University of Southern Queensland

Faculty of Health, Engineering and Sciences

Design of a Truss Bridge for Low Cost using Structural Topology Optimisation

A dissertation submitted by

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Abstract

This dissertation explores methods to reduce the cost of a steel truss bridge. It is focused on determining how effective Structural Topology Optimisation (STO) is in reducing costs in a real design problem and therefore gauging how practical STO is for use as a design tool.

Structural Topology Optimisation (STO) is the most general form of structural optimisation and uses rigorous computing methods to determine the optimum shape for a structure. STO is regularly used in automotive and aerospace but not is commonly employed in building structures.

The truss in this dissertation is a simply supported steel truss for an industrial plant with a 46 metre span. It has many potential alternative layouts and is an ideal test of the effectiveness of STO.

By applying STO to the concept design via an 88 line MATLAB program, a range of optimised geometry was produced. The STO procedure indicated a strong preference towards the warren truss as being the optimal shape for a bridge of this type.

The truss bridge was designed to determine member sizes, extract a bill of materials and apply live project cost rates for a range of geometry. The results showed an average reduction in cost for the truss bridge of approximately 3% by using the optimised geometry.

Other methods of structural optimisation such as changing to high strength steel, using hollow steel sections and increasing the truss depth in conjunction with the optimised geometry increased the estimated cost savings to approximately 9%. This larger reduction appeared to indicate a compounded effect from optimising several parameters of the design together.

It was identified from the results of this dissertation that having a combined model for STO, analysis and design and the ability to include cost rates and discrete member sizes into the optimisation to cater for their significant effect would likely increase the benefits gained by STO.

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Certification

I certify that the ideas, designs and experimental work, results, analysis and conclusions set out in this dissertation are entirely of my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Signature ______________________________

Date ______________________________

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There have been several people who have been of significance in assisting with this dissertation and who I would like to thank.

It was Dr Kazem Ghabraie who casually suggested that he would be happy to supervise my proposed project, as “I have experience in this field”. His understated experience guided me to the fascinating topic of structural topology optimisation and for this I am grateful.

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My colleagues at Sedgman. Christian English provided guidance on much of the practical project considerations, along with transportation and costing criteria. Keith Hungerford showed extreme patience and incredible depth of knowledge in fielding my (many) questions on the intricacies of structural design, the use of Spacegass software and the requirements of the Australian Standards.

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Also my sincere thanks to my wife Catriona, who has added a number of my usual tasks and chores to her own substantial workload to the aim of increasing my available time to complete this project. Along with the proofreading the many drafts, her love and moral support have been unfaltering and an essential aid.

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Nomenclature

Acronyms

BESO	Bidirectional Evolutionary Structural Optimisation
BOM	Bill of Materials
DOF	Degrees of Freedom
ESO	Evolutionary Structural Optimisation
FE	Finite Element
FEA	Finite Element Analysis
RHS	Rectangular Hollow Section
SHS	Square Hollow Section
SIMP	Solid Isotropic Material with Penalisation
STO	Structural Topology Optimisation
UB	Universal Beam
UC	Universal Column
UDL	Uniformly Distributed Load

Glossary

Evolutionary Algorithm	An algorithm that mimics natural evolutionary processes by selecting the fittest of a range of options, usually generated with some amount of randomness.
Continuum Structure	A structure comprising of a region filled with continuous material with smoothly varying properties.
Heuristic	A “rule of thumb” method. The method is likely to work but is not guaranteed.

Chapter 1 Introduction

1.1 Overview

This dissertation explores methods to reduce the cost of a steel truss bridge. It is focused on determining how effective Structural Topology Optimisation (STO) is in reducing costs in a real design problem and therefore gauging how practical STO is for use as a design tool.

The truss bridge which is the design problem for this dissertation is for an industrial plant, has a 46 metre span and is simply supported at both ends.

Determining the practicality and effectiveness of STO was achieved by:

1. Applying STO to generate the optimal geometry for the truss bridge.
2. Conducting structural analysis and designing the bridge to determine member sizes and material quantities.
3. Applying estimated cost rates to determine total cost.
4. Comparison to an already completed design “base case” to determine the net benefit.

Cost rates are used for comparison as they are a more direct method of determining the benefit to a commercial project rather than minimising material as commonly used in research. In practice a simple and heavier structure is likely to cost less than a lightweight yet complex structure. Also this method can better capture the full range and magnitude of the effect of STO as it relates to a project.

1.2 Background and Significance

Optimisation of structures is fundamental to the role of structural engineers. Structures are routinely analysed to ensure their strength and stiffness are sufficient to meet project demands, yet are not too strong or stiff that they are wasteful of materials and or excessively costly.

Over recent decades the growth in computing power has aided this task. Numerical computing methods enable rapid analysis and design of complex structures and are an essential and established tool for engineers. However the effectiveness of the established analysis and design tools is of limited use during the concept design phase where there is a great range of potential solutions. Established methods of computer analysis determine the stress and strains *for a given layout*. In concept design and evaluation of many layouts the experience and intuition of the engineer, not computer analysis, plays a key role.

Structural Topology Optimisation (STO) has been explored by academic researchers with increasing interest in recent years. It uses analytical mathematical theory and numerical computing methods to perform a rigorous analysis of a design space to identify the optimum geometry. It is commonly used as an iterative finite element method where the supports, loads and overall boundary limit is defined. The inefficient material is removed through successive iterations and material deposited in more effective locations. The optimum shape results from this process. STO is currently being used as a powerful design tool by aerospace and automotive industries to speed concept development time and improve the performance of mechanical and structural components (Rozvany 2009). There is little evidence of STO being in regular use on building design (Baldock 2007). From anecdotal enquiries there appears to be little knowledge of STO amongst practising Structural Engineers in Queensland.

STO tends to produce complex, organic or natural looking shapes with material eroded from unnecessary areas. Refer to Figure 1.1. In automotive and aerospace industries, high performance structures and high volume production runs offset any increase in part complexity and increased design costs. Usually in building structures standardised shapes, ease of construction and additional design costs tend to reduce any benefits gained through STO.

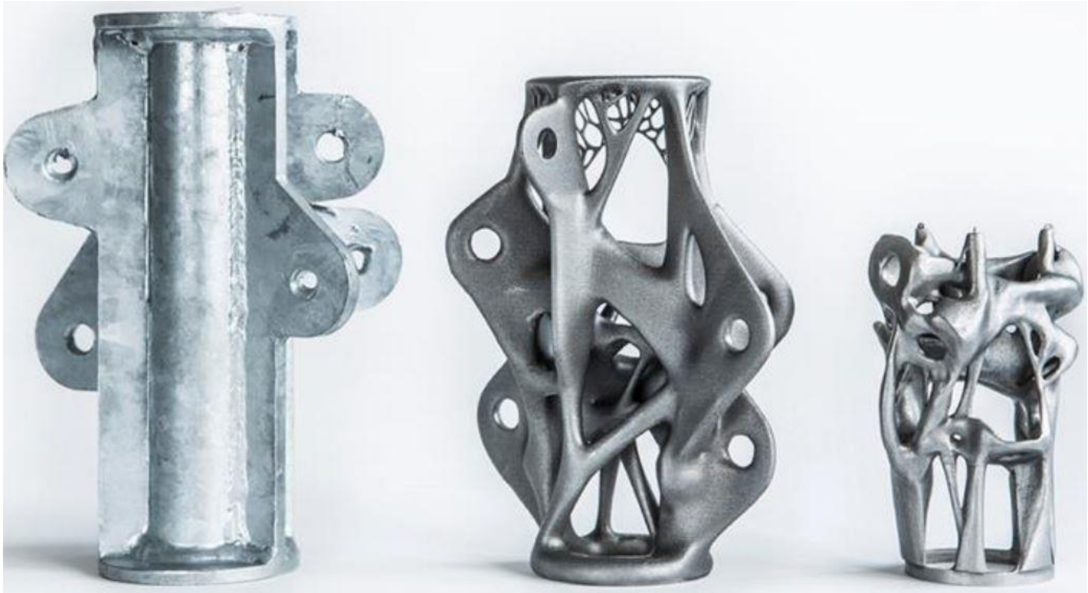


Figure 1.1–Organic optimised shapes produced by topology optimisation. From (Galjaard et al. 2015)

In truss design there are a large range of potential truss layouts. The range of potential layout increases as the size of the truss and the number of members increases. Refer Figure 1.2. The designer is faced with the task of determining which option is best. Short of designing for each layout the engineer must use some intuition or have an educated guess at the best solution(s) for detailed design. The truss bridge problem used in this project is considered to be an ideal test case for determining the effectiveness of STO in identifying the optimum geometry.

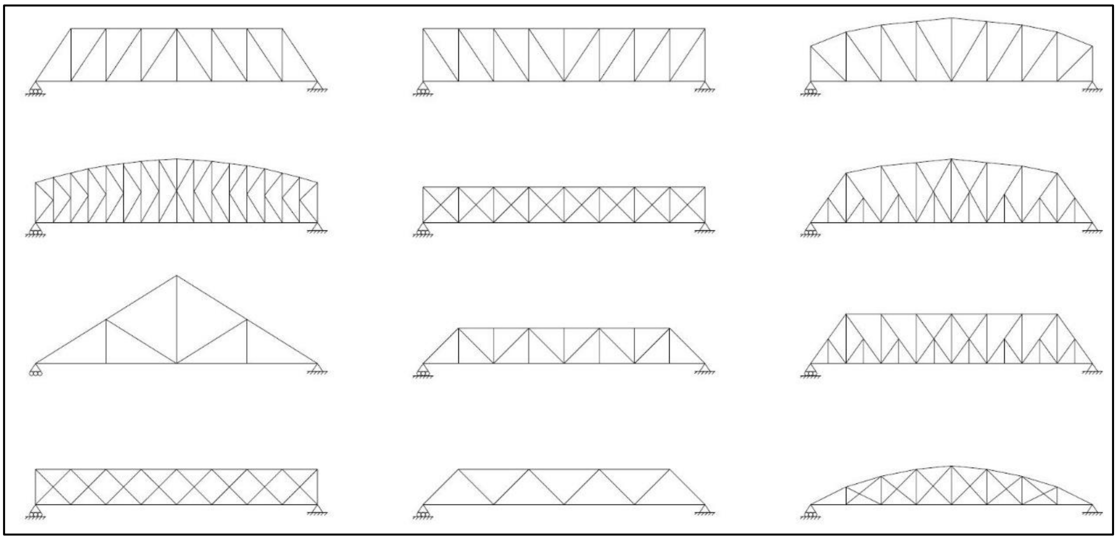


Figure 1.2–Truss layout options.

1.2.1 Structural Topology Optimisation

The Oxford dictionary defines topology as: "the study of geometrical properties and spatial relations" and "the way in which constituent parts are arranged". STO is arranging the shape and size of structural components in a way that is optimum, for given set of constraints. It is also called layout optimisation.

STO is applied by:

1. Defining the boundary.
2. Apply loads.
3. Define support locations.
4. Define objective.
5. Apply constraints.

A schematic showing the problem definition for a simple cantilever is shown in Figure 1.3 below.

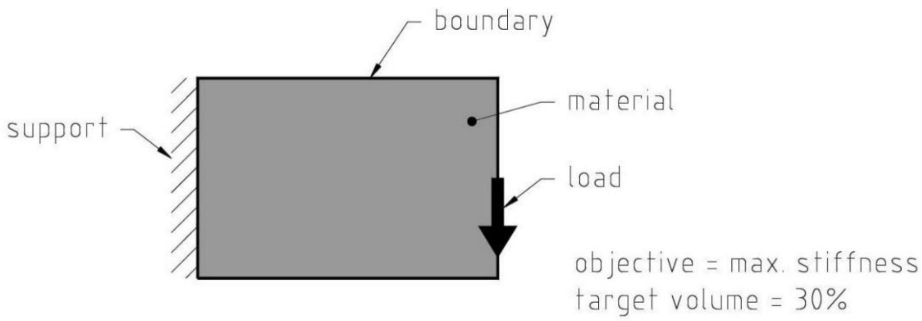


Figure 1.3–Topology optimisation example - problem definition

The resulting optimum material distribution is shown in Figure 1.4. It can be seen the material has been distributed towards the top and bottom extremities of the region for efficiency and converges towards the point load. There is internal bracing for stiffness.

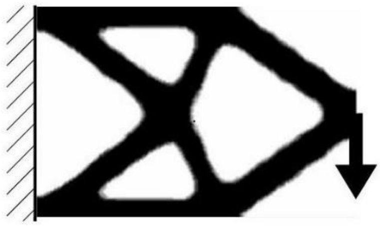


Figure 1.4–Topology optimisation example - problem solution

1.3 Objectives and Scope

This dissertation explores the methods which have been developed for STO and the application of STO to a real world structural design problem.

It aims to determine the practical benefits and drawbacks of topology optimisation by comparing a range of optimised designs to a completed design done without using topology optimisation.

The project is trying to isolate and highlight any benefits or drawbacks that STO methods can bring to a project during the design phase. To answer the question “should we be currently using topology optimisation as a design tool?”

The objectives of this paper are:

1. To review the current methods of STO and select one which is suitable to apply to an industrial structural design problem, using materials and fabrication technologies that are currently available to industry.
2. By applying the selected method to a truss design and using current cost rates, quantify any cost savings which can be achieved using the optimised design when compared to a base case design.
3. To compare the results of STO with other methods of structural optimisation to understand whether equivalent or better cost savings can be achieved without STO.
4. To look at the benefits and drawbacks of using topology optimisation and assess whether STO has a practical application within the commercial design environment.
5. To look at ways in which STO can improve the design process and ultimately achieve a better project outcome, indicated by a reduction in project costs.

Design, fabrication, transport and erection costs are included in the comparison in addition to the material cost as these are a major consideration in real project.

This project is uses live project cost data at 2016 obtained from project engineers at Sedgman Ltd. The construction materials and methods considered are typical of a current industrial project.

This dissertation does **not** look at alternative methods of optimising the design by methods such as:

1. Using unusual or high tech materials in the construction.
2. New manufacturing technologies (e.g. additive manufacturing).

The project specification is presented in Appendix A

1.4 Method of Investigation

The method used is described in brief below.

1. Simplification of the problem from 3D design to 2D planar truss.
2. Preparation of base case data:
    a. Take the data that is available from the initial design “base case”.
    b. Simplify the design problem to a plane truss.
    c. Verify the plane truss is an accurate representation of the complete 3D design model including the following aspects
        i. Support reactions
        ii. Deflections
        iii. Bill of materials (BOM)
3. Apply STO to the design problem to obtain the optimal topology:
    a. Determine the appropriate criteria, which are to be used in the topology optimisation.
        i. Sizes and scales.
        ii. Boundary size.
        iii. Element mesh size.
        iv. Minimum radius.
        v. Volume fraction.
        vi. Output.
4. Create an analysis and design model to match the optimal topology:
    a. Build the geometry
    b. Apply the loads, supports
    c. Check design using
        i. Support reactions
        ii. Deflections
        iii. Bill of materials (BOM)
5. Apply the appropriate the costs for the optimal topology and compare to the base case.

1.5 Structure of Report

This dissertation is organised as follows:

Chapter 2 summarises the traditional design process as commonly followed in a structural design office and an introduction to general optimisation is given.

Chapter 3 A brief history of STO is provided to give context to the many methods available. .A literature review of the available methods for STO is conducted. The more significant methods are highlighted and a discussion of the merits of these are presented. One method of STO is selected for use in this project.

Chapter 4 presents the design problem for the truss bridge which is the subject of the optimisation exercise. It also details the "base case" design completed without using topology optimisation which is the benchmark to compare with the topology optimisation results. The applicable loads and costs are given.

Chapter 5 applies STO to the design problem and presents the results of the optimisation exercise.

Chapter 6 details the structural design and analysis procedure used to obtain steel member sizes for elements of the truss. The test cases used for comparison are shown. The bill of materials (BOM) is exported from the structural design model for each of the test case. Cost rates are applied to the bill of materials. The results of the test cases are compared to determine which optimisation techniques are most effective and why

Chapter 7 presents the conclusions and recommendations for future work.

Chapter 8 lists the references used in the dissertation.

1.6 Consequential Effects

This report concerns an academic review and a computational design and analysis procedure. There will be no model or construction physically built or physically tested. This means that common safety concerns regarding bodily injury due to physical activities are not applicable in this instance.

A risk assessment to comprehensively assess the risks has been conducted is detailed in Appendix B – Project Risks

Chapter 2 Background

This chapter provides a review of: the traditional procedure for structural design and the role of STO within the design process.

2.1 General Categories of Structural Optimisation

Structural optimisation techniques are commonly grouped into the following categories. Refer to Figure 2.1 below.

1. *Material Selection* is using alternative materials or combinations of materials, for example timber, steel or reinforced concrete. The material selection can dramatically influence the construction process.
2. *Size optimisation* is determining the minimum size of material required by changing the dimensions such as the cross section of beams or the cross sectional size of elements in a truss. This is the simplest and oldest method of optimising a structure.
3. *Shape optimisation* focuses on increasing structural performance by changing the cross sectional shape of beam (say from rectangular to I shape) or varying the length of elements in a truss.
4. *Topology optimisation* changes the shape and size of a cross section of beam or the profile along length of beam, or changes the cross section size and/or length of any element in a truss. It is modifying the *layout* of the beam or truss, and is a combination of size and shape optimisation. Topology optimisation is also called *layout optimisation* and is the most general type of structural optimisation.

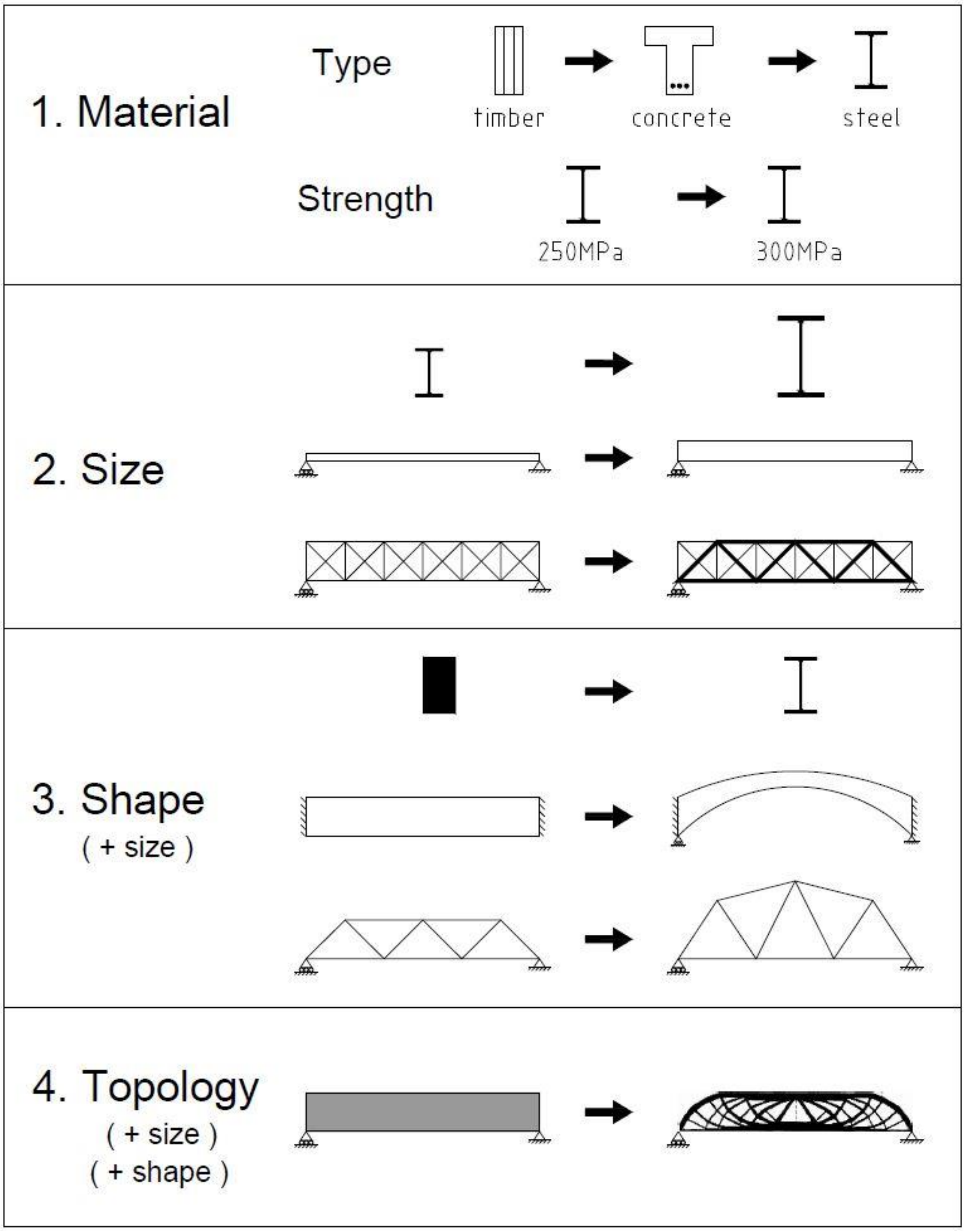


Figure 2.1– Structural optimisation methods Adapted from (Bendsoe & Sigmund 2003) (Baldock 2007)

2.2 The Traditional Design Process and the Potential Role of STO

The commercial engineering design process typically goes through several phases before the design is ready for construction. The results of each phase are used as a basis for a decision as to which direction to take the next phase.

The staged process is important because allows for a smaller initial commitment of resources until the point is reached where the viability of the project as whole is determined and the decision to proceed can be taken. A building project will have a multidiscipline team, so time in between phases allows for sharing and dissemination of information between teams and an amendment to the direction of the project can be taken, if required.

In the *concept phase (option study)* a number of alternative competing structural designs are developed and compared relatively quickly and at a high level. Factors such as the type of project, materials available, construction methods, equipment availability and the experience and skills of the engineer responsible guide the range of options developed. The experience and knowledge of the engineer is significant as more experience infers a broader range and better quality of options. Broad cost metrics or rules of thumb may be used to determine the preferred shape and forms (*layout,* or *topology*) of the structure.

In the *preliminary design phase (feasibility study)* a small number of options are looked at in closer detail in preparation for the selection of the preferred option. Analysis is more rigorous than concept phase and is likely to involve some structural analysis and iterative improvement to produce a small and well defined range of options.

In *detailed design phase* the materials to be used and structural system have been decided upon. The decision to proceed with the project is given. A large amount of resources are committed to produce a fully detailed design ready for construction in compliance with the relevant codes and standards. Thorough analysis using computer is done to efficiently size the structure to ensure material efficiency.

A summary of the trends is noted below:

1. As the design moves through the phases the amount of manhours committed to the project increase
2. The "big decisions" or decisions that have most influence of the structural system and topology are made earlier in the design process.
3. Once a decision is made, resources are committed to progress the design along that chosen path and the alternative paths are effectively closed.
4. The design focus narrows from broad to detail.
5. There is more application of rigorous computing methods in the later detailed phases.

The trends listed above highlight the lack of rigorous methods at concept phase and the significant potential benefit to be gained through application of topology optimisation during concept development. It is here the large decisions regarding the structural system are usually made, and specifically, that the methods commonly employed to arrive at such a decision are relatively haphazard and guided in a large way by the experience and knowledge of the team responsible and not by rigorous analysis as is used in the later phases of design. Topology optimisation can potentially be a valuable tool to apply rigorous computing methods to the concept phase of the project.

2.3 Optimisation Overview

Optimisation is the process of looking for the best or the *optimal* solution from a range of alternatives. General optimisation is a large field of study with a range algorithms developed to suit particular problem types and classes. Some of the many areas of application noted in literature include:

- All disciplines of engineering.
- Economics.
- Medicine and pharmaceuticals.
- Logistics and transportation.
- Computing and information technology.

The forces of nature optimise towards the most efficient use of materials. “Physical systems tend to a state of minimum energy.” (Nocedal & Wright 1999, p. 24)

<u>Numerical Optimisation</u>

The aim of optimisation is usually to look for extrema such as the maximum strength or minimum cost. Extrema are key component of calculus, and mathematical theory plays a key role in optimisation.

When computers are used for optimisation the methods employed are termed **numerical optimisation** and are an approximation of mathematical theory. (Zaslavski 2016) notes the following trends about numerical optimisation:

1. Numerical optimisation has been rapidly expanding.
2. There is a recent emergence of new algorithms and theories.
3. The interdisciplinary nature of optimisation is increasing.

2.3.1 Topology

Topology is a branch of mathematics concerned with distortion of material in space. It is concerned with how parts of a shape are related to each other rather than the exact shape.

Topology is commonly used to study the ways in which objects can be transformed without changing the way the object is put together.

An example of the way we use topology is the development of a schematic transport map showing the connectedness of rail to road networks which represents the way in which the stations and lines are connected, without being restricted to the shape and scale of the landform on which they are located in the real world. Another example is the use in schematics of computer networks that show how the elements of the network interact.

Topology is not related to topography which is concerned with geometric measurement of shapes and features.

2.3.2 Topology Optimisation

Topology optimisation is used across many fields in engineering and is adapted by defining the *objective function* to suit the field and specific objectives of the problem. A sample of the fields of application is shown in Figure 2.2.

Structural Topology Optimisation is a specific area of topology optimisation which relates to the optimisation of structural components.

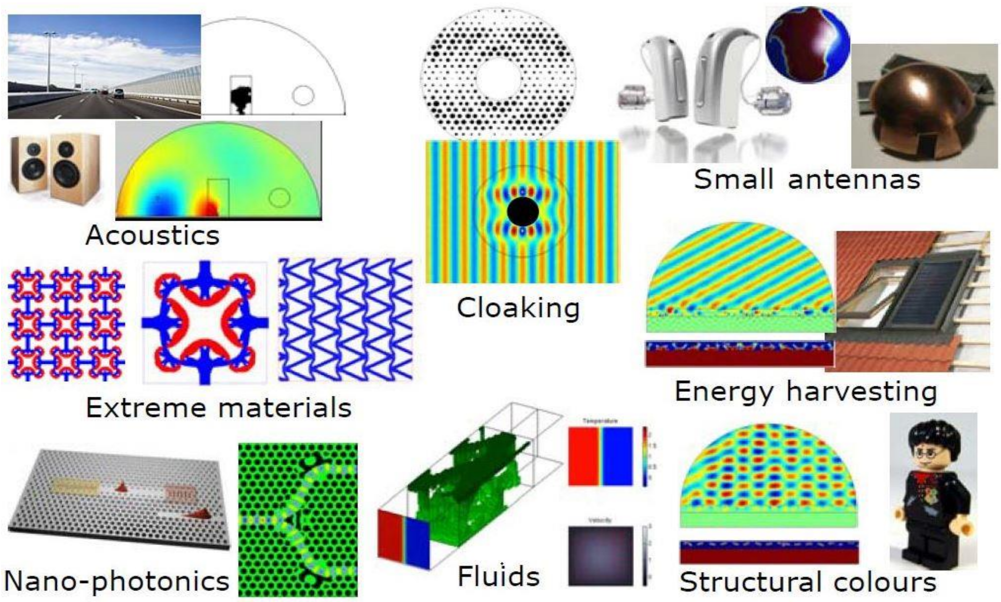


Figure 2.2– Topology Optimisation applications. Adapted from (Sigmund 2015)

Chapter 3 Literature Review

3.1 Overview

A study of available literature was performed to provide an overview of the field of STO, and review the information available on STO methods. This chapter provides a review of:

- The range of methods used for STO, and some of the advantages and disadvantages associated with each method.
- How STO may be applied to structural design.
- Selection of the most appropriate STO methods for use in this project.

3.2 Overview of Structural Topology Optimisation methods

3.2.1 Introduction to Structural Topology Optimisation

A large range of STO methods have been explored in academic research and there are almost as many research papers as there are methods.

Some reasons for the large variety of methods are:

1. The conflicting goals of topology optimisation. It is desirable for the method to be rigorous in finding the optimum as well as being computationally efficient (i.e. quick at producing a solution). However to be rigorous a method must use many iterations to be sure of finding the optimum solution, and this is demanding of computing power and will take long time. Therefore a compromise is required between true optimality and analysis times. (Nocedal 1999)
2. The complexity of many real life optimisation problems increase the number of variables to number in th

Of invaluable assistance in understanding the range of methods and their relevance are the structural topology optimization review papers of George Rozvany and Ole Sigmund. (Rozvany 2009; Sigmund & Maute 2013). These were used to guide the literature review below which outlines some of the more significant works in the development of STO techniques.

3.2.2 History and Development of Structural Topology Optimisation

Pioneering works

The Australian engineer Anthony Michell's 1904 paper "The limit of economy in frame structures" is considered the birth of structural topology optimisation. In this paper Michell developed general analytical (mathematical) techniques to find least material for some limited types of truss structures. An example is shown in Figure 3.1. Michell's ideas were a purely academic exploration and lay dormant for nearly 50 years before they were revisited by others. Due to the exact nature of analytical methods, his structures have been used as benchmarks for evaluation of modern numerical methods.

