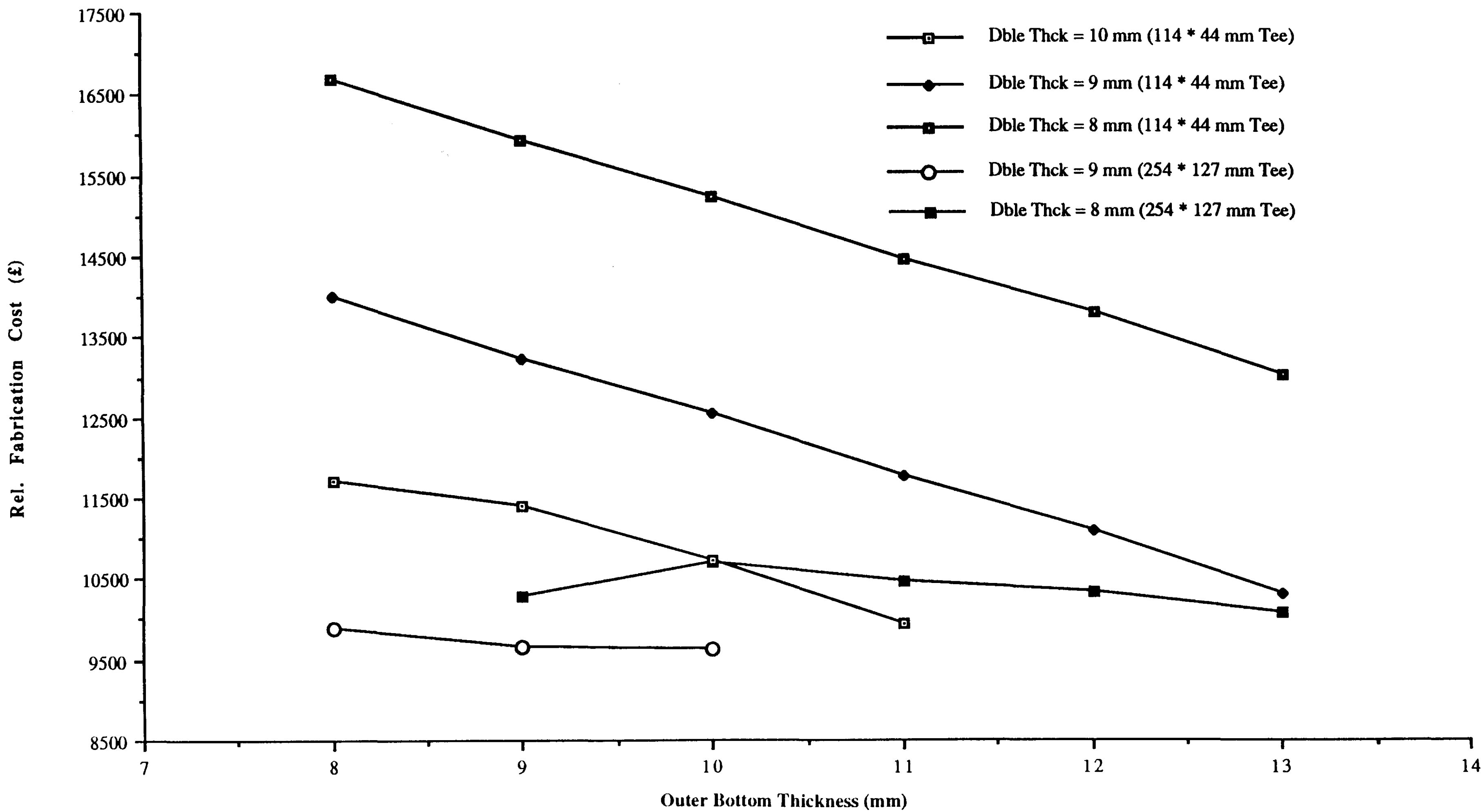


Fig. 6.14 - Double Bottom Construction Sequence 1 - Double Thickness of Tank Top and Plate Long. Plating Outer Bottom Thickness vs Total Rel. Fabrication Cost for varying Double Thicknesses and two stiffener sizes

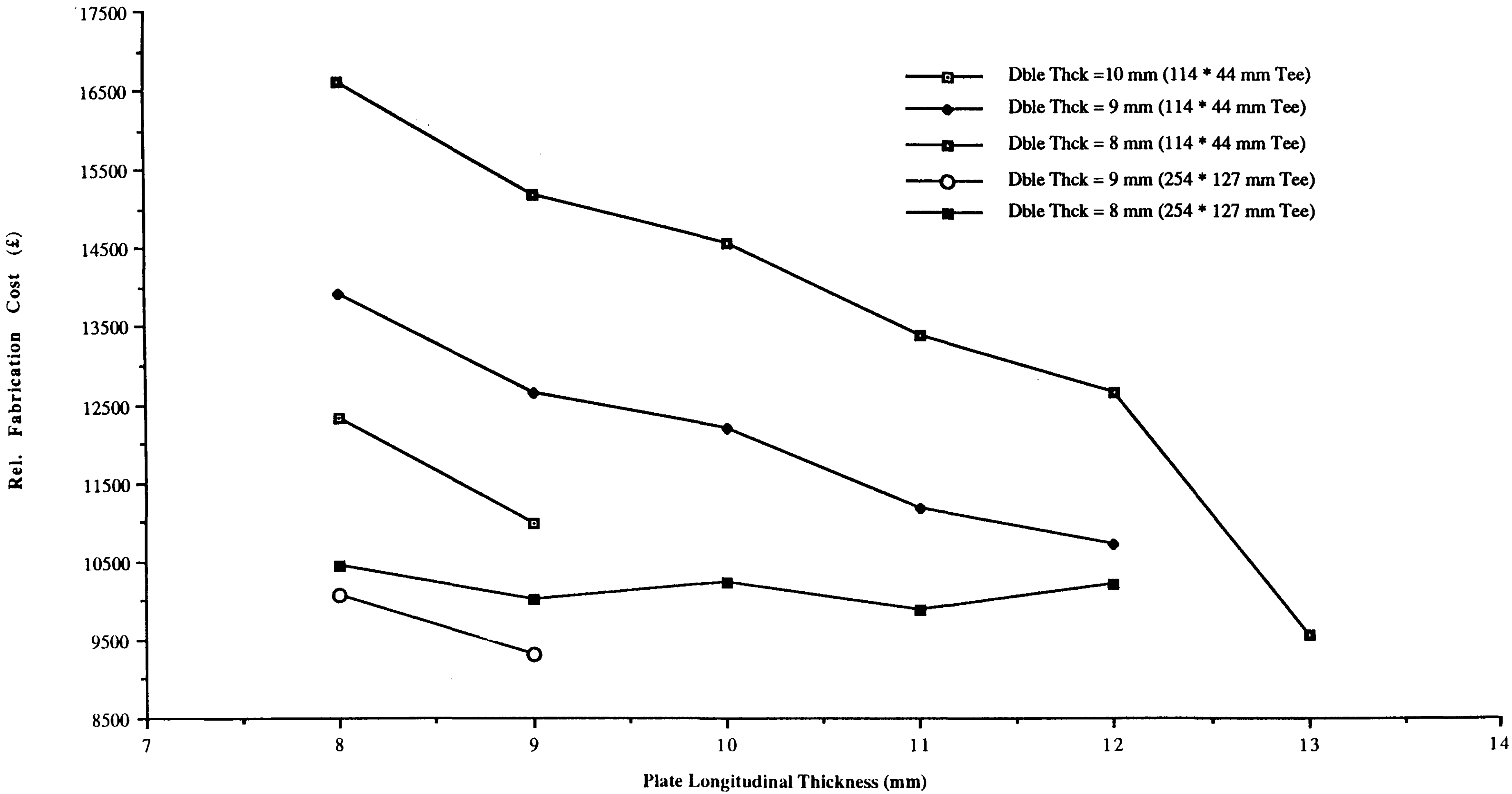


Fig. 6.15 - Double Bottom Construction Sequence 2 - Double Thickness of Tank Top and Outer Bottom Plating Plate Longitudinal Thickness vs Total Rel. Fabrication Cost for varying Double Thicknesses and two stiffener sizes

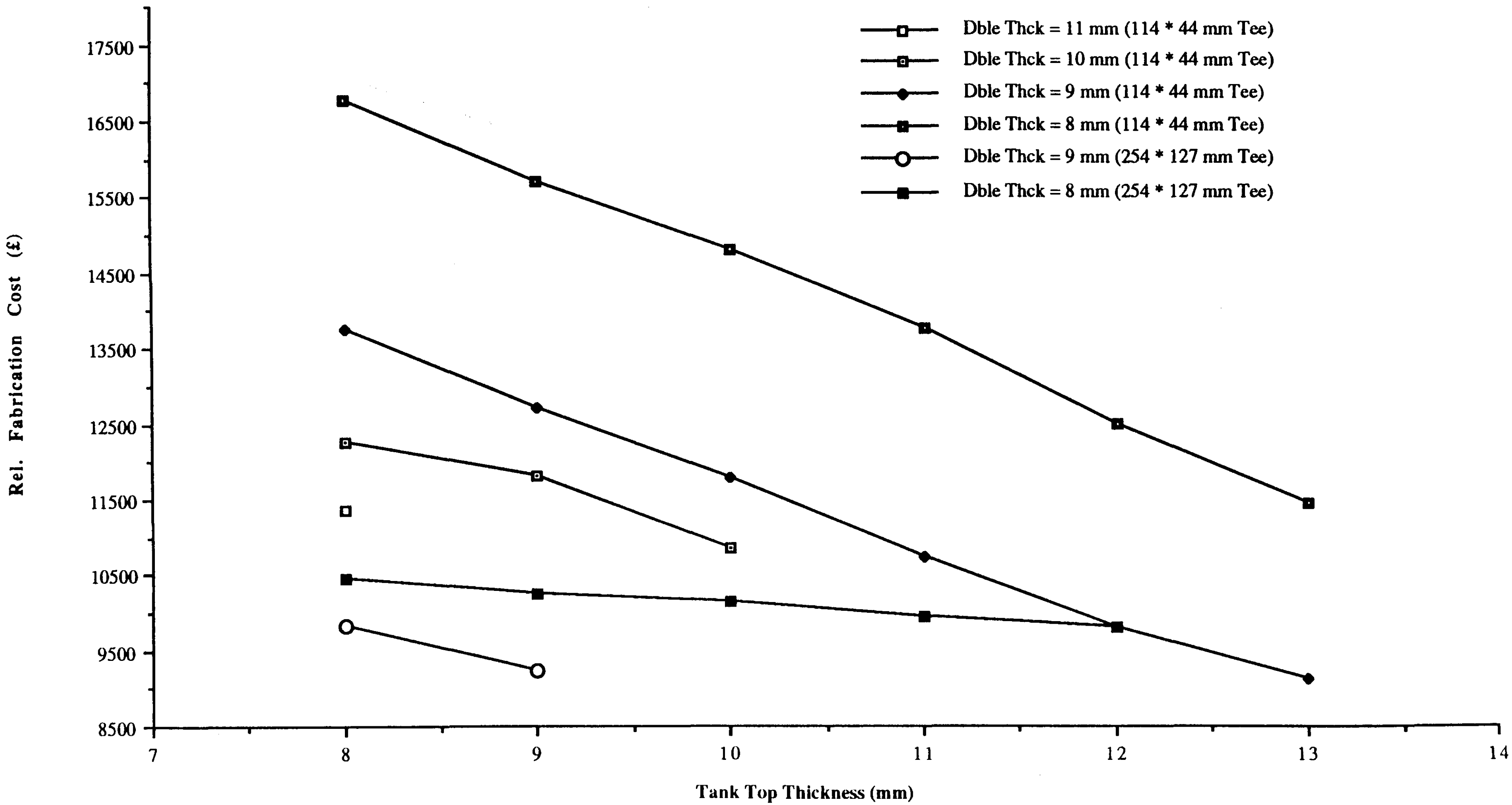


Fig. 6.16 - Double Bottom Construction Sequence 2 - Double Thickness of Plate Long. and Outer Bottom Plating Tank Top Thickness vs Total Rel. Fabrication Cost for varying Double Thicknesses and two stiffener sizes

