WARREN TRUSS: DESIGN THE IMPACT OF CONNECTION TYPE AND MEMBER LENGTH ON STRUCTURAL EFFICIENCY AND SAFETY

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Diploma in Civil Engineering

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WARREN TRUSS DESIGN: THE IMPACT OF CONNECTION TYPE AND MEMBER LENGTH ON STRUCTURAL EFFICIENCY AND SAFETY

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ABSTRAK

Kajian ini bertujuan untuk menyiasat reka bentuk Warren Truss yang optimal berdasarkan bilangan anggota yang tetap dengan panjang yang berbeza, dan kesan pemasangan dan pengelasan pada kekuda. Metodologi yang digunakan dalam kajian ini termasuk pengiraan secara manual dan penggunaan perisian SAP 2000. Carta alir telah dibangunkan untuk memudahkan proses reka bentuk, dan tindak balas dalaman dan pemeriksaan struktur truss dilakukan mengikut *Eurocode 3: Design of Steel Structures – Part 1-1: General Rules and Rules for Buildings*. Keputusan kajian menunjukkan bahawa terdapat kesan yang signifikan pada kecekapan struktur apabila jenis sambungan dan panjang anggota Warren Truss berubah. Pengunaan cara sambungan *bolting* menghasilkan kecekapan struktur yang sama dengan cara sambungan *welding.* Peningkatan panjang member individu akan menghasilkan kecekapan struktur yang rendah. Kajian ini mempunyai implikasi penting bagi reka bentuk dan pembinaan struktur Warren Truss dan boleh memberi maklumat kepada penyelidikan masa depan dalam bidang ini. Secara keseluruhan, kajian ini memberikan analisis yang menyeluruh tentang reka bentuk Warren Truss dan menjadi sumber yang bernilai bagi jurutera dan pakar dalam bidang reka bentuk struktur.

ABSTRACT

This study aims to investigate the optimal design of Warren Truss based on a fixed number of members with different lengths, and the effect of bolting and welding on the truss. The methodology employed in this study includes both manual calculation and the utilization of the SAP 2000 software. A flowchart was developed to guide the design process, and the internal reactions and structural checking of the truss were performed in accordance with Eurocode 3: Design of Steel Structures – Part 1-1: General Rules and Rules for Buildings. The results of the study indicate that there is a significant impact on structural efficiency when the connection type and member length of the Warren Truss are varied. The use of bolting and welding results in the same structural efficiency compared to welding and increasing the member length however results in a lower structural efficiency. These findings have important implications for the design and construction of Warren Truss structures and may inform future research in the field. Overall, the study provides a comprehensive analysis of the Warren Truss design and serves as a valuable resource for engineers and practitioners in the field of structural design.

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LIST OF SYMBOLS

ε	coefficient depending on f_y
f_U	ultimate strength
f_y	yield strength
A	area of cross-section
γ_{M0}	partial factor for resistance of cross-sections whatever the class is
$N_{pl,\,Rd}$	design plastic resistance to normal forces of the gross cross-section
N_{Ed}	design normal force
$N_{t,Rd}$	design values of the resistance to tension forces
$N_{c,\,Rd}$	design resistance to normal forces of the cross-section for uniform compression
L_{cr}	critical length
λ_1	slenderness value to determine the relative slenderness
λ_{y-y}	slenderness value to determine the relative slenderness (y-y axis)
λ_{z-z}	slenderness value to determine the relative slenderness (z-z axis)
$\lambda_{eff,y}$	effective slenderness value to determine the relative slenderness (y-y axis)
$\lambda_{eff,z}$	effective slenderness value to determine the relative slenderness (z-z axis)
α	the imperfection factor
Φ_{y-y}	value to determine the reduction factor (y-y axis)
Φ_{z-z}	value to determine the reduction factor (z-z axis)
χ_{y-y}	reduction factor due to flexural buckling (y-y axis)
χ_{z-z}	reduction factor due to flexural buckling (z-z axis)
$N_{b,\,Rd\,(y-y)}$	design buckling resistance of a compression member (y-y axis)
$N_{b,\,Rd\,(z-z)}$	design buckling resistance of a compression member (z-z axis)
i_{y-y}	radius of gyration (y-y axis)
i_{z-z}	radius of gyration (z-z axis)

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The Warren Truss, patented in 1848 by James Warren and Willoughby Theobald Monzani, is a type of truss design that uses an equilateral triangle framework (MONKOVA *et al.*, 2016). This design was widely used to construct bridges, especially in Great Britain and India during the British Raj, as well as traditional railway infrastructure. In the 20th century, the Warren Truss was also adapted and used by the United States and has gained immense popularity. Many bridges using this design still exist today (Chase, 2015).