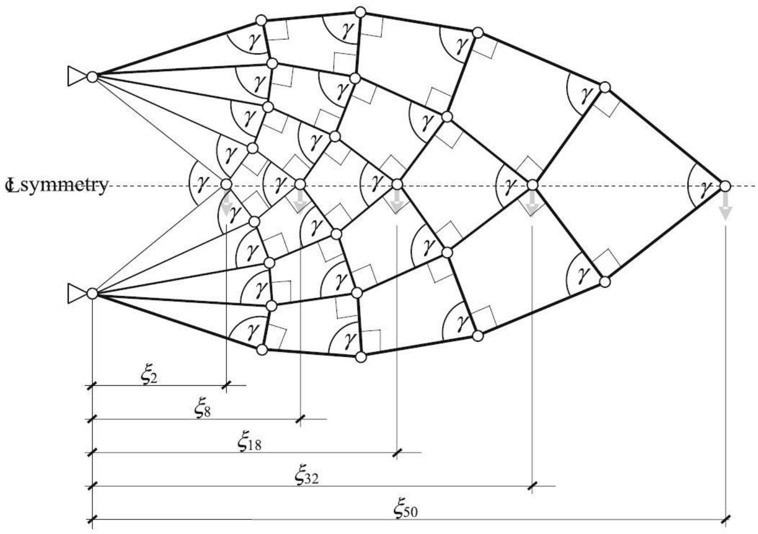


Figure 3.1–Optimised Michell cantilever, taken from (Mazurek, Baker & Tort 2011)

(Dorn, Gomory & Greenberg 1964) introduced the ground structure approach to truss optimisation in which the starting point is a grid of nodes that are fully connected by elements representing structural members (Refer Figure 3.2). The elements are assigned a cross sectional area that may be continuously variable (including zero area) or the element may be assigned a discrete variable (1 or 0) representing inclusion or exclusion. Elements are removed until the optimum structure is found. Due to the restricted geometry of the elements aligning to grid nodes it is possible that the global optimum solution is not found. In addition the number of potential elements and combinations of elements increases massively as the grid size increases, which leads to problems in applying this method to practical problems.

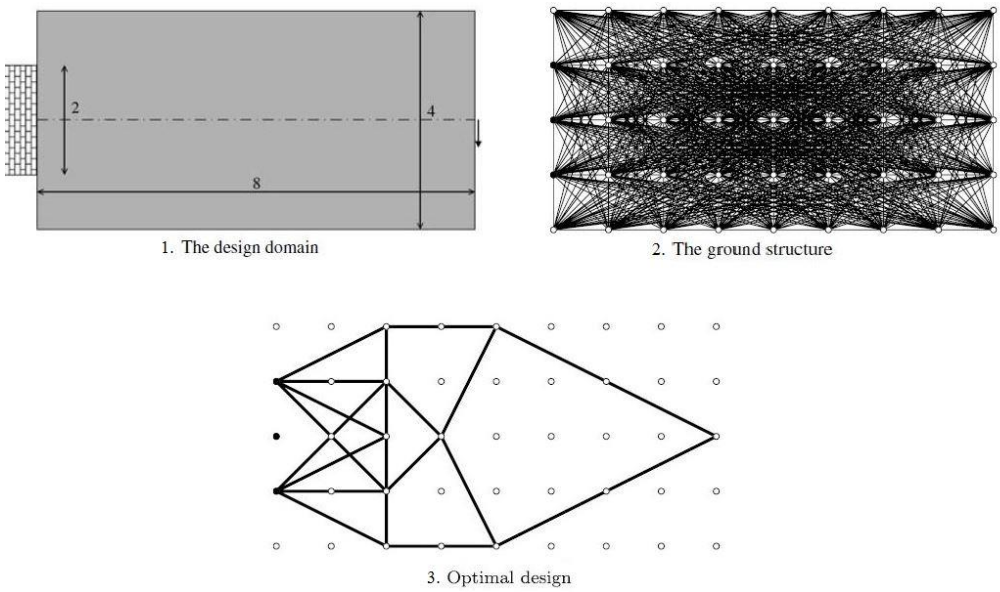


Figure 3.2– Ground structure with discrete elements applied to the Michell truss, taken from (Achtziger & Stolpe 2009)

W. S. Hemp and his co-workers devoted significant amounts time to studying Michell structures, and their work expanded the range of structures analysed. In the book "Optimum Structures" (Hemp 1973) the author presented the outcomes of their study. The solutions presented in this book are also used as benchmarks for modern numerical methods.

<u>Development of numerical (finite element) methods</u>

(Rossow & Taylor 1973) developed the first generalised topology shape optimisation method using the finite element method and applied it to varying thickness sheets of material. The concept of varying the thickness of a plate to reduce it to an optimal shape is analogous to changing the density of elements used later in numerical methods described below.

<u>Development of stochastic methods</u>

The Genetic Algorithm was developed by John Holland in the 1970s to mimic the process of natural selection for artificial intelligence systems. His 1975 book "Adaptation in Natural and Artificial Systems" spawned a whole new field of research which has expanded into many sub fields, all grouped under the term evolutionary algorithms. Holland's method was applied to optimisation problems in 1975 by Ken De Jong, a student of Holland's, and this gained the attention of researchers in the optimisation field (Reeves 2003). It has since been used for general optimisation problems and subsequently topology optimisation. It is a stochastic approach where some randomness is used in the generation of available options. The options are assessed to find the "fittest" candidates which are then used to produce the next stage of evolution.

<u>Growth in computer technology and numerical techniques for real applications</u>

(Bendsøe & Kikuchi 1988)* developed a finite element-based numerical **homogenisation method** for finding the optimal shape of a mechanical element. This method introduced the use of artificial material properties (homogenisation) to simulate solid/void topology which enabled the efficient use of numerical methods. The artificial material properties were varied by the application of microscopic holes in the finite elements which altered the stiffness of the element in the mesh. The method was applied to a 2D problem but the method is also directly applicable for 3D problems.

(Bendsøe 1989) & (Zhou & Rozvany 1992)* further refined the (Bendsøe & Kikuchi 1988) finite element method, using a method known as the **Solid Isotropic Microstructures with Penalisation (SIMP)** approach. This method directly varied the density of the elements to find the ideal topology and introduced penalisation to push the areas of intermediate density to either solid or void to improve the manufacturability of the structure.

> *The homogenisation and SIMP methods are considered to be a breakthrough as they make topology optimisation practical for real applications.

(Eschenauer, Kobelev & Schumacher 1994) developed the **bubble-method**, by positioning holes (bubbles) of different sizes into the structure to develop optimised topology.

(Xie & Steven 1993) developed the **Evolutionary Structural Optimization (ESO)** finite element based approach. This is a very simple method that removes material from low stressed areas to in a domain to produce an optimised shape. It involves a relatively minor amendment to the finite element method. However it is possible the global optimum may not be found because material removed in the early stages of optimisation may be required to form the final optimal shape.

(Young et al. 1999) (Yang et al. 1999) addressed the weakness of ESO by adding additional steps which added material, to create **Bi Directional Evolutionary Structural Optimisation (BESO).** This method uses the removal of inefficient material from low stressed areas along with the addition of material adjacent highly stressed areas to ensure the method is better capable of finding the global optimum.

(Wang, Wang & Guo 2003) and (Allaire, Jouve & Toader 2004) introduced the **level set approach**. This method defines the boundary of the structure at the solid/void interface as the zero level of a function. This method has many of the advantages of the density (SIMP) methods however does not require penalisation of the intermediate densities as the level set naturally defines the boundary. This method can have problems with poor convergence to the optimum solution. (Norato, Bell & Tortorelli 2015) Refer to Figure 3.3 where the use of the level to define the boundary of the optimum topology can be seen.

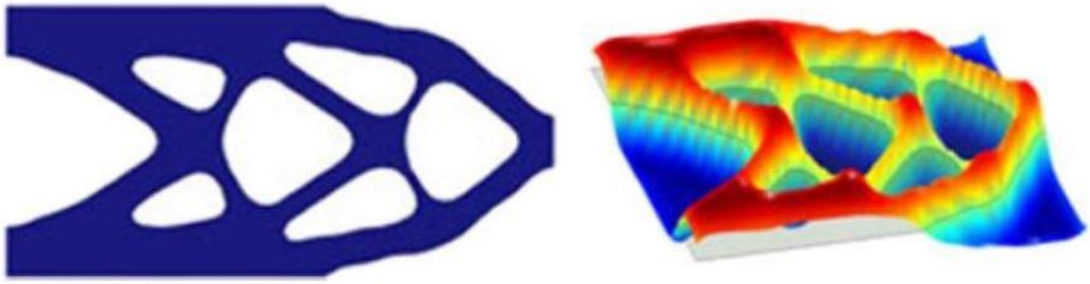


Figure 3.3– Optimal Topology from the level set method (left) showing the function values (right). Image taken from (Deaton & Grandhi 2014)

3.2.3 Grouping of Structural Topology Optimisation Methods

The STO methods may be grouped in different ways. An outline of the groupings is provided to provide some clarity to the often confusing terminology used in association with STO. It is common in literature for methods to be referred to with broad and seemingly unrelated categorisations. Understanding the types of categorisations is necessary to understand the range of methods that have been developed so far.

Topology optimisation methods can be grouped by:

1) The search method employed. Figure 3.4 illustrates the various STO methods, grouped by search method.

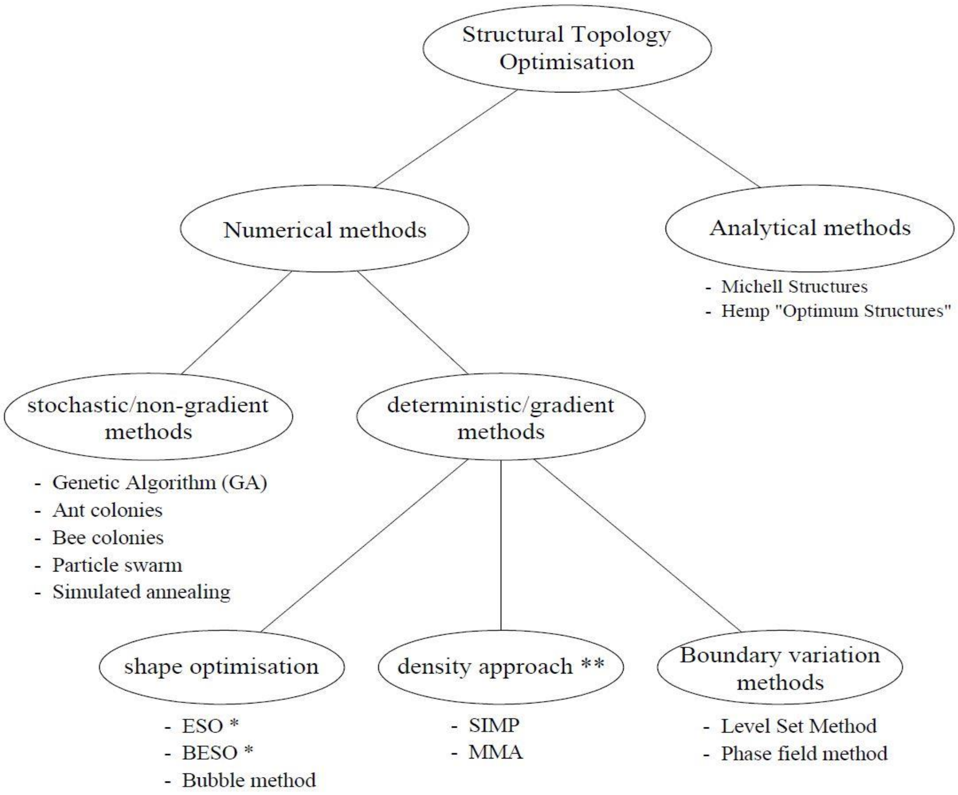


Figure 3.4– STO methods grouped by the search method.

* these methods are popular, they are the most cited methods on Google Scholar (Rozvany 2009)

** The density approach accounts for a significant portion of recent STO papers (Sigmund & Maute 2013)

2) The material representation:
   a) *Discrete elements.* Ground structure and other optimisation methods specifically used for trusses. The structure is modelled as interconnected elements and nodes. Topology optimisation using discrete elements is programmatically much more difficult than continuum.
   b) *Continuum structure.* A structure consisting of a region filled with continuous material such as may be used for a mechanical part or continuous frame. This region is often discretised into a finite element mesh for analysis.

3) The type of variable used in the programming:
   a) *Discrete* variables such as the use of integers or discrete member sizes.

   Discrete problems are considerably harder to solve due to the integral mathematics used in optimisation theory.

> "The obvious strategy of solving the problem using real variables, and then rounding all the components to the nearest integer is by no means guaranteed to give solutions that are close to optimal. Problems of this type should be handled using the tools of discrete optimization." (Nocedal & Wright 1999, p. 4)

b) *Continuous variables* where the density or other variable use a continuous range. This is usually easier programmatically and computationally more efficient.

3.2.4 Analytical Methods

These methods use mathematical theory and calculus to determine the optimum layout. They are suitable for simple or small structures with simple loading. Practical real life problems are too complex for use with analytical techniques as they contain too many variables and constraint. Analytical methods are important in the development of topology optimisation because they provide optimal benchmark problems against which the effectiveness of numerical methods can be measured (Rozvany 1998).

3.2.5 Numerical Methods

Numerical methods use mathematical programming techniques to approximate exact analytical methods. These methods are good for large scale practical problems involving lots of variables and constraints.

3.2.6 Stochastic Methods

Stochastic methods involve some type of randomness generator in an algorithm, usually with the aim of spreading the search over a large area of the solution space to increase the chance of finding the global optimum solution. A characteristic of this search method is that the same input data may result in differing solutions as a result of the randomness.

These methods evaluate several possibilities in one iteration to allow comparison of results before starting the next iteration so tend to be very computationally expensive. (Rozvany 2009) (Sigmund 2011)

(Sigmund 2011) is highly critical of the performance and merit of stochastic methods used for STO when faced with the size and complexity of real problems. The criticism is due to the inefficient use of computational power.

Stochastic methods are of benefit is when the optimisation model cannot be fully specified, as happens frequently with economic and financial models. If the modellers are able to assign probabilities to scenarios, the stochastic methods use the predictions to optimise the performance of the model. (Nocedal & Wright 1999)

3.2.7 Deterministic Methods

Deterministic methods use relationships between the constraints to find the solution. A characteristic of this search method is that repeating the model evaluation with the same input data will result in the same solution every time (in contrast to the variation of stochastic methods).

3.2.8 Gradient Methods

Gradient based methods define the problem as a function with many variables representing the design conditions. This is the objective (or compliance) function $\boldsymbol{f}(\mathbf{x})$. The objective function represents the quality of the structure for optimisation.

The aspect of performance that is optimised can vary by changing the objective function. A structure may be optimised for:

- Maximum strength for a given volume of material.
- Optimum stiffness (by minimising the total work-energy).
- Resistance to vibration, seismic forces or a certain range of natural frequency.

<u>Optimisation statement</u>

Minimise**:** $\boldsymbol{f}(\mathbf{x})$ *(Compliance function)*

Subject to: $g(\mathrm{x}) \leq 0$

$h(\mathrm{x}) = 0$

Where: $g(\mathrm{x})$: Equality constraints

$h(\mathrm{x})$: Inequality constraints (mass, etc.)

x : Design variables

The objective function is subject to constraints which represent real life design criteria such as mass, volume, stiffness, maximum stress, permissible displacement or natural frequency. So the feasible region for the solution is bounded by these constraints. Refer Figure 3.5.

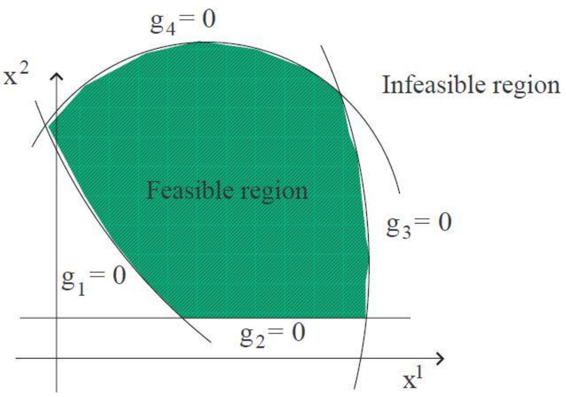


Figure 3.5– The feasible region for the compliance function, taken from (Astolfi 2006)

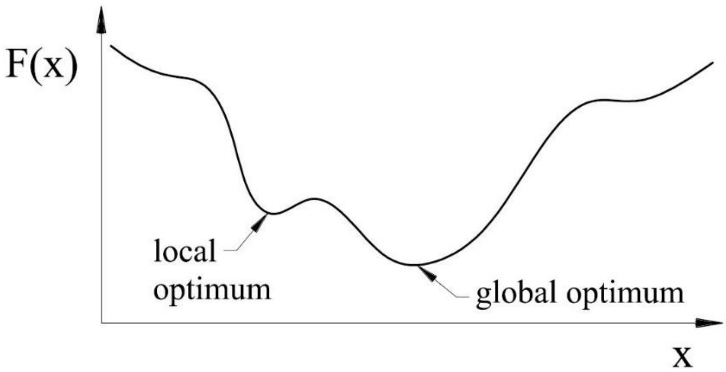


Figure 3.6– A simplified 2D representation of global and local optimum for the gradient method.

Gradient based algorithms use the gradient as a way to rapidly find the minimum without having to work through unnecessary and computationally expensive iterations. There are different methods of using the gradient to achieve this aim.

The global optimum solution is found at the global minimum of the compliance function (refer Figure 3.6). It is important that the method is robust enough to ensure that it does actually find the global optimum rather than come to rest at the turning point of the local minimum. Figure 3.7 provides a pictorial representation of the global minimum for the objective function subject to constraints for one variable. An optimisation problem with 2 variables would be represented as a surface. With more variables as commonly encountered pictorial representation becomes difficult.

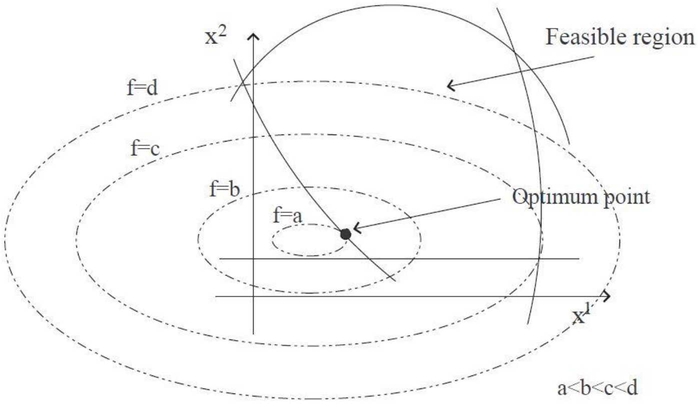


Figure 3.7– The optimum point for the compliance function. (Astolfi 2006)

<u>Bidirectional Evolutionary Topology Optimisation (BESO), also called Sequential Element Rejections and Admissions (SERA)</u>

Evolutionary topology optimisation works by defining a boundary area with a solid material and the external forces and supports locations. A Finite Element Analysis (FEA) of the material determines relative stress levels. Inefficient material is removed from the low stress areas and the geometry is updated. The evolution continues until the rate of material removal reaches a predetermined (low) rate. The result is an optimised structural shape.

The process is very simple to understand, involving the addition of a few lines of code to the finite element method. It is also very popular and accessible due to the publishing of a text book on the method. (Rozvany 2009)

While the method appears to work well, it has attracted criticism due and its development from a heuristic model. (Rozvany 2001)

3.2.9 Discrete Truss Methods

An example of discrete truss methods it the ground structure approach. This approach works well with standard structural sizes, for example beams and tubes. There is difficulties with programming complexity due to discrete variables required for standard structural sizes. Also the optimisation analysis has simplifications which reduces its accuracy.

Also discrete truss methods can have difficulties with: (Ohsaki & Swan 2002)

1. Too many members in the initial ground structure make it computationally expensive.

2. The optimal topology is strongly dependant on the node and member placement initial ground structure.
3. The truss becomes unstable (ie a mechanism) if too many members are removed.
4. Unrealistic optimal solutions result.

3.3 Comparing and Evaluating the Performance of Optimisation Methods

The three key criteria for the performance of optimisation methods are:

1. **Efficiency.** How *quickly* the method finds the solution, i.e. how many iterations are required to converge to a minimum compliance or how much *computational effort* is required to arrive at the global optimum solution.
2. **Robustness.** The ability of the method to consistently find the global optimum for a range of problems. The reliability of the method can be demonstrated by comparing the solutions of a wide diversity of problems with known optimum solutions as well as unsolved problems. (Stolpe 2016)
3. **Accuracy.** Being able to identify a precise solution. (Nocedal & Wright 1999)

There are not algorithms that excel in all areas of performance so a tradeoff in criteria is usually required. It may be preferred to use a method that is slower but explores a greater range of solutions.

<u>Efficiency</u>

To give a gauge of the computational requirements of a realistic topology optimisation problem, it is worth considering the method used to find the solution. Using a common iterative FEA approach there is likely need to be somewhere in the order of hundreds to a thousand iterations to find the optimum. For each iteration there needs to be a solution of the FEA. With current computing power the FEA of a problem with only one iteration will take a length of time in the order of seconds or minutes to solve. Applying the multiples of iterations of the magnitudes hundreds or thousands mean the overall processing time is likely to take several hours. Efficient use of computing power is a definite consideration in the effectiveness of the method.

Robustness

Optimisation problems for real design problems quickly become extremely complex and without comparison to benchmark problems that evaluate performance in key areas there are no metrics to gauge the practical usefulness of the method. It is also important to determine if the method does in fact find the global *optimum* rather than finding merely an *optimised* solution which may be somewhat less ideal than the true global optimum.

The number of topology optimisation methods being developed and research papers being published is increasing annually. In many cases the poor level of documentation and lack of "standard" library of benchmark problems means it is difficult to compare the relative merits and drawbacks of the proposed methods. It is "impossible for the reader to judge if the proposed method/heuristic is efficient or robust" (Stolpe 2016)

3.4 Application of STO to Design

3.4.1 Use in aerospace and automotive

In the space of 20 years topology optimisation methods have gone "from being an academic exercise to being the preferred tool for advanced mechanical, automotive and aerospace industries throughout the world" (Sigmund 2011) There is much evidence of this use in literature from design software companies promoting the use of their software for these high performance applications. This is a marked contrast to literature for structural design software which rarely includes examples of topology optimisation application.

3.4.2 Use in Building Structures

There is some evidence of exploratory use of STO in structural engineering. Some examples are listed below:

- For concept design lateral bracing for high rise buildings. (Stromberg et al. 2012).
- To obtain optimal layout of outrigger bracing panels in high rise buildings. (Lee & Tovar 2014)
- It has been applied to the optimisation of castellated steel beams used in buildings to allow passage of ducting and other services between floors. (Tsavdaridis, Kingman & Toropov 2015)
- (Schevenels et al. 2014) applied an optimality criteria method to a sizing problem of a fixed layout warren truss.

- (Achtziger 2007) Applied simultaneous sizing and topology optimisation. Difficulties were encountered with the complexity.
- (Ohsaki 1998) Simultaneous optimisation of topology and geometry of a plane truss. Had difficulties.
- (Asadpoure, Guest & Valdevit 2015) applied the MMA method to discrete truss optimisation applying a fabrication cost constraint to the problem. The results appear to have a real practical use.

In summary, there is evidence of moderate level of exploratory research on building type structures. There was little evidence of STO in regular use on structures.

3.4.3 Commercial Software with STO

A range of commercial software has been developed with topology optimisation capabilities. Most software has adopted the SIMP method in some form. (Rozvany 2009):

- Optistruct
- Genesis
- MSC/Nastran
- Ansys
- Tosca
- Autodesk Inventor

3.4.4 Why has STO been Adopted in Only Some Industries?

STO has been adopted by aerospace and automotive industries yet has seen little application in building structures. Baldock (2007, p. 26) found that in automotive and aerospace industries, low performance and high weight structures give “knock on effects” of reduced vehicle efficiency, which will also result in increased operating costs. Also high volume production runs can dilute any extra design costs incurred using through using STO.

In building structures, usually the design is bespoke and required for each structure. With “one off” designs practical construction aspects dominate costs and economy is dictated by the use of regular (easy to build) shapes or standard steel sizes.

3.4.5 Practical Considerations in Application of STO to Building Structures

When looking to apply STO to building and industrial structures the considerations below are important:

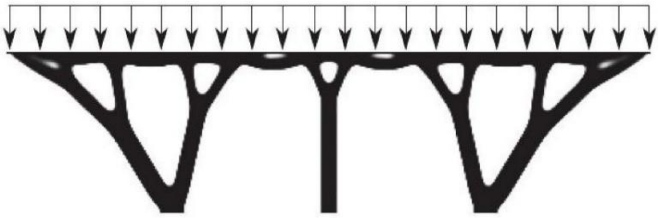
1. The organic shapes produced by STO
2. The discrete standard structural steel sizes readily available
3. Inclusion of costs into the optimisation
4. Practical limit to member lengths and sizes

These points are discussed in more detail below.

<u>Organic shapes</u>

A significant drawback for application to building structures is that the optimised shapes are often flowing organic structures, with constantly changing section size and curved or irregular boundaries. Refer Figure 3.8. These shapes are contrast to the standard hot rolled steel sections and rectangular shaped reinforced concrete members economically used today.

The flowing shapes do not lend themselves to easy standardisation in materials other than steel, such as concrete, rather they infer that significant labour is required for construction and are therefore likely to be difficult or more expensive to construct than standardized members. In most cases this is detrimental to the success of a project and are a barrier to the adoption of STO techniques.



(a)– An optimised structure subject to a uniformly distributed load with multiple supports

(b) A pictorial view from below

Figure 3.8 -The organic shape of an optimised structure. Image from (Clausen, Andreassen & Sigmund 2015)

<u>Discrete standard structural steel sections</u>

Structural grade steel is available in standardised sizes, shapes and grades (as discussed in Section 4.4) to enable economical design and production methods.

<u>Inclusion of cost into the optimisation</u>

Cost is a significant criteria for many applications and not including cost is limiting the effectives of the optimisation and not likely to lead to the true global optimum.

<u>Practical limit to member sizes and lengths</u>

Control of the optimisation algorithm is needed to produce results suitable for the manufacturing process of the structure.

In summary, for global optimisation it is necessary for the optimisation algorithm be adapted to suit the proposed fabrication method or devise construction methods suitable to for application to the shapes obtained by STO.

3.5 Selection of STO Method for Application to the Design Problem

3.5.1 Characteristics of the Design Problem

The problem to be optimised has the following features.

1. It is to be constructed from a linear material, that is, its deformation varies linearly in response to the stress applied and resumes its original shape once the load is removed.
2. The loads applied will cause only small deformations of the structure relative to its overall length.

These two points above mean the optimisation problem is a linear problem which is a relatively simple class of problem to solve. Problems involving plastic deformation or non-linear materials are classed as non-linear optimisation problems which are considerably more difficult to solve.

3.5.2 Method Selected

The options below were considered for use with the design problem.

1. The discrete truss approach.
2. The SIMP method.
3. The BESO method.
4. A trial version of commercial software.

The SIMP method was chosen due to the following:

1. Its accessibility. The method is readily available for use via two open source MATLAB programs. (Sigmund 2001) (Andreassen et al. 2011). The discrete truss method developed by (Asadpoure, Guest & Valdevit 2015) with the inclusion of cost parameters appears ideal and preferred for this type of problem however is not accessible to the author so is not able to be used.
2. The SIMP method has been adopted by many of the commercial design software developers. (Rozvany 2009) This implies it is robust and gives confidence in its ability to find the global optimum.

3. It is computationally efficient. Trial versions of commercial optimisation software are available however with a quick evaluation of a couple of option in a short amount of time they did not appear likely to suitable for this project. Autodesks Inventor Shape Generator and Altair Optistruct were trialled on an Intel i7 laptop. The computational requirements of commercial software meant it was not suitable for use on this project.
4. There is a variety of literature available to understand the SIMP method.

The SIMP method is used for design of continuum material. As the optimum layout tendsn assumption is made that

we could be able to take the optimum solution, modify it to make it a more regular structure and commercially practical and although less than "perfect" this should still give the best layout ready for further refinement.

3.6 The SIMP Method

Solid Isotropic Material with Penalisation Method (SIMP)

"Solid" refers to the material assigned to each element and differentiates this method from earlier methods that modify the micro structure of each element as a tool to arrive at the optimum topology.

"Isotropic material" refers to the material properties being constant in all directions.

"Penalisation" is the filtering process to push the design towards a solid/void solution for ease of manufacturing.

The SIMP method breaks the design domain into finite elements and aims to minimise the compliance function (hence optimise the topology) by determining the appropriate density each element.

The method uses the following procedure as shown in Figure 3.9 (Sigmund 2001):

1. Define the boundary area, loads, supports and mesh size.
2. Discretise boundary area into a finite element mesh and distribute material. Each element has a density variable assigned.
3. Use FEA to determine displacement vector for current densities.

4. Loop over all elements to give objective function and determine the sensitivities for each element to the overall stiffness of the shape. The sensitivity is derived using the gradient.
5. Apply sensitivity analysis (with checkerboard and minimum radius filter) to update density variable for each element and overall compliance value.
6. Test for the change in variables and if less than 1% stop, otherwise repeat iteration from step 3.

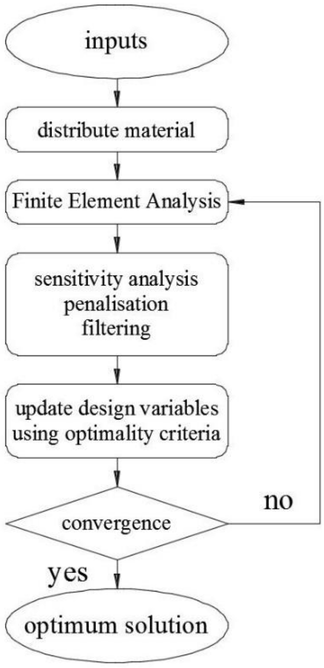


Figure 3.9 –The SIMP algorithm

This method uses FEA with a continuous variable for the density parameter. The continuous variable simplifies the algorithm by avoiding the need to redefine the FE mesh at each iteration to remove the void elements. As noted above, the method uses a "power law" penalisation factor on the density variable that pushes the density towards a state of 1 or 0 (solid or void). The void elements do not have a value of 0 but a very small number that for computational effects is the same. These two arrangements allow the use of continuous variables giving a method that is significantly easier to solve than by using a programmatically troublesome discrete variable for the density. A zero element would result in the stiffness matrix becoming singular and complicate the inclusion of the element at a later iteration. The effect of the "power law" penalisation is illustrated in Figure 3.10.