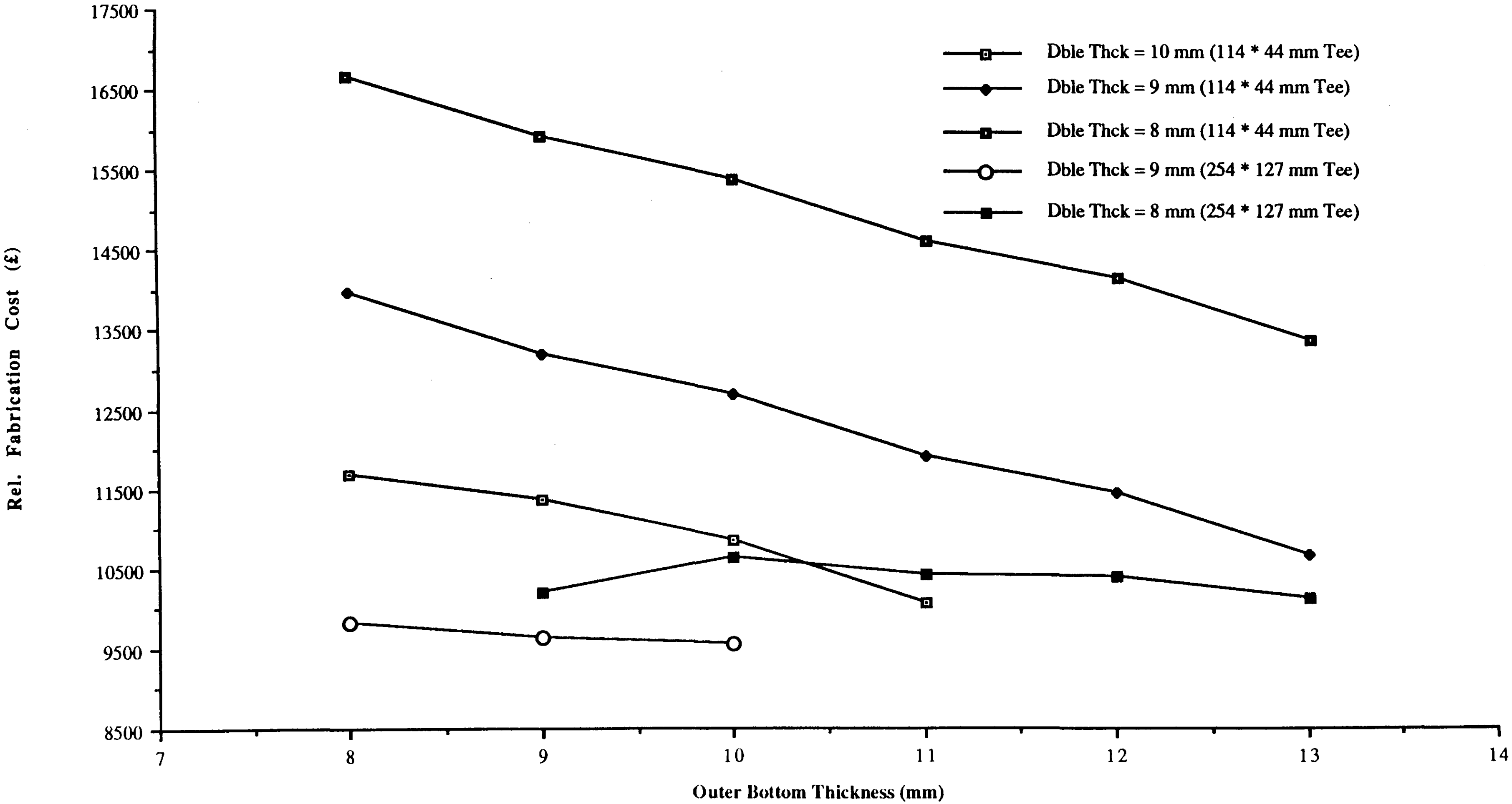


Fig. 6.17 - Double Bottom Construction Sequence 2 - Double Thickness of Tank Top and Plate Long. Plating Outer Bottom Thickness vs Total Rel. Fabrication Cost for varying Double Thicknesses and two stiffener sizes

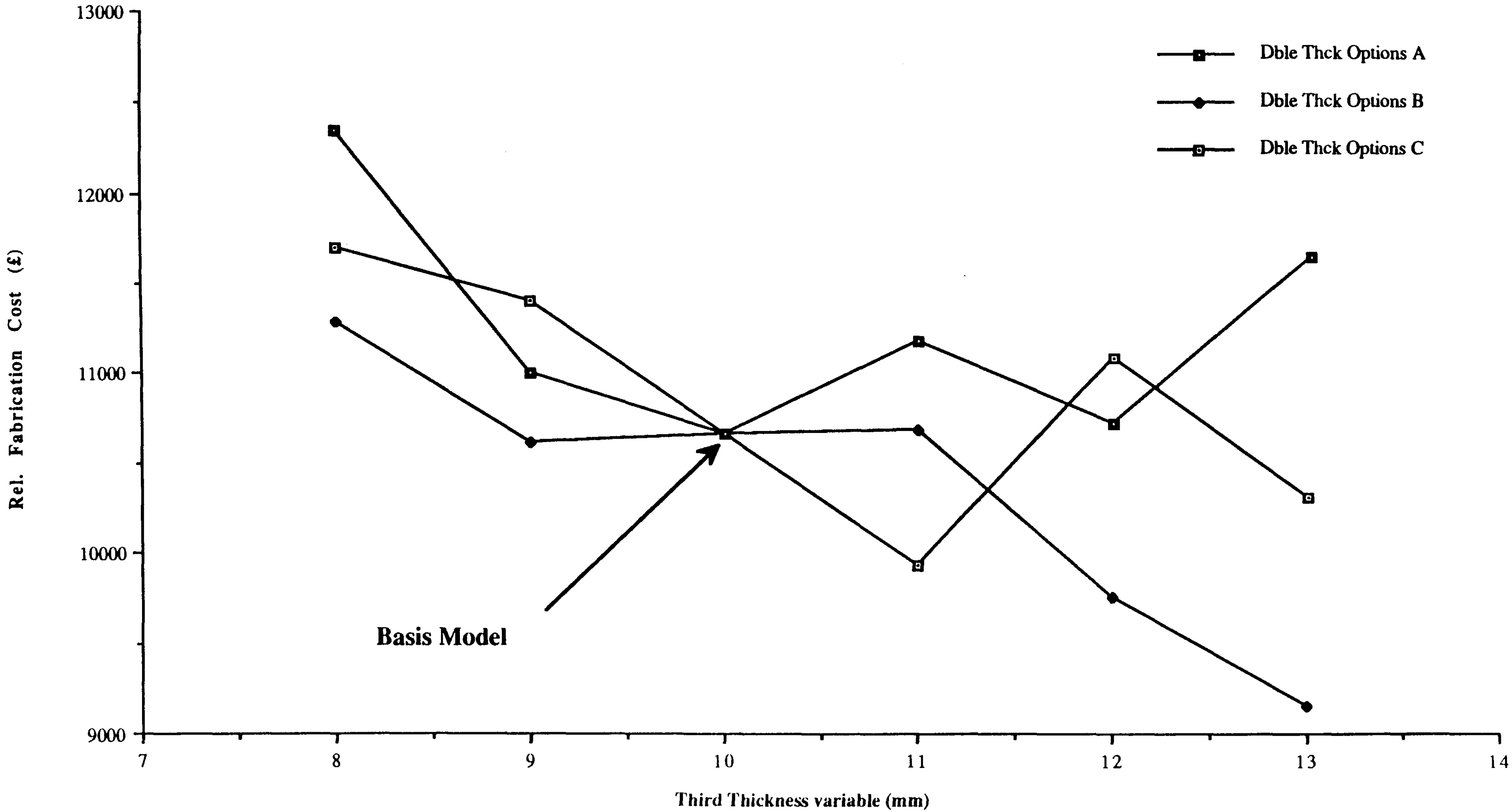


Fig. 6.18 - Double Bottom Construction Sequence 2 - Local Optima of Double Bottom Structural Options Third thickness variable vs Total Rel. Fabrication Cost for 114* 44 mm Tee Stiffener

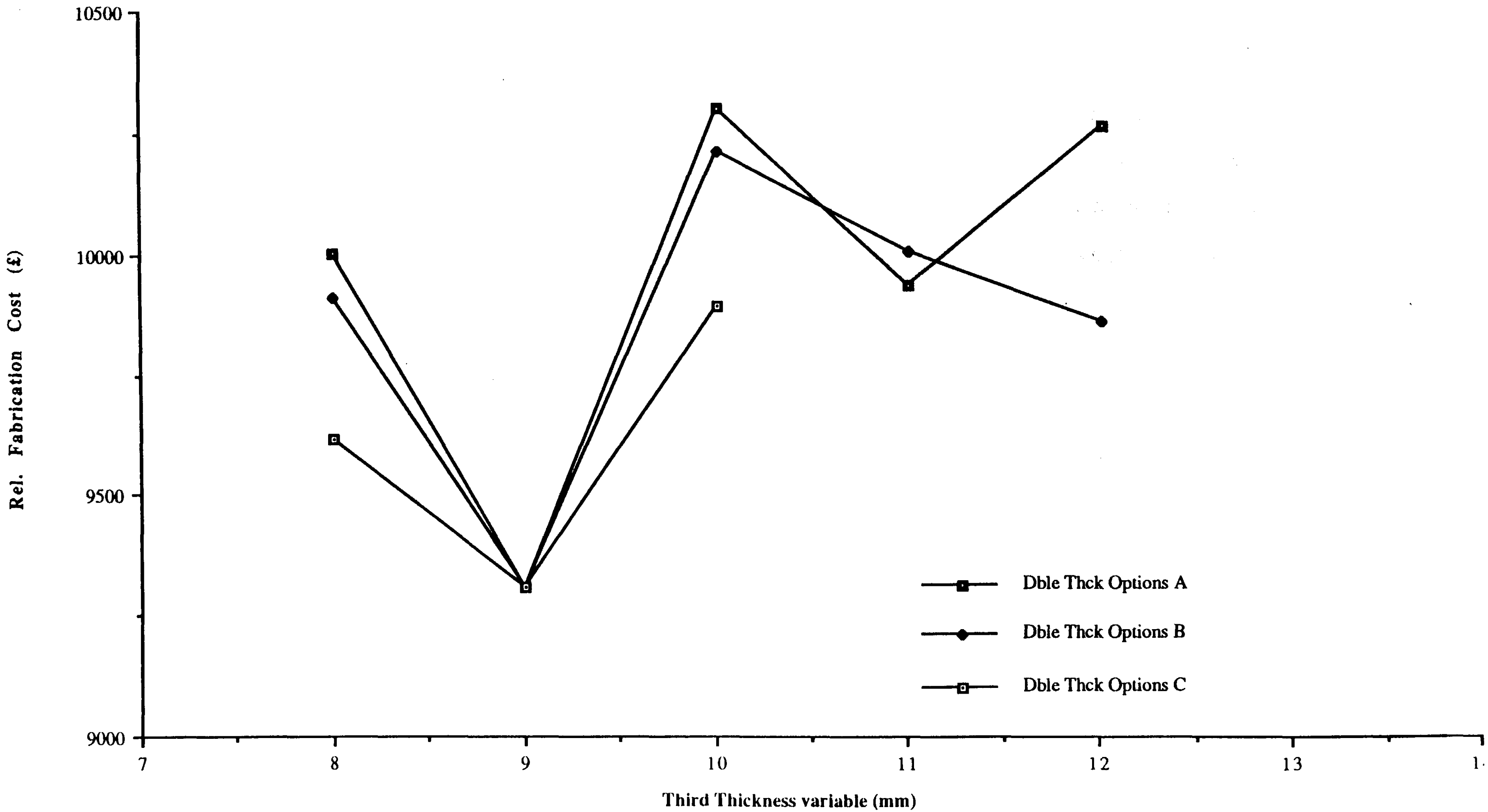


Fig. 6.19 - Double Bottom Construction Sequence 2 - Local Optima of Double Bottom Structural Options Third thickness variable vs Total Rel. Fabrication Cost for 254 * 127 mm Tee Stiffener