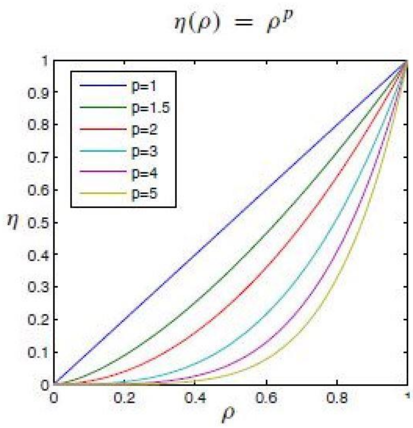


Figure 3.10 –The effect of power law penalisation on the density. Adapted from (Deaton & Grandhi 2014)

The effect of penalisation to the example of a simple cantilever shown in Figure 3.11. The optimised result on the left tends to have large areas of greyscale which represents intermediate destiny and is likely to difficult to manufacture. Penalisation is applied which pushes the result towards solid/void and results in and optimised solution with full density material for ease of manufacture, where required.

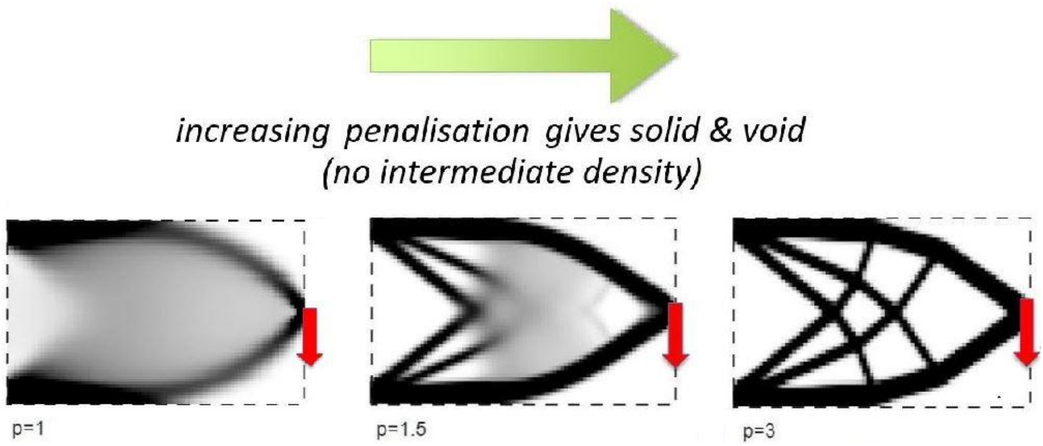


Figure 3.11 –The effect of the penalisation on optimised topology. Adapted from (Bendsøe & Sigmund 1999)

The density variable describes the elements density relative to other elements.

Optimised topology with areas of checkerboard structure is a numerical instability problem from the finite element method and is not an optimal design. (Edwards 2007). The checkerboard structure has an artificially high stiffness, resulting in an erroneous topology and needs to be removed. The checkerboard areas are removed through the use of filtering technique to smooth the sensitivities after the analysis. The smoothed sensitivities are used for the optimisation.

The range of the filtering can be changed via a variable for the minimum radius and this effectively places a minimum size on elements to be considered for the solution. The filtering removes elements below the size of the minimum radius. It is important the filter radius be comparable to the element size as the thickness of the 2D planar is problem is equal to one element. The use of filter radius is illustrated in Figure 3.12.

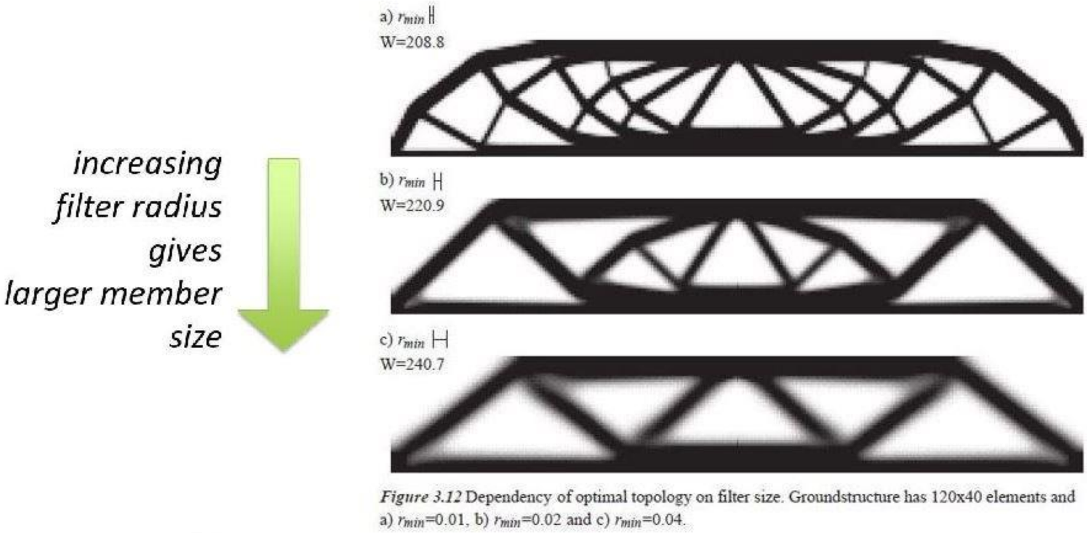


Figure 3.12 –The effect of the SIMP filtering radius. Adapted from (Sigmund 1994)

The SIMP method is simple to understand and apply. This has been aided by the availability of a free downloadable MATLAB script along with explanatory notes. The method has a natural ability to accommodate changes in topology, circumvent remeshing, response sensitives to be computed. (Norato, Bell & Tortorelli 2015) It generally considered robust and computationally efficient.

3.7 Conclusions

From the research conducted it is possible to conclude:

1. There are many available methods. One method (SIMP) has been applied to nearly all commercial software and is available to the public as open source code.
2. There is limited use of STO currently in commercial structural design.
3. The results of topology optimisation are often organically shaped flowing structures which may be difficult to manufacture. For successful application in a commercial environment an assumption is modify it to make it a more regular structure and commercially practical and although less than "perfect" this should still give the best solution for further refinement.

Chapter 4 Design problem

4.1 Overview

The design problem is the optimisation of a bridge structure. The bridge to be optimised is to be used within an industrial plant. It has a span of 46.0m, simply supported with a fixed pin at one end and sliding pin at the other. The bridge spans a mainline railway track and the clearance envelope below the bridge is required to suit railway requirements. Refer to Figure 4.1 below for an illustration of the bridge components. The primary function of the bridge is to support a conveyor belt, with walkways on both sides to allow for maintenance personnel to access to the conveyor components.

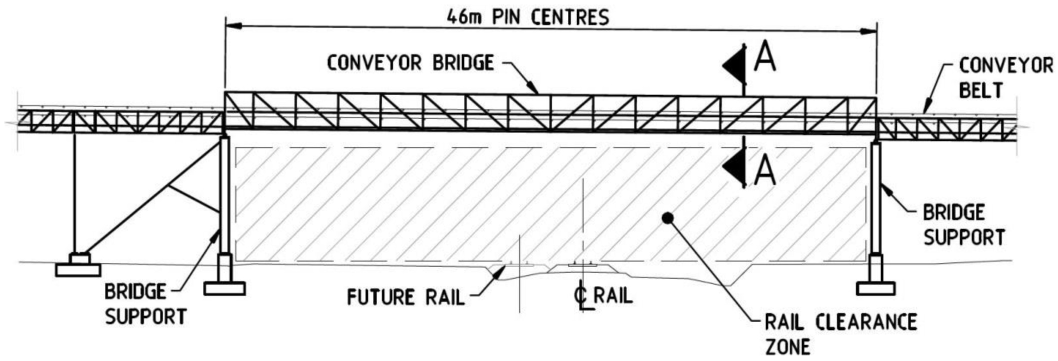


Figure 4.1– Elevation of bridge

The conveyor equipment and access requirements governs the minimum required width of 4.0m. This is shown in Figure 4.2

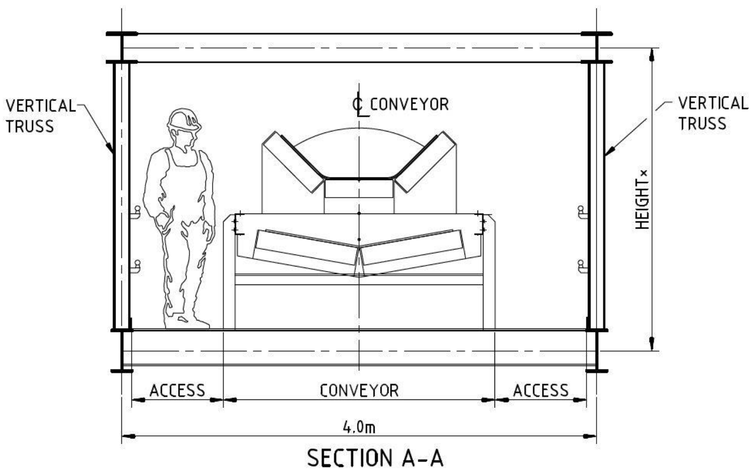


Figure 4.2– Bridge cross section.

The site is in a remote rural environment so architectural aesthetic qualities are of low importance; if there is any aesthetic requirement it would be that the bridge should look robust and fit for purpose.

The bridge is an open frame and does not require cladding.

4.2 Design Aim

The design aim for the bridge is to maximise structural performance of the structure to suit the applied loads whilst minimising cost.

These are competing criteria, as increasing the structural performance by using more material is likely to add an undesirable and corresponding increase in cost. Reducing the cost by using less steel is likely to reduce the strength and could impair the ability of the bridge to carry the service loads. The focus of this project is to find the most cost effective way to construct the bridge and also satisfy the structural performance requirements of the structure.

4.3 Bridge Topology/Shape

The shape of the bridge is driven by function. The bridge is effectively a box shape in cross section, as shown in Figure 4.2. Trusses on the two vertical sides of the bridge carry the vertical component of the loads. The horizontal trusses resist the horizontal (wind) loads and provide lateral support to the vertical trusses. The lateral support to the vertical trusses is an important part of the design- a vertical truss spanning the distance required of this bridge without lateral support would require a stiffness many magnitudes greater than the slender members used in this design.

It is possible for there to be different configurations of horizontal and vertical trusses.

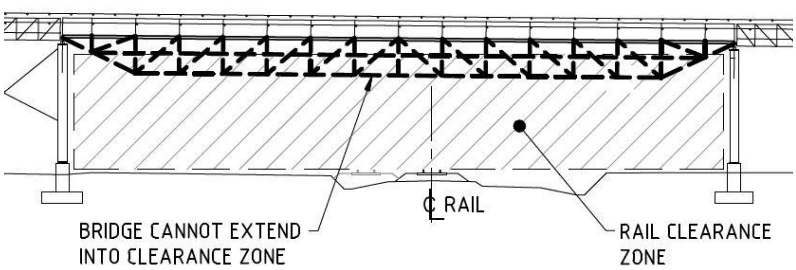


Figure 4.3– Bridge clearance requirements

The clearance envelope required below the bridge (refer Figure 4.3) limits the range of truss types suitable for consideration. The truss design needs to avoid geometry that extends excessively below the conveyor, as this would require additional height to the support structures to maintain that clearance. Lifting the profile of the conveyor would also add extra length to the conveyor and the corresponding increase in cost would far outweigh any potential savings related to the truss structure.

4.4 Materials

Structural grade steel in standard section sizes is to be used for the bridge construction. These sections are readily available from steel merchants and are cost effective. They are fabricated into the required shape by cutting to the length required and welding into the required truss shape.

An alternative method of using steel would be to fabricate steel plate into required shapes by cutting and welding to create custom section shapes. The high cost of fabrication and transport of the bridge using this method would be excessive and so is not considered further.

There are two types of section profiles used in the design:

1. Hot rolled steel.
2. Hollow sections.

Apart from the difference in their shapes the most important difference between the two types is the yield strength of the steel used in each type of section profile. The hot rolled sections used steel with a yield strength of 300MPa and the hollow sections use steel with a yield strength of 450MPa. This means a change in section type is also a change in material type.

4.4.1 Hot Rolled Sections

The original design (base case) of the bridge uses hot rolled steel sections. The steel used has a minimum yield strength of 300MPa.

The hot rolled section shapes are shown in Figure 4.4 and can be divided into:

1. Universal Beams.
2. Universal Columns.
3. Parallel Flange Channels.
4. Equal Angeles.

5. Unequal Angles.

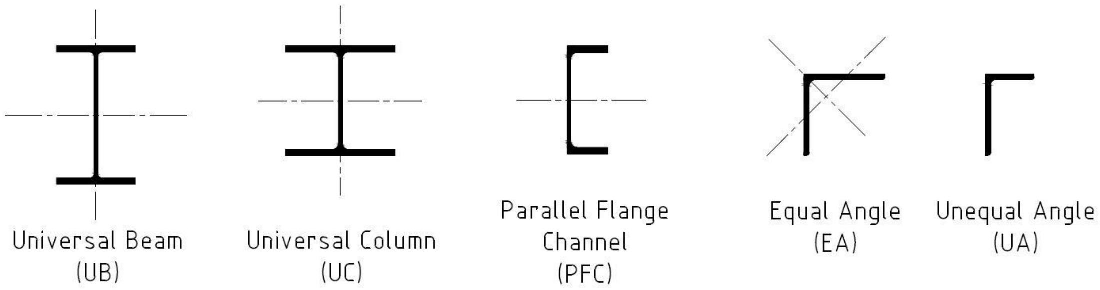


Figure 4.4– Hot Rolled Structural steel sections

For each shape type there are a range of standard sizes. The appropriate size to suit the required loads is selected by the designer. These standard sizes meet the requirements of Australian Standard AS3679.1 Structural Steel Part 1: Hot rolled bars and sections.

Hot rolled steel sections have the advantages of being efficient structural forms, and are easy to connect with bolted connections.

4.4.2 Hollow Steel Sections

The hollow section shapes are available in steel with a yield strength of 450MPa. The shapes regularly available are shown in Figure 4.5 and can be divided into:

1. Rectangular Hollow Sections.
2. Square Hollow Sections.
3. Circular Hollow Sections.

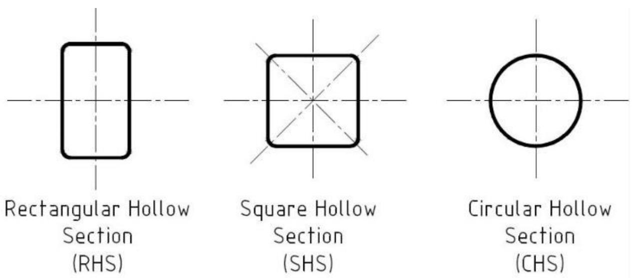


Figure 4.5–Structural Steel Hollow Sections

The sections are manufactured to meet the requirements of Australian Standard AS1163 Cold formed Structural Steel Hollow sections.

In comparison to hot rolled sections, the hollow sections have the following advantages:

1. They can be more efficient for some types of loading (eg torsion & compression) due to the way the material is distributed toward the perimeter of the shape. The sections with thinner walls end to have a higher radius of gyration than a comparable hot rolled section when compared by weight.
2. They are available in higher strength grade of steel which is an advantage where strength is the limiting factor in the design. This is not an advantage where deflections is the limiting criteria.
3. They can be better for corrosion resistance due to the smooth outer surface. This can be easier to prepare and paint. The members need to be fully seal welded to avoid internal corrosion.
4. The clean tubular shape can be better for appearance where this is a requirement.

Hollow sections have the following disadvantages when compared to hot rolled sections:

1. They are more expensive when measured by the cost per tonne.
2. Bolted connections between members can be more complex. They are more time consuming and expensive than welded connections as used in this project.
3. Thin walled (slender) members can be subject to local buckling effects. The design needs to consider these effects.

For each shape type there are a range of standard sizes. The appropriate size to suit the required loads is selected by the designer.

4.5 Construction Considerations

In the design stage, it is necessary to consider the ease with which the structure can be fabricated, transported and erected. Consideration is required of:

- fabrication
- site assembly methods
- transportation
- The need for specialist site equipment required for erection such as lifting cranes.

<u>Fabrication and site assembly methods</u>

The truss is fully welded in the fabrication workshop to reduce the amount of work required for onsite assembly. Previous work by experienced engineers at Sedgman has indicated that a fully welded truss is more economical for a truss of this size. Further consideration of alternate assembly methods requiring significant onsite assembly and bolting of components was not done.

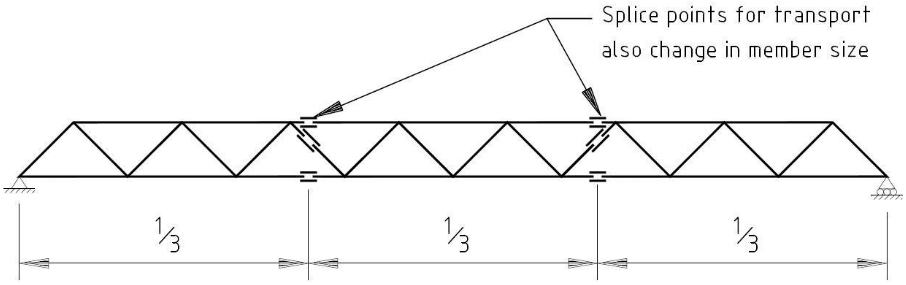


Figure 4.6–Truss splice points

Transportation and erection

The frame has bolted splices at 1/3 points along the length for transportation requirements as illustrated in Figure 4.6. This will result in 3 pieces of approximately 16m in length which roughly corresponds to the maximum length commonly used on road truck haulage. The splice points will require bolted connections and are a logical place to allow for a change in steel member size, if required during design.

Transportation envelope

Consideration of the transport envelope is important because it dictates the maximum overall size of the structure. Refer to Figure 4.7. For this bridge design the overall height is the critical dimension and is limited in height to approximately 3.3m between top and bottom chord centrelines for transportation purposes.

It is possible to change the site assembly method to allow different transportation methods or use different transportation arrangements to allow for a larger overall size. These would require different cost rates than have been used here and are considered beyond the scope of this project.

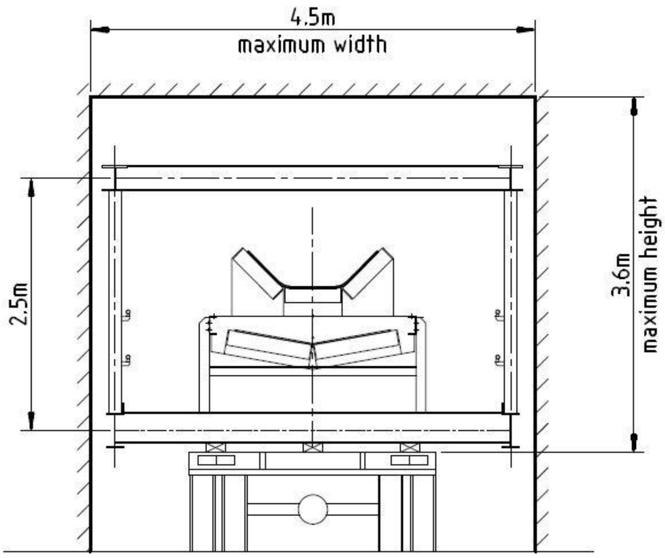


Figure 4.7–Transportation envelope

4.6 Simplification to 2D Truss

To allow for rapid evaluation of many different types of geometry, the decision to simplify the design problem from 3D to 2D was taken. It was deemed more valuable to compare the effect of many different changes on geometry on the cost rather than aim for a more exact solution with less exploration of geometry. As highlighted in Section 4.9 cost estimation is an indicative and comparative exercise with regular price fluctuations due to local and international market conditions.

Simplification to 2D also allowed the use of a readily accessible STO program as detailed in Chapter 5 .

The bridge contains components which are replicated within the design. Refer Figure 4.8 and Figure 4.9. There are two vertical trusses which are the load bearing component of the structure and for design purposes are the same.

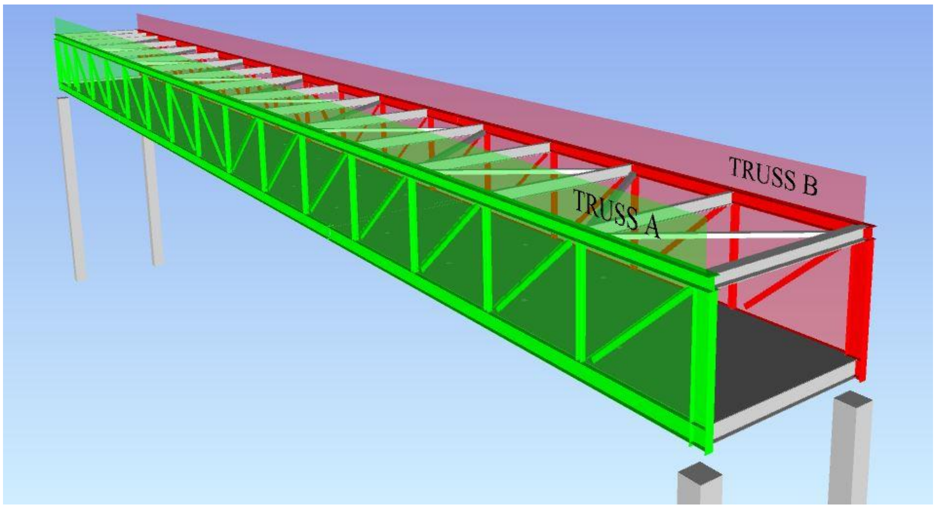


Figure 4.8–Bridge symmetry

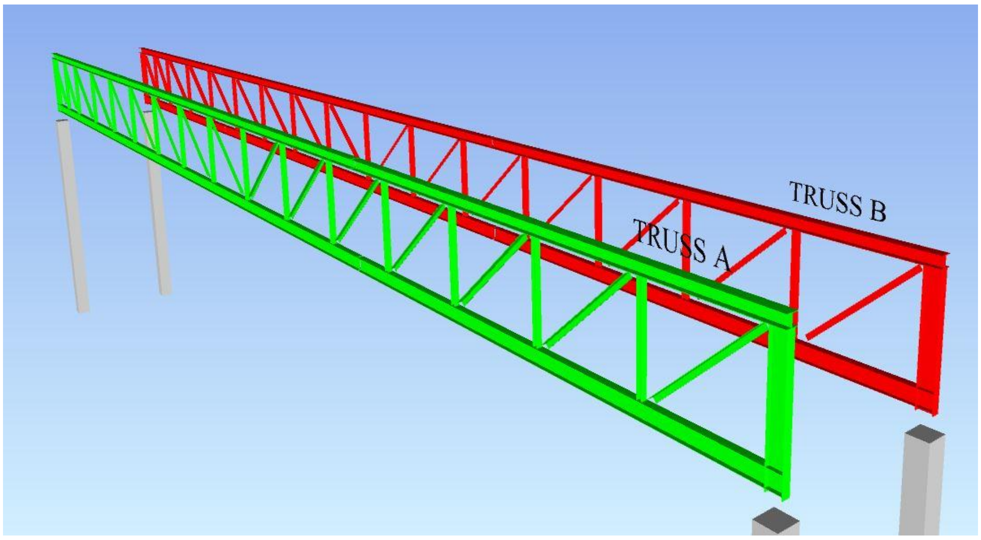


Figure 4.9–Truss A & Truss B are duplicate vertical load bearing trusses

There is symmetry down the longitudinal centreline that means the 2 vertical trusses are a mirror image of each other with similar loads. This similarity means there is effectively only one planar truss to design.

This will save time required for manual editing when creating new geometry in the analysis/design model. It also means that analysis processing time for each variation in geometry is reduced.

The disadvantage of converting to 2D is a rise in uncertainty or inaccuracy within the results because the results for the 2D planar problem may not be directly proportional to the real 3D problem. However as the aim of this project is to look at the relative merits of various modifications to the truss geometry it is important the relative impacts are realistic. That is, the comparison of costs for one case relative to the cost of a different case. It is deemed acceptable to have some loss in the accuracy in the total magnitude of the costs to allow exploration of a greater range of bridge geometries.

It is important that the loads and reactions on the planar truss are comparative to the full 3D situation, to the extent that it is possible. The verification used is the reactions at the support pins. By having matching reactions at pins for the same loadcases between the 2D and 3D design/analysis models we can be confident the extra applied loads to account for the missing midspan structure have been correctly calculated.

The effects of optimisation in for the 2D plane are likely to be indicative of the effects for full 3D.

4.6.1 Preparation of Base Case Data for Comparison

The data from the already designed base case was sorted to allow for comparison.

The bill of materials (BOM) is sorted to determine the masses of steel attributed to:

1. The vertical trusses. This is to allow for subsequent comparison with the BOM of the trusses with revised geometry.
2. Mid sections of the bridge. This is to allow for the mass to be converted to a dead load to be applied during the design of the vertical trusses.

4.6.2 Verification of Plane Truss Loads

To determine the accuracy of the simplified 2D model, a comparison was made of the loads on the support pins and the deflections to the original 3D model. The comparison was done for two loadcases, the serviceability loadcase and the ultimate strength loadcase. The results are presented in Table 4.1.

Table 4.1 – Plane truss verification results

2D Plane “base case” truss model verification Results				
	3D base case		**2D plane base case**	
Loadcase	support reaction (kN)	deflection at mid point (mm)	support reaction (kN)	deflection at mid point (mm)
100	333	196	326	199
212	206	119	200	121

4.7 Design Loads Requirements

The vertical truss is loaded by:

1. The mass of the bridge truss structure (self-weight). This includes the main steel members which are the load carrying component of the truss and subject to design and optimisation in this dissertation.
2. The mass of the horizontal support structures and lateral bracing. This structure was not included in this optimisation and is included as a dead load. The magnitude of the load was calculated from the base case design.
3. The mass of mechanical equipment associated with the conveyor. This includes the conveyor belt, idler carry and return pulleys and conveyor support framing. The conveyor support frame does not add any capacity to the overall truss structure so is considered separate for design purposes.
4. The mass of material (burden) carried by the conveyor belt.
5. Material spillage from the conveyor belt. This will accumulate on the floor of the structure and needs to be considered.
6. Additional services supported by the bridge. Piping and electrical cables for operation of the plant which add to the supported loads.
7. Walkway live loads which arise from plant personnel and maintenance activities.

The loads have been calculated per linear metre of span for application to the analysis model.

The loads are summarised in Table 4.2 along with the design loadcase number allocated in the analysis model.

Table 4.2 – Design loads and load combinations

Dead loads (per linear metre of truss length)		
Loadcase number	Description	Magnitude
1	Self-weight (truss structure)	1 x G
2	Mid structure weight	1.98 kN/m
3	Conveyor dead loads	1.10 kN/m
4	Plant Services (pipes, cables)	1.50 kN/m
9	Material spillage	2.50 kN/m
10	**DL** (sum of dead loads less spillage)	
Live loads		
11	**LL** (walkway loads)	1.25 kN/m
21	**Mo** (conveyor operating loads)	1.20 kN/m
22	**Mb** (conveyor flooded belt condition)	2.20 kN/m
Combination Loadcases		
100	1.2 **DL** + 1.5 **LL** + 1.5 **Mo**	
113	1.2 **DL** + 0.6 **LL** + 1.2 **Mb**	
212	**DL** + **LL** + **Mo**	
213	**DL** + **LL** + **Mo** **+** spillage	

During design and analysis it was found:

- loadcase **100** is the maximum loading to suit the strength limit state.
- loadcase **212** was the governing load for serviceability requirements

The loads listed below also need to be considered to meet the requirements of the Australian Standards. As this dissertation is a comparative exercise and the magnitude of the loads below is likely small compared to the loads in Table 4.2 they have not been considered further.

1. Wind loads.
2. Dynamic loads and natural frequency.
3. Earthquake loads.

Loads in this section are in taken from the following Australian Standards:

- AS 1170.0 Structural Design Actions.
- AS1170.1 Structural design actions Part 1: Permanent, imposed and other actions.
- AS5100.2 Bridge Design Part 2: Design Loads.

4.8 Structural Design Requirements

4.8.1 General

The structural design of the bridge is to meet the requirements of Australian Standards:

- AS4100 – Steel Structures.
- AS5100 – Bridge Design.

From the standards listed above, the following criteria are important to the design of this structure:

- Strength.
- Stiffness.
- Stability.
- Durability (brittle fracture, fatigue and corrosion resistance).
- Fire resistance.

This project focuses on strength, stiffness and stability of the structure as the purpose is comparative cost estimation. Durability and fire resistance requirements were assumed to be similar regardless of the layout of the structure and have not been considered further.

The stiffness of the structure is measured by the maximum deflection of the structure under load and meet the serviceability criteria of ASA4100. The point of maximum deflection for this truss bridge this is measured at the midpoint of the bottom chord. The maximum deflection for the structure is span/450 or 102mm. The truss is precambered during fabrication to match the dead load deflections. The meet the deflection requirements the deflection at serviceability load subtract the dead load deflection must be less than 102mm.

4.8.2 Potential Failure modes

The steel structure may fail if any of its members fail by any of the following mechanisms:

- Axial tension
    - Gross section failure
- Axial compression
    - Gross section buckling
    - Local buckling
- Bending
    - Gross section yielding

    - Local yielding
- Shear
    - Gross shear yielding
    - Web buckling
    - Web failure

To manually check each member for all of these requirements for many different case studies is a very large design task. The design and analysis software has automated checks to meet the requirements of AS4100 and these have been used for this study.