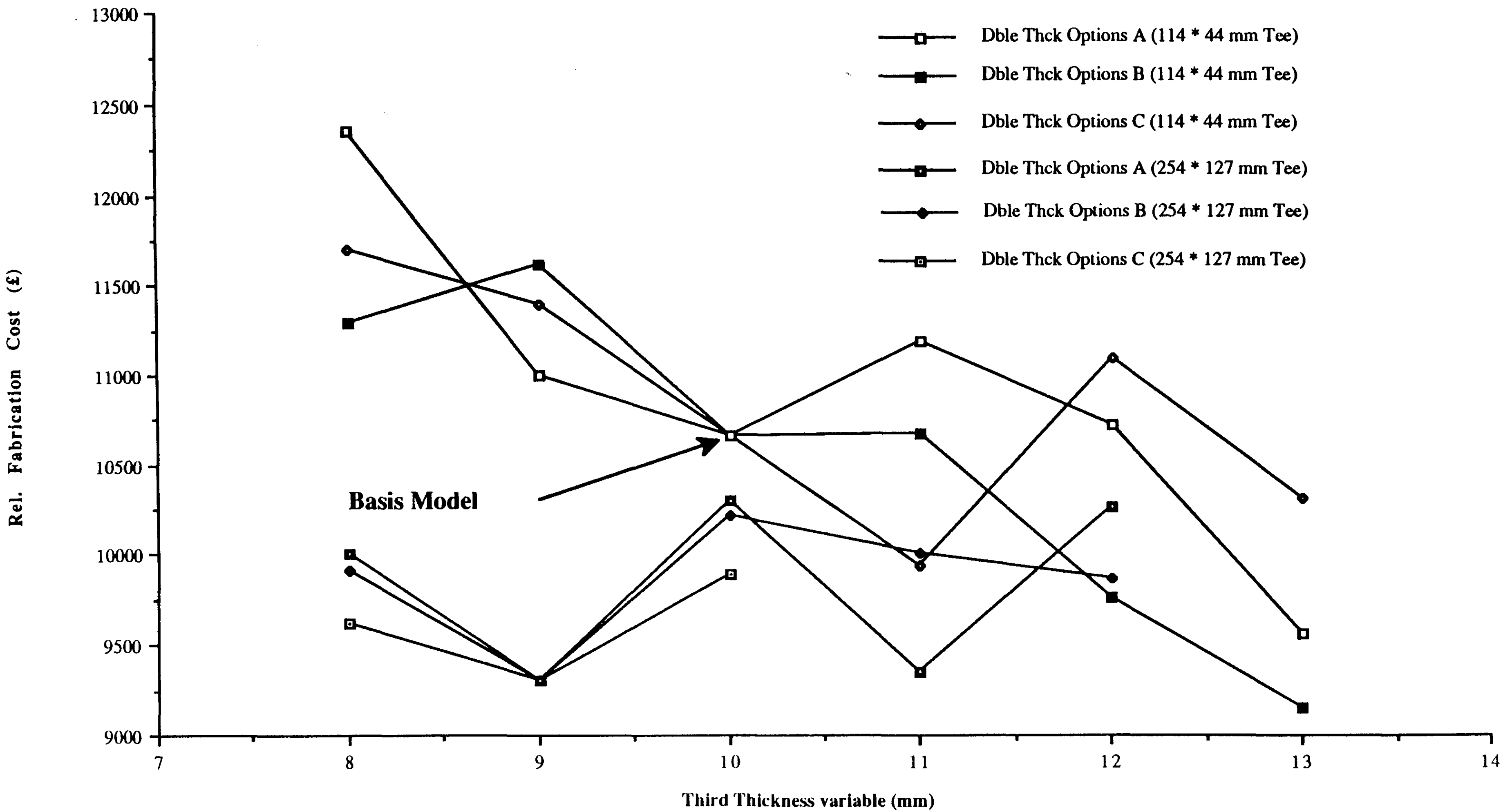


Fig. 6.20 - Double Bottom Construction Sequence 2 - Local Optima of Double Bottom Structural Options Third Thickness variable vs Total Rel. Fabrication Cost for two stiffener sizes

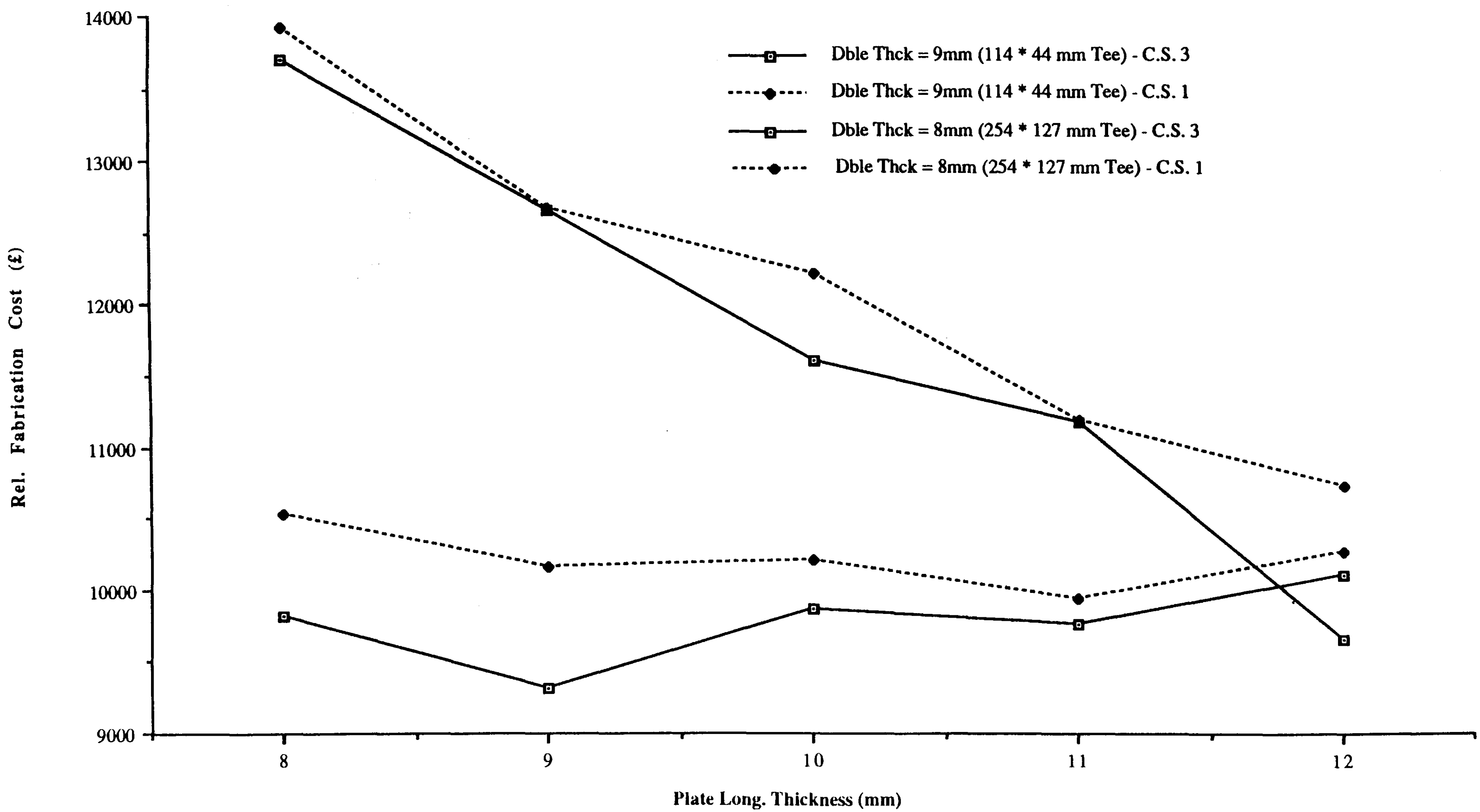


Fig. 6.21 - Comparisons between Double Bottom Construction Sequences 1 and 3 - Double Thickness of Tank Top and Outer Bottom Plating Plate Longitudinal Thickness vs Total Rel. Fabrication Cost for two Double Thicknesses and stiffener sizes

OPTION	OBP (mm)	C. S. 1 £	C. S. 2 £	C. S. 3 £	C. S. 4 £
9A8	220 * 9	10371	10165	9913	10129
8A10	**280 * 12**	**9660**	**9454**	**9165***	**9379**
8A9	220 * 9	10651	10445	10193	10406
8A9	220 * 10	10338	10133	9882	10092
8B10	220 * 9	10431	10226	9960	10173
8B10	220 * 10	10562	10356	10083	10305
8B9	220 * 9	10816	10610	10358	10577
8B9	220 * 10	10502	10297	10046	10262
8B8	220 * 9	11275	11070	10818	11034
8B8	220 * 10	10962	10756	10506	10720
8B8	220 * 11	10651	10445	10193	10408
8B8	220 * 12	10338	10133	9882	10097
8B8	240 * 9.5	10812	10606	10353	10569
8B8	240 * 10	10812	10605	10353	10569
9C8	220 * 9	10190	9984	9732	9948
8C10	220 * 9	10800	10793	10442	10535
8C9	220 * 9	11145	10940	10687	10902
8C9	220 * 10	10832	10627	10374	10589
8C9	220 * 11	10519	10314	10062	10278
8C9	240 * 9.5	10667	10462	10211	10426
8C8	220 * 9	11275	11071	10818	11034
8C8	220 * 10	10961	10758	10506	10721
8C8	220 * 11	10651	10445	10193	10406
8C8	220 * 12	10338	10132	9882	10097
8C8	240 * 10	10812	10606	10353	10566
8C8	240 * 11	10486	10281	10030	10245

OPTIONS A :
The value to the left of A refers to the Outer Bottom and Tank top thicknesses and the value to the right of A refers to the longitudinal plate girder thickness.

OPTIONS B :
The value to the left of B refers to the Outer Bottom and longitudinal plate girder thicknesses and the value to the right of A refers to the tank top thickness.

OPTIONS C :
The value to the left of C refers to the Tank Top and longitudinal plate girder thicknesses and the value to the right of C refers to the Outer Bottom thickness.

*** Optimum Rel. Fabrication Cost**

Table 6.5
Double Bottom Alternative Structural Designs using OBP Stiffeners

OPTION	FLAT BAR (mm)	C.S.1 £	C.S.2 £	C.S.3 £	C.S.4 £
9A8	130 * 20	10165	9959	9707	9923
8A10	120 * 20	10559	10354	10064	10279
8A10	130 * 20	10477	10358	10068	10197
8A9	120 * 20	10620	10501	10249	10539
8A9	120 * 25	10010	9890	9838	9768
8A9	130 * 20	1045	10331	10079	10208
8A8	110 * 30	10102	9983	9731	9860
8A8	120 * 20	11153	11034	10782	10911
8A8	120 * 25	10574	10455	10203	10332
8A8	130 * 20	10997	10878	10626	10755
8A8	130 * 25	10368	10249	9997	10126
9B9	120 * 20	9862	9742	9453	9582
9B8	120 * 20	10014	9895	9643	9773
8B11	120 * 20	10251	10122	9855	9985
8B10	120 * 20	10654	10534	10267	10396
8B10	130 * 20	10444	10342	10057	10186
8B9	120 * 20	10796	10677	10425	10555
8B9	120 * 25	10186	10067	9815	9944
8B9	130 * 20	10626	10507	10255	10384

OPTION	FLAT BAR (mm)	C.S.1 £	C.S.2 £	C.S.3 £	C.S.4 £
8B8	110 * 30	10102	9983	9731	9860
8B8	120 * 20	11153	11034	10782	10911
8B8	120 * 25	10574	10455	10203	10332
8B8	130 * 20	10997	10876	10626	10755
8B8	130 * 25	10368	10249	9997	10126
9C9	120 * 20	10368	10249	9997	10126
9C8	120 * 20	9924	9805	9553	9682
9C8	130 * 20	9997	9876	9626	9755
8C11	**120 * 20**	**9806**	**9687**	**9435***	**9559**
8C10	120 * 20	10605	10579	10228	10340
8C10	130 * 20	10947	10921	10570	10682
8C9	120 * 20	10770	10744	10393	10505
8C9	120 * 25	10814	10695	10443	10572
8C9	130 * 20	10204	10084	9833	9962
8C8	110 * 30	10644	10525	10273	10402
8C8	120 * 20	10102	9983	9731	9860
8C8	120 * 25	11153	11034	10782	10911
8C8	130 * 20	10574	10455	10203	10332
8C8	130 * 25	10997	10878	10626	10755

*** Optimum Rel. Fabrication Cost**

OPTIONS A :

The value to the left of A refers to the Outer Bottom and Tank top thicknesses and the value to the right of A refers to the longitudinal plate girder thickness.

OPTIONS B :

The value to the left of B refers to the Outer Bottom and longitudinal plate girder thicknesses and the value to the right of A refers to the tank top thickness.

OPTIONS C :

The value to the left of C refers to the Tank Top and longitudinal plate girder thicknesses and the value to the right of C refers to the Outer Bottom thickness.

Table 6.6
Double Bottom Alternative Structural Designs using OBP Stiffeners

CHAPTER 7

CONCLUSIONS FROM RELATIVE FABRICATION COST STUDIES AND AREAS FOR FUTURE DEVELOPMENT.

The general conclusion that can be made is that the original aims and objectives, as described in Chapter 1, have been achieved. That is to say, that when both programs developed throughout the course of this project are used in tandem, they can be regarded as a program package which has the capability to integrate design of structure with the cost of it's fabrication at the preliminary design stage.

The usefulness of the computer package as a design tool that can be used in a design office environment has yet to be demonstrated. However, from the trends demonstrated in Chapter 6, it is believed that the approach used and the method developed could be used to the designer's advantage at the preliminary design stage, if a cost optimum solution is sought.

The program **FRIGATE** offers the facility to generate alternative structural designs of ship's structural components by simply re-defining the section type used as structural members, albeit to one set of design rules.

The program **SHIPCOST** contains the database of cost elements identified as representing general warship-building fabrication techniques. Further cost elements relating to the detail of the structure (i.e. brackets, lugs etc) have also been developed. This then allows the designer to quantify their contribution to the relative fabrication cost of the structure when generally they have been neglected in this sense. At the completion of this project there is a series of construction task algorithms available to the designer which enable the relative fabrication cost of several structural components to be calculated. Admittedly these could be enhanced by incorporating more modern fabrication techniques and allowing greater flexibility in the sequencing of construction tasks.

When run as a package, the relative fabrication cost optimisation of a basis model midship section, on average , could be available within the hour. This is of course highly dependent on system availability and choice of replacement section type. In percentage terms, **FRIGATE** occupies 70% of the run-time and for the remaining 30% **SHIPCOST** calculates the relative fabrication cost of the optimised structure.

As with most computer program suites there are limitations in their application, **FRIGATE** and **SHIPCOST** are no exceptions to this general rule. As ship structural design is a highly complex and involved process when approached from first principles, it was decided that such a rigorous approach to the subject was outwith the scope of such a general design evaluation tool. Consequently, various design factors (e.g. the design bending moments of the hull girder) must be evaluated by other means and be available as input to **FRIGATE**. Also, the pre-requisite for a basis model structural definition indicates that the general midship section topography has been conceived and that **FRIGATE** cannot be used to generate the initial design which would be then subject to further optimisation.

Those structures generated by **FRIGATE** as suitable alternatives to the basis model are subject to the following constraints :

i the stiffeners of any ship structural component being of uniform size

ii fixed number of stiffeners on side shell panels

iii fixed number of stiffeners on the bilge structure

iv fixed position of plate longitudinals

These factors are a function of the data handling processes used in **FRIGATE** and should not be regarded as insurmountable.

To date, **FRIGATE** deals with the design of the mid-third length of a typical Royal Navy frigate with no attempt being made to model other hull areas remote from midships. It is assumed that the relative fabrication costs of the end hull regions will be proportional to those of the near parallel mid-region. The midship section employed comprised three deck structures,side shell, bilge, tank top and outer bottom. The existence of all these structural components (with the exception being Nº 2 deck) is required in any basis model different from the one described in Chapter 5 in order that **FRIGATE** will operate in the manner described. The capacity to change the basis ship model used rests with the user and his/her familiarity with the running of the program and the format of the datafiles.

During each design run of **FRIGATE**, the user has the opportunity to change the width and height above the baseline of the deck structures within an overall depth envelope. To alter this overall depth envelope, changes to the bilge and side shell plating dimensions must be carried out through revised datafiles.

One aspect of ship's structural design that appears to have been neglected at the preliminary design stage, is the the provision of a rational design-redesign process for the transverse structure. Available means of determing transverse structure scantlings are design by Classification Society Rules and assessing suitability of chosen scantling by finite element methods. The incorporation of a finite element analysis appendage to **FRIGATE** was never considered possible, although it was used to try and derive a useful general algorithm for the design of transverse members. Following the lack of success in the area, the usefulness of Classification Society Rules was appraised. The application of these types of Rules is a well established and accepted practise. However, there are various aspects of such "design by rule" methods that make them unwieldy when applied to the transverse structure of warships. In Lloyds Rules for example, there are a large quantity of constants applied to the calculation of scantlings. The derivations of such constants are vague and apparently unrelated to warship structural design formulations. Consequently, the lack of background information provided with these types of design rules indicates that a more rationally based design regime would be more appropriate to apply when designing warship's transverse structure. Ref. 43 appear to offer such a set of design formulations, whereby the transverse structure is regarded as part of a grillage and is thus subject to interaction with the longitudinal structure and loading. By applying these Rules to each structural component's transverse members, a satisfactory design can be rapidly achieved to withstand the loading expected of a warship structure.

The construction task algorithms compiled during this project and incorporated in **SHIPCOST** reflect the fabrication techniques and production practises used in warship-building in recent years. As a consequence of the industry wide decision to no longer record, by method study techniques, information relating to task times these algorithms may appear to be slightly dated. However, they can be used to compare the relative fabrication costs of alternative structures in order to establish trends, which in turn should indicate to the designer those structures that will incur least relative fabrication costs.

The welding methods assumed to be applied during fabrication of structural components is an area where greater flexibility would be advantageous. However, due to the intensity of manual input required in order to achieve this flexibility, it is not currently permitted in the normal operation of **SHIPCOST**. If alterations to the assumed welding procedures are considered desirable then this can only be done by changing the Fortran source code of the program. Although work study techniques are no longer generally applied in shipbuilding, more modern data could be used for state of the art welding techniques. This information can be found in Technical Specifications and publications from the Institute of Welding. However, this data is "pure" data and does not contain any allowances for the human factor and therefore requires careful consideration in application if the results are to be meaniful with respect to results presented in Chapter 6.

7.1 Conclusions from Flat Deck Panel Studies.

For flat panel deck structures of constant longitudinal area and for cases of both constant and varying transverse structure and spacing, clear trends of relative fabrication cost for a variety of plate thicknesses and longitudinal stiffener types have been demonstrated. In general, labour costs increase with a corresponding increase of longitudinal stiffener numbers and decreasing transverse frame spacing.

In the studies using different Tee bar sizes, cost optima are all associated with maximum plate thickness and the stiffener offering the greatest sectional area to satisfy the required area. However, in this study, Section 6.1.1 and Fig. 6.2, the variation of section costs is such that these effects can be seen to cancel out to produce optimum relative costs with both the 114 * 44mm and the 254 * 127mm Tee bar sections when the plating thicknesses are 11mm and 8mm respectively.

By replacing the Tee bars by commercially available rolled sections savings can be achieved on the relative fabrication cost of the basis model flat deck panel structure.However in these studies, cost optima are all associated with minimum plate thickness and the largest stiffener size to satisfy the required area. This is a direct result of the dominance of thicker plate material costs over the labour costs when the labour rate is assumed at £15/manhour. At the same time, minimum relative fabrication cost is also associated with the minimum acceptable values of interframe panel buckling criterion. This can be expressed simply as, increased safety factors result in increased relative fabrication costs.

The relative fabrication cost optimum when using OBP sections is 9.0% less expensive than when Tee sections were used although in this case the structure is 2.7% lighter than the basis model flat deck panel. This small weight variation is an accident of rounding to integer stiffener numbers in a constant area study.

A saving of 10.2% on the basis model flat deck panel structure can be realised when flat bars are used to replace the Tee sections.

7.2 Conclusions from Double Bottom Study.

For a double bottom unit of constant transverse area, clear trends have been demonstrated for differing plate thickness of tank top, longitudinal plate girders and mainly one size of Tee bar stiffener. The general trend for light Tee stiffened structures is that as the single variable thicknesses increase the relative fabrication cost of the double bottom unit decreases. The major influence on this decreasing is the labour cost. This is so because, with a 4.3% increase in material costs between the basis model and the least favourable alternative results in a 15% increase in total relative fabrication cost. Similarly, a saving of 40% on material costs results in only a 14 % saving on total relative fabrication cost when the optimum and basis model are compared. This is then a clear indication that differences between the relative fabrication costs of alternative double bottom unit structural configurations are highly dependent on how labour intensive the options are. This can be extended further to say that as plating activities, such as marking off, rough positioning of sections etc, are generally independent of material thickness, the difference in relative fabrication costs are largely attributable to the amount of welding that is required on the structure.

In almost all selections of plate thickness, the structure using the heavier section has lower relative fabrication costs than the structure using the lighter section. The instances in which cost optima for light and heavy stiffened structure coincide are those in which, the lighter stiffened structure, would require a more detailed structural analysis to ensure the design criteria applied are not being violated.

It is possible to make savings on the basis model double bottom unit in some instances when using the 114 * 44mm LST and in all cases when using the heavier 254 * 127mm LST.

Of the four Construction sequences identified, Sequence 3 invariably incurs the least relative fabrication cost. Therefore, the greater proportion of work that can be associated with both the tank top and the outer bottom positioned such that the welder is working downhand, the greater the labour savings that can be achieved. Furthermore, the more longitudinals that can be associated with the outer bottom rather than the tank top, the greater the labour savings that can be achieved.

The results of the extensive investigation of the relative fabrication costs of a constant transverse area double bottom unit indicate that savings on the cost of the basis model can be achieved. The maximum savings of 10.5% on the cost of the basis model (10mm plating thicknesses and 114 * 44mm Tee) can be achieved if the double bottom is considered to have the following plating thicknesses and OBP dimensions -:

Tank top	= 8mm
Plate Longitudinals	= 10mm
Outer Bottom	= 8mm
OBP dimensions	= 280 * 12mm

Although savings of 7.9% of the cost of the basis model double bottom unit appear possible when a particular Flat Bar section is used as the longitudinal stiffener, further investigation of the fabrication practicalities would be required. For the purposes of this study, it is assumed that fillet welds of similar size and nature are used on this structural arrangement of 20mm thick flat bar welded to 8mm thick plating as were used on the structural arrangement it is replacing. This is sufficiently unusual to warrant evaluation tests on joint shock and impact load survivability.

Various Construction Sequences for a typical frigate's double bottom unit have been demonstrated. The method of fabrication that always incurs least cost is Sequence 3. However, a major assumption inherent with all the Sequences is that the double bottom unit is completed in the fabrication shop prior to installation on the building berth.

The use of the model to firstly generate equivalent structures and secondly to evaluate alternative configurations and build methods, in terms of relative fabrication costs, has been demonstrated. The results presented in Chapter 6 indicate the ability of the model to demonstrate substantial relative savings on a panel by panel basis. Advancing from the midship area where the main structural component is the flat panel it is believed that similar savings can be shown for end regions of the hull when subjected to a similar modelling procedure. Further savings maybe possible if the midship section neutral axis position is allowed to vary and redistribution of the section material is carried out.

7.2 Areas for Future Development.

A development of both programs compiled during the course of this project would be to include structures removed from the mid-third length of the vessel. In relation to **FRIGATE** this could involve the structural design of hull areas such as the bow, where slamming loads would have to be taken into consideration.

In relation to **SHIPCOST**, dealing with structures such as the bow, would require the generation of further construction task algorithms to take into account the high degree of curvature normally associated with this particular hull component. Furthermore, a means of rapidly assessing which welding process would yield the least fabrication time would be an advantage. Also, data gathered under method study conditions, relating to the manhours recorded against current fabrication techniques, would enhance the existing database of elemental task times and would reflect accurately the incurred fabrication cost of building warships in the present day.

Hardcopy results from both **FRIGATE** and **SHIPCOST** are only available by means of lineprinter output of the various files to which are written to during execution. A graphical presentation of results from both **FRIGATE** and **SHIPCOST** would be an advantage and would be a method by which design trends could be readily identified. In general terms interaction from the keyboard needs to be improved in the longer term.

The combined package of **FRIGATE** and **SHIPCOST** would benefit from an interactive graphics facility at both the pre and post processing stage. This of course would be enhanced if the graphics suite operational on a modern high performance workstation. At present, the interface between the two programs requires some human intervention and elimination of this by automating the interface would be an advantage. The elimination of manual data checking to ensure integrity would also be an enhancement on the operational aspect of the complete package.

For the expansion of **FRIGATE,** if other design code formulations could be used, this would give the designer access to a greater selection of design criteria. In terms of **SHIPCOST**, integrating individual shipyard cost element databases would allow specific usage and application for the designer in a more direct sense.