4.9 Costs

Cost is one of the most important criteria for structural design on a project of this type. The lowest price solution that fulfils the performance requirements is likely to be the preferred option, as reducing costs is a major factor in the competitive advantage of the contractor.

Reducing cost also increases project viability for the client by reducing financial risk, through reduced overheads and reduced payback times.

During the literature review the common measure for effectiveness of STO methods was the mass of the structure. The reasons above are highlight the importance of cost rather than material minimisation and why cost was chosen as the comparative measure for this project.

4.9.1 Cost Components

The total cost for the structure is broken into 4 components that also correspond to the stages of construction:

1. *Design costs* are a tally of the manhours required for the design and documentation.
2. *Fabrication costs* include the cost of the raw steel, the labour and consumables required to cut and weld the steel into the required form, the surface preparation and painting. Using standard steel sections with standard connections enables the use of workshops with large automated machines and can significantly reduce the cost of the structure. Complex and bespoke designs with large amounts of welding are more labour intensive and result in higher fabrication costs per unit tonne.
3. *Transport costs* are incurred in moving the completed fabricated component from the workshop location to the construction site. A key consideration for transport costs is the size and weight of the component and how efficiently they can be stacked. Oversize items incur additional costs.

4. *Erection costs* are due to labour and equipment required to erect the structure at the project site. For structural steel components they are composed of
    i. *Assembly* costs account for the manhours and equipment for the components to be bolted or welded together to form a complete unit ready for installation.
    ii. *Installation costs* include craneage.

    Another important factor for erection costs is the location of the site relative to the workforce. A remote site such as the one in this project has higher manhour cost due to the overheads of the workforce. The overheads include travel cost, travel time accommodation.

The following equation summarises the project costs for the bridge component:

Design cost
+ Fabrication cost
+ Transport cost
+ Erection cost

Total project cost

4.9.2 Cost Rates

Costs are applied at unit rates (per tonne) to suit the type of construction. Rate are applied for design, fabrication, transportation and erection.

Design costs

Design costs were calculated by using hourly rates and includes an allowance for drafting. The hourly rate for design was **$150 per hour**. For a structure of this type 2 weeks of design were allowed at 40 hours per week giving a total of 80 hours.

Fabrication Costs

The fabrication rates for this project are shown in Table 4.3. The steel sections are categorised in light, medium and heavy steel depending on the weight per linear metre of the steel section. Experienced project engineers at Sedgman provided a suitable fabrication cost breakdown.

Table 4.3 – Cost rates for fabrication

	Steel Section Type			
	Hot rolled		**Hollow**	
Steel weight	Mass(kg/m)	Cost ($/tonne)	Mass(kg/m)	Cost ($/tonne)
Light steel	<20	7850	<16	8100
Medium steel	20-50	5670	16-45	6830
Heavy steel	>50	4550	>45	5555

<u>Transportation and site erection costs</u>

The cost rates for transportation and erection are shown in Table 4.4

Table 4.4 – Cost rates for transportation and erection

	Transportation	**Erection**
Steel weight	($/tonne)	($/tonne)
Light steel	652	2040
Medium steel	652	1320
Heavy steel	652	720

The cost rates in Table 4.3 and Table 4.4 show a trend towards higher costs for lighter steel due to the higher labour requirements for fabrication and erection. Light steel has more linear metres per tonne, which means it has an increased number of cutting and welding procedures per tonne. This is reflected in the higher fabrication cost per tonne for light steel.

The cost rates shown above are a broad metric used for estimating the costs for large industrial process plants ranging in size from a hundred tonnes of steel up to projects with many thousands of tonnes of steel, with many different types of structures used in the project. It is possible that the actual cost for the specific structure in the dissertation would vary from the rates above. The above rates were considered indicative and suitable for comparative purposes and further detailed exploration of cost rates was considered beyond the scope of this project.

In practice, the advantage of cheaper material and fabrication costs can be depleted by higher transportation costs, high cost of defect rectification or an increase in schedule time required to complete the project. This means there is a qualitative attribute to these processes which may not accounted by pure costs comparison.

Project costs are always changing in line with construction activity and nationwide economic conditions. The cost rates used in this report have been sourced from recently completed projects and tender data and are current at the time of conducting this analysis in 2016. The cost rates have been obtained from Sedgman Ltd.

4.10 Conclusions

It is possible to simplify the design problem from 3D to 2D and maintain a suitable level of accuracy.

There are a range of practical aspects to the project that influence the cost of the bridge.

Costs are regularly change due to extrenal factors so broad metrics are often used.

Chapter 5 Structural Topology Optimisation using the SIMP Method with an 88 line MATLAB code.

5.1 Overview

The application of STO to the problem of a plane truss is described in this section. The STO procedure gives the optimised layout for the truss by determining the ideal material distribution minimising the strain energy of the shape within the design domain. The solutions obtained by this method are presented and the trends observed during the optimisation process are noted. The optimised geometry obtained from the STO was used later to determine the truss member locations for analysis and design models. Further analysis and design is required to determine local stresses and buckling effects and this is detailed in Chapter 6 .

5.1.1 Background

The MATLAB programming environment is much used in academia and scientific research. It’s relatively simple syntax and mathematical, plotting and charting capabilities remove the some of the technical demands from programming and allow the user to focus on the problem of interest.

A 99 line MATLAB program (Sigmund 2001) was produced for education to demonstrate the principles and methods of STO using the SIMP method.

(Andreassen et al. 2011) used 88 lines of code to produce an updated and much improved version of the 99 MATLAB program. This program preserved much of the syntax of the original 99 line version but took advantage of the strengths of MATLAB to increase speed of the routine by a factor in the magnitude of 100x.

The 88 line version is used for the STO in this project.

The 88 and 99 line MATLAB codes and associated papers give a good explanation in the principles of topology optimisation for the user and do aid in understanding the procedure.

Also unpublished notes produced by Dr Kazem Ghabraie were used to aid in understanding the code and modifications required for application to the design problem.

5.2 88 line MATLAB program

The 88 line MATLAB program is used for solving planar topology optimisation problems.

It has the advantages of being computationally quick to process for reasonably sized meshes. With a mesh size of approximately 47 500 elements (a rectangular grid 920x52) the program takes about 1 to 2 minutes to run on a laptop with i7 processor. This enables a range of variations in input parameters to be trialled in a time efficient manner.

The routine uses Finite Element (FE) method and does not perform buckling analysis or design code checks. Further analysis of the results is required to ensure the structure is suitable to the intended purpose. For the truss bridge problem in question these checks are done by the analysis and design software in Chapter 6.

The program code is modified to suit the parameters of the problem of interest. This means there a base level of proficiency required by the user in reading, understanding and modifying the MATLAB code. There is a moderate level of difficulty to this and it takes some time with basic problems to understand. Incorrect modification of the code is a potential source of error and is mitigated by sufficient practice by the user and some intuition of the ideal topology and load paths likely to be produced.

The program is planar however for the FE calculations it is assumed the depth of the planer problem is equivalent to the size of the square mesh elements. Effectively the design mesh is a solid plate of material with the thickness of the plate equivalent to one mesh unit in depth. It is required to calculate size and scales of the mesh and units appropriate to the problem size. This is to ensure the results are representative of the design problem. It is important to use a minimum resolution of mesh to suit the problem.

When using the software there is a payoff between the mesh size and the processing time. Using a higher resolution and larger mesh size will increase the resolution and accuracy but will also result in longer processing times.

The code editing required for the program means it is not likely to be used in the time sensitive environment of an engineering design office.

5.2.1 Program Input Parameters

The following variables are required to be defined by the user:

1. The domain size of the problem.

2. The boundary conditions.
    a. The support locations.
    b. The loading conditions.
3. The target volume fraction.
4. The minimum radius of members.
5. The penalization factor.
6. The engineering properties of the material of interest.

5.2.2 Program Outputs

1. Images of optimised topology at various iterations
2. Graph of Compliance value vs iterations

5.3 Program Inputs

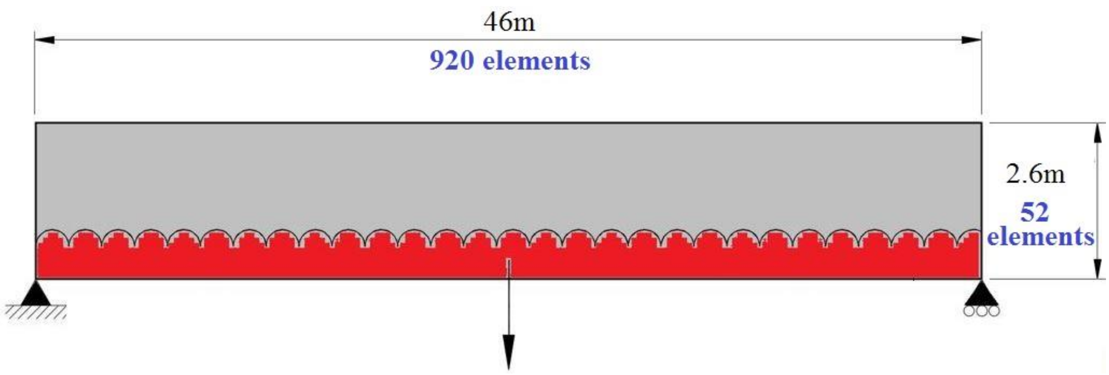


Figure 5.1–The design domain

5.3.1 The Domain Size of the Problem.

The domain is the area of material subject to topology optimisation. The code is written for a mesh of square elements. Defining the number of elements in the x direction and the number of elements in the y direction relates the domain to the dimensional size of the real problem. Refer to Figure 5.1. The input for the code is the number of elements in the x direction and the number of elements in the y direction. An element size of 0.05m was used giving 920 elements in the x direction and 52 elements in the y direction.

5.3.2 The Boundary Conditions.

The support locations. These are elements defined with fixed degrees of freedom (DOF). A fixed pin is modelled as an element with both the x and y vectors being fixed. A sliding pin (roller support) is modelled with only the y vector being fixed, so the element is free to move in the x direction.

The loading conditions. These are defined by forces assign to elements, in the direction of the action of the force. A uniformly distributed load (UDL) is a force applied to each individual element of a string of elements in the position of the load.

5.3.3 Target Volume Fraction

The target volume fraction is the percentage of the original material used for distribution by STO. Using the mesh sizes from Section 5.3.1 above and a density of steel of 7.85kg/m^3 we get a total domain mass of 46.9t and the target design mass is ~ 7.8t. This gives a target volume fraction of ~17%.

There is an important difference between the way STO distributes the material and the standard steel sections used for fabrication of the truss bridge. STO is distributing material along the optimal path of members as a solid mass of material, however standard steel sections as used for fabrication have different cross sectional shapes to increase the stiffness and efficiency and do not exactly match the topology optimisation process.

This means the volume fraction is indicative only and a range of values for the volume fraction have been used to best capture the features important for optimum topology of the bridge.

5.3.4 Member Minimum Radius

Members with a size less than the nominated minimum radius are penalized and the material redistributed by the algorithm. The minimum radius gives the user control over minimum member size to allow for efficiency to suit the proposed manufacturing process.

It is also important that the minimum member size is matched to the element size. The element size also represents the thickness of the plane problem. The minimum radius needs to be in proportion to this. It is not feasible to use a minimum radius smaller than the element size.

A range of minimum member sizes were used to determine the effect of the optimised topology.

5.3.5 The Penalization Factor

This should match the inverse of the Poisson's ratio for the material. (Sigmund 2001) For steel with a Poisson's ratio =0.333 the penalization factor used is 3.

5.3.6 The Engineering Properties of the Material

For the truss bridge this is steel with a Young's modulus of 200GPa And Poisson's ratio of 0.333.

5.4 Results of Topology Optimisation

The optimised geometry was generated for the truss for a range of different Volume Fractions and minimum member sizes are shown in Figure 5.2 and Figure 5.3.

There was no unique solution produced, but a variety of layouts which have some similar desirable traits for optimised geometry and some differences depending on the input parameters used. These traits and differences are discussed in Section 5.4.1.

The Matlab code used is attached in Appendix C.

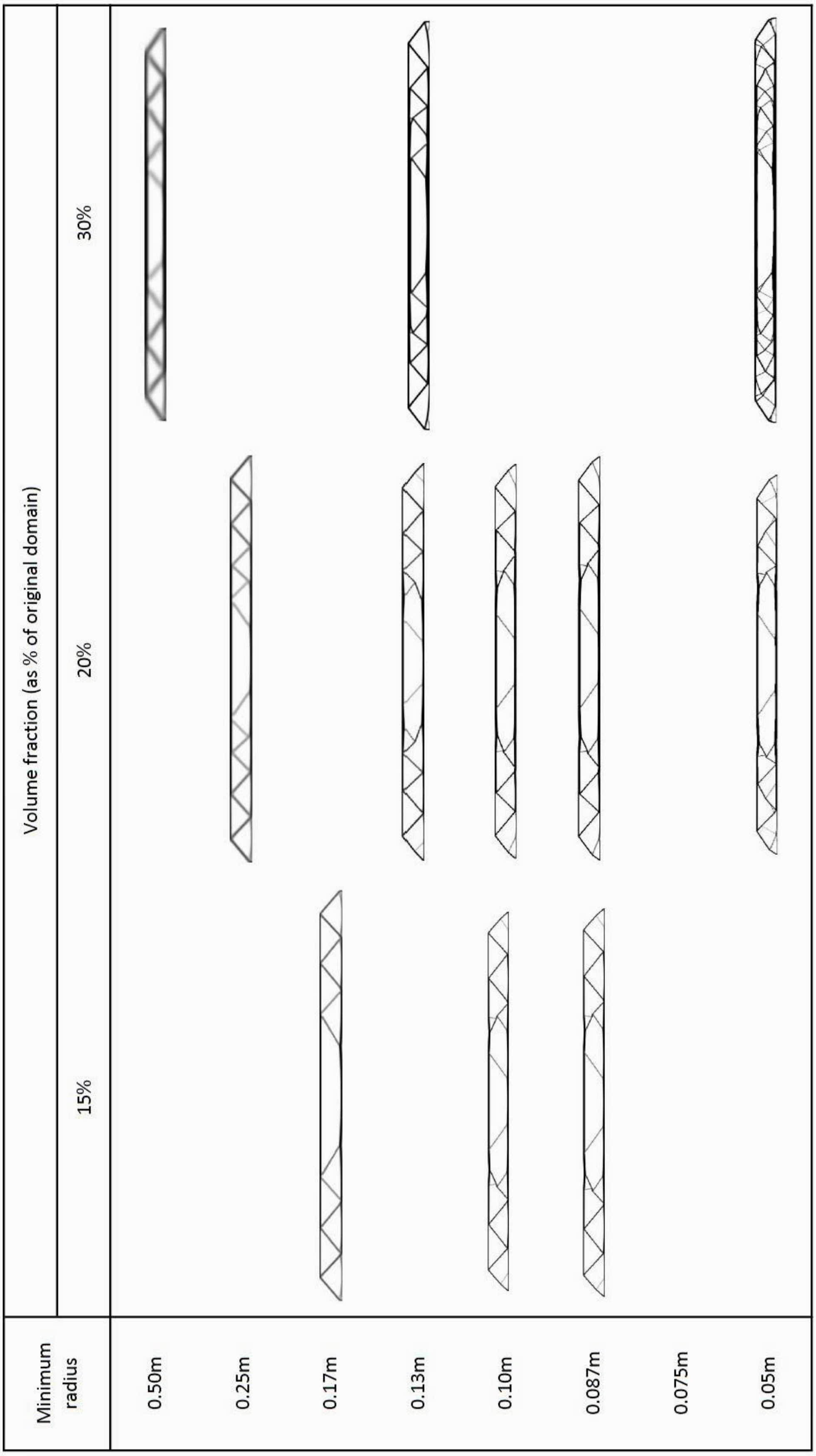


Figure 5.2– Optimised geometry at volume fractions of 15, 20 & 30%

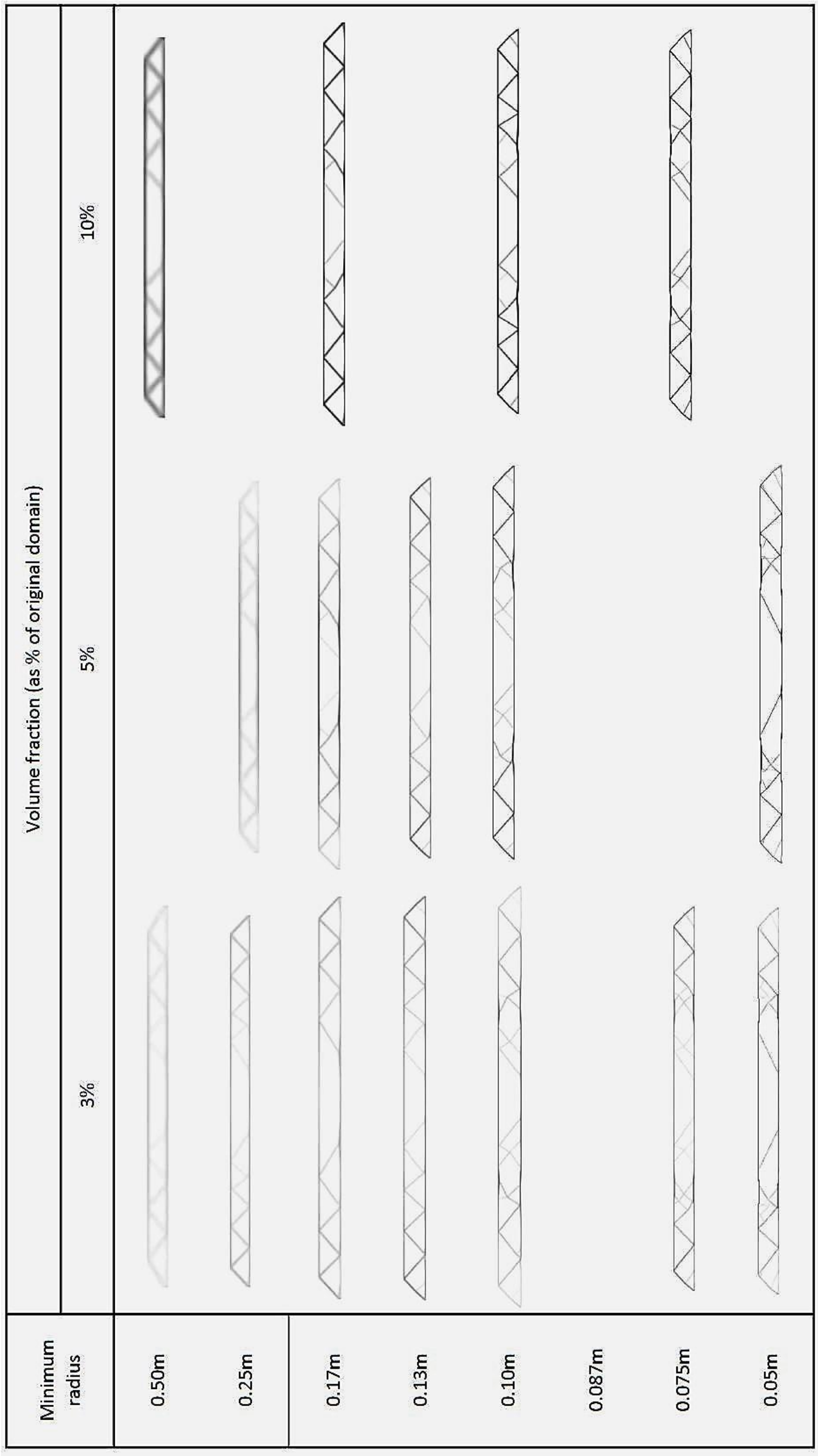


Figure 5.3– Optimised geometry at volume fractions of 3, 5 & 10%

5.4.1 Discussion of Results

There was a range of resultant geometry from the topology optimisation process.

The following trends were noted:

1. There was a tendency towards the warren truss shape
2. At low volume fractions or with larger minimum member sizes there was a tendency towards straight members. At low volume fractions the shape becomes less organic shaped and more truss like. This implies that at the smaller volume fractions which we could associate with lighter loading pattern the triangulated truss shape is the more efficient structure.
3. With large volume fractions and thinner minimum member sizes there was a tendency towards arch shapes in the diagonal bracing members. Also the results indicated a higher number of bracing members with smaller members was more efficient.
4. The bracing pattern in the middle of the structure tended to be thinner and lighter to the middle of the truss. Also there was some variability in the position of the bracing. It did still tend toward diagonal bracing similar to the warren truss shape.
5. There was no bracing in the very middle of the truss.
6. The thickness of the chords was highest towards the middle of the structure. This implies heavier loading in this area.

Given the range and variety of topology produced by the STO process it appears logical to assume that features that are common to all the results are important features to produce an efficient structure for the bridge. As a corollary, is also appears logical to assume that features that varied between the cases were of relatively minor importance to producing optimum topology. That is, by varying these features there is likely to be little effect to the overall efficiency of the bridge structure. This approach in weighing up the relative merits of the different features in the results from STO has been using in selecting the geometry for the analysis and design stage. The geometry used for the next stage is shown in Figure 5.4.

It is noted there is a large amount of interpretation required in determining the important features from the range of results of STO. This implies that although the topology optimisation is a rigorous approach to layout optimisation, there is still considerable input required from the design engineer to interpret and use the results in practical manner to suit the larger objectives of the project.

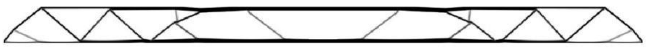
	Optimised Topology	Volume Fraction	Minimum Member Size (m)
1		30%	0.50
2		20%	0.10
3		10%	0.50
4		3%	0.15

Figure 5.4– Selection of optimised topology to be used for analysis and design

5.5 Conclusions

From the topology optimisation process it can be concluded:

1. A warren truss shape is the optimal shape at low volume fractions.
2. The following features are common and appear important to optimal topology:
    a. Truss top chord at the top limit of the design domain
    b. The bottom chord at the bottom limit of the design domain
    c. A diagonal member at each end of the domain leading down to the support
3. The bracing requirements in the middle of the truss between the top and bottom chords varied depending on the parameters used and the optimum geometry is uncertain.
    a. The bracing towards either end of the truss is optimum in the warren truss layout. The optimum span of the braced bay is undetermined from the topology optimisation
    b. There was an absence of bracing in the middle section of the truss and the requirements for bracing in the middle section of the truss are undetermined.

Chapter 6 Structural Analysis and Design Modelling

6.1 Overview

The results from STO in Chapter 5 are used to build the geometry for analysis and design as detailed in this chapter. The following procedure is used:

1. The analysis and design model is created using the geometry obtained from STO.
2. Structural analysis is performed to determine the forces of individual members within the truss, due to the external loads.
3. Design is completed to size the individual members to suit the loads specific to that member. Member sizes are to suit the range of standard structural steel sizes.
4. A bill of materials (BOM) is exported from the completed design model to be used for cost comparisons.
5. The bill of material is sorted into categories by the section type and weight per metre. Cost rates are applied to suit these categories.
6. A comparison of the total cost for different geometry is conducted.

This chapter describes the use of the interpretation of the STO results, the structural analysis and design, and the results obtained from the cost comparison.

6.2 Model Creation

6.2.1 Background and Capabilities of Software

Commercially available software called Spacegass was used for the computer analysis and design modelling part of the project. The software has the following capabilities for the design of structures:

- Analysis of 2D and 3D structures with complex geometry and large numbers of node and elements.
- linear and non-linear analysis of structures.
- checks for buckling and second order effects.

The software is powerful and is capable of significantly more complex analysis than is required for this project. The software has been used in industry since 1983 and undergone regular enhancements since this time. The extended period of use gives confidence that the software has been tested appropriately and that the results obtained from the use of the software are reliable.

The software can check the design against the requirements of Australian Standard AS4100 – Steel Structures design code. This allows different analysis cases with different truss geometry to be efficiently checked to ensure they meet the minimum requirements of the standard. This is to ensure the design is satisfactory and the results for different cases modelled are comparable to each other. This feature was used for this dissertation to

The disadvantage of using the software is that it is complex and does require a significant investment in time to understand the use of it and become familiar with the operation. There is access to online training modules to ensure the user is aware of the subtleties of using the software to achieve the design aim. The training modules were completed by the author prior to the start of the analysis modelling for this project.

6.2.2 Program Input Parameters

The model was built in the following manner:

1. Geometry of the structure was created using the output from STO. First the nodes representing connections, then elements representing beams.
2. Supports positions were defined. Supports were either fixed, pin or roller.
3. Fixity of end connections was applied to each member.
4. Restraints
    a. Lateral restraints were placed a truss node points to represent the full 3D design problem
    b. Flange restraints for local buckling were applied.
5. Loads and load combinations.
6. Member sizes.

6.2.3 Program Outputs

The software has a large range of output. It is possible to get a full report of all the loads and calculations for all the members needed to comply with the requirements of AS4100. A small selection of the output was used for this project. The items presented below were used for verification and quality checking of the modelling and to determine the effect of the geometry on the materials required.

Output used for model verification:

1. Graphical load representation
2. Deflected shape diagram.
3. Axial loads, bending moments, shear force diagrams.
4. Load factor on each of the truss elements
5. Support reactions

Output used for comparison between cases.

1. Bill of materials containing:
    a. The member sizes and lengths used in the model
    b. The overall mass of the structure

6.2.4 Model Setup

The following procedure was used for building the models.

1. One model was set up and checked for loads and support reactions
2. This model was copied to create new models and nodes and members altered to create different geometry.

Linear analysis was used for the bridge structure and second order effects were checked as the truss was modelled as a welded frame with fixity at the node connections.

6.2.5 Model Checking and Validation

The computer model is reasonably complex, in that there are a large number of loadcases, members, nodes and supports that interact in a different manner. There does need to be some caution by the user to ensure the computer modelled structure is representative of the intended real life structure and that there were not errors resulting from incorrect modelling. Checking of the model is required to ensure accuracy and completeness of the model and for confidence in the results. The checking was done in a methodical manner prior to logging of the results. The following checks were conducted on the models:

1. Visual inspection of the:
    a. Loadcases.
    b. Deflected shape.
    c. Axial loads, bending moments, shear force diagrams.
    d. Support reactions.

2. A check of the member connectivity. This shows errors in joining members to nodes or members to each other.
3. Flange restraints to ensure they are in the correct locations
4. Lateral restraints to prevent frame buckling. This were modelled as node restraints at the location representing the members that would be used in the full 3D model. The locations were checked by turning on the restraints display.

The models were checked by a highly experienced senior engineer prior to collating the results.

6.2.6 Considerations in 2D Analysis for the Full 3D Design

Whilst a 2D analysis and design model is being used, consideration of the structural effects of being part of a larger structure is required. This is to ensure both the vertical 2D truss and the overall structure will be stable. There are two effects that were considered during design and analysis of the 2D vertical trusses:

1. The connection node points for the horizontal trusses which are required to resist horizontal load actions. For this part of design it was assumed that node points for the vertical truss would also be node points for the horizontal trusses. These nodes were modelled as being fixed in the horizontal plane in the 2D to simulate the stabilizing effect of the horizontal trusses in the full 3D bridge structure. This means the 2D planar truss has lateral restraints applied in the design and analysis model at these node points. It was also assumed the horizontal truss member in the 3D design would be of sufficient stiffness to provide twist restraint to both top and bottom flanges of the top and bottom chord members at these node points.

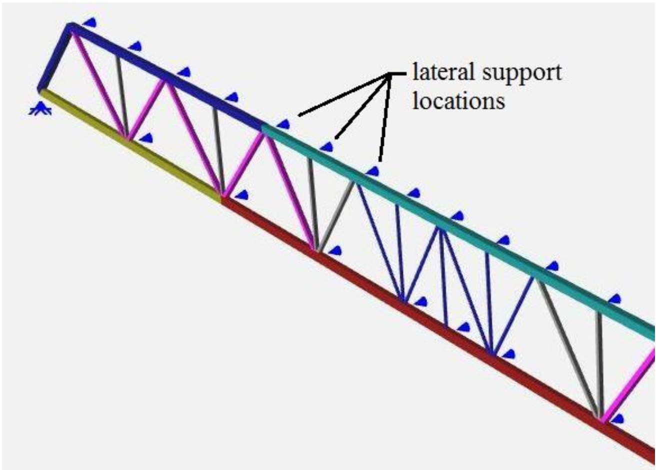


Figure 6.1– Location of lateral supports in the design and analysis model

Refer to Figure 6.1 which shows the lateral support points applied to the bracing node points for Case B4. The lateral supports are indicated by the blue conical pointers.

2. The portal stability of the structure is important to resist lateral loads applied at the top chord. Lateral load at the top need to be transferred through the 3D structure into the pin supports at the bottom chord. This is assumed to be through a portal action of the bridge in cross section. Indicative checks were done on the truss in cross section to confirm the stability of the structure in for these effects. Refer to Figure 6.2. These checks were done by creating a new model containing a rigid frame and applying a nominal horizontal load the top corner, for which it was possible to obtain a deflection. From the deflection and load it was possible to obtain a spring rate to apply as a support on the corresponding node in the planar 2D truss model. This check showed there was sufficient strength by portal action to resist nominal lateral loads as required by AS4100 and this was considered sufficient for this dissertation. For detailed design future checks would be required.