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APPENDIX 1

CONSTRUCTION TASK ALGORITHMS USED IN "SHIPCOST"

1. Orthogonally Stiffened Flat Panel
2. Orthogonally Stiffened Curved Panel
3. Fitting and Welding Grillage Marrying Piece
4. Fitting and Welding Knee Bracket
5. Fitting and Welding Transverse Frame web Doubler Plate
6. Fabricating Large Tee Structural Members
7. Double Bottom Unit Assembly - Sequence 1
8. Double Bottom Unit Assembly - Sequence 2
9. Double Bottom Unit Assembly - Sequence 3
10. Double Bottom Unit Assembly - Sequence 4

CONSTRUCTION TASK ALGORITHM 1 - ORTHOGONALLY STIFFENED FLAT PANEL ASSEMBLY

JOB DESCRIPTION: Flat Panel Sub-Assembly

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
1	Clear	Shop Floor	Job	191
2	Transport by Pallet	Plates	Job	171
3	Layout	Plates	Plate	176
4	Align	Flat Plates	Plate	177
5	Fair and Tack	Plate Seam	Plate Seam Length	84
6	Attach and Remove	Mini-deck Welder	Job	215
7	Weld	Run off Pieces	Job	216
8	Position	Mini-deck Welder	Seam	218
9	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111011
10	Aside	Mini-deck Welder	Seam	219
11	Turn	Panel	Job	224
12	Position	Mini-deck Welder	Seam	218
13	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111012
14	Aside	Mini-deck Welder	Seam	219
15	Mark Off	Longitudinal Positions	Longitudinal Length	2.1
16	Mark Off	Transverse Positions	Transverse Length	2.1
17	Transport by Crane	Sections	Job	154
18	Collect/Rough position	Longitudinals	Longitudinal	3.34
19	Fair & Tack(downhand)	Longitudinals	Longitudinal Length	22.2
20	Man. F/Weld(downhand)	Longitudinals	Longitudinal Length	100110
21	Collect/Rough Position	Transverses	Transverse	3.34
22	Fair & Tack(downhand)	Transverses	Transverse Length	22.2
23	Man. F/Weld(downhand)	Transverse	Transverse Length	100110
24	Man. Fillet Weld	Connection/Lug	Intersection	YSL1
25	Chip Fairing Scars	Panel Seam	Panel Seam Length	2.0
26	Chip Fairing Scars	Longitudinal to Panel	Longitudinal Length	2.0
27	Chip Fairing Scars	Transverse to Panel	Transverse Length	2.0
28	Inspect	Job	Job	160

Total Manhours for Flat Panel Sub-Assembly =

$$2.286 + 0.3 * NPLATE + [(NSEAMS * PLEN) * (0.1644 + \Sigma f_n(PT))]$$

$$+ [(NPLATE * PLEN) + (NTRANS * PWIDTH)] * 0.1985 + (NLONG$$

$$+ NTRANS) * 0.0622 + (NLONG * (PLEN-1) * f_3(PT)) + (NTRANS$$

$$* PWIDTH * f_4(PT)) + (NLONG * NTRANS * f_n(PT))$$

SUMMARY OF VARIABLES USED IN ALGORITHM

NPLATE	=	Number of Plates in Flat Panel
NSEAMS	=	Number of Seams
NLONG	=	Number of Longitudinal Stiffeners
NTRANS	=	Number of Transverse Sections
PLEN	=	Plate Length
PWIDTH	=	Plate Width
f_n	=	Welding Rate for Thickness (PT)

CONSTRUCTION TASK ALGORITHM 2 - ORTHOGONALLY STIFFENED CURVED PANEL ASSEMBLY

JOB DESCRIPTION: Curved Panel Sub Assembly

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
1	Clear	Shop Floor	Job	191
2	Transport by Pallet	Plates	Job	171
3	Layout	Shaped Plates < 0.0125	Plate	180
		" " < 0.0254	Plate	179
4	Collect	Shaped Plate Fair. Aids	Job	181
5	Align	Shaped Plate	Metre	182
6	Fair	Shaped Plates < 0.0125	Seam Length	86
		Shaped Plates < 0.0254	Seam length	87
7	Manual Butt Weld	Shaped Panel	Seam Length	136211
8	Mark off	Stiffener Positions	Longitudinal Length	2.1
9	Mark off	Transverse Positions	Transverse length	2.1
10	Transport	Shaped Sections	Job	163
11	Collect	Shaped Section Supports	Job	164
12	Erect	Shaped Section Supports	Longitudinal	165
13	Erect	Shaped Section Supports	Transverse	165
14	Collect & Rough Posit	Longitudinals	Longitudinal	3.34
15	Fair & Tack	Shaped Sections < 0.3m	Metre Longitudinal	77
		" " > 0.3m		78
16	Man Fillet Weld	Longitudinals	Metre Longitudinal	100110
17	Collect & Rough Posit	Transverses	Transverse	3.34
18	Fair & Tack	Shaped Sections < 0.3m	Metre Transverse	77
		" " > 0.3m	Metre Transverse	78
19	Man Fillet Weld	Transverse	Metre Transverse	100110
20	Man Fillet Weld	Trans./Long. Connection	Connection	YSL1
21	Chip Fairing Scars	Panel Seam	Metre Seam	2.0
22	Chip Fairing Scars	Longitudinal to Panel	Metre Longitudinal	2.0
23	Chip Fairing Scars	Transverse to Panel	Metre Transverse	2.0
24	Inspect	Job	Job	160

Curved Panel Algorithm

Total Manhours for Curved Panel Assembly =

$$
\begin{aligned}
1.91 &+ (NPLATE * (OPT1 + (PLEN * 0.0380))) \\
&+ (NSEAMS + (OPT2 + (PLEN * 0.0384))) \\
&+ ((NLONGT + NTRANS) * 0.0949) \\
&+ (NLONGT * (0.0622 + (OPT3 * PLEN))) \\
&+ (NTRANS * (0.0622 + (OPT4 * PWIDTH))) \\
&+ (NLONGT * (PLEN-1) * 0.0384) + (NTRANS * (PWIDTH-1) * 0.384) \\
&+ (NSEAMS * f_1(PT) * PLEN) + (NLONGT * (PLEN-1) * f_2(PT)) \\
&+ (NTRANS + (PWIDTH-1) * f_3(PT)) + (NTRANS * NLONGT * f_n(PT))
\end{aligned}
$$

SUMMARY OF VARIABLES USED IN ALGORITHM

NPLATE = Number of Plates in the Curved Panel
NSEAMS = Number of Seams
NLONGT = Number of Longitudinals on the Curved Panel
PLEN = Plate Length
PWIDTH = Aggregate width of the plates in the Curved Panel
OPT1 = Aligning variable for shaped plates, dependant on plate thickness
OPT2 = Fairing variable for shaped plates, dependant on plate thickness
OPT3 = Fairing variable for shaped sections, dependant upon section length
OPT4 = Fairing variable for shaped sections, dependant upon section length.
f_n = Welding rate for material thickness PT

CONSTRUCTION TASK ALGORITHM 3 - FITTING AND WELDING OF GRILLAGE MARRYING PIECE

JOB DESCRIPTION: Fitting and Welding of Grillage Marrying Piece

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
1	Transport by crane	Marrying Pieces	Job	154
2	Collect/Rough Position	Marrying Piece	Marrying Piece	3.34
3	Fair Vertical	M.P. To Plating	Metre M.P.	11
4	Fair Horizontal	M.P. to Grillage Member	M.P. Flange Width	68
5	Fair Vertical	M.P. to Grillage Member	M.P. Stalk Height	45
6	Weld (d/hand)	M.P. to Plating	M.P. Metre	100110
7	Weld (d/hand)	M.P. Flange to Grillage Member Flange	M.P. Flange Width	134211
8	Weld (vertical)	M.P. Stalk to Grillage Member Stalk	M.P. Stalk Height	134211
9	Chip	Fairing Scars	M.P. Metre Butt	271
10	Inspect	M.P. to Grillage Connections	Job	160

Total Manhours to Fit Grillage Marrying Pieces =

$$0.312 + 0.0622 * NMPC + 0.51 * NMPC + (STLEN * 0.2910 * 2) * NMPC + (FWIDTH * 0.3604 * 2) * NMPC + (((STLEN + FWIDTH) * 2 + 1) * 0.078) * NMPC + \Sigma f_n(PT) * NMPC$$

SUMMARY OF VARIABLES USED IN THE ALGORITHM

NMPC = Number of Marrying Pieces
STLEN = Stalk Length of Marrying Piece
FWIDTH = Flange Width of Marrying Piece

CONSTRUCTION TASK ALGORITHM 4 - FITTING AND WELDING KNEE BRACKET

JOB DESCRIPTION: Fitting and Welding Knee Bracket

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
1	Clear	Shop Floor	Job	191
2	Transport by Pallet	Webs and Flanges	Job	171
3	Layout	Webs and Flanges	Bracket	176
4	Position T-Fashion	Web to Flange < 2.5m	Bracket	172
		Web to Flange > 2.5m	Bracket	173
5	Align T-Fashion	Web and Flange < 2.5m	Bracket	174
		Web to Flange > 2.5m		175
6	Fair and Tack	Web to Flange	Metre	22.2
7	Weld (d/hand)	Web to Flange	Metre	100110
8	Chip Fairing Scars	Web to Flange	Metre	2.0
9	Inspect	Bracket	Job	160
10	Transport by Crane	Bracket	Job	154
11	Mark Off	S/Shell Transverse	Metre	2.1
12	Layout by Hand	Bracket	Bracket	236
13	Fair Vertical	Bracket	Metre	12
14	Weld Vertical	Bracket Vertical Length	Vertical Metre	100120
15	Weld O/head	Bracket Horz Length	Horizontal Length	100130
16	Inspect	Bracket Installation	Bracket	160

TOTAL MANHOURS TO FIT AND WELD KNEE BRACKET =

$$2.727 + [OPT1 + OPT2 + (0.1985 * WEBLEN) + ((f_1(PT) + f_2(PT)) * WEBLEN) + f_3(PT) * DEPTH] * NBRCKT$$

SUMMARY OF VARIABLES USED IN ALGORITHM

NBRCKT = Number of brackets
WEBLEN = Web length of brackets
DEPTH = Maximum depth of brackets
OPT 1 = Positioning variable, dependant on web length
OPT 2 = Aligning variable, dependant on web length

CONSTRUCTION TASK ALGORITHM 5 - FITTING AND WELDING TRANSVERSE FRAME WEB DOUBLER PLATE

JOB DESCRIPTION: Fitting and Welding Transverse Frame Web Doubler Plate

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
1	Mark Off	Frame Web	Metre Doubler Plate	2.1
2	Fit and Tack	Doubler Plate	Doubler Plate	274
3	Weld (horz)	Doubler Plate	Horz Metre	100130
4	Weld (vert)	Doubler Plate	Vertical Metre	100120
5	Chip Fairing Scars	Doubler Plate	Doubler Plate	272
6	Inspect	Job	Doubler Plate	160

Total Manhours Taken to fit one Doubler Plate =

$(0.3981 + (f_1(PT) * HORZ) + (f_2(PT) * VERT)) * NDBPLT$

Summary of Variables used in Algorithm

NDBPLT = Number of Doubler Plates
HORZ = Horizontal Dimension of Doubler Plate
VERT = Vertical Dimension of Doubler Plate
f_n = **Welding** Rate for Material Thickness PT

CONSTRUCTION TASK ALGORITHM 6 - FABRICATING LARGE TEE STRUCTURAL MEMBERS

JOB DESCRIPTION: Fabricating Large Tee Sections

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
1	Clear	Shop Floor	Job	191
2	Transport by Pallet	Webs and Flanges	Job	171
3	Layout	Webs and Flanges	Section	176
4	Position T-fashion	Webs and Flanges	Section < 2.5m	172
			Section > 2.5m	173
5	Align T-fashion	Webs to Flanges	Section < 2.5m	174
			Section > 2.5m	175
6	Mark Off	Web Stiffeners	Stiffener Metre	2.1
7	Collect/Rough Position	Web Stiffener	Stiffener	3.34
8	Fair (d/hand)	Stiffener to Web	Stiffener Metre	22.2
9	Fair (d/hand)	Web to Flange	Metre	22.2
10	Weld (d/hand)	Stiffener to Web	Stiffener Metre	100110
11	Weld (d/hand)	Web to Flange	Metre	100110
12	Chip Fairing Scars	Web Stiffeners	Stiffener Metre	2.0
13	Chip Fairing Scars	Web to Flange	Metre	2.0
14	Inspect	Job	Job	160

Total Manhours to Fabricate Tee Section =
1.544 + (TEELEN * 0.1492) + ATFASH + PTFASH + (NSTIF * WDEPTH * 0.0109) + (NSTIF * WDEPTH * 0.1492) + (NSTIF *).0622) + (NSTIF * WDEPTH * 0.0384) + (TEELEN * 0.0384) + Σf_n(PT)

SUMMARY OF VARIABLES USED IN ALGORITHM

TEELEN = Section Length
ATFASH = Align Plates T-fashion
PTFASH = Position Plates T-fashion
NSTIF = Number of Web Stiffeners
WDEPTH = Web Depth

CONSTRUCTION TASK ALGORITHM 7 - DOUBLE BOTTOM UNIT ASSEMBLY - Sequence 1

JOB DESCRIPTION: Tank Top Flat Panel Sub-Assembly

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
1	Clear	Shop Floor	Job	191
2	Transport by Pallet	Plates	Job	171
3	Layout	Plates	Plate	176
4	Align	Flat Plates	Plate	177
5	Fair and Tack	Plate Seam	Plate Seam Length	84
6	Attach and Remove	Mini-deck Welder	Job	215
7	Weld	Run off Pieces	Job	216
8	Position	Mini-deck Welder	Seam	218
9	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111011
10	Aside	Mini-deck Welder	Seam	219
11	Turn	Panel	Job	224
12	Position	Mini-deck Welder	Seam	218
13	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111012
14	Aside	Mini-deck Welder	Seam	219
15	Mark Off	Longitudinal Positions	Longitudinal Length	2.1*
16	Mark Off	Transverse Positions	Transverse Length	2.1*
17	Transport by Crane	Sections	Job	154
18	Collect/Rough position	Longitudinals	Longitudinal	3.34*
19	Fair & Tack(downhand)	Longitudinals	Longitudinal Length	22.2*
20	Man. F/Weld(downhand)	Longitudinals	Longitudinal Length	100110
21	Collect/Rough Position	Transverses	Transverse	3.34*
22	Fair & Tack(downhand)	Transverses	Transverse Length	22.2*
23	Man. F/Weld(downhand)	Transverse	Transverse Length	100110
24	Man. Fillet Weld	Connection/Lug	Intersection	YSL1
25	Chip Fairing Scars	Panel Seam	Panel Seam Length	2.0*
26	Chip Fairing Scars	Longitudinal to Panel	Longitudinal Length	2.0*
27	Chip Fairing Scars	Transverse to Panel	Transverse Length	2.0*
28	Inspect	Job	Job	160

Total Manhours for Tank Top Flat Panel Sub-Assembly = Total 1 =

$$2.286 + 0.3 * NPLTT + [(NSEAMS * PLEN) * (0.1644 + \Sigma f_n(PT))]$$
$$+ [(NPLTT * PLEN) + (NTRTT * PWIDTH)] * 0.1985 + (NLLTT$$
$$+ NTRTT) * 0.0622 + (NLTT * (PLEN-1) * f_3(PT)) + (NTRTT$$
$$* PWIDTH * f_4(PT)) + (NLTT * NTRTT * f_n(PT))$$

JOB DESCRIPTION: Plate Longitudinal Sub-Assembly

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
29	Clear	Shop floor	Job	191
30	Transport by Pallet	Plates	Job	171
31	Mark Off	Stiffener Positions	Stiffener Length	2.1*
32	Transport by Crane	Stiffeners	Job	154
33	Collect/Rough	Stiffeners	Stiffener	3.34
34	Fair & Tack(downhand)	Stiffeners	Stiffener Length	22.2
35	Man F/Weld(downhand)	Stiffeners	Stiffener Length	1100110
36	Chip Fairing Scars	Stiffeners	Stiffener Length	2.0*

Total Manhours for Plate Longitudinal Sub-Assembly = Total 2 =

$$1.492 + (0.0736 + (f_5(PT) * 0.1876) * STLEN) * NSTIFF$$

JOB DESCRIPTION: **Plate Longitudinal to Tank Top**

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
37	Mark off Tank Top	Plate Longitudinal Position	Plate Long. Length	2.1*
38	Position T-fashion	Plate Longitudinal	Plate Longitudinal	172/175
39	Fair and Tack	Plate Longitudinal	Plate Long. Length	80/81
40	Man F/Weld(downhand)	Plate Longitudal	Plate Long. Length	1100110
41	Man Fillet Weld	Plate Longitudinals/T. Top Transverses Connections	Intersection	YSL1
42	Chip Scars	Girder Fairing	Plate Long. Length	271

Total Manhours per Plate Longitudinal to Tank Top = Total 3 =

$0.24 + (0.4599 + f_6(PT) * PLEN) + (f_7(PT) * NTRTT)$

JOB DESCRIPTION: Vertical Floors to Tank Top

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
43	Fair Downhand	Vertical Floors	Vert. Floor Length	47
44	Fair Vertical	Vertical Floor to Girder	Vertical Fl/Hght	46
45	Man F/Weld(downhand)	Vertical Floor to T/Top	Vertical Fl/Lngth	0011002
46	Man F/Weld(downhand)	Vertical Floor to Girder	Vertical Floor Hght	0011002
47	Connections	Vertical Floor to T/Top	Intersection	YSL1
48	Chip Fairing Scars	Tank Top to Vertical Floors	Vertical Floor Length	270
49	Chip Fairing Scars	Vertical Floor to Girders	Vertical Floor Hght	270

Total Manhours per Vertical Floor to Tank Top = Total 4 =

$(NPPART * FLRGHT * NPLNGL * (0.366 + f_9(PT)) + (PWIDTH *$

$(0.536 + f_8(PT)) + (f_{10}(PT) * NLTT)$

JOB DESCRIPTION: Outer Bottom Flat Panel Sub-Assembly

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
50	Clear	Shop Floor	Job	191
51	Transport by Pallet	Plate	Job	171
52	Layout	Plates	Plate	176
53	Align	Flat Plates	Plate	177
54	Fair and Tack	Plate Seam	Plate Seam Length	84
55	Attach and Remove	Mini-deck Welder	Job	215
56	Weld	Run off Pieces	Job	216
57	Position	Mini-deck Welder	Seam	218
58	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111011
59	Aside	Mini-deck Welder	Seam	219
60	Turn	Panel	Job	224
61	Position	Mini-deck Welder	Seam	218
62	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111012
63	Aside	Mini-deck Welder	Seam	219
64	Mark Off	Longitudinal Positions	Longitudinal Length	2.1*
65	Mark Off	Transverse Positions	Transverse Length	2.1*
66	Transport by Crane	Sections	Job	154
67	Collect/Rough position	Longitudinals	Longitudinal	3.34*
68	Fair & Tack(downhand)	Longitudinals	Longitudinal Length	22.2*
69	Man. Fillet Weld	Longitudinals	Longitudinal Length	100110
70	Collect/Rough Position	Transverses	Transverse	3.34*
71	Fair & Tack(downhand)	Transverses	Transverse Length	22.2*
72	Man. Fillet Weld	Transverse	Transverse Length	100110
73	Man. Fillet Weld	Connection/Lug	Intersection	YSL1
74	Chip Fairing Scars	Panel Seam	Panel Seam Length	2.0*
75	Chip Fairing Scars	Longitudinal to Panel	Longitudinal Length	2.0*
76	Chip Fairing Scars	Transverse to Panel	Transverse Length	2.0*
77	Inspect	Job	Job	160

Total Manhours for Outer Bottom Flat Panel Sub-Assembly = Total 5 =

$$2.286 + 0.3 * NPLOB + [(NSEAMS * PLEN) * (0.1644 + \Sigma f_n(PT))] + [(NPLOB * PLEN) + (NTROB * PWIDTH)] * 0.1985 + (NLOB + NTROB) * 0.0622 + (NLOB * (PLEN-1) * f_3(PT)) + (NTROB * PWIDTH * f_4(PT)) + (NLOB * NTROB * f_n(PT))$$

JOB DESCRIPTION: Tank Top to Outer Bottom Link Up

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
78	Shackle On	Lugs	Job	205
79	Turn + Berth	Bottom Plating	Job	108
80	Stiffener to Neat Notch	P/Long to Bottom Shell Trans.	Intersection	133
81	Stiffener to Neat Notch	V/Floors to B/Shell Longnl	Intersection	133
82	Connection	P/Longs. to B/Shell Trans.	Connection	100230
83	Connection	Floors to B/Shell Longitud.	Connection	100230
84	Man Fillet Weld	Plate Longs. to Btm Shell	Plate Length Longitud	100230
85	Man Fillet Weld	V/Floors to Bottom Shell	Vertical Floor Length	100230
86	Man Fillet Weld	T/Top Plat. to B/Shell Pltg	Tank Top Length	100230
87	Unshackle	Crane	Job	213

Total Manhours for Tank Top to Outer Bottom Link Up = Total 6 =

$$2.3708 + (0.122 * NTROB * NPLNGL) + (0.122 * NVRFLR * NLOB) + (f_{13}(PT) * NVRFLR * NLOB) + (f_{14}(PT) * NTROB * NPLNGL) + (f_{15}(PT) * NPLNGL * PLEN) + (f_{16}(PT) * NVRFLR * PWIDTH) + (f_{17}(PT) * PLEN * 2)$$

TOTAL MANHOURS FOR DOUBLE BOTTOM UNIT ASSEMBLY =

$$\text{Total 1} + (NPLNGL * \text{Total 2}) + (NPLNGL * \text{Total 3}) + (NVRFLR * \text{Total 4}) + \text{Total 5} + \text{Total 6}$$

SUMMARY OF VARIABLES USED IN THE ALGORITHMS

NPLTT = Number of Plates on the Tank Top
NSEAMS = Number of Seams
NLTT = Number of Longitudinals on the Tank Top
NTRTT = Number of Transverses on the Tank Top
PLEN = Plate Length
PWIDTH = Plate Width
NPLNGL = Number of Plate Longitudinals
NSTIFF = Number of Plate Longitudinal Stiffeners
STLEN = Plate Longitudinal Stiffener Length
NVRFLR = Number of Vertical Floors
NPPART = Number of Piece Parts to each Vertical Floor
FLRHGT = Vertical Floor Height
NPLOB = Number of Plates on Outer Bottom
NLOB = Number of Longitudinals on the Outer Bottom
NTROB = Number of Transverses on the Outer Bottom
f_n = Welding Rate for Thickness PT.

CONSTRUCTION TASK ALGORITHM 8 - DOUBLE BOTTOM UNIT ASSEMBLY - Sequence 2

JOB DESCRIPTION: Tank Top Flat Panel Sub-Assembly

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
1	Clear	Shop Floor	Job	191
2	Transport by Pallet	Plates	Job	171
3	Layout	Plates	Plate	176
4	Align	Flat Plates	Plate	177
5	Fair and Tack	Plate Seam	Plate Seam Length	84
6	Attach and Remove	Mini-deck Welder	Job	215
7	Weld	Run off Pieces	Job	216
8	Position	Mini-deck Welder	Seam	218
9	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111011
10	Aside	Mini-deck Welder	Seam	219
11	Turn	Panel	Job	224
12	Position	Mini-deck Welder	Seam	218
13	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111012
14	Aside	Mini-deck Welder	Seam	219
15	Mark Off	Longitudinal Positions	Longitudinal Length	2.1*
16	Mark Off	Transverse Positions	Transverse Length	2.1*
17	Transport by Crane	Sections	Job	154
18	Collect/Rough position	Longitudinals	Longitudinal	3.34*
19	Fair & Tack(downhand)	Longitudinals	Longitudinal Length	22.2*
20	Man/Fillet Weld(d/hand)	Longitudinals	Longitudinal Length	100110
21	Collect/Rough Position	Transverses	Transverse	3.34*
22	Fair & Tack(downhand)	Transverses	Transverse Length	22.2*
23	Man/Fillet Weld(d/hand)	Transverse	Transverse Length	100110
24	Man. Fillet Weld	Connection/Lug	Intersectionm	YSL1
25	Chip Fairing Scars	Panel Seam	Panel Seam Length	2.0*
26	Chip Fairing Scars	Longitudinal to Panel	Longitudinal Length	2.0*
27	Chip Fairing Scars	Transverse to Panel	Transverse Length	2.0*
28	Inspect	Job	Job	160

Total Manhours for Tank Top Flat Panel Sub-Assembly = Total 1 =

$$2.286 + 0.3 * NPLTT + [(NSEAMS * PLEN) * (0.1644 + \Sigma f_n(PT))]$$
$$+ [(NPLTT * PLEN) + (NTRTT * PWIDTH)] * 0.1985 + (NLLTT$$
$$+ NTRTT) * 0.0622 + (NLTT * (PLEN-1) * f_3(PT)) + (NTRTT$$
$$* PWIDTH * f_4(PT)) + (NLTT * NTRTT * f_n(PT))$$

JOB DESCRIPTION: Plate Longitudinal Sub-Assembly

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
29	Clear	Shop floor	Job	191
30	Transport by Pallet	Plates	Job	171
31	Mark Off	Stiffener Positions	Stiffener Length	2.1*
32	Transport by Crane	Stiffeners	Job	154
33	Collect/Rough	Stiffeners	Stiffener	3.34
34	Fair & Tack(downhand)	Stiffeners	Stiffener Length	22.2
35	Man F/Weld(downhand)	Stiffeners	Stiffener Length	1100110
36	Chip Fairing Scars	Stiffeners	Stiffener Length	2.0*