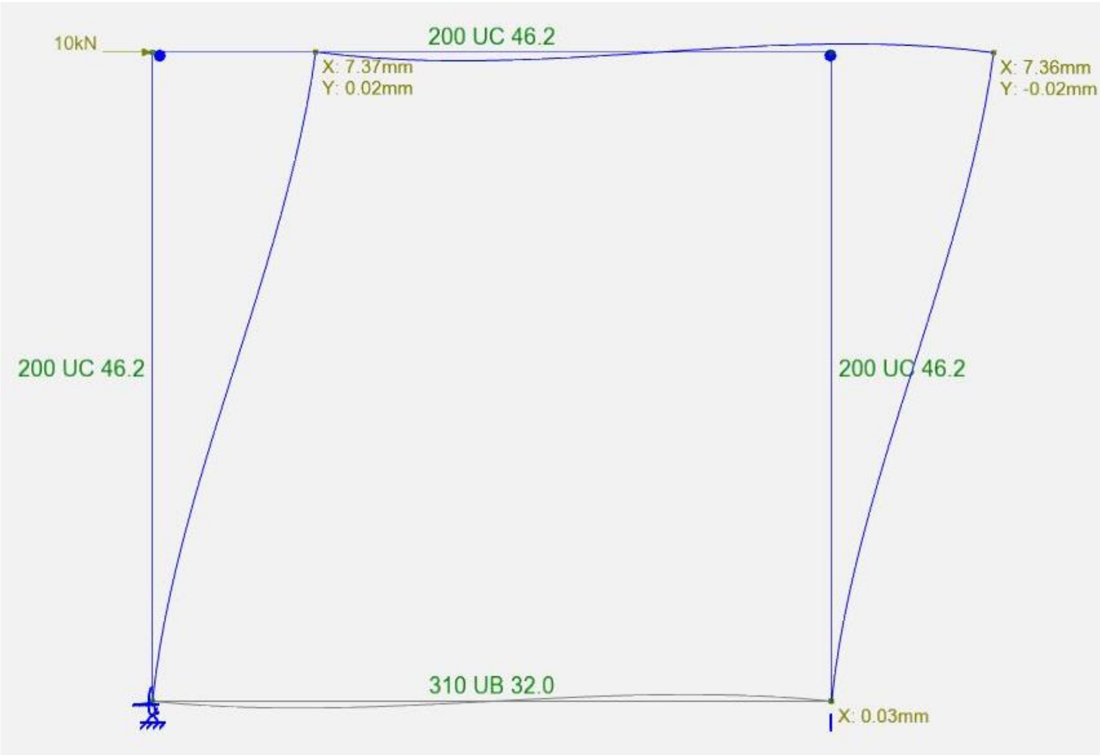


Figure 6.2– Check of frame cross section to resist lateral loads

6.2.7 Practical Considerations in Member Sizing

During analysis and design it is apparent that loading for each member of the truss is different. To obtain the optimum efficiency it is possible to use a different steel section size for different loading on each member. This theoretical optimum is not achieved in practice as it would require the steel fabricator to keep in stock a very large range of steel sizes to enable fabrication of the bridge. There can be little to determine one size from the next to the naked eye and using a large variety of sizes is likely to increase the chance of the wrong steel size being accidently used and fabricated in place.

Some rationalisation of sizes is desirable. The approach used in the design of the chords was to have a maximum change of one section size per chord if a change in size was needed, and to use the splice points at 1/3 points as indicated in Section 4.5. For the bracing three changes in sizes were used.

6.3 Analysis and Design Cases

Several stages of analysis and design were completed to isolate the effect of a particular change on the mass and cost of the truss. The stages conducted were:

Case A – Comparison of the Effect of STO Only

Case B – Change the Type of Steel Section and Material Strength

Case C – The Effect of Increasing the Depth of the Truss

Case D - The Combined Effect of Increasing the Depth of the Truss, Changing Steel Section Type and Increasing Material Strength.

A simplified representation of the differences between cases is shown in Figure 6.3.

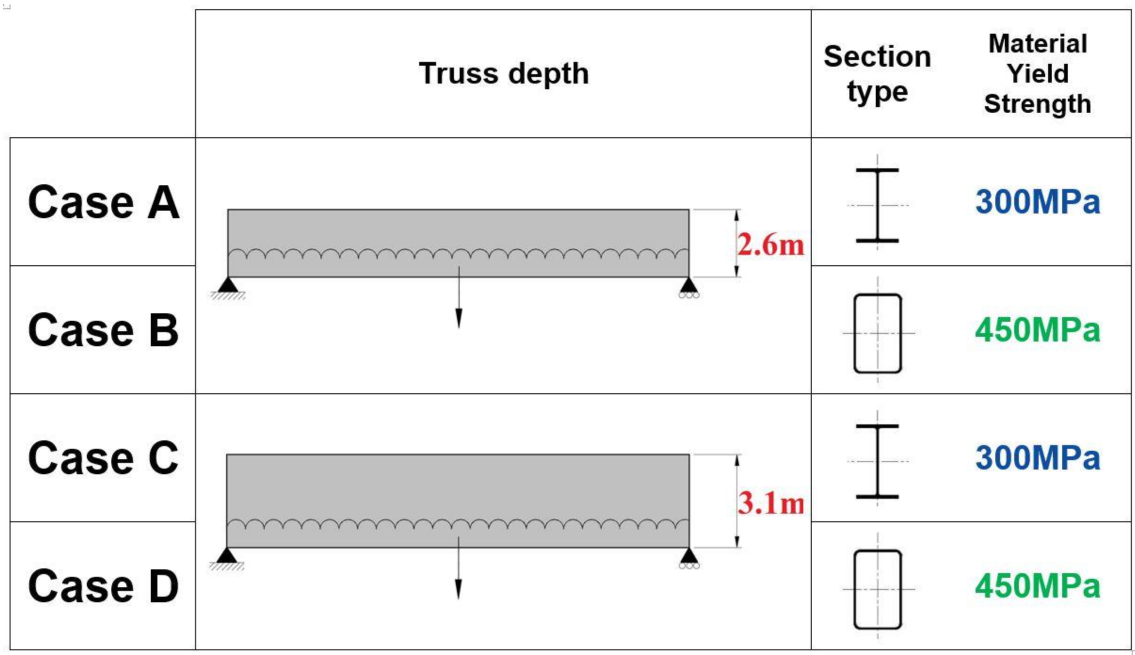


Figure 6.3– Summary of design cases parameters

6.3.1 Application of Cost Data

On completion of analysis and design the Bill of Materials (BOM) was exported from the design model. The BOM was sorted into section type and categorised by the mass per metre. The cost rates from Section 4.9.2 were applied and tallied to give an overall cost for the truss.

An estimate was required of the effect of using STO on the design costs. This was a very subjective estimate as it was considered unlikely that applying STO via the MATLAB program as used in this dissertation was a viable option in a design office. So an assumption as to the method used for STO and the effect it may have on design time was needed. The assumption used for the purpose of estimating was that:

1. commercial STO software would be "user friendly" and suitable for a design office
2. the overall the cost of purchasing and using STO on the project would be equivalent to increasing the project design time by 10%.

As noted above, this is very subjective estimate without any live data to use as a basis, so this assumption needs to be noted when comparing the results of this dissertation.

6.3.1 Manual Check of Design Model

A check by manual calculations of the design for one member for Case A4 loadcase 100 has been done and is attached in Appendix D.

6.3.2 Case A – Comparison of the Effect of STO Only

For this case the depth of the truss were left unchanged from the base case at 2.1m. The geometry of the truss bracing was changed to match the geometry from the topology optimisation and used in case A1 to A6. As the topology optimisation results were not definitive a range of geometry was used to mimic different features obtained from the topology optimisation results. The geometry tested is shown in Figure 6.4. A stress analysis was conducted and the members were designed (sized) to suit.

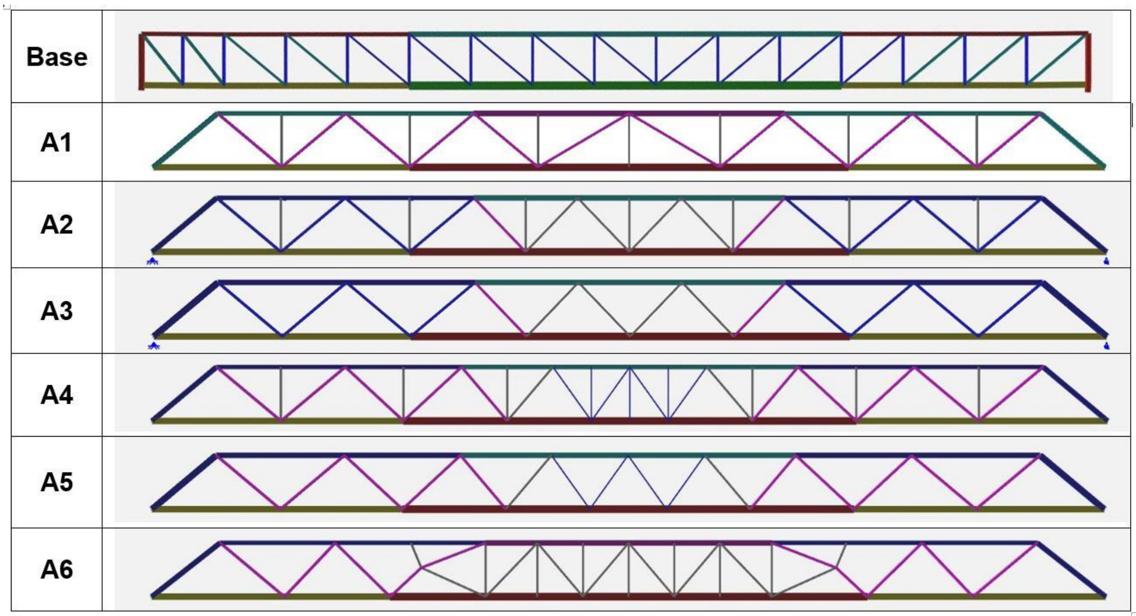


Figure 6.4– Geometry analysed in Case A

The results of the analysis and design for one case, Case A4 is presented in the following figures to show the method used to calculate the results for all cases.

The figures show the following data in sequential order:

1. The results of the structural analysis showing the resulting force distribution in each of the members within the truss.
    a. The axial force diagram
    b. The bending moment diagram
    c. The shear force diagram
2. The designed results:
    a. Member sizes to suit the forces.
    b. The load factor for each of the members

3. The bill of materials sorted into weight classes
4. The cost rates applied to the truss

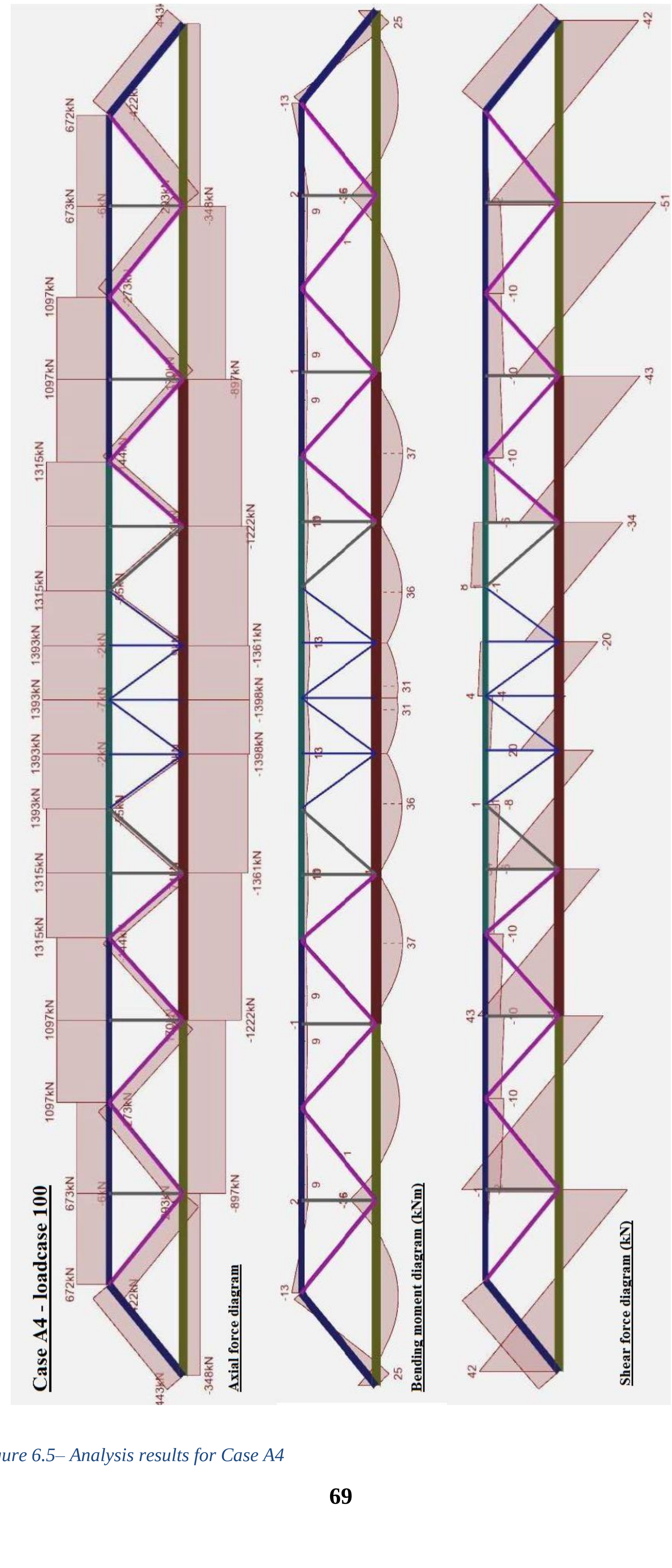


Figure 6.5– Analysis results for Case A4

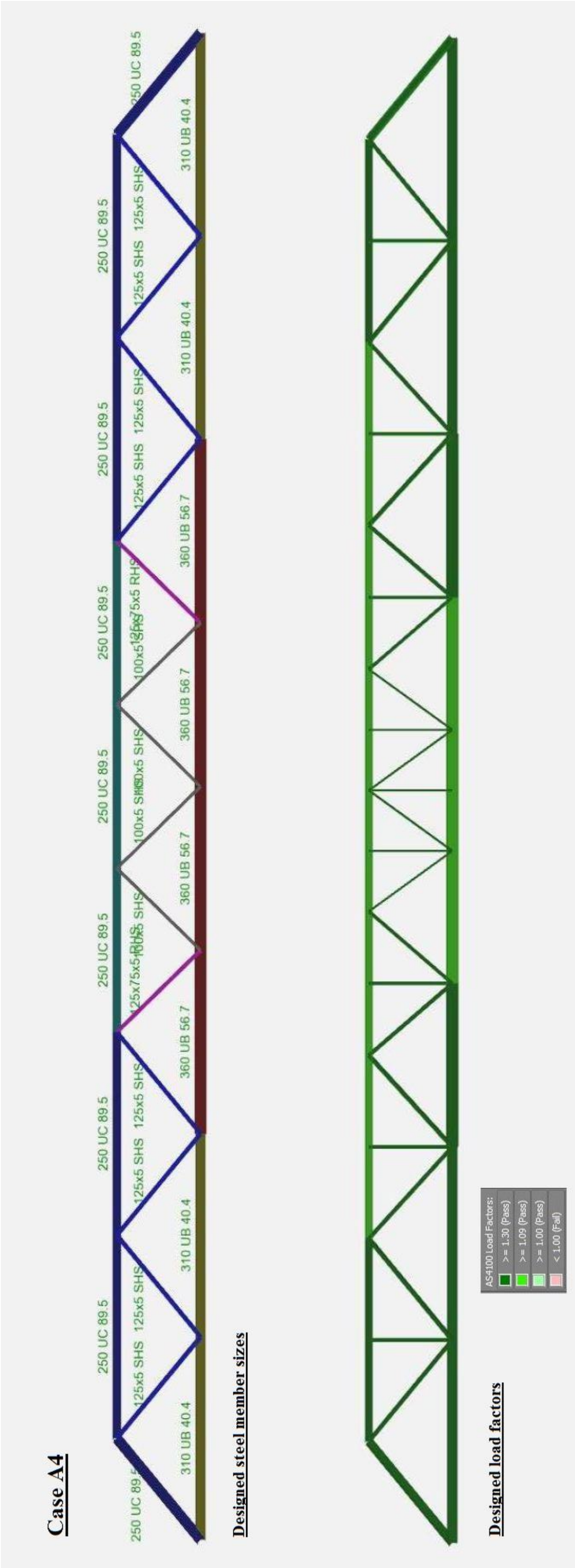


Figure 6.6– Designs results for Case A4

Case A4- Bill of Materials Sorted by Steel Weight

Member #	Unit Qty	Section type			Length/ member (m)	Total length (m)	Mass/ section (t)	Total mass (t)	mass (kg/lm)	Total mass per steel category- hot rolled (t)			Total mass per steel category- hollow (t)		
		Depth	Name	Mass						light <20kg/m	medium 20-50 kg/m	heavy >50kg/m	light <16kg/m	medium 16-45 kg/m	heavy >45kg/m
Hot Rolled															
1	2	310	UB	40	6.2	12.4	0.254	0.507	40.9	0	0.507	0			
2	2	310	UB	40	5.9	11.8	0.241	0.483	40.9	0	0.483	0			
3	2	360	UB	57	5.0	10.0	0.284	0.568	56.8	0	0	0.568			
4	2	360	UB	57	4.1	8.1	0.230	0.460	56.8	0	0	0.460			
5	2	360	UB	57	1.9	3.7	0.105	0.210	56.8	0	0	0.210			
6	2	200	UC	52	4.0	8.1	0.212	0.423	52.3	0	0	0.423			
14	4	200	UC	52	3.1	12.4	0.162	0.648	52.3	0	0	0.648			
15	4	200	UC	52	2.8	11.2	0.146	0.586	52.3	0	0	0.586			
16	4	200	UC	60	2.2	8.8	0.132	0.526	59.8	0	0	0.526			
17	4	200	UC	60	1.9	7.4	0.111	0.443	59.9	0	0	0.443			
Hollow Section															
7	4	125x5	SHS		4.0	16.2	0	0.293	18.1				0	0.293	0
8	6	100x5	SHS		2.6	15.6	0	0.222	14.2				0.222	0	0
9	4	125x5	SHS		3.8	15.3	0	0.277	18.1				0	0.277	0
10	2	125x5	SHS		3.4	6.8	0	0.124	18.2				0	0.124	0
11	2	100x5	SHS		3.4	6.8	0	0.097	14.2				0.097	0	0
12	4	65x5	SHS		3.2	12.8	0	0.111	8.7				0.111	0	0
13	3	65x5	SHS		2.6	7.8	0	0.068	8.7				0.068	0	0
Sub Totals										**0**	**0.990**	**3.864**	**0.498**	**0.694**	**0**
Total Mass (tonnes)										**6.046**					

Figure 6.7– Bill of materials sorted by weight for Case A4

Case A4- Cost Summary

	Steel category		Mass (t)	Fabrication rate ($/t)	Fabrication cost ($)	Freight rate ($/t)	Freight cost ($)	Installation rate ($/t)	Installation cost ($)	Design rate ($/hr)	Design hours	Design Cost ($)	Total Cost
Hot Rolled													
Light	light	<20kg/m	**0**	7,850	0	652	0	2,040	0				
Medium	medium	20-50kg/m	**0.990**	5,670	5,613	652	645	1,320	1,307				
Heavy	heavy	>50kg/m	**3.864**	4,550	17,581	652	2,519	720	2,782				
Hollow Section													
Light	light	<16kg/m	**0.498**	8,100	4,034	652	325	2,040	1,016				
Medium	medium	16-45kg/m	**0.694**	6,830	4,740	652	452	1,320	916				
Heavy	heavy	>45kg/m	**0**	5,555	0	652	0	720	0				
Design										150	44	6,600	
Total			**6.046**		**31,968**		**3,942**		**6,021**			**6,600**	**$48,531**

Figure 6.8– Cost summary for Case A4

6.3.3 Case A Results summary

The results of the design and analysis for all geometry from Case A has been condensed and presented in the figures which follow. The figures show:

1. The models cases analysed
2. The cost breakdown and total estimated cost of the structure
3. The overall mass of the structure
4. The average cost of the optimised topology cases. This average does not include the base case and is used as conservative estimate of the benefit of the topology optimisation. It was deemed desirable to be conservative due to the significant variation between individual test cases.

Figure 6.9 gives details of the cost breakdown and average contribution of each cost component to convey the relative importance of each component.

Figure 6.10 shows the results in graphical form to easily compare the total cost for all of the Case A options.

Case A Results Summary

Case	Truss Type	No. Bracing Bays	Steel Section Type	Steel Mass (t)	Deflection at mid-point (mm)		Cost ($)				
					Ultimate	Serviceability	Design	Fabrication	Freight	Installation	Total
Base	Pratt	16	original design hot rolled sections	7.82	195	120	$6,000	$39,195	$5,099	$7,374	$57,668
Base0A	Pratt	16	redesign hot rolled seection	6.99	210	127	$6,000	$35,788	$4,557	$6,974	**$53,320**
A1	Warren	7	hot rolled sections	6.70	175	107	$6,600	$34,667	$4,373	$6,331	$51,971
A2	Warren	8	hot rolled sections	6.44	180	109	$6,600	$33,767	$4,196	$6,342	$50,905
A3	Warren	8	hot rolled sections	7.40	164	100	$6,600	$37,225	$4,823	$6,692	$55,341
A4	Warren	9	hot rolled sections	6.05	191	116	$6,600	$31,968	$3,942	$6,021	$48,531
A5	Warren	9	hot rolled sections	6.64	175	107	$6,600	$33,610	$4,325	$6,061	$50,595
A6	Warren	12	hot rolled sections	6.60	177	107	$6,600	$34,864	$4,296	$6,582	$52,342
Average optimised case A1-A6				**6.64**	**177**	**108**	**$6,600**	**$34,350**	**$4,326**	**$6,338**	**$51,614**
% Contribution							**13%**	**67%**	**8%**	**12%**	**100%**

Figure 6.9– Case A results summary

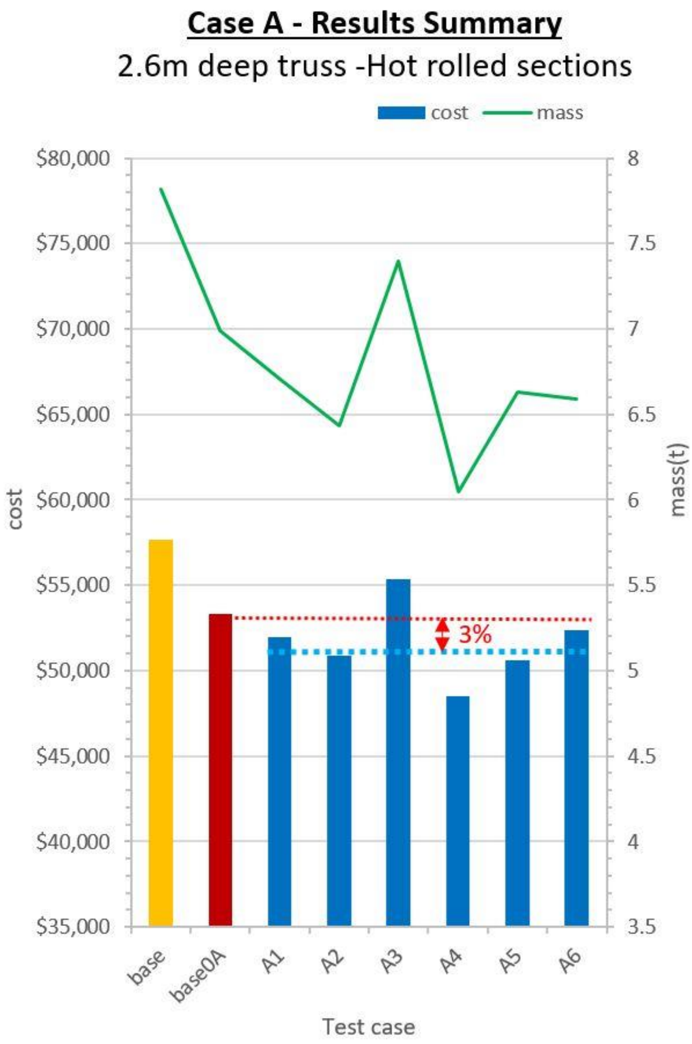


Figure 6.10– Case A results summary graph

The results show:

1. The original design (base) was so conservative it was not useful for comparison purposes in this dissertation. A revised base design for was completed (base0A) using similar member sizing principles as used for all other test cases in this report to enable effective comparison. The geometry for (base) and (base0A) is identical, only the member sizing has been updated.
2. There is a cost reduction from using the optimised topology.
3. The lowest cost option was A4.
4. There is some variation between the optimised cases.

6.3.4 Case B – Change the Type of Steel Section and Material Strength

For this case the depth of the truss was left unchanged at 2.6m. The geometry of the trusses matches the geometry used in Case A (i.e. Case A1 and B1 have the same geometry). The members were changed to hollow sections which are made from steel with a higher yield strength. A stress analysis was conducted and the members were designed (sized) to suit. A summary of the results are shown in Figure 6.13.

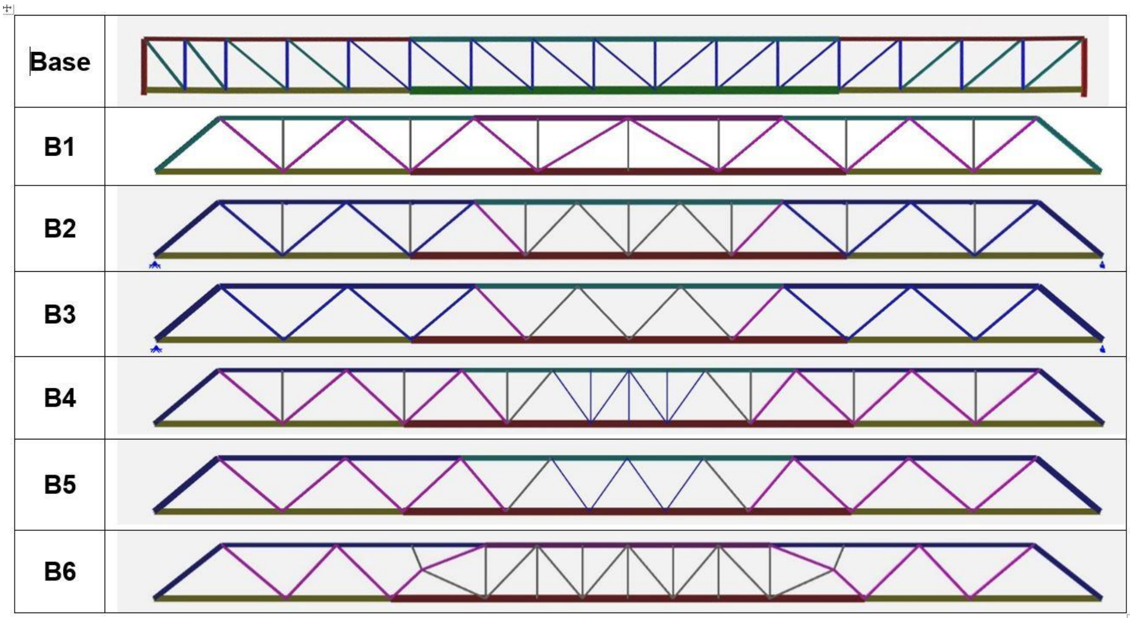


Figure 6.11– Geometry analysed in Case B

The results for all the options explored in Case B have been presented in Figure 6.12 and Figure 6.13 in a similar style to the style previously used for Case A.

Case B Results Summary

Case	Truss Type	No. Bracing Bays	Steel Section Type	Steel Mass (t)	Deflection at mid-point (mm)		Cost ($)				
					Ultimate	Serviceability	Design	Fabrication	Freight	Installation	Total
Base0B	Pratt	16	original geometry redesigned for SHS/RHS	6.17	239	143	$6,000	$36,036	$4,023	$8,202	**$54,261**
B1	Warren	7	SHS/RHS	5.29	219	132	$6,600	$35,827	$3,449	$6,919	$52,795
B2	Warren	8	SHS/RHS	5.36	217	131	$6,600	$36,158	$3,491	$6,944	$53,193
B3	Warren	8	SHS/RHS	5.56	208	125	$6,600	$34,740	$3,623	$5,860	$50,823
B4	Warren	9	SHS/RHS	4.95	234	141	$6,600	$32,162	$3,225	$5,828	$47,814
B5	Warren	9	SHS/RHS	5.21	214	129	$6,600	$34,632	$3,393	$6,474	$51,099
B6	Warren	12	SHS/RHS	5.04	233	140	$6,600	$33,077	$3,282	$6,115	$49,074
Average optimised case B1-B6				**5.24**	**221**	**133**	**$6,600**	**$34,433**	**$3,411**	**$6,357**	**$50,800**
% Contribution							**13%**	**68%**	**7%**	**13%**	**100%**

Figure 6.12– Case B results summary

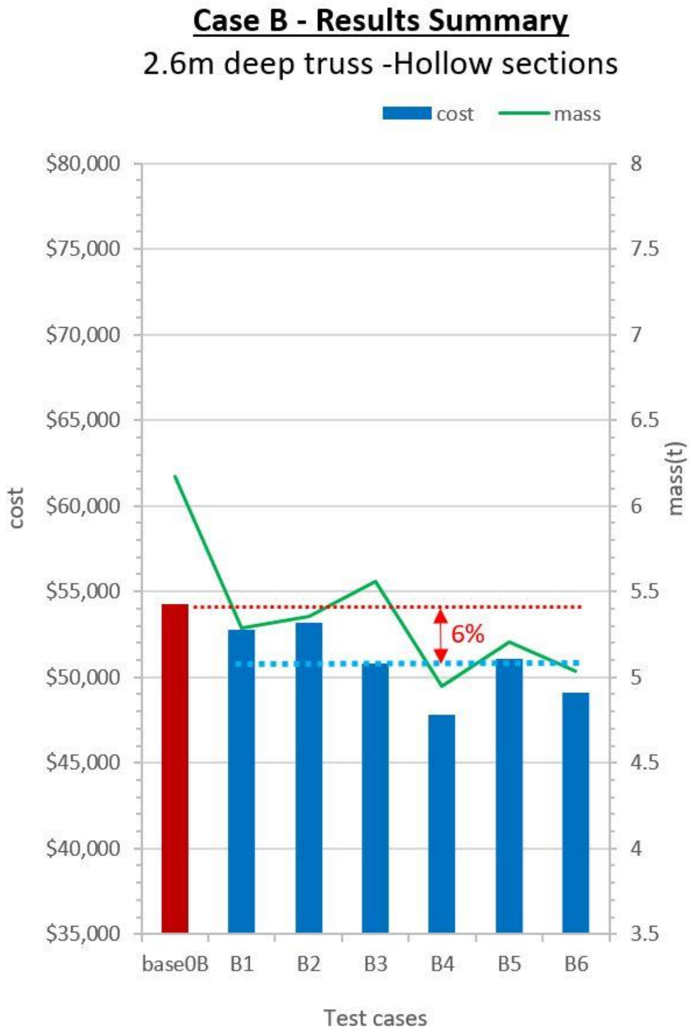


Figure 6.13– Case B results summary graph

The results show:

1. There is a cost reduction from using the optimised topology.
2. The lowest cost option was B4.
3. There is some variation between the optimised cases.

6.3.5 Case C – The Effect of Increasing the Depth of the Truss

For this case the depth of the truss was changed from 2.6m to 3.1m. The geometry of the truss mimics different features the topology optimisation results and is shown in Figure 6.14. The steel members used were hot rolled as used for Case A. A stress analysis was conducted and the members were designed (sized) to suit.

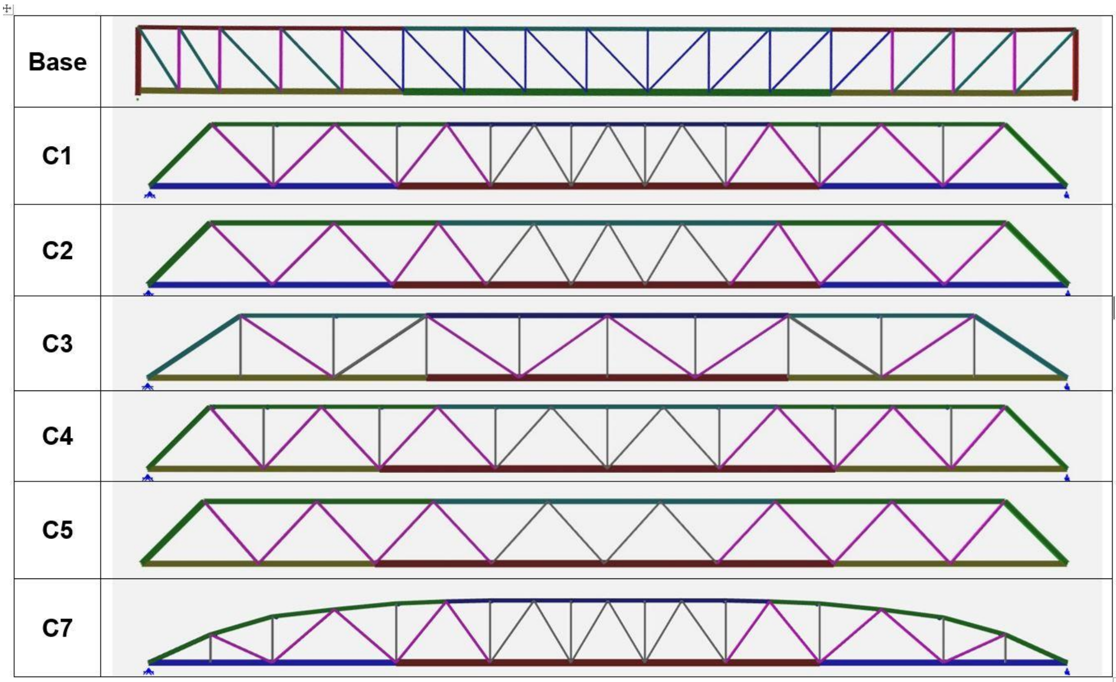


Figure 6.14– Geometry analysed in Case C

The geometry for Case C7 was not a result from the STO. The geometry for C7 is an exploration of the effect of using a bowstring arch on the cost.

The results for all the options explored in Case C have been presented in Figure 6.15 and Figure 6.16 in a similar style to the style previously used for earlier cases.

Case C Results Summary

Case	Truss Type	No. Bracing Bays	Steel Section Type	Steel Mass (t)	Deflection at mid-point (mm)		Cost ($)				
					Ultimate	Serviceability	Design	Fabrication	Freight	Installation	Total
Base0C	Pratt	16	original geometry stretched to 3.1m truss depth	6.07	174	105	$6,000	$36,115	$3,958	$7,938	**$54,011**
C1	Warren	9	hot rolled sections	5.74	159	96	$6,600	$34,071	$3,740	$7,542	$51,953
C2	Warren	9	hot rolled sections	6.59	139	84	$6,600	$35,024	$4,296	$6,794	$52,714
C3	Warren	5	hot rolled sections	6.45	141	86	$6,600	$34,083	$4,208	$6,389	$51,281
C4	Warren	8	hot rolled sections	5.90	145	88	$6,600	$33,206	$3,844	$6,870	$50,520
C5	Warren	8	hot rolled sections	6.94	126	77	$6,600	$35,221	$4,524	$6,337	$52,682
C7	Bowstring arch	9	hot rolled sections	5.80	167	101	$6,600	$32,572	$3,779	$6,666	$49,618
Average optimised case C1-C6				**6.24**	**146**	**89**	**$6,600**	**$34,029**	**$4,065**	**$6,767**	**$51,461**
% Contribution							**13%**	**66%**	**8%**	**13%**	**100%**

Figure 6.15– Case C results summary

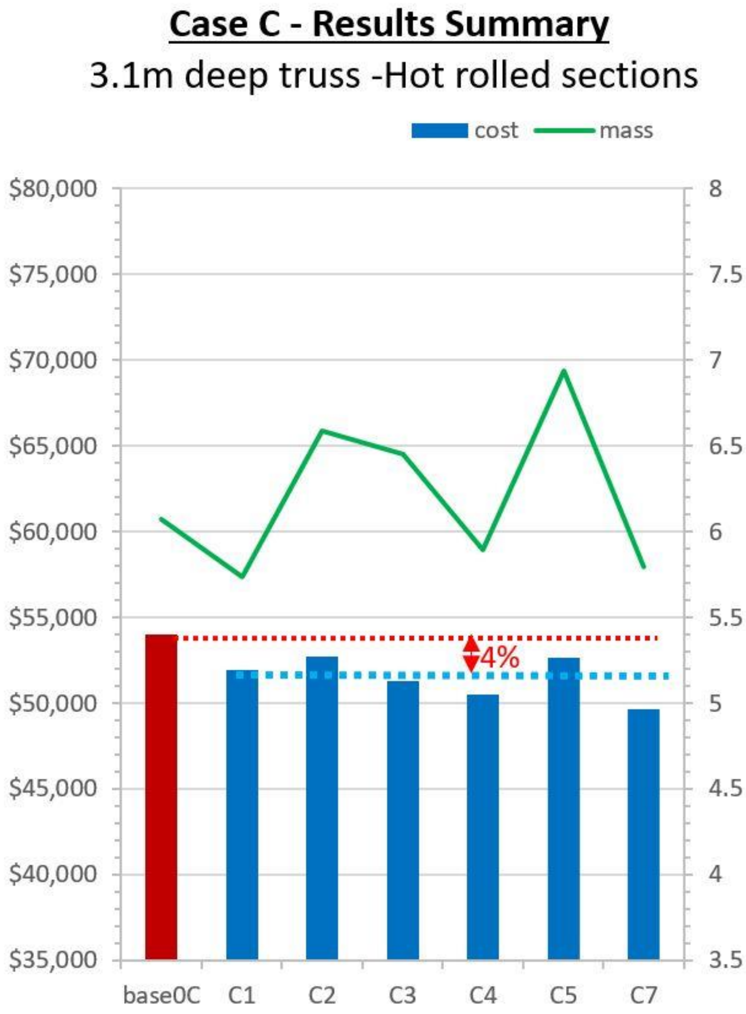


Figure 6.16– Case C results summary graph

The results show:

1. There is a cost reduction from using the optimised topology.
2. The lowest cost option was C3.
3. There is some variation between the optimised cases.

6.3.6 Case D - The Combined Effect of Increasing the Depth of the Truss, Changing Steel Section Type and Increasing Material Strength.

For this case the depth of the truss was the same as Case C at 3.1m. The geometry of the truss matches the geometry used in Case C also (i.e. Case C1 and D1 have the same geometry). The members were changed to hollow sections which are made from steel with a higher yield strength. A stress analysis was conducted and the members were designed (sized) to suit.

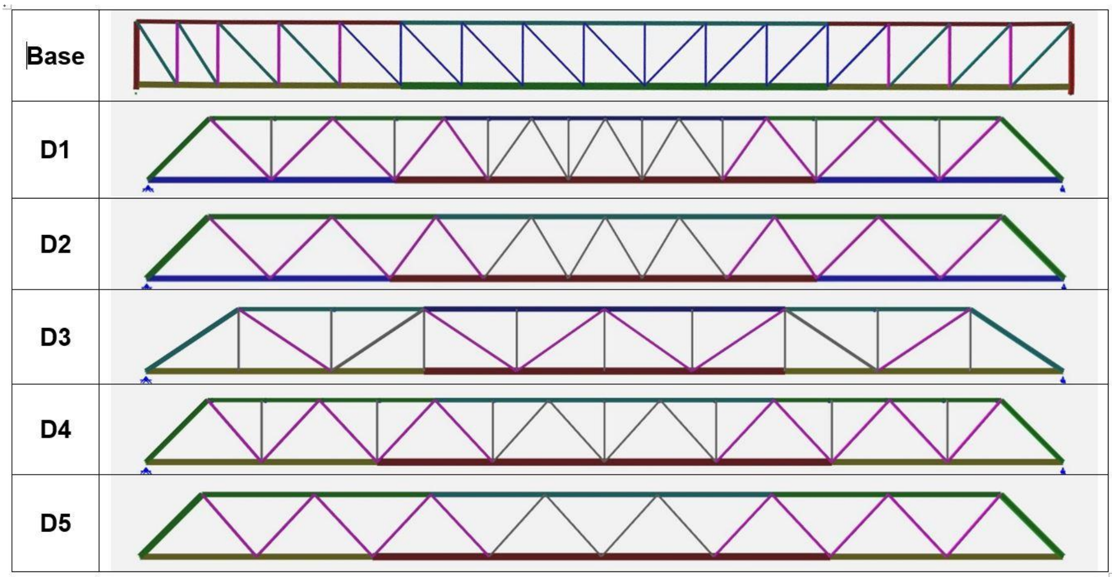


Figure 6.17– Geometry analysed in Case D

The results for all the options explored in Case D have been presented in Figure 6.18 and Figure 6.19 in a similar style to the style previously used for earlier cases.

Case D Results Summary

Case	Truss Type	No. Bracing Bays	Steel Section Type	Steel Mass (t)	Deflection at mid-point (mm)		Cost ($)				
					Ultimate	Serviceability	Design	Fabrication	Freight	Installation	Total
Base0D	Pratt	16	original geometry with SHS/RHS stretched to 3.1m truss depth	5.45	216	129	$6,000	$37,922	$3,553	$7,590	**$55,065**
D1	Warren	9	SHS/RHS	4.68	201	121	$6,600	$32,618	$3,047	$6,566	$48,830
D2	Warren	9	SHS/RHS	4.36	200	120	$6,600	$30,042	$2,839	$5,917	$45,398
D3	Warren	5	SHS/RHS	4.83	192	115	$6,600	$32,372	$3,145	$6,147	$48,263
D4	Warren	8	SHS/RHS	4.54	204	122	$6,600	$31,714	$2,961	$6,388	$47,663
D5	Warren	8	SHS/RHS	4.76	182	109	$6,600	$29,956	$3,105	$5,104	$44,766
Average optimised case D1-D5				**4.63**	**196**	**117**	**$6,600**	**$31,340**	**$3,020**	**$6,024**	**$46,984**
% Contribution							**14%**	**67%**	**6%**	**13%**	**100%**

Figure 6.18– Case D results summary

Figure 6.19– Case D results summary graph

The results show:

1. There is a cost reduction from using the optimised topology of approximately 12%.
2. The lowest cost option was B4 & D5.
3. There is some variation between the optimised cases.

6.4 Comparison of Results for All Cases.

There are two graphs shown in this section to enable comparison between Cases A to D. Also the pictorial reference of differences between cases is reprinted here in Figure 6.20 to allow easy comparison between cases.

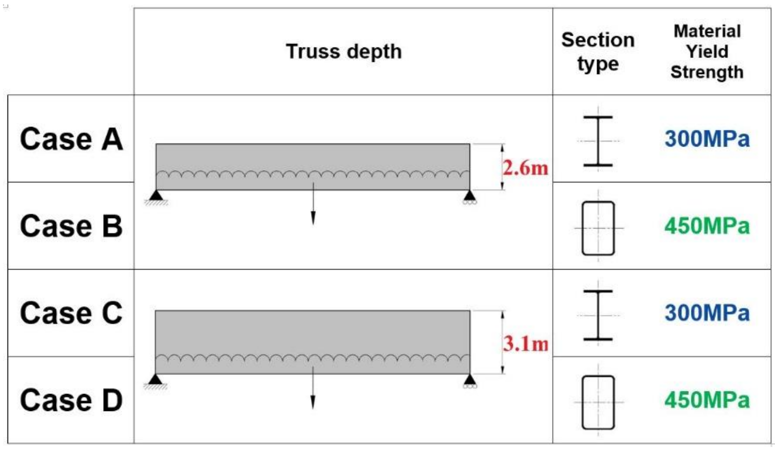


Figure 6.20– Summary of design case parameters

The first graph in Figure 6.21 shows the effect of changing the steel section and truss depth for the different base cases. There has been no change in the bracing layout, it is as used in the original "base case". It can been seen from the graph there is considerable reduction in steel mass for the structure for Case A to D, however the overall cost has remained relatively unchanged or has increased slightly in Case B,C and D .

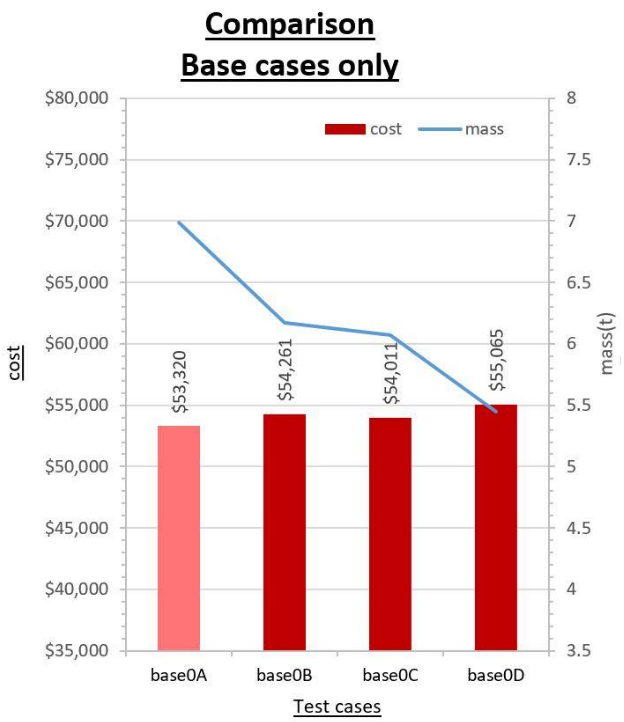


Figure 6.21– Cost of "base case" geometry with different steel section and truss depths

The reason for the price not dropping in line with the mass is:

1. The fabrication cost rates increase when the steel member size for the chords drops from heavy class to medium class of steel weight.
2. The fabrication cost rates increase when using hollow sections rather than hot rolled sections.

The increase in cost for the two factors above is enough to offset the benefit obtained the large reduction obtained in overall mass of the structure in Case D. As mentioned in Section 4.9 regarding the broad nature of costing and application of the classes of steel weights, it is considered necessary for further exploration of cost rates to validate the results indicated by Figure 6.21.

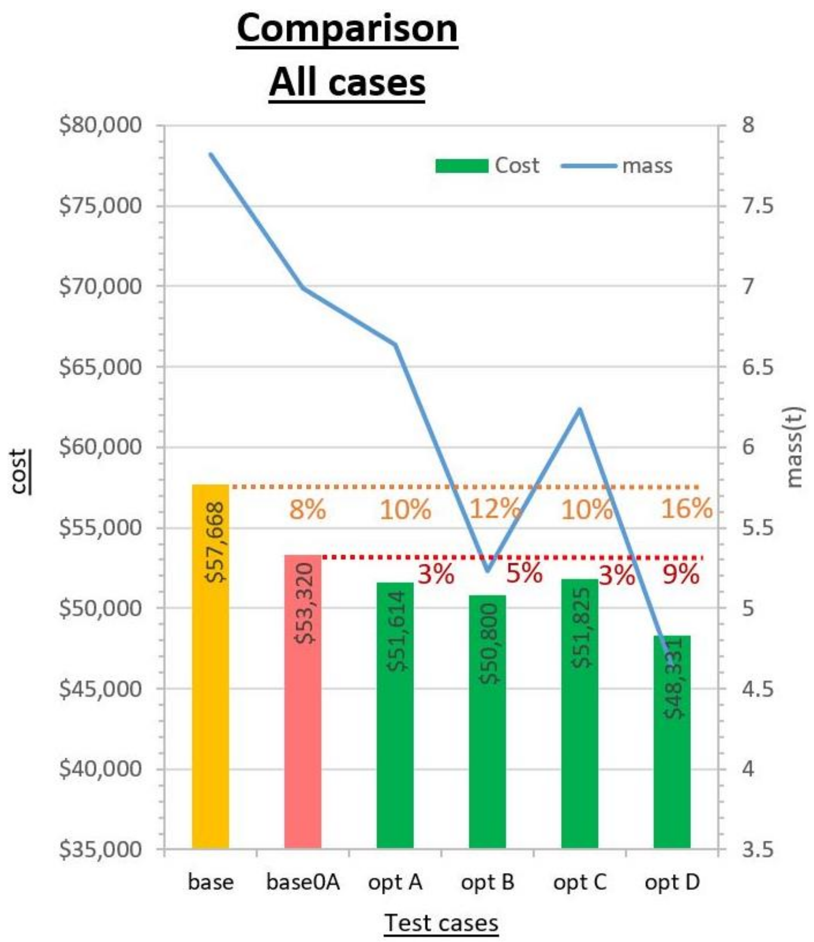


Figure 6.22– Results comparison between STO geometry Cases A to D against "base case"

The summary of results obtained by applying the STO geometry to Cases A to D is presented in the graph in Figure 6.22. Here it can be seen:

1. There is a very significant reduction in average **mass** for the optimised structures in Cases A, B C and D
2. There is a moderate beneficial reduction in average **cost** for the optimised structures in Cases B and Case D of 5% and 9% respectively.
3. There appears to be a “compounding” effect of the:
    a. STO geometry;
    b. increase in truss depth from 2.6m to 3.1m;
    c. larger radius of gyration for the hollow sections;
    d. and higher strength steel used in the hollow sections;

    which all combine to produce an average reduction in cost for Case D.

The raw BOM data is attached in Appendix E.

6.5 Observations During Analysis and Design

The following points were observed during the design and analysis of the truss structure.

6.5.1 Axial Loads in the Chords.

The vertical uniformly distributed loads (UDLs) become high axial (horizontal) loads in the top and bottom chords of the truss. The force distribution is indicated in Figure 6.23. The bottom chord is under high tension forces and the top chord undergoes high compression forces. The peak forces are comparable between cases. For Case A3 and A4 the peak axial forces are 1393kN and 1434kN respectively, a difference of less than 3%. The contrasting effective length on the top chord between the two cases is indicated on the figure by ***le***.

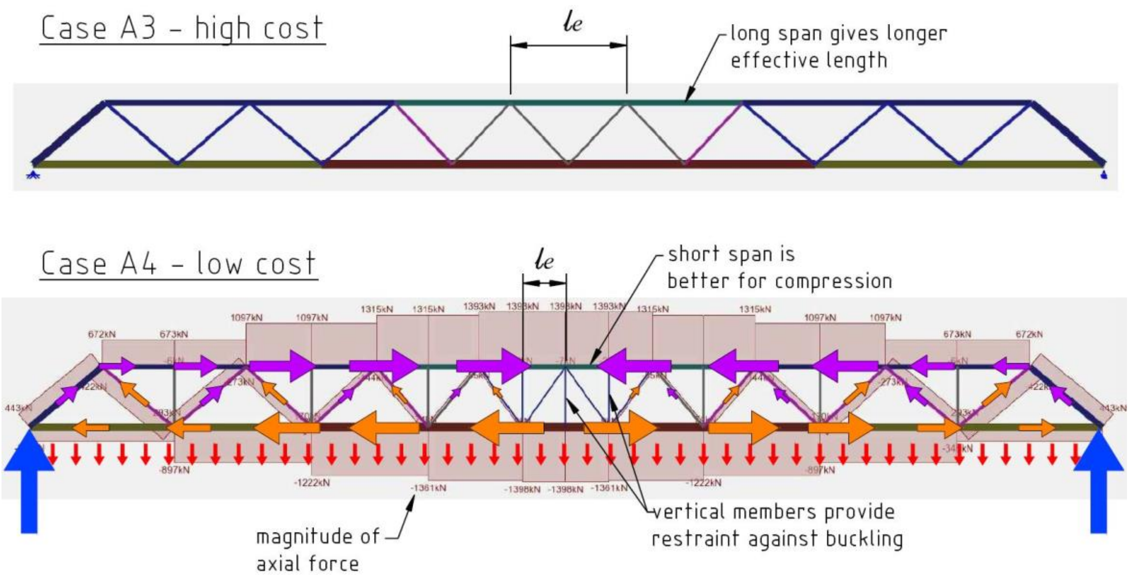


Figure 6.23– Typical forces developed within the truss.

The high compression loads and the tendency of the top chord to buckle was the driving factor for the member size during design. In AS4100, once the member's length is above that of a short stub, the characteristic used to determine the capacity of a member to resist buckling is its slenderness ratio. The lower the slenderness ratio the more axial load the member can resist. The major factors determining slenderness ratio is the effective length and the radius of gyration (or stiffness of the member).

- More material towards the extremities of the section increases the radius of gyration and reduces the slenderness.
- Reducing the effective length between supports also reduces the slenderness.

To determine the best design a balance was required between the effective length, slenderness of the member and the ability of the member to carry the nominal axial load.

The chord tendency to buckle was of similar magnitude in both the vertical and horizontal planes so a steel section with similar stiffness in both planes was desirable. In practice, this meant choosing either a UC or SHS, as UB's or RHS sections have quite different stiffness between the x and y planes.

The buckling effects in the top chord were significant to the design of the overall truss structure due to the high mass per metre of steel section required. Because the chord was such a large size it contributed to a significant portion of the overall mass and cost for the structure. Inefficiency in the chords and the top chord in particular would have a deleterious effect the overall efficiency and cost of the structure.

The large variation in effective lengths between models was one of the reasons for the large variation in costs between different geometry within the same case.

During design and analysis, it appeared the hollow sections had an advantage, and generally a hollow section with a smaller mass per metre was able to be used. It was not clear during design whether the more efficient shape of the hollow sections would be enough to offset their higher material cost. From the results it appears they provide a greatly increased benefit in structural efficiency which is enough to offset their higher material cost.

6.5.2 Combined Loads

The vertical loads translated to tension forces in the bottom chord, which also underwent local bending due to the applied UDL. This results in a combined effect for the bottom chord. However the UDL is a small magnitude relative to the axial tension so the net effect of the combined loads was of small significance for the design of the bottom chord members.

The vertical load translates to a high compression force in the top chord of the truss. There is also a small gravity load of the top chord self-weight causing a combined load effect on the top chord.

In practice the combined load effects were was small enough to be of little consideration in the sizing of members for the top and bottom chords.

6.5.3 Shear Loads.

There was little shear or vertical load in the mid-section of the truss. This means the bracing members in this area could be relatively small compared to the bracing members at either end of the truss. The primary role of the bracing in the mid section of the truss was a restraint against buckling of the top chord under the compression forces.

6.5.4 Truss Depth

Changing the depth of the truss has a large effect on the efficiency of the truss by changing the magnitude of the axial forces in the top and bottom chord. Increasing the depth decreased the axial forces. As noted in Section 6.5.1 above, the axial forces in the chords are a large contributor to the overall weight of the truss. Increasing the truss depth also increases the length of the bracing members, which tend to increase the cost of the truss. To achieve the low cost solution there is a balance required in changing the depth of the truss, between the effect of reducing the axial forces and increasing the bracing lengths. The results from Cases C & D indicated there was a net benefit in increasing the depth from 2.6 to 3.1m. Further increase in depth was limited by the transportation requirements of the project.

6.5.5 Interpretation of STO Results and Geometry

There was a requirement to interpret the results from STO. This is because STO is uses a solid material distribution, not the sparse shapes of standard structural steelwork sizes.

The magnitude of the axial forces in the chords design appeared to correspond to the change in thickness of the chords visible in the results of the STO.

6.5.1 Discrete Steel Sizes

The available range of the discrete sections size had a large effect on the efficiency of the truss.

There is large jump in capacity from one section size to the next largest available section size. An example of this is the jump from a 200UC59.5 to a 250UC79.2 is shown in Table 6.1.

Table 6.1 – Comparison of engineering properties between adjacent member sizes.

	200UC59.5	**250UC79.2**	**% increase**
Steel mass (kg/m)	59.5	79.2	33%
Gross cross sectional area A_g (mm^2)	7620	9320	28%
Plastic Modulus ($10^3 mm^3$)	656	992	51%
Radius of gyration (mm)	51.7	65.4	25%

The jump between the member sizes is particularly large in the example shown above. Not all the adjacent member sizes had jumps similar in size to those indicated in Table 6.1. This example is relevant because on some cases during design, the decision needed to be made between which of the two members in the example above needed to be used.

If there was a case where the two largest members in the truss, the top and bottoms chord, were only marginally of insufficient capacity and it was necessary to use the next largest available standard section size, there is a correspondingly large jump in the quantities and cost for that option also.

The large jump in capacity and cost of the standard steel members was one of the reasons for the large variation in costs between different options within the same case. For example, the large variation in cost between Cases A1 to A6. It was also the reason it was decided to average the cost of all the optimised cases for comparison to the "base case" to enable an effective comparison.

It is possible that a similar situation could occur in the design of the "base cases", Base 0A to Base 0D, if the member sizes were particularly large in proportion to the design forces. If the jump to the next member size was oversize and inefficient, then the cost for the "base case" would not be a true indication of the cost of that geometry. However, the results showed that when different steel types (i.e. hollow sections) or truss depths (3.1m) were used for the "base case" Pratt geometry the STO nearly always had reduced cost. As the trend was similar across all the Cases A to D this indicates that the comparison is likely to be fair and realistic.

It was noted during design that large jump in capacity can be mitigated if there is the possibility of changing the truss geometry. Changing the geometry slightly by moving the node points can reduce the loads on an individual member and mean it is possible to use smaller section size for that member. An example of this could be to move the bracing node points of the truss geometry slightly closer together to reduce the member effective length. This indicated that to be truly effective, the STO and design and analysis model and cost rates should be combined to work in an iterative manner together.

To do the STO without consideration of big influences such as the large jump between discrete member sizes and cost necessitated the large number of options (as used in this dissertation) to be evaluated. If it is possible to combine the operations in one model this would result in a very powerful design aid.

Chapter 7 Conclusions and Recommendations

This dissertation found that Structural Topology Optimisation (STO) is the most general form of structural optimisation. By applying STO to the concept design of a steel truss bridge via an 88 line MATLAB program, a range of optimised geometry was produced. The STO procedure indicated a strong preference towards the warren truss as being the optimal shape a bridge of this type.

The truss bridge was designed to determine member sizes, extract a bill of materials and apply live project cost rates for a range of geometry and the results showed an avarage reduction in cost for the truss bridge of approximately 3% by using the optimised geometry. Other methods of structural optimisation such as changing to high strength steel, using hollow steel sections and increasing the truss depth in conjunction with the optimised geometry increased the estimated cost savings to approximately 9%. This larger reduction appeared to indicate a compounded effect from optimising several parameters of the design together.

A range of methods for using STO were evaluated and the robustness of the SIMP method and the ready availability of the MATLAB program favoured its use. However editing the MATLAB program to suit the parameters of the project required some detailed understanding of the program and a significant investment in time. There was a large amount of interpretation required by the designer to use the results of STO with the discrete size range of structural steel sections. A large jump between the nearest available steel sizes of more than 20% and the heavy compression and buckling forces in the top chord of the truss produced some large variations in results for different truss geometry. As the application of STO is relatively new and without prior experience there is some uncertainty to estimating the cost of using STO on future projects.

STO is regularly used in automotive and aerospace but not in building structures. This is predominantly due to the relatively complex shapes which result from STO. In automotive and aerospace industry lightweight structures reduce the operating costs, high volumes of production cater for complex parts. In contrast, building structures require simple structural shapes for ease and speed of construction which tend to limit the benefit to be gained from STO, or increase the complexity in applying it successfully to structural projects such as this dissertation as noted above.