Total Manhours for Plate Longitudinal Sub-Assembly = Total 2 =

$$1.492 + (0.0736 + (f_5(PT) * 0.1876) * STLEN) * NSTIFF$$

JOB DESCRIPTION: Plate Longitudinal to Tank Top

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
37	Mark off Tank Top	Plate Long. Positions	Plate Long. Length	2.1*
38	Position T-fashion	Plate Longitudinal	Plate Longitudinal	172/175
39	Fair and Tack	Plate Longitudinal	Plate Long. Length	80/81
40	Man F/Weld(downhand)	Plate Longitudal	Plate Long. Length	1100110
41	Man Fillet Weld	Plate Longitudinals/T. Top Transverses Connections	Intersection	YSL1
42	Chip Scars	Girder Fairing	Plate Long. Length	271

Total Manhours per Plate Longitudinal to Tank Top = Total 3 =

$0.24 + (0.4599 + f_6(PT) * PLEN) + (f_7(PT) * NTRTT)$

JOB DESCRIPTION: Vertical Floors to Tank Top

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
43	Fair Downhand	Vertical Floors	Vert. Floor Length	47
44	Fair Vertical	Vertical Floor to Girder	Vertical Fl/Hght	46
45	Man F/Weld(downhand)	Vertical Floor to T/Top	Vertical Fl/Lngth	0011002
46	Man F/Weld(downhand)	Vertical Floor to Girder	Vertical Floor Hght	0011002
47	Connections	Vertical Floor to T/Top	Intersection	YSL1
48	Chip Fairing Scars	Tank Top to Vertical Floors	Vertical Floor Length	270
49	Chip Fairing Scars	Vertical Floor to Girder	Vertical Floor Hght	270

Total Manhours per Vertical Floor to Tank Top = Total 4 =

$(NPPART * FLRGHT * NPLNGL * (0.366 + f_9(PT)) + (PWIDTH *$

$(0.536 + f_8(PT)) + (f_{10}(PT) * NLTT)$

JOB DESCRIPTION: Outer Hull Longitudinals and Transverses to Tank Top Assembly

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
50	Transport	Sections	Job	154
51	Transport	Shaped Sections	Job	163
52	Thread	Outer Bottom Longitudinals	Intersection	273
53	Thread	Outer Bottom Transverses	Intersection	273
54	Connection	Out/Bot Long - Vert. Floors	Intersection	100110
55	Connection	Out/Bot Trans/Pl long O.B Long	Intersection	100110

Total Manhours for Outer Hull Longitudinals and

Transverses to Tank Top Assembly = Total 5 =

$$0.442 + ((0.121 + f_{12}(PT)) * NLOB * NVRFLR) + ((0.121 + f_{13}(PT) * NPLNGL * NLOB * NTROB)$$

JOB DESCRIPTION: Outer Bottom Plating

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
56	Clear	Shop Floor	Job	191
57	Transport by Pallet	Plates	Job	171
58	Layout	Plates	Plate	176
59	Align	Flat Plates	Plate	177
60	Fair and Tack	Plate Seam	Plate Seam Length	84
61	Attach and Remove	Mini-deck Welder	Job	215
62	Weld	Run off Pieces	Job	216
63	Position	Mini-deck Welder	Seam	218
64	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111011
65	Aside	Mini-deck Welder	Seam	219
66	Turn	Panel	Job	224
67	Position	Mini-deck Welder	Seam	218
68	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111012
69	Aside	Mini-deck Welder	Seam	219
70	Mark Off	Longitudinal Positions	Longitudinal Length	2.1*
71	Mark Off	Transverse Positions	Transverse Length	2.1*
72	Inspect	Job	Job	160

Total Manhours for Outer Bottom Panel Sub-Assembly = Total 6 =

$$2.15 + (0.3 * NPLOB) + [(NSEAMS * PLEN) * (0.1644 * \Sigma f_n(PT))]$$

$$+ (NTROB + NLOB) * 0.0109$$

JOB DESCRIPTION: Tank Top to Outer Bottom Link Up

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
73	Shackle On	Lugs	Job	205
74	Turn + Berth	Bottom Plating	Job	108
75	Man Fillet Weld	Btm Trans to Btm Plating	Bottom Trans Length	100230
76	Man Fillet Weld	Btm Long to Btm Plating	Bottom Long Length	100230
77	Man Fillet Weld	Plate Longs to Btm Shell	Plate Length Long.	100230
78	Man Fillet Weld	V/Floors to Btm Shell	Vertical Floor Length	100230
79	Man Fillet Weld	T/Top Plat. to B/Shell Plating	Tank Top Length	100230
80	Unshackle	Crane	Job	213

Total Manhours for Tank Top to Outer Bottom Link Up = Total 7 =

$$2.306 + (f_{14}(PT) * PWIDTH * NTROB) + (f_{15}(PT) * PLEN * NLOB)$$

$$+ (f_{16}(PT) * PLEN * NPLNGL) + (f_{17}(PT) * PWIDTH * NVRFLR)$$

TOTAL MANHOURS FOR DOUBLE BOTTOM UNIT ASSEMBLY =

Total 1 +(NPLNGL * Total 2) +(NPLNGL * Total 3) + (NVRFLR * Total 4)

+ Total 5 + Total 6 + Total 7

SUMMARY OF VARIABLES USED IN THE ALGORITHMS

NPLTT = Number of Plates on the Tank
NSEAMS = Number of Seams
NLTT = Number of Longitudinals in the Tank Top
NTRTT = Number of Transverses in the Tank Top
PLEN = Plate Length
PWIDTH = Plate Width
NPLNGL = Number of Plate Longitudinals
NSTIFF = Number of Plate Longitudinal Stiffeners
STLEN = Plate Longitudinal Stiffener Length
NVRFLR = Number of Vertical Floors
NPPART = Number of Piece Parts to each Vertical Floor
FLRHGT = Vertical Floor Height
NPLOB = Number of Plates on the Outer Bottom
NLOB = Number of Longitudinals on the Outer Bottom
NTROB = Number of Transverses on the Outer Bottom
f_n = Welding Rate for Thickness PT.

CONSTRUCTION TASK ALGORITHM 9 - DOUBLE BOTTOM UNIT ASSEMBLY - Sequence 3

JOB DESCRIPTION: Tank Top Flat Panel Sub-Assembly

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
1	Clear	Shop Floor	Job	191
2	Transport by Pallet	Plates	Job	171
3	Layout	Plates	Plate	176
4	Align	Flat Plates	Plate	177
5	Fair and Tack	Plate Seam	Plate Seam Length	84
6	Attach and Remove	Mini-deck Welder	Job	215
7	Weld	Run off Pieces	Job	216
8	Position	Mini-deck Welder	Seam	218
9	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111011
10	Aside	Mini-deck Welder	Seam	219
11	Turn	Panel	Job	224
12	Position	Mini-deck Welder	Seam	218
13	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111012
14	Aside	Mini-deck Welder	Seam	219
15	Mark Off	Longitudinal Positions	Longitudinal Length	2.1*
16	Mark Off	Transverse Positions	Transverse Length	2.1*
17	Transport by Crane	Sections	Job	154
18	Collect/Rough position	Longitudinals	Longitudinal	3.34*
19	Fair & Tack(downhand)	Longitudinals	Longitudinal Length	22.2*
20	Man. F/Weld(downhand)	Longitudinals	Longitudinal Length	100110
21	Collect/Rough Position	Transverses	Transverse	3.34*
22	Fair & Tack(downhand)	Transverses	Transverse Length	22.2*
23	Man. F/Weld(downhand)	Transverse	Transverse Length	100110
24	Man. Fillet Weld	Connection/Lug	Intersection	YSL1
25	Chip Fairing Scars	Panel Seam	Panel Seam Length	2.0*
26	Chip Fairing Scars	Longitudinal to Panel	Longitudinal Length	2.0*
27	Chip Fairing Scars	Transverse to Panel	Transverse Length	2.0*
28	Inspect	Job	Job	160

Total Manhours for Tank Top Flat Panel Sub-Assembly = Total 1 =

$$2.286 + 0.3 * NPLTT + [(NSEAMS * PLEN) * (0.1644 + \Sigma f_n(PT))]$$
$$+ [(NPLTT * PLEN) + (NTRTT * PWIDTH)] * 0.1985 + (NLLTT$$
$$+ NTRTT) * 0.0622 + (NLTT * (PLEN-1) * f_3(PT)) + (NTRTT$$
$$* PWIDTH * f_4(PT)) + (NLTT * NTRTT * f_n(PT))$$

JOB DESCRIPTION: Plate Longitudinal Sub-Assembly

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
29	Clear	Shop floor	Job	191
30	Transport by Pallet	Plates	Job	171
31	Mark Off	Stiffener Positions	Stiffener Length	2.1*
32	Transport by Crane	Stiffeners	Job	154
33	Collect/Rough	Stiffeners	Stiffener	3.34
34	Fair & Tack(downhand)	Stiffeners	Stiffener Length	22.2
35	Man F/Weld(downhand)	Stiffeners	Stiffener Length	1100110
36	Chip Fairing Scars	Stiffeners	Stiffener Length	2.0*

Total Manhours for Plate Longitudinal Sub-Assembly = Total 2 =

$$1.492 + (0.0736 + (f_5(PT) * 0.1876) * STLEN) * NSTIFF$$

JOB DESCRIPTION: **Plate Longitudinal to Tank Top**

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
37	Mark off Tank Top	Plate Longnl Positions	Plate Long. Length	2.1*
38	Position T-fashion	Plate Longitudinal	Plate Longitudinal	172/175
39	Fair and Tack	Plate Longitudinal	Plate Long. Length	80/81
40	Man F/Weld(downhand)	Plate Longitudal	Plate Long. Length	1100110
41	Man Fillet Weld	Plate Longitudinals/T. Top Transverses Connections	Intersection	YSL1
42	Chip Scars	Girder Fairing	Plate Long. Length	271

Total Manhours per Plate Longitudinal to Tank Top = Total 3 =

$0.24 + (0.4599 + f_6(PT) * PLEN) + (f_7(PT) * NTRTT)$

JOB DESCRIPTION: **Vertical Floors to Tank Top**

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
43	Fair Downhand	Vertical Floors	Vert. Floor Length	47
44	Fair Vertical	Vertical Floor to Girder	Vertical Fl/Hght	46
45	Man F/Weld(downhand)	Vertical Floor to T/Top	Vertical Fl/Lngth	0011002
46	Man F/Weld(downhand)	Vertical Floor to Girder	Vertical Floor Hght	0011002
47	Connections	Vertical Floor to T/Top	Intersection	YSL1
48	Chip Fairing Scars	Tank Top to Vertical Floors	Vertical Floor Length	270
49	Chip Fairing Scars	Vertical Floor to Girders	Vertical Floor Hght	270

Total Manhours per Vertical Floor to Tank Top = Total 4 =

$(NPPART * FLRGHT * NPLNGL * (0.366 + f_9(PT)) + (PWIDTH *$

$(0.536 + f_8(PT)) + (f_{10}(PT) * NLTT)$

JOB DESCRIPTION: Outer Bottom Flat Panel Sub-Assembly

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
50	Clear	Shop Floor	Job	191
51	Transport by Pallet	Plate	Job	171
52	Layout	Plates	Plate	176
53	Align	Flat Plates	Plate	177
54	Fair and Tack	Plate Seam	Plate Seam Length	84
55	Attach and Remove	Mini-deck Welder	Job	215
56	Weld	Run off Pieces	Job	216
57	Position	Mini-deck Welder	Seam	218
58	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111011
59	Aside	Mini-deck Welder	Seam	219
60	Turn	Panel	Job	224
61	Position	Mini-deck Welder	Seam	218
62	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111012
63	Aside	Mini-deck Welder	Seam	219
64	Mark Off	Longitudinal Positions	Longitudinal Length	2.1*
65	Mark Off	Transverse Positions	Transverse Length	2.1*
66	Transport by Crane	Sections	Job	154
67	Collect/Rough position	Longitudinals	Longitudinal	3.34*
68	Fair & Tack(downhand)	Longitudinals	Longitudinal Length	22.2*
69	Man. Fillet Weld	Longitudinals	Longitudinal Length	100110
70	Collect/Rough Position	Transverses	Transverse	3.34*
71	Fair & Tack(downhand)	Transverses	Transverse Length	22.2*
72	Man. Fillet Weld	Transverse	Transverse Length	100110
73	Man. Fillet Weld	Connection/Lug	Intersection	YSL1
74	Chip Fairing Scars	Panel Seam	Panel Seam Length	2.0*
75	Chip Fairing Scars	Longitudinal to Panel	Longitudinal Length	2.0*
76	Chip Fairing Scars	Transverse to Panel	Transverse Length	2.0*
77	Inspect	Job	Job	160