It was determined from the results of this dissertation that having a combined model for STO, analysis and design and the ability to include cost rates and discrete member sizes into the optimisation to cater for their significant effect would likely increase the benefits gained by STO.

A huge variety of other STO algorithms exist and a discrete truss methods have been developed in research which are more suited to this bridge design, although not readily available for trial.

For future work, it is recommended that:

1. Incorporation of the discrete steel section sizes and cost rates into the STO procedure is required to realise the true benefit of STO.
2. More accurate data is obtained to reduce the uncertainty of the results surrounding:
    a. Whether the cost rates for the different classes of steel weights (light, medium and heavy) do actually reflect the true cost for a structure of this type.
    b. The assumption allowing for an increase in design costs of 10% for STO is reflective of the true cost.
3. A similar exercise be completed for a 3D design problem using 3D topology optimisation. A full 3D optimisation and design problem has increased complexity and testing the use of STO would give a more effective:
    a. Gauge of the costs in terms of design hours
    b. Benefits to be gained which may be amplified by the non-intuitive nature optimised designs produced by STO.
    c. Exploration of the method developed by (Asadpoure, Guest & Valdevit 2015) for using discrete steel sizes and the inclusion of cost constraints into the topology optimisation.

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Appendix A – Project Specification

ENG4111/4112 Research Project

For: Wayne Sutcliffe

Title: Design of truss bridge with optimisation for low construction cost.

Major: Civil Engineering

Supervisor: Dr Kazem Ghabraie USQ
Dr Sourish Banerjee
Christian English, Manager Structures, Sedgman Ltd

Enrolment: ENG4111 – EXT S1, 2016
ENG4112 – EXT S2, 2016

Project Aim: To design a bridge spanning 46m and explore methods using topology optimisation to achieve the lowest cost solution and report on the effectiveness of the methods.

Programme: Issue B, 27th September 2016

1. Search for methods of topology optimisation and evaluate them for relevance to this application.
2. Gather design data applicable to this situation:
    a. Appropriate service loads
    b. Applicable standards
    c. Costing data (from recently completed projects)
3. Determine the constraints applicable to this design. For example: maximum transportation sizes and readily available structural steel sizes.
4. Gather design data on the existing design – the “base case”. Apply relevant costing data to the “base case” for later comparison.
5. Choose a topology optimisation method and build a design model in matlab. Run the design model to obtain an “optimised” member geometry.
6. Modify “the base case” spacegass design to conform to the optimised geometry – the optimised layout. Apply costings and compare the results to the original base case.
7. Analyse the results to determine where, if any, improvements have occurred.
8. Make a recommendation on the most appropriate method to achieve the lowest cost solution.

If time and resources permit:

9. Modify the geometry further or apply different topology optimisation methods to further explore methods to achieve the lowest cost solution.

Appendix B – Project Risks

Table B1 – Risk Assessment

The "Risk Likelihood Levels" presented in Table **B2**, "Risk Consequence Levels" presented in Table **B3** and the "Risk Consequence Levels" presented in Table **B4** have been used.

Hazard	Risk Rating	Control Measures
Electrical equipment (computer) causing injury, electrical shock, burns, fire	Likelihood: Unlikely Consequence: Major **Risk: Medium**	Use up to date equipment, check of cords and connections before use. Switch off equipment when not in use Ensure sufficient power sockets; use extension leads and adaptors only where necessary.
Fatigue related injury due to reduced ability to concentrate e.g. on driving or physical task	Likelihood: Possible Consequence: Moderate **Risk: Medium**	Schedule study workload to minimise excessive peaks. Use personal leave where necessary to reduce working hours during periods of high intensity study workload. Regularly review fatigue levels and adjust risk mitigation measures appropriately e.g. elect to take public transport rather than drive if excessively tired.
Physical strain injuries from computer work (eye strain; repetitive strain injuries, back pain due to incorrect desktop setup) Upper limb disorders muscular skeletal injury Headaches Eye strain	Likelihood: Possible Consequence: Moderate **Risk: Medium**	Ensure desktop is set up appropriately to maximise ergonomic comfort, apply the USQ ergonomic factsheet. Take regular breaks during periods of extended desk work No obstructions under desks. Ensure adequate work space is available Adequate lighting with blinds on windows to reduce glare and reflection. Position, height and layout of the workstation appropriate.
Misuse of information contained in this report leading to unsafe design	Likelihood: Rare Consequence: Moderate **Risk: Low**	Disclaimer on page ii

Table B2 - Risk likelihood levels

Level	Descriptor	Qualitative Description
A	Almost certain	The event is expected to occur; event will occur on an annual basis (or more frequent).
B	Likely	Probable that it will occur; event has occurred several times before.
C	Possible	May or may not occur; event may occur once.
D	Unlikely	The event may occur at some time but is unlikely; heard of happening from time to time.
E	Rare	The event may occur in exceptional circumstances; not heard of.

Table B3 – Risk Consequence Levels

Level	Descriptor	Qualitative Description
1	Insignificant	People: Event does not result in injury (i.e. no medical treatment required). Environment: No damaged detected. Property: No damage to property.
2	Minor	People: Reversible injury or illness. Environment: Minor impact of short duration or short term damage. Property: Minor damage to property (<$5,000 to repair).
3	Moderate	People: Irreversible disability or impairment (30%) to one or more persons. Environment: Short term damage resulting in complaints, localised impact. Property: Moderate damage to property (<$50,000 to repair).
4	Major	People: Severe injuries to one or more persons, single fatality. Environment: Significant impact locally and potential for off-site impacts. Property: Major damage to property (<$500,000 to repair).
5	Catastrophic	People: Multiple fatalities, or irreversible injuries. Environment: Significant impacts to regional ecosystems and threatened species, potential for widespread off site impacts. Property: Significant loss to property (>$1,000,000 to repair).

Table B4 – Risk Matrix

	CONSEQUENCES				
LIKELIHOOD	Catastrophic Irreversible Permanent	Major Long Term	Moderate Medium Term	Minor Short Term Manageable	Insignificant Manageable
Almost Certain	Extreme	Extreme	High	Medium	Medium
Likely	Extreme	High	High	Medium	Low
Possible	High	High	Medium	Medium	Low
Unlikely	Medium	Medium	Medium	Low	Low
Rare	Medium	Low	Low	Low	Low

Appendix C – Matlab Code

```
%%%% A SIMPLIFIED TOPOLOGY OPTIMIZATION CODE, April 2011 %%%%
% modified by Wayne Sutcliffe 27 June 2016
% toptest9a(920,52,0.03,3)
%for testing purposes
function toptest9a(nelx,nely,volfrac,penal)
rmin=nely/10;                  %******min radius is 1/10 depth of beam
%% MATERIAL PROPERTIES
E0 = 1;                                    %********************
Emin = 1e-9;
nu = 0.35;                                     %********************
%% PREPARE FINITE ELEMENT ANALYSIS
A11 = [12  3 -6 -3;  3 12  3  0; -6  3 12 -3; -3  0 -3 12];
A12 = [-6 -3  0  3; -3 -6 -3 -6;  0 -3 -6  3;  3 -6  3 -6];
B11 = [-4  3 -2  9;  3 -4 -9  4; -2 -9 -4 -3;  9  4 -3 -4];
B12 = [ 2 -3  4 -9; -3  2  9 -2;  4  9  2  3; -9 -2  3  2];
KE = 1/(1-nu^2)/24*([A11 A12;A12' A11]+nu*[B11 B12;B12' B11]);
nodenrs = reshape(1:(1+nelx)*(1+nely),1+nely,1+nelx);
edofVec = reshape(2*nodenrs(1:end-1,1:end-1)+1,nelx*nely,1);
edofMat = repmat(edofVec,1,8)+repmat([0 1 2*nely+[2 3 0 1] -2 -
1],nelx*nely,1);
iK = reshape(kron(edofMat,ones(8,1))',64*nelx*nely,1);
jK = reshape(kron(edofMat,ones(1,8))',64*nelx*nely,1);
% DEFINE LOADS AND SUPPORTS (half beam)
F(2*(nely+1):(2*(nely+1)):2*(nelx+1)*(nely+1),1=-(nelx/51.1e6)
%%%%%%%%force is 9kN UDL on bottom edge
display(F);
U = zeros(2*(nely+1)*(nelx+1),1);
fixeddofs = union(2*(nely+1)-1:1:2*(nely+1),2*(nelx+1)*(nely+1) );
%%(full truss
%fixeddofs = union([1:2:2*(nely+1)],[2*(nelx+1)*(nely+1)]); %%(half
truss
alldofs = [1:2*(nely+1)*(nelx+1)];
freedofs = setdiff(alldofs,fixeddofs);
%% PREPARE FILTER
iH = ones(nelx*nely*(2*(ceil(rmin)-1)+1)^2,1);
jH = ones(size(iH));
sH = zeros(size(iH));
k = 0;
for i1 = 1:nelx
  for j1 = 1:nely
    e1 = (i1-1)*nely+j1;
    for i2 = max(i1-(ceil(rmin)-1),1):min(i1+(ceil(rmin)-1),nelx)
      for j2 = max(j1-(ceil(rmin)-1),1):min(j1+(ceil(rmin)-1),nely)
        e2 = (i2-1)*nely+j2;
        k = k+1;
        iH(k) = e1;
        jH(k) = e2;
        sH(k) = max(0,rmin-sqrt((i1-i2)^2+(j1-j2)^2));
      end
    end
  end
end
H = sparse(iH,jH,sH);
Hs = sum(H,2);
%% INITIALIZE ITERATION
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
x = repmat(volfrac,nely,nelx);
```

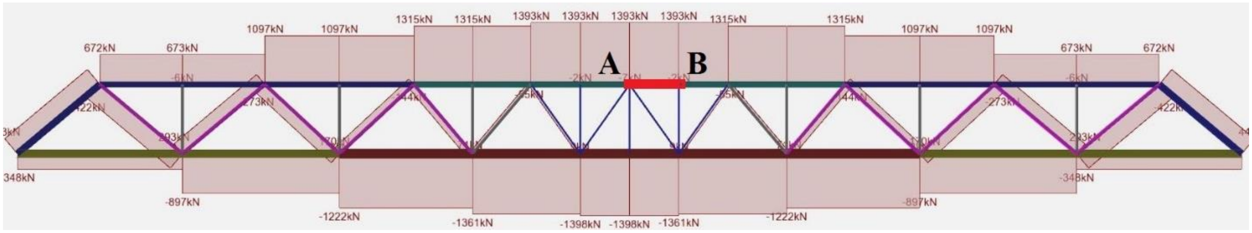
```
loop = 0;
change = 1;
colormap(gray); imagesc(1-x); caxis([0 1]); axis equal; axis off;
drawnow;
print('-depsc2','T0000.eps');
%% START ITERATION
while change > 0.005       %<<<-------
  loop = loop + 1;
  %% FE-ANALYSIS
  sK = reshape(KE(:)*(Emin+x(:)'.^penal*(E0-Emin)),64*nelx*nely,1);
  K = sparse(iK,jK,sK); K = (K+K')/2;
  U(freedofs) = K(freedofs,freedofs)\F(freedofs);
  %% OBJECTIVE FUNCTION AND SENSITIVITY ANALYSIS
  ce = reshape(sum((U(edofMat)*KE).*U(edofMat),2),nely,nelx);
  c = sum(sum((Emin+x.^penal*(E0-Emin)).*ce));
  dc = -penal*(E0-Emin)*x.^(penal-1).*ce;
  %% FILTERING OF SENSITIVITIES
  dc(:) = H*(x(:).*dc(:))./Hs./max(1e-3,x(:));
  %% OPTIMALITY CRITERIA UPDATE OF DESIGN VARIABLES
  l1 = 0; l2 = 1e9; move = 0.2;
  while (l2-l1)/(l1+l2) > 1e-4               %*******************
    lmid = 0.5*(l2+l1);
    xnew = max(0,max(x-move,min(1,min(x+move,x.*sqrt(-dc./lmid)))));
    if sum(xnew(:)) > volfrac*nelx*nely, l1 = lmid; else l2 = lmid;
end
  end
  change = max(abs(xnew(:)-x(:)));
  x = xnew;
  %% PRINT RESULTS
  fprintf(' It.:%5i Obj.:%11.4f Vol.:%7.3f
ch.:%7.3f\n',loop,c*106e6/(nelx^2), ...
    mean(x(:)),change);
%*******************
  objhis(loop) = c;
  %% PLOT DENSITIES
  colormap(gray); imagesc(1-x); caxis([0 1]); axis equal; axis off;
drawnow;
  if mod(loop,10)==0
    tfname = sprintf('T%04i.eps',loop);
    print('-depsc2',tfname);
  end
end

%% FINAL OUTPUTS
% print the final topology
tfname = sprintf('T%04i.jpg',loop);
print('-depsc2',tfname);
% write the history of the objectve function values to the file
his.csv
fh=fopen('his.csv','w');
for i=1:loop
  fprintf(fh,'%i , %f \n',i,objhis(i));
end
fclose(fh);
% plot the evolution of the objective function and print it to
his.eps
figure;
plot(1:loop,objhis,'r','LineWidth',2);
ylabel('objective function'); xlabel('Iteration');
print('-depsc2','his.jpg');
```

Appendix D – Check calculations

Case A4 loadcase 100

The calculations to determine the capacity of Member A-B as shown on Figure D1 below.



Loads from analysis BMD & AFD

Axial load = N* = 1393 kN

Bending moment = M_x* = 13kNm

Bending moment = M_y* = 0

Step 1: Member and section data - Trial section 250UC89.5 Grade 300

ℓ_e = 1850mm

A_n = 11400mm^2

k_f = 1.0 *from steel capacity tables*

Z_{ex} = 1230 x 10^3 mm^3

Z_{ey}= 567 x 10^3 mm^3

I_x = 143 x 10^6 mm^4

I_y = 48.4 x 10^6 mm^4

J = 1040 x 10^3 mm^3

I_w = 713 x 10^9 mm^4

r_x = 112 mm

r_y = 65.2 mm

Step 2: Net section properties

There are no holes or cuts

A_d = 0

A_n = A_g = 11400mm2

Step 3: Effective lengths for column action

The structure is welded so there is likely to be some reduction in the effective length.

The effective length factor has been conservatively taken as

$k_{ex} = k_{ey} = 1$

$\ell_{ex} = \ell_{ey} = 1850\text{mm}$

Step 4: Column slenderness reduction factor

$k_f = 1.0$

$\alpha_b = 0$ AS4100 table 6.3.3(1)

Calculate slenderness ratio about *x* axis

$\lambda_n = \left(\frac{\ell e}{r}\right) \sqrt{(k_f)}\sqrt{\left(\frac{f_y}{250}\right)}$ AS4100 Cl. 6.3.3

$= \left(\frac{1850}{112}\right) \sqrt{(1)}\sqrt{\left(\frac{280}{250}\right)}$

$= 17.4$

Calculate slenderness ratio about *y* axis

$\lambda_n = \left(\frac{\ell e}{r}\right) \sqrt{(k_f)}\sqrt{\left(\frac{f_y}{250}\right)}$ AS4100 Cl. 6.3.3

$= \left(\frac{1850}{65.2}\right) \sqrt{(1)}\sqrt{\left(\frac{280}{250}\right)}$

$= 30$

Member slenderness reduction factors AS4100 table 6.3.3(3)

$\alpha_{cx} = 0.962$

$\alpha_{cy} = 0.943$

Step 5: Calculate section axial compression capacity

$N_s = k_f A_n f_y$ AS4100 table 6.2.1

$= 1 \times 11400 \times 280$

$= 3190$ kN

$\phi N_s = 3192 \times 0.9$

$= 2870$ kN

Check about x axis

$N_{cx} = \alpha_{cx} N_s$

$= 0.962 \times 3190$

$= 3070$ kN

$\phi = 0.9$ AS4100 table 3.4

$\phi N_{cx} = 0.9 \times 3070$

$= 2760$ kN

$N^* = 1390 \leq \phi N_{cx}$ → OK

Check about y axis

$N_{cy} = \alpha_{cy} N_s$

$= 0.943 \times 3190$

$= 3010$ kN

$\phi N_{cy} = 0.9 \times 3010$

$= 2760$ kN

$N^* = 1390 \leq \phi N_{cy}$ → OK

Step 6: Calculate section moment capacity

$M_{sx} = f_y Z_{ex}$ AS4100 Cl 5.2.1

$= \frac{280 \times 1230 \times 10^3}{10^6}$

$= 344$ kNm

$\phi M_{sx} = 0.9 \times 344$

$= 310$ kNm

$M_{sy} = f_y Z_{ey}$

$= \frac{280 \times 567 \times 10^3}{10^6}$

$= 159$ kNm

ϕM_{sy}= 0.9 x 159

= 143 kNm

Step 7: Calculate reduced section moment capacity about *x* axis

$M_{rx} = 1.18\ M_{sx}\left[1 - \frac{N^*}{(\phi N_s)}\right] \ \leq\ M_{sx}$ AS4100 Cl 8.3.2 & 8.3.3

$= 1.18 \text{ x}344\left[1 - \frac{1390}{(2780)}\right] \ \leq\ M_{sx}$

= 203 ≤ 310 kNm → OK *loadfactor of 1.53*

Step 8: Calculate combined actions section capacity check

$$\gamma = 1.4 + \left(\frac{N^*}{(\phi N_s)}\right) \leq 2.0$$

$$\gamma = 1.4 + \left(\frac{1390}{2780}\right) \leq 2.0$$

$\gamma = 0.678 \leq 2.0$ → OK

Step 9: Calculate biaxial section capacity check

$\left[\frac{M_x^*}{\phi M_{rx}}\right]^{\gamma} + \left[\frac{M_y^*}{\phi M_{ry}}\right]^{\gamma} \leq 1$ AS4100 Cl 8.3.4

$$\left[\frac{13}{203}\right]^{0.68} + \ 0\ \leq 1$$

$0.155\ \leq 1$ → OK

Step 10: Calculate moment modification factor

$$\alpha_m = \frac{1.7\ M_m^*}{\sqrt{(M_2^2 + M_3^2 + M_4^2)}} \quad \leq 2.5$$

$$\alpha_m = \frac{1.7\ \times 13}{\sqrt{\left(10^2\ + 13^2\ + 13^2\ \right)}} \quad \leq 2.5$$

$\alpha_m =\ 1.06\ \leq 2.5$ → OK

Step 11: Calculate member moment capacity

ϕM_{bx1} = 302 kNm from AISC table 5.3-6 250UC89

$\phi M_{bx} = \alpha_m\ \phi M_{bx1}$

= 1.06 x 302

= 320kNm

$\phi M_{bx} \leq \phi M_{sx}$

$320 \leq 310$ → false → $\phi M_{bx} = 310$kNm

$M_x \leq \phi M_{sx}$

$13 \leq 310$ → OK

$$M_{bx} = \frac{\phi M_{sx}}{0.9}$$

$$= \frac{310}{0.9}$$

$= 344$ kNm

Step 12: Calculate out of plane member moment capacity

$$M_{ox} = M_{bx}\left[1 - \frac{N^*}{(\phi N_{cy})}\right]$$ AS4100 Cl 8.3.4.1

$$= 344\left[1 - \frac{1390}{3010}\right]$$

$= 185$ kNm

x axis as principal axis

$$M_{ix} = M_{sx}\left[1 - \frac{N^*}{(\phi N_{cx})}\right]$$ AS4100 Cl 8.3.2.2

$$= 344\left[1 - \frac{1390}{2764}\right]$$

$= 171$ kNm

Nominal member capacity about x axis

M_{cx} = *lesser of* M_{ix} *and* M_{ox}

$= 171$ kNm

$\phi M_{cx} = 171 \times 0.9$

$= 154$ kNm

$M_x^* = 13$

y axis as principal axis

$$M_{iy} = M_{sy}\left[1 - \frac{N^*}{(\phi N_{cy})}\right]$$ AS4100 Cl 8.4.2.2

$$= 159\left[1 - \frac{1390}{2704}\right]$$

$= 77.4$ kNm

ϕM_{iy} = 77.4 x 0.9

= 69.7 kNm

<u>Step 13:</u> Check out of plane member moment capacity

$$\left[\frac{M_x^*}{\phi M_{cx}}\right]^{1.4} + \left[\frac{M_y^*}{\phi M_{cy}}\right]^{1.4} \leq 1$$ AS4100 Cl 8.4.5.1

$$\left[\frac{13}{154}\right]^{1.4} + \left[\frac{0}{69.7}\right]^{1.4} \leq 1$$

0.0314 ≤ 1 → OK

Appendix E – Design and analysis BOM raw data

Case0A

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...Y -MOD TO 2D PLANAR_REV_E _COMPARITIVE RATIONALISATION - HOT ROLLED
Designer: Date: Monday, September 12, 2016 7:50 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	31	1	200 UC 52.2	2.50	2.50	0.13	0.13
2	31	1	200 UC 52.2	0.25	0.25	0.01	0.01
3	32	1	310 UB 32.0	1.00	1.00	0.03	0.03
4	31	2	200 UC 52.2	2.00	4.00	0.10	0.21
5	17	2	EA125x12	3.21	6.43	0.07	0.15
6	32	2	310 UB 32.0	0.50	1.00	0.02	0.03
7	2	1	HW125x125	2.50	2.50	0.06	0.06
8	32	3	310 UB 32.0	0.67	2.00	0.02	0.06
9	2	14	HW125x125	1.75	24.50	0.04	0.58
10	2	14	HW125x125	0.75	10.50	0.02	0.25
11	32	24	310 UB 32.0	0.75	18.00	0.02	0.58
12	31	6	200 UC 52.2	3.00	18.00	0.16	0.94
13	17	4	EA125x12	3.91	15.62	0.09	0.35
14	20	9	EA100x8	3.91	35.15	0.05	0.43
15	33	28	410 UB 53.7	0.75	21.00	0.04	1.14
16	8	7	250 UC 72.9	3.00	21.00	0.22	1.54
17	32	12	310 UB 32.0	0.25	3.00	0.01	0.10
18	31	1	200 UC 52.2	3.00	3.00	0.16	0.16
19	17	1	EA125x12	3.92	3.92	0.09	0.09
20	31	1	200 UC 52.2	1.75	1.75	0.09	0.09
21	31	1	200 UC 52.2	0.75	0.75	0.04	0.04
22	31	1	200 UC 52.2	0.38	0.38	0.02	0.02

Total mass = 6.99
Center of gravity = 22.20,13.33,1.33

Case0B

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...D TO 2D PLANAR_REV_E _COMPARITIVE RATIONALISATION - HOLLOW SECTIONS
Designer: Date: Monday, September 12, 2016 7:52 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	31	1	250x6 SHS	2.50	2.50	0.11	0.11
2	31	1	250x6 SHS	0.25	0.25	0.01	0.01
3	32	1	250x150x6 RHS	1.00	1.00	0.04	0.04
4	31	2	250x6 SHS	2.00	4.00	0.09	0.18
5	17	2	EA125x12	3.21	6.43	0.07	0.15
6	32	2	250x150x6 RHS	0.50	1.00	0.02	0.04
7	2	1	125x5 SHS	2.50	2.50	0.05	0.05
8	32	3	250x150x6 RHS	0.67	2.00	0.02	0.07
9	2	14	125x5 SHS	1.75	24.50	0.03	0.44
10	2	14	125x5 SHS	0.75	10.50	0.01	0.19
11	32	24	250x150x6 RHS	0.75	18.00	0.03	0.64
12	31	6	250x6 SHS	3.00	18.00	0.13	0.81
13	17	4	EA125x12	3.91	15.62	0.09	0.35
14	20	9	100x5 SHS	3.91	35.15	0.06	0.50
15	33	28	300x200x6 RHS	0.75	21.00	0.03	0.94
16	8	7	250*8 SHS	3.00	21.00	0.18	1.24
17	32	12	250x150x6 RHS	0.25	3.00	0.01	0.11
18	31	1	250x6 SHS	3.00	3.00	0.13	0.13
19	17	1	EA125x12	3.92	3.92	0.09	0.09
20	31	1	250x6 SHS	1.75	1.75	0.08	0.08
21	31	1	250x6 SHS	0.75	0.75	0.03	0.03
22	31	1	250x6 SHS	0.38	0.38	0.02	0.02

Total mass   = 6.22
Center of gravity = 22.19,13.28,1.32

Case0C

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...D TO 2D PLANAR_REV_E _COMPARITIVE RATIONALISATION - HOLLOW SECTIONS
Designer: Date: Monday, September 12, 2016 7:52 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	31	1	250x6 SHS	2.50	2.50	0.11	0.11
2	31	1	250x6 SHS	0.25	0.25	0.01	0.01
3	32	1	250x150x6 RHS	1.00	1.00	0.04	0.04
4	31	2	250x6 SHS	2.00	4.00	0.09	0.18
5	17	2	EA125x12	3.21	6.43	0.07	0.15
6	32	2	250x150x6 RHS	0.50	1.00	0.02	0.04
7	2	1	125x5 SHS	2.50	2.50	0.05	0.05
8	32	3	250x150x6 RHS	0.67	2.00	0.02	0.07
9	2	14	125x5 SHS	1.75	24.50	0.03	0.44
10	2	14	125x5 SHS	0.75	10.50	0.01	0.19
11	32	24	250x150x6 RHS	0.75	18.00	0.03	0.64
12	31	6	250x6 SHS	3.00	18.00	0.13	0.81
13	17	4	EA125x12	3.91	15.62	0.09	0.35
14	20	9	100x5 SHS	3.91	35.15	0.06	0.50
15	33	28	300x200x6 RHS	0.75	21.00	0.03	0.94
16	8	7	250*8 SHS	3.00	21.00	0.18	1.24
17	32	12	250x150x6 RHS	0.25	3.00	0.01	0.11
18	31	1	250x6 SHS	3.00	3.00	0.13	0.13
19	17	1	EA125x12	3.92	3.92	0.09	0.09
20	31	1	250x6 SHS	1.75	1.75	0.08	0.08
21	31	1	250x6 SHS	0.75	0.75	0.03	0.03
22	31	1	250x6 SHS	0.38	0.38	0.02	0.02

Total mass = 6.22
Center of gravity = 22.19,13.28,1.32

Case0D

SPACE GASS 12.50 - SEDGMAN LTD
Path: ....1M DEEP TRUSS_REV_E _COMPARITIVE RATIONALISATION - HOLLOW SECTIONS
Designer: Date: Monday, September 12, 2016 9:07 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	31	1	200x6 SHS	3.10	3.10	0.11	0.11
2	31	1	200x6 SHS	0.25	0.25	0.01	0.01
3	32	1	250x150x6 RHS	1.00	1.00	0.04	0.04
4	31	2	200x6 SHS	2.00	4.00	0.07	0.14
5	17	2	125x5 SHS	3.70	7.40	0.07	0.13
6	32	2	250x150x6 RHS	0.50	1.00	0.02	0.04
7	2	1	125x5 SHS	3.10	3.10	0.06	0.06
8	32	3	250x150x6 RHS	0.67	2.00	0.02	0.07
9	2	14	125x5 SHS	2.35	32.90	0.04	0.60
10	2	14	125x5 SHS	0.75	10.50	0.01	0.19
11	32	24	250x150x6 RHS	0.75	18.00	0.03	0.64
12	31	6	200x6 SHS	3.00	18.00	0.11	0.64
13	17	4	125x5 SHS	4.31	17.26	0.08	0.31
14	20	9	100x5 SHS	4.31	38.83	0.06	0.55
15	33	28	250x150x6 RHS	0.75	21.00	0.03	0.75
16	8	7	200x6 SHS	3.00	21.00	0.11	0.75
17	32	12	250x150x6 RHS	0.25	3.00	0.01	0.11
18	31	1	200x6 SHS	3.00	3.00	0.11	0.11
19	17	1	125x5 SHS	4.34	4.34	0.08	0.08
20	31	1	200x6 SHS	2.35	2.35	0.08	0.08
21	31	1	200x6 SHS	0.75	0.75	0.03	0.03
22	31	1	200x6 SHS	0.38	0.38	0.01	0.01

Total mass   = 5.43
Center of gravity = 22.08,13.46,1.33

CaseA1

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...ED TOPOLOGY 1.0C_WARREN TRUSS_WAS_LOAD CASES_H-HOT ROLLED MEMBERS_R
Designer: Date: Saturday, September 10, 2016 5:20 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	4	310 UB 40.4	6.200	24.800	0.254	1.014
2	4	2	360 UB 56.7	6.200	12.400	0.352	0.705
3	4	2	360 UB 56.7	4.400	8.800	0.250	0.500
4	8	2	200 UC 59.5	4.046	8.092	0.242	0.484
5	3	10	125x5 SHS	4.046	40.460	0.073	0.734
6	1	7	100x5 SHS	2.600	18.200	0.037	0.259
7	3	2	125x5 SHS	5.111	10.222	0.093	0.185
8	8	8	200 UC 59.5	3.100	24.800	0.185	1.483
9	9	2	250 UC 89.5	3.100	6.200	0.277	0.555
10	9	2	250 UC 89.5	4.400	8.800	0.394	0.788

Total mass = 6.707
Center of gravity = 23.000,1.418,0.000

CaseA2

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...D CASES_H-EXTRA MID BRACING - MINIMUM VERTICALS-HOT ROLLED SECTIONS
Designer: Date: Saturday, September 10, 2016 5:22 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	4	310 UB 40.4	6.200	24.800	0.254	1.014
2	4	2	360 UB 56.7	5.600	11.200	0.318	0.637
3	4	4	360 UB 56.7	2.500	10.000	0.142	0.568
4	7	2	200 UC 59.5	4.046	8.092	0.242	0.484
5	11	8	125x5 SHS	4.046	32.368	0.073	0.587
6	10	7	100x5 SHS	2.600	18.200	0.037	0.259
7	3	2	125x75x5 RHS	3.607	7.214	0.051	0.102
8	1	4	100x5 SHS	3.607	14.428	0.051	0.205
9	7	8	200 UC 59.5	3.100	24.800	0.185	1.483
10	8	6	250 UC 72.9	2.500	15.000	0.183	1.097

Total mass = 6.437
Center of gravity = 23.000,1.373,0.000

CaseA3

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...S_LOAD CASES_H-EXTRA MID BRACING - NO VERTICALS-HOT ROLLED SECTIONS
Designer: Date: Saturday, September 10, 2016 5:25 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	4	310 UB 40.4	6.200	24.800	0.254	1.014
2	4	2	360 UB 56.7	5.600	11.200	0.318	0.637
3	4	2	360 UB 56.7	5.000	10.000	0.284	0.568
4	7	2	250 UC 89.5	4.046	8.092	0.362	0.724
5	11	8	125x5 SHS	4.046	32.368	0.073	0.587
6	3	2	125x75x5 RHS	3.607	7.214	0.051	0.102
7	1	4	100x5 SHS	3.607	14.428	0.051	0.205
8	7	4	250 UC 89.5	6.200	24.800	0.555	2.219
9	8	3	250 UC 89.5	5.000	15.000	0.447	1.342

Total mass = 7.399
Center of gravity = 23.000,1.536,0.000

CaseA4

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...Y 1.3A_WARREN TRUSS_WAS_LOAD CASES_H-EXTREME MID BRACING_HOT ROLLED
Designer: Date: Saturday, September 10, 2016 5:26 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	2	310 UB 40.4	6.200	12.400	0.254	0.507
2	5	2	310 UB 40.4	5.900	11.800	0.241	0.483
3	4	2	360 UB 56.7	5.000	10.000	0.284	0.568
4	4	2	360 UB 56.7	4.050	8.100	0.230	0.460
5	4	2	360 UB 56.7	1.850	3.700	0.105	0.210
6	7	2	200 UC 52.2	4.046	8.092	0.212	0.423
7	3	4	125x5 SHS	4.046	16.184	0.073	0.293
8	10	6	100x5 SHS	2.600	15.600	0.037	0.222
9	3	4	125x5 SHS	3.821	15.284	0.069	0.277
10	3	2	125x5 SHS	3.406	6.812	0.062	0.124
11	1	2	100x5 SHS	3.406	6.812	0.048	0.097
12	11	4	65x5 SHS	3.191	12.764	0.028	0.111
13	11	3	65x5 SHS	2.600	7.800	0.023	0.068
14	7	4	200 UC 52.2	3.100	12.400	0.162	0.648
15	7	4	200 UC 52.2	2.800	11.200	0.146	0.586
16	8	4	200 UC 59.5	2.200	8.800	0.132	0.526
17	8	4	200 UC 59.5	1.850	7.400	0.111	0.443

Total mass = 6.046
Center of gravity = 23.000,1.294,0.000

<u>CaseA5</u>

SPACE GASS 12.50 - SEDGMAN LTD
Path: ... TRUSS_WAS_LOAD CASES_H-EXTREME MID BRACING-NO VERTICALS_HOT ROLLED
Designer: Date: Saturday, September 10, 2016 5:27 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	2	310 UB 40.4	6.200	12.400	0.254	0.507
2	5	2	310 UB 40.4	5.900	11.800	0.241	0.483
3	4	2	360 UB 56.7	5.000	10.000	0.284	0.568
4	4	2	360 UB 56.7	4.050	8.100	0.230	0.460
5	4	1	360 UB 56.7	3.700	3.700	0.210	0.210
6	7	2	250 UC 72.9	4.046	8.092	0.296	0.592
7	3	4	125x5 SHS	4.046	16.184	0.073	0.293
8	3	4	125x5 SHS	3.821	15.284	0.069	0.277
9	3	2	125x5 SHS	3.406	6.812	0.062	0.124
10	1	2	100x5 SHS	3.406	6.812	0.048	0.097
11	11	4	65x5 SHS	3.191	12.764	0.028	0.111
12	7	2	250 UC 72.9	6.200	12.400	0.454	0.907
13	7	2	250 UC 72.9	5.600	11.200	0.410	0.819
14	8	2	250 UC 72.9	4.400	8.800	0.322	0.644
15	8	2	250 UC 72.9	3.700	7.400	0.271	0.541

Total mass = 6.635
Center of gravity = 23.000,1.434,0.000

CaseA6

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...GNS\A6_OPTIMISED TOPOLOGY 2.0C_ARCHED WARREN TRUSS_WAS_LOAD CASES_H
Designer: Date: Saturday, September 10, 2016 5:27 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	2	310 UB 40.4	6.400	12.800	0.262	0.524
2	5	2	310 UB 40.4	5.100	10.200	0.209	0.417
3	4	2	360 UB 56.7	4.600	9.200	0.261	0.523
4	1	2	100x5 SHS	3.607	7.214	0.051	0.102
5	1	7	100x5 SHS	2.600	18.200	0.037	0.259
6	4	4	360 UB 56.7	2.200	8.800	0.125	0.500
7	1	4	100x5 SHS	3.406	13.624	0.048	0.194
8	3	2	125x5 SHS	2.052	4.104	0.037	0.074
9	1	2	100x5 SHS	3.401	6.803	0.048	0.097
10	7	2	200 UC 59.5	4.201	8.402	0.251	0.503
11	3	2	125x5 SHS	4.046	8.092	0.073	0.147
12	3	2	125x5 SHS	3.572	7.145	0.065	0.130
13	3	2	125x5 SHS	3.712	7.425	0.067	0.135
14	9	2	250 UC 72.9	2.500	5.000	0.183	0.366
15	9	4	250 UC 72.9	2.200	8.800	0.161	0.644
16	4	2	360 UB 56.7	2.500	5.000	0.142	0.284
17	1	2	100x5 SHS	1.300	2.600	0.018	0.037
18	3	2	125x5 SHS	3.324	6.648	0.060	0.121
19	7	2	200 UC 59.5	5.550	11.100	0.332	0.664
20	7	2	200 UC 59.5	3.650	7.300	0.218	0.437
21	7	2	200 UC 59.5	3.600	7.200	0.215	0.431

Total mass = 6.586
Center of gravity = 23.000,1.359,0.000

CaseB1

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...TIMISED TOPOLOGY 1.0D_WARREN TRUSS_WAS_LOAD CASES_H-HOLLOW SECTIONS
Designer: Date: Saturday, September 10, 2016 5:28 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	9	4	250x150x6 RHS	6.200	24.800	0.220	0.882
2	10	2	300x200x6 RHS	6.200	12.400	0.279	0.558
3	10	2	300x200x6 RHS	4.400	8.800	0.198	0.396
4	12	2	250x6 SHS	4.046	8.092	0.182	0.364
5	3	6	125x5 SHS	4.046	24.276	0.073	0.440
6	1	7	100x5 SHS	2.600	18.200	0.037	0.259
7	5	4	125x4 SHS	4.046	16.184	0.060	0.239
8	5	2	125x4 SHS	5.111	10.222	0.075	0.151
9	12	8	250x6 SHS	3.100	24.800	0.139	1.116
10	13	2	250x8 SHS	3.100	6.200	0.183	0.366
11	13	2	250x8 SHS	4.400	8.800	0.260	0.519

Total mass = 5.289
Center of gravity = 23.000,1.341,0.000

CaseB2

SPACE GASS 12.50 - SEDGMAN LTD
Path: ..._LOAD CASES_H-EXTRA MID BRACING - MINIMUM VERTICALS-HOLLOW SECTIONS
Designer: Date: Saturday, September 10, 2016 5:29 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	4	250x150x6 RHS	6.200	24.800	0.220	0.882
2	4	2	300x200x6 RHS	5.600	11.200	0.252	0.504
3	4	2	300x200x6 RHS	5.000	10.000	0.225	0.450
4	7	2	250x6 SHS	4.046	8.092	0.182	0.364
5	11	8	125x5 SHS	4.046	32.368	0.073	0.587
6	10	7	100x5 SHS	2.600	18.200	0.037	0.259
7	3	2	125x75x5 RHS	3.607	7.214	0.051	0.102
8	1	4	100x5 SHS	3.607	14.428	0.051	0.205
9	7	8	250x6 SHS	3.100	24.800	0.139	1.116
10	8	6	250x8 SHS	2.500	15.000	0.148	0.885

Total mass = 5.353
Center of gravity = 23.000,1.340,0.000

CaseB3

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...S_WAS_LOAD CASES_H-EXTRA MID BRACING - NO VERTICALS-HOLLOW SECTIONS
Designer: Date: Saturday, September 10, 2016 5:30 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	4	250x150x6 RHS	6.200	24.800	0.220	0.882
2	4	2	300x200x6 RHS	5.600	11.200	0.252	0.504
3	4	2	300x200x6 RHS	5.000	10.000	0.225	0.450
4	7	2	250x8 SHS	4.046	8.092	0.239	0.478
5	11	8	125x5 SHS	4.046	32.368	0.073	0.587
6	3	2	125x75x5 RHS	3.607	7.214	0.051	0.102
7	1	4	100x5 SHS	3.607	14.428	0.051	0.205
8	7	4	250x8 SHS	6.200	24.800	0.366	1.464
9	8	3	250x8 SHS	5.000	15.000	0.295	0.885

Total mass = 5.557
Center of gravity = 23.000,1.420,0.000

CaseB4

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...B_WARREN TRUSS_WAS_LOAD CASES_H-EXTREME MID BRACING_HOLLOW SECTIONS
Designer: Date: Saturday, September 10, 2016 5:31 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	2	250x150x6 RHS	6.200	12.400	0.220	0.441
2	5	2	250x150x6 RHS	5.900	11.800	0.210	0.420
3	4	2	250x150x8 RHS	5.000	10.000	0.232	0.465
4	4	2	250x150x8 RHS	4.050	8.100	0.188	0.376
5	4	2	250x150x8 RHS	1.850	3.700	0.086	0.172
6	7	2	200x6 SHS	4.046	8.092	0.144	0.288
7	3	4	125x5 SHS	4.046	16.184	0.073	0.293
8	10	6	100x5 SHS	2.600	15.600	0.037	0.222
9	3	4	125x5 SHS	3.821	15.284	0.069	0.277
10	3	2	125x5 SHS	3.406	6.812	0.062	0.124
11	1	2	100x5 SHS	3.406	6.812	0.048	0.097
12	11	4	65x5 SHS	3.191	12.764	0.028	0.111
13	11	3	65x5 SHS	2.600	7.800	0.023	0.068
14	7	4	200x6 SHS	3.100	12.400	0.110	0.441
15	7	4	200x6 SHS	2.800	11.200	0.100	0.398
16	8	4	200x8 SHS	2.200	8.800	0.102	0.409
17	8	4	200x8 SHS	1.850	7.400	0.086	0.344

Total mass = 4.945
Center of gravity = 23.000,1.226,0.000

CaseB5

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...S_WAS_LOAD CASES_H-EXTREME MID BRACING-NO VERTICALS_HOLLOW SECTIONS
Designer: Date: Saturday, September 10, 2016 5:32 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	2	250x150x6 RHS	6.200	12.400	0.220	0.441
2	5	2	250x150x6 RHS	5.900	11.800	0.210	0.420
3	4	2	300x200x6 RHS	5.000	10.000	0.225	0.450
4	4	2	300x200x6 RHS	4.050	8.100	0.182	0.364
5	4	1	300x200x6 RHS	3.700	3.700	0.166	0.166
6	7	2	250x6 SHS	4.046	8.092	0.182	0.364
7	3	4	125x5 SHS	4.046	16.184	0.073	0.293
8	3	2	125x5 SHS	3.821	7.642	0.069	0.139
9	3	4	125x5 SHS	3.607	14.428	0.065	0.262
10	1	2	100x5 SHS	3.406	6.812	0.048	0.097
11	1	4	100x5 SHS	3.191	12.764	0.045	0.181
12	7	2	250x6 SHS	6.200	12.400	0.279	0.558
13	7	2	250x6 SHS	5.300	10.600	0.238	0.477
14	8	2	250x8 SHS	4.700	9.400	0.277	0.555
15	8	2	250x8 SHS	3.700	7.400	0.218	0.437

Total mass = 5.203
Center of gravity = 23.000,1.346,0.000

CaseB6

SPACE GASS 12.50 - SEDGMAN LTD
Path: ... TOPOLOGY 2.0D_ARCHED WARREN TRUSS_WAS_LOAD CASES_H_HOLLOW SECTIONS
Designer: Date: Saturday, September 10, 2016 5:33 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	2	250x150x6 RHS	6.400	12.800	0.228	0.455
2	5	2	250x150x6 RHS	5.100	10.200	0.181	0.363
3	4	2	250x150x8 RHS	4.600	9.200	0.214	0.428
4	1	2	100x5 SHS	3.607	7.214	0.051	0.102
5	1	7	100x5 SHS	2.600	18.200	0.037	0.259
6	4	4	250x150x8 RHS	2.200	8.800	0.102	0.409
7	1	4	100x5 SHS	3.406	13.624	0.048	0.194
8	3	2	125x5 SHS	2.052	4.104	0.037	0.074
9	1	2	100x5 SHS	3.401	6.803	0.048	0.097
10	7	2	200x6 SHS	4.201	8.402	0.149	0.299
11	3	2	125x5 SHS	4.046	8.092	0.073	0.147
12	3	2	125x5 SHS	3.572	7.145	0.065	0.130
13	3	2	125x5 SHS	3.712	7.425	0.067	0.135
14	9	2	200x8 SHS	2.500	5.000	0.116	0.232
15	9	4	200x8 SHS	2.200	8.800	0.102	0.409
16	4	2	250x150x8 RHS	2.500	5.000	0.116	0.232
17	1	2	100x5 SHS	1.300	2.600	0.018	0.037
18	3	2	125x5 SHS	3.324	6.648	0.060	0.121
19	7	2	200x6 SHS	5.550	11.100	0.197	0.395
20	7	2	200x6 SHS	3.650	7.300	0.130	0.260
21	7	2	200x6 SHS	3.600	7.200	0.128	0.256

Total mass = 5.031
Center of gravity = 23.000,1.215,0.000

CaseC1

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...ARREN TRUSS_WAS_LOAD CASES_H_HT_3.10-EXTREME MID BRACING_HOT ROLLED
Designer: Date: Saturday, September 10, 2016 5:33 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	2	4	310 UB 40.4	6.200	24.800	0.254	1.014
2	4	2	360 UB 44.7	4.700	9.400	0.211	0.422
3	4	2	360 UB 44.7	4.050	8.100	0.182	0.364
4	4	2	360 UB 44.7	1.850	3.700	0.083	0.166
5	6	2	200 UC 46.2	4.384	8.768	0.203	0.406
6	3	6	125x5 SHS	4.384	26.304	0.079	0.477
7	10	6	100x5 SHS	3.100	18.600	0.044	0.264
8	3	2	125x5 SHS	3.982	7.965	0.072	0.144
9	3	2	125x5 SHS	3.801	7.603	0.069	0.138
10	1	2	100x5 SHS	3.801	7.603	0.054	0.108
11	1	4	100x5 SHS	3.610	14.440	0.051	0.205
12	6	6	200 UC 46.2	3.100	18.600	0.144	0.861
13	6	2	200 UC 46.2	2.500	5.000	0.116	0.232
14	7	4	200 UC 52.2	2.200	8.800	0.115	0.460
15	7	4	200 UC 52.2	1.850	7.400	0.097	0.387
16	1	2	100x5 SHS	3.100	6.200	0.044	0.088

Total mass = 5.737
Center of gravity = 23.000,1.543,0.000

CaseC2

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...SS_WAS_LOAD CASES_H_HT_3.10-EXTREME MID BRACING_NO VERTS_HOT ROLLED
Designer: Date: Saturday, September 10, 2016 5:34 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	2	3	310 UB 40.4	6.200	18.600	0.254	0.761
2	2	1	310 UB 40.4	6.000	6.000	0.245	0.245
3	4	1	360 UB 44.7	4.700	4.700	0.211	0.211
4	4	2	360 UB 44.7	4.250	8.500	0.191	0.382
5	4	1	360 UB 44.7	3.700	3.700	0.166	0.166
6	8	2	250 UC 72.9	4.800	9.600	0.351	0.702
7	4	1	360 UB 44.7	4.500	4.500	0.202	0.202
8	6	2	250 UC 72.9	4.384	8.768	0.321	0.641
9	3	5	125x5 SHS	4.384	21.920	0.079	0.397
10	3	1	125x5 SHS	4.245	4.245	0.077	0.077
11	3	1	125x5 SHS	3.860	3.860	0.070	0.070
12	3	2	125x5 SHS	3.920	7.841	0.071	0.142
13	1	2	100x5 SHS	3.920	7.841	0.056	0.111
14	1	4	100x5 SHS	3.610	14.440	0.051	0.205
15	3	1	125x5 SHS	3.744	3.744	0.068	0.068
16	6	2	250 UC 72.9	6.200	12.400	0.454	0.907
17	6	2	250 UC 72.9	5.200	10.400	0.380	0.761
18	8	2	250 UC 72.9	3.700	7.400	0.271	0.541

Total mass = 6.591
Center of gravity = 22.998,1.772,0.000

CaseC3

SPACE GASS 12.50 - SEDGMAN LTD
Path: ... 7.2C_WARREN TRUSS_WAS_LOAD CASES_H_HT_3.10_WIDE BRACING_HOT ROLLED
Designer: Date: Saturday, September 10, 2016 5:35 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	6	310 UB 40.4	4.650	27.900	0.190	1.141
2	4	2	360 UB 50.7	4.650	9.300	0.236	0.472
3	4	2	360 UB 50.7	4.400	8.800	0.223	0.447
4	8	2	200 UC 59.5	5.589	11.177	0.334	0.669
5	3	4	125x5 SHS	5.589	22.354	0.101	0.405
6	1	9	100x5 SHS	3.100	27.900	0.044	0.396
7	3	2	125x5 SHS	5.382	10.765	0.098	0.195
8	10	2	150x6 SHS	5.589	11.177	0.146	0.292
9	8	4	200 UC 59.5	4.650	18.600	0.278	1.113
10	7	2	250 UC 72.9	4.400	8.800	0.322	0.644
11	7	2	250 UC 72.9	4.650	9.300	0.340	0.680

Total mass = 6.455
Center of gravity = 23.000,1.640,0.000

CaseC4

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...7.3A_WARREN TRUSS_WAS_LOAD CASES_H_HT_3.10_EQUAL_BRACING_HOT ROLLED
Designer: Date: Saturday, September 10, 2016 5:37 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	4	310 UB 40.4	5.800	23.200	0.237	0.949
2	4	2	360 UB 50.7	5.800	11.600	0.295	0.589
3	4	2	360 UB 50.7	2.800	5.600	0.142	0.284
4	4	1	360 UB 50.7	2.200	2.200	0.112	0.112
5	4	1	360 UB 50.7	3.400	3.400	0.173	0.173
6	6	2	200 UC 46.2	4.384	8.768	0.203	0.406
7	3	2	125x5 SHS	4.111	8.222	0.075	0.149
8	10	7	100x5 SHS	3.100	21.700	0.044	0.308
9	3	8	125x5 SHS	4.245	33.960	0.077	0.616
10	1	4	100x5 SHS	4.177	16.709	0.059	0.237
11	6	2	200 UC 46.2	2.700	5.400	0.125	0.250
12	6	6	200 UC 46.2	2.900	17.400	0.134	0.806
13	8	2	200 UC 59.5	2.900	5.800	0.173	0.347
14	8	4	200 UC 59.5	2.800	11.200	0.167	0.670

Total mass = 5.896
Center of gravity = 23.000,1.541,0.000

CaseC5

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...EN TRUSS_WAS_LOAD CASES_H_HT_3.10_EQUAL_BRACING_NO VERTS_HOT ROLLED
Designer: Date: Saturday, September 10, 2016 5:40 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	4	310 UB 40.4	5.800	23.200	0.237	0.949
2	4	2	360 UB 50.7	5.800	11.600	0.295	0.589
3	4	2	360 UB 50.7	5.600	11.200	0.284	0.569
4	6	2	250 UC 72.9	4.384	8.768	0.321	0.641
5	3	2	125x5 SHS	4.111	8.222	0.075	0.149
6	3	8	125x5 SHS	4.245	33.960	0.077	0.616
7	1	4	100x5 SHS	4.177	16.709	0.059	0.237
8	6	2	250 UC 72.9	5.600	11.200	0.410	0.819
9	6	2	250 UC 72.9	5.800	11.600	0.424	0.849
10	8	2	250 UC 89.5	5.700	11.400	0.510	1.020
11	8	1	250 UC 89.5	5.600	5.600	0.501	0.501

Total mass   = 6.940
Center of gravity = 23.000,1.792,0.000

CaseC7

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...H_WAS_LOAD CASES_H_HT_3.10-BOWSTRING_EXTREME MID BRACING_HOT ROLLED
Designer: Date: Tuesday, September 13, 2016 7:00 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	2	4	310 UB 40.4	3.100	12.400	0.127	0.507
2	2	2	310 UB 40.4	6.200	12.400	0.254	0.507
3	4	2	360 UB 44.7	4.700	9.400	0.211	0.422
4	4	2	360 UB 44.7	4.050	8.100	0.182	0.364
5	4	2	360 UB 44.7	1.850	3.700	0.083	0.166
6	6	2	200 UC 52.2	3.401	6.803	0.178	0.356
7	3	2	125x5 SHS	3.401	6.803	0.062	0.123
8	10	1	100x5 SHS	2.300	2.300	0.033	0.033
9	3	4	125x5 SHS	4.078	16.313	0.074	0.296
10	10	2	100x5 SHS	2.950	5.900	0.042	0.084
11	3	2	125x5 SHS	3.944	7.887	0.072	0.143
12	3	2	125x5 SHS	3.761	7.521	0.068	0.136
13	10	2	100x5 SHS	3.100	6.200	0.044	0.088
14	1	2	100x5 SHS	3.801	7.603	0.054	0.108
15	1	4	100x5 SHS	3.610	14.440	0.051	0.205
16	10	1	100x5 SHS	2.250	2.250	0.032	0.032
17	6	1	200 UC 52.2	3.228	3.228	0.169	0.169
18	6	1	200 UC 52.2	3.120	3.120	0.163	0.163
19	6	2	200 UC 52.2	3.114	6.229	0.163	0.326
20	6	2	200 UC 52.2	2.502	5.004	0.131	0.262
21	7	4	200 UC 52.2	2.201	8.802	0.115	0.460
22	7	4	200 UC 52.2	1.850	7.400	0.097	0.387
23	6	1	200 UC 52.2	3.126	3.126	0.163	0.163
24	6	1	200 UC 52.2	3.214	3.214	0.168	0.168
25	1	2	100x5 SHS	3.100	6.200	0.044	0.088
26	10	2	100x5 SHS	1.400	2.800	0.020	0.040

Total mass = 5.796
Center of gravity = 22.997,1.359,0.000

CaseD1

SPACE GASS 12.50 - SEDGMAN LTD
Path: ... TRUSS_WAS_LOAD CASES_H_HT_3.10-EXTREME MID BRACING_HOLLOW SECTIONS
Designer: Date: Saturday, September 10, 2016 5:41 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	4	250x150x6 RHS	6.200	24.800	0.220	0.882
2	4	2	250x150x6 RHS	4.700	9.400	0.167	0.334
3	4	2	250x150x6 RHS	4.050	8.100	0.144	0.288
4	4	2	250x150x6 RHS	1.850	3.700	0.066	0.132
5	6	2	200x6 SHS	4.384	8.768	0.156	0.312
6	3	6	125x5 SHS	4.384	26.304	0.079	0.477
7	10	6	100x5 SHS	3.100	18.600	0.044	0.264
8	3	2	125x5 SHS	3.982	7.965	0.072	0.144
9	3	2	125x5 SHS	3.801	7.603	0.069	0.138
10	1	2	100x5 SHS	3.801	7.603	0.054	0.108
11	11	4	65x5 SHS	3.610	14.440	0.031	0.126
12	6	6	200x6 SHS	3.100	18.600	0.110	0.661
13	6	2	200x6 SHS	2.500	5.000	0.089	0.178
14	6	2	200x6 SHS	2.200	4.400	0.078	0.156
15	8	2	200x6 SHS	2.200	4.400	0.078	0.156
16	8	4	200x6 SHS	1.850	7.400	0.066	0.263
17	11	2	65x5 SHS	3.100	6.200	0.027	0.054

Total mass = 4.674
Center of gravity = 23.000,1.477,0.000

CaseD2

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...S_LOAD CASES_H_HT_3.10-EXTREME MID BRACING_NO VERTS_HOLLOW SECTIONS
Designer: Date: Saturday, September 10, 2016 5:42 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	4	250x150x6 RHS	6.200	24.800	0.220	0.882
2	4	2	250x150x6 RHS	4.700	9.400	0.167	0.334
3	4	2	250x150x6 RHS	4.050	8.100	0.144	0.288
4	4	2	250x150x6 RHS	1.850	3.700	0.066	0.132
5	6	2	200x6 SHS	4.384	8.768	0.156	0.312
6	3	6	125x5 SHS	4.384	26.304	0.079	0.477
7	3	2	125x5 SHS	3.982	7.965	0.072	0.144
8	3	2	125x5 SHS	3.801	7.603	0.069	0.138
9	1	2	100x5 SHS	3.801	7.603	0.054	0.108
10	11	4	65x5 SHS	3.610	14.440	0.031	0.126
11	6	6	200x6 SHS	3.100	18.600	0.110	0.661
12	6	2	200x6 SHS	2.500	5.000	0.089	0.178
13	6	2	200x6 SHS	2.200	4.400	0.078	0.156
14	8	2	200x6 SHS	2.200	4.400	0.078	0.156
15	8	4	200x6 SHS	1.850	7.400	0.066	0.263

Total mass = 4.356
Center of gravity = 23.000,1.472,0.000

CaseD3

SPACE GASS 12.50 - SEDGMAN LTD
Path: ..._WARREN TRUSS_WAS_LOAD CASES_H_HT_3.10_WIDE BRACING_HOLLOW SECTIONS
Designer: Date: Saturday, September 10, 2016 5:43 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	6	250x150x6 RHS	4.650	27.900	0.165	0.992
2	4	2	250x150x6 RHS	4.650	9.300	0.165	0.331
3	4	2	250x150x6 RHS	4.400	8.800	0.156	0.313
4	8	2	200x6 SHS	5.589	11.177	0.199	0.397
5	3	4	125x5 SHS	5.589	22.354	0.101	0.405
6	1	9	100x5 SHS	3.100	27.900	0.044	0.396
7	3	2	125x5 SHS	5.382	10.765	0.098	0.195
8	10	2	150x6 SHS	5.589	11.177	0.146	0.292
9	8	4	200x6 SHS	4.650	18.600	0.165	0.661
10	7	2	200x8 SHS	4.400	8.800	0.204	0.409
11	7	2	200x8 SHS	4.650	9.300	0.216	0.432

Total mass   = 4.825
Center of gravity = 23.000,1.507,0.000

CaseD4

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...WARREN TRUSS_WAS_LOAD CASES_H_HT_3.10_EQUAL_BRACING_HOLLOW SECTIONS
Designer: Date: Saturday, September 10, 2016 5:44 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	4	250x150x5 RHS	5.800	23.200	0.173	0.694
2	4	2	250x150x6 RHS	5.800	11.600	0.206	0.413
3	4	2	250x150x6 RHS	5.600	11.200	0.199	0.398
4	6	2	200x6 SHS	4.384	8.768	0.156	0.312
5	3	2	125x5 SHS	4.111	8.222	0.075	0.149
6	10	7	100x5 SHS	3.100	21.700	0.044	0.308
7	3	8	125x5 SHS	4.245	33.960	0.077	0.616
8	1	4	100x5 SHS	4.177	16.709	0.059	0.237
9	6	2	200x6 SHS	2.700	5.400	0.096	0.192
10	6	6	200x6 SHS	2.900	17.400	0.103	0.619
11	8	2	200x6 SHS	2.900	5.800	0.103	0.206
12	8	4	200x6 SHS	2.800	11.200	0.100	0.398

Total mass = 4.542
Center of gravity = 23.000,1.520,0.000

CaseD5

SPACE GASS 12.50 - SEDGMAN LTD
Path: ...USS_WAS_LOAD CASES_H_HT_3.10_EQUAL_BRACING_NO VERTS_HOLLOW SECTIONS
Designer: Date: Saturday, September 10, 2016 5:45 PM Page: 1

BILL OF MATERIALS (m,m^2,T)

Memb	Sect	Qty	Section Name	Unit Length	Total Length	Unit Mass	Total Mass
1	5	4	250x150x5 RHS	5.800	23.200	0.173	0.694
2	4	2	250x150x6 RHS	5.800	11.600	0.206	0.413
3	4	2	250x150x6 RHS	5.600	11.200	0.199	0.398
4	6	2	200x8 SHS	4.384	8.768	0.204	0.407
5	3	2	125x5 SHS	4.111	8.222	0.075	0.149
6	3	8	125x5 SHS	4.245	33.960	0.077	0.616
7	1	4	100x5 SHS	4.177	16.709	0.059	0.237
8	6	2	200x8 SHS	5.600	11.200	0.260	0.520
9	6	2	200x8 SHS	5.800	11.600	0.270	0.539
10	8	2	200x8 SHS	5.700	11.400	0.265	0.530
11	8	1	200x8 SHS	5.600	5.600	0.260	0.260

Total mass   = 4.764
Center of gravity = 23.000,1.662,0.000