Total Manhours for Outer Bottom Flat Panel Sub-Assembly = Total 5 =

$$2.286 + 0.3 * NPLOB + [(NSEAMS * PLEN) * (0.1644 + \Sigma f_n(PT))] + [(NPLOB * PLEN) + (NTROB * PWIDTH)] * 0.1985 + (NLOB + NTROB) * 0.0622 + (NLOB * (PLEN-1) * f_3(PT)) + (NTROB * PWIDTH * f_4(PT)) + (NLOB * NTROB * f_n(PT))$$

JOB DESCRIPTION: **Tank Top to Outer Bottom Link Up**

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
78	Shackle On	Lugs	Job	205
79	Turn + Berth	Tank top sub-assembly	Job	108
80	Stiffener to Neat Notch	P/Long to Btm Shell Trans.	Intersection	133
81	Stiffener to Neat Notch	V/Floors to B/Shell Longl.	Intersection	133
82	Connection	P/Longs. to B/Shell Trans.	Connection	100210
83	Connection	Floors to B/Shell Longitud.	Connection	100210
84	Man Fillet Weld	Plate Longs. to Btm Shell	Plate Length Longitud	100210
85	Man Fillet Weld	V/Floors to Bottom Shell	Vertical Floor Length	100210
86	Man Fillet Weld	T/Top Plt. to B/Shell Plt	Tank Top Length	100210
87	Unshackle	Crane	Job	213

Total Manhours for Tank Top to Outer Bottom Link Up = Total 6 =

$$2.3708 + (0.122 * NTROB * NPLNGL) + (0.122 * NVRFLR * NLOB) + (f_{13}(PT) * NVRFLR * NLOB) + (f_{14}(PT) * NTROB * NPLNGL) + (f_{15}(PT) * NPLNGL * PLEN) + (f_{16}(PT) * NVRFLR * PWIDTH) + (f_{17}(PT) * PLEN * 2)$$

TOTAL MANHOURS FOR DOUBLE BOTTOM UNIT ASSEMBLY =

$$Total\ 1 + (NPLNGL * Total\ 2) + (NPLNGL * Total\ 3) + (NVRFLR * Total\ 4) + Total\ 5 + Total\ 6$$

SUMMARY OF VARIABLES USED IN THE ALGORITHMS

NPLTT = Number of Plates on the Tank Top
NSEAMS = Number of Seams
NLTT = Number of Longitudinals on the Tank Top
NTRTT = Number of Transverses on the Tank Top
PLEN = Plate Length
PWIDTH = Plate Width
NPLNGL = Number of Plate Longitudinals
NSTIFF = Number of Plate Longitudinal Stiffeners
STLEN = Plate Longitudinal Stiffener Length
NVRFLR = Number of Vertical Floors
NPPART = Number of Piece Parts to each Vertical Floor
FLRHGT = Vertical Floor Height
NPLOB = Number of Plates on Outer Bottom
NLOB = Number of Longitudinals on the Outer Bottom
NTROB = Number of Transverses on the Outer Bottom
f_n = Welding Rate for Thickness PT.

CONSTRUCTION TASK ALGORITHM 10 - DOUBLE BOTTOM UNIT ASSEMBLY - Sequence 4

JOB DESCRIPTION: Tank Top Flat Panel Sub-Assembly

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
1	Clear	Shop Floor	Job	191
2	Transport by Pallet	Plates	Job	171
3	Layout	Plates	Plate	176
4	Align	Flat Plates	Plate	177
5	Fair and Tack	Plate Seam	Plate Seam Length	84
6	Attach and Remove	Mini-deck Welder	Job	215
7	Weld	Run off Pieces	Job	216
8	Position	Mini-deck Welder	Seam	218
9	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111011
10	Aside	Mini-deck Welder	Seam	219
11	Turn	Panel	Job	224
12	Position	Mini-deck Welder	Seam	218
13	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111012
14	Aside	Mini-deck Welder	Seam	219
15	Mark Off	Longitudinal Positions	Longitudinal Length	2.1*
16	Mark Off	Transverse Positions	Transverse Length	2.1*
17	Transport by Crane	Sections	Job	154
18	Collect/Rough position	Longitudinals	Longitudinal	3.34*
19	Fair & Tack(downhand)	Longitudinals	Longitudinal Length	22.2*
20	Man/Fillet Weld(d/hand)	Longitudinals	Longitudinal Length	100110
21	Collect/Rough Position	Transverses	Transverse	3.34*
22	Fair & Tack(downhand)	Transverses	Transverse Length	22.2*
23	Man/Fillet Weld(d/hand)	Transverse	Transverse Length	100110
24	Man. Fillet Weld	Connection/Lug	Intersection	YSL1
25	Chip Fairing Scars	Panel Seam	Panel Seam Length	2.0*
26	Chip Fairing Scars	Longitudinal to Panel	Longitudinal Length	2.0*
27	Chip Fairing Scars	Transverse to Panel	Transverse Length	2.0*
28	Inspect	Job	Job	160

Total Manhours for Tank Top Flat Panel Sub-Assembly = Total 1 =

$$2.286 + 0.3 * NPLTT + [(NSEAMS * PLEN) * (0.1644 + \Sigma f_n(PT))] + [(NPLTT * PLEN) + (NTRTT * PWIDTH)] * 0.1985 + (NLLTT + NTRTT) * 0.0622 + (NLTT * (PLEN-1) * f_3(PT)) + (NTRTT * PWIDTH * f_4(PT)) + (NLTT * NTRTT * f_n(PT))$$

JOB DESCRIPTION: Plate Longitudinal Sub-Assembly

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
29	Clear	Shop floor	Job	191
30	Transport by Pallet	Plates	Job	171
31	Mark Off	Stiffener Positions	Stiffener Length	2.1*
32	Transport by Crane	Stiffeners	Job	154
33	Collect/Rough	Stiffeners	Stiffener	3.34
34	Fair & Tack(downhand)	Stiffeners	Stiffener Length	22.2
35	Man F/Weld(downhand)	Stiffeners	Stiffener Length	1100110
36	Chip Fairing Scars	Stiffeners	Stiffener Length	2.0*

Total Manhours for Plate Longitudinal Sub-Assembly = Total 2 =

$$1.492 + (0.0736 + (f_5(PT) * 0.1876) * STLEN) * NSTIFF$$

JOB DESCRIPTION: Plate Longitudinal to Tank Top

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
37	Mark off Tank Top	Plate Longitudinal Position	Plate Long. Length	2.1*
38	Position T-fashion	Plate Longitudinal	Plate Longitudinal	172/175
39	Fair and Tack	Plate Longitudinal	Plate Long. Length	80/81
40	Man F/Weld(downhand)	Plate Longitudal	Plate Long. Length	1100110
41	Man Fillet Weld	Plate Longitudinals/T. Top Transverses Connections	Intersection	YSL1
42	Chip Scars	Girder Fairing	Plate Long. Length	271

Total Manhours per Plate Longitudinal to Tank Top = Total 3 =

$0.24 + (0.4599 + f_6(PT) * PLEN) + (f_7(PT) * NTRTT)$

JOB DESCRIPTION: Vertical Floors to Tank Top

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
43	Fair Downhand	Vertical Floors	Vert. Floor Length	47
44	Fair Vertical	Vertical Floor to Girder	Vertical Fl/Hght	46
45	Man F/Weld(downhand)	Vertical Floor to T/Top	Vertical Fl/Lngth	0011002
46	Man F/Weld(downhand)	Vertical Floor to Girder	Vertical Floor Hght	0011002
47	Connections	Vertical Floor to T/Top	Intersection	YSL1
48	Chip Fairing Scars	Tank Top to Vertical Floors	Vertical Floor Length	270
49	Chip Fairing Scars	Vertical Floor to Girders	Vertical Floor Hght	270

Total Manhours per Vertical Floor to Tank Top = Total 4 =

$(NPPART * FLRGHT * NPLNGL * (0.366 + f_9(PT)) + (PWIDTH *$

$(0.536 + f_8(PT)) + (f_{10}(PT) * NLTT)$

JOB DESCRIPTION: Outer Hull Longitudinals and Transverses to Tank Top Assembly

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
50	Transport	Sections	Job	154
51	Transport	Shaped Sections	Job	163
52	Thread	Outer Bottom Longitudinals	Intersection	273
53	Thread	Outer Bottom Transverses	Intersection	273
54	Connection	Out/Bot Long - Vert. Floors	Intersection	100110
55	Connection	Out/Bot Trans/Pl long O.B Long	Intersection	100110

Total Manhours for Outer Hull Longitudinals and

Transverses to Tank Top Assembly = Total 5 =

$$0.442 + ((0.121 + f_{12}(PT)) * NLOB * NVRFLR) + ((0.121 + f_{13}(PT) * NPLNGL * NLOB * NTROB)$$

JOB DESCRIPTION: **Outer Bottom Plating**

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
56	Clear	Shop Floor	Job	191
57	Transport by Pallet	Plates	Job	171
58	Layout	Plates	Plate	176
59	Align	Flat Plates	Plate	177
60	Fair and Tack	Plate Seam	Plate Seam Length	84
61	Attach and Remove	Mini-deck Welder	Job	215
62	Weld	Run off Pieces	Job	216
63	Position	Mini-deck Welder	Seam	218
64	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111011
65	Aside	Mini-deck Welder	Seam	219
66	Turn	Panel	Job	224
67	Position	Mini-deck Welder	Seam	218
68	Butt Weld	Plate Seams (unrestricted)	Plate Seam Length	111012
69	Aside	Mini-deck Welder	Seam	219
70	Mark Off	Longitudinal Positions	Longitudinal Length	2.1*
71	Mark Off	Transverse Positions	Transverse Length	2.1*
72	Inspect	Job	Job	160

Total Manhours for Outer Bottom Panel Sub-Assembly = Total 6 =

$$2.15 + (0.3 * NPLOB) + [(NSEAMS * PLEN) * (0.1644 * \Sigma f_n(PT))]$$

$$+ (NTROB + NLOB) * 0.0109$$

JOB DESCRIPTION: Tank Top to Outer Bottom Link Up

SEQUENCE	ACTIVITY	OBJECT	APPLIED PER	RECORD
73	Shackle On	Lugs	Job	205
74	Turn + Berth	Tank top sub-assembly	Job	108
75	Man Fillet Weld	Bottom Trans to Btm Plt	Bottom Trans Length	100210
76	Man Fillet Weld	Bottom Long to Btm Plt	Bottom Long Length	100210
77	Man Fillet Weld	Plate Longs to Bottom Shell	Plate Length Long.	100210
78	Man Fillet Weld	V/Floors to Bottom Shell	Vertical Floor Length	100210
79	Man Fillet Weld	T/Top Plat. to B/Shell Plt	Tank Top Length	100210
80	Unshackle	Crane	Job	213

Total Manhours for Tank Top to Outer Bottom Link Up = Total 7 =

$$2.306 + (f_{14}(PT) * PWIDTH * NTROB) + (f_{15}(PT) * PLEN * NLOB)$$

$$+ (f_{16}(PT) * PLEN * NPLNGL) + (f_{17}(PT) * PWIDTH * NVRFLR)$$

TOTAL MANHOURS FOR DOUBLE BOTTOM UNIT ASSEMBLY =

Total 1 +(NPLNGL * Total 2) +(NPLNGL * Total 3) + (NVRFLR * Total 4)

+ Total 5 + Total 6 + Total 7

SUMMARY OF VARIABLES USED IN THE ALGORITHMS

NPLTT = Number of Plates on the Tank
NSEAMS = Number of Seams
NLTT = Number of Longitudinals in the Tank Top
NTRTT = Number of Transverses in the Tank Top
PLEN = Plate Length
PWIDTH = Plate Width
NPLNGL = Number of Plate Longitudinals
NSTIFF = Number of Plate Longitudinal Stiffeners
STLEN = Plate Longitudinal Stiffener Length
NVRFLR = Number of Vertical Floors
NPPART = Number of Piece Parts to each Vertical Floor
FLRHGT = Vertical Floor Height
NPLOB = Number of Plates on the Outer Bottom
NLOB = Number of Longitudinals on the Outer Bottom
NTROB = Number of Transverses on the Outer Bottom.