The Warren Truss design is known for its strength and cost-efficiency, as it uses equilateral triangles to distribute the load evenly across the truss. This allows each strut, beam, or tie to only undergo tension or compression forces, eliminating the need for bending or torsional forces. In cases where the upper part of the bridge is not stiff or strong enough, engineers may add vertical beams dividing each triangle at the center to prevent buckling under the load. Variations of the Warren Truss include the Quadrangular Warren Truss, which utilizes numerous diagonal ridges, and the Double Warren Truss, which has intersecting triangle parts (Praisach & Pîrșan, 2022).

Despite its widespread use, there are currently no pre-existing standards or references for civil engineers to use as a benchmark when designing or building a truss (Humphreys *et al.*, 1999). This can lead to a time-consuming and resource-intensive design process. Therefore, this study aims to determine the most effective connections and acceptable dimensions for the Warren Truss with a fixed number of members, in order to provide a reference for civil engineers and avoid poorly designed trusses. Analysis will be conducted using manual calculation method, such as the joint method as well as modern techniques like the SAP 2000 software, to check the validity of results and simulate the actual condition of each member of the truss under tension and compression.

1.2 Problem Statement

The Warren Truss is widely used in the construction of various structures such as bridges, warehouses, and aeroplane hangars due to its strength and cost-efficiency. Despite its popularity, there are currently no pre-existing standards or references available for civil engineers to use as a benchmark when designing or building a Warren Truss. This lack of a reference can causes the design process to be more time consuming and resource intensive as engineers must start from scratch, leading to potential issues in terms of efficiency and accuracy. The aim of this study is to address this issue by providing a reference or benchmark for civil engineers to use when designing Warren Truss-related structures, allowing them to save time and resources while ensuring the safety and strength of the final product.

1.3 Objective

This study mainly focuses on two factors which impacts the safety and strength of the Warren Truss:

i. To determine the best connection for the Warren Truss.

ii. To determine the optimal dimensions of the Warren Truss in terms of height and length, while the maximum number of members of the Warren Truss remains constant.

1.4 Scope of Study

This study focuses on factors that will impact the strength, performance, and efficiency of the Warren Truss. The main objective of the study is to determine the most efficient connection for the Warren Truss by evaluating a selection of bolts, rivets, pins, and welded connectors. Additionally, the study aims to determine the optimal dimensions of the Warren Truss in terms of height and length, while keeping the number of members fixed and the loading acting on the truss constant.

Two methods will be used in this study, the first being a manual calculation method, where the resultant forces,tension, compression and buckling will be calculated by hand using the method of joints and referring to Eurocode 3. The second method involves the use of the SAP2000 software, where the data will be inputted to generate the results. The results obtained from the manual calculation will be compared with the results from the SAP2000 software to obtain the most accurate results. This will help to ensure the safety and strength of the Warren Truss while also considering the cost-efficiency.

1.5 Significance of Study

This study aims to create a reference for civil engineers today who plans to design and build Warren Trusses. It can be used to shorten the amount of time required design and build Warren Trusses, thus making it more economical to build. At the same time, these references can play a role in investigating that has succumbed to failure, without requiring using too much time to carry out the investigation especially the structure related problems. Lastly, the study aims to prevent poorly built and designed Warren Trusses in the future, by providing this reference for civil engineers this can assist them in making the right and appropriate decisions. The goal of this study is not only to improve the efficiency of the Warren Truss design and construction process, but also to ensure the safety of the structure and its users, aligning with the United Nations Sustainable Development Goal 11 of making cities and human settlements inclusive, safe, resilient and sustainable.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This literature review aims to provide a comprehensive understanding of the design and analysis of Warren Truss structures. The review begins by discussing the theoretical background of Warren Truss, including its history and development, as well as its characteristics and advantages. The literature review then examines the methodology and research methods used in the study of Warren Truss, including the use of both manual calculations and computer software such as SAP2000. The rationale and relevance of the study are also discussed, highlighting the importance of investigating Warren Truss structures and the impact it can have on the field of structural engineering. Overall, the literature review provides a thorough and in-depth understanding of the current state of knowledge in the field of Warren Truss design and analysis. Also, this topic sets the foundation for the research that follows.

2.2 Theoretical Background

The theoretical background of this study is based on the mechanics of structures and the behaviour of trusses under different loads.

A truss is a type of structure that is composed of triangular units, which are formed by connecting several straight members. The Warren truss is a specific type of truss that is characterized by its equilateral triangle pattern, which is created by the intersection of diagonal and vertical members.

The behaviour of a truss, including a Warren truss, is governed by the principles of statics and mechanics of materials. The statics of trusses is based on the equilibrium of forces, which states that the sum of all the forces acting on a body must be equal to zero. In the case of a Warren truss, the loads are distributed evenly among all members, which allows the truss to resist bending and torsional moments, making it suitable for use in bridges and other structures that are subject to these types of loads.

On the other hand, truss needs to deal with the behaviours of materials under loads as a reaction. The study of the behaviours of the Warren Truss under different loads is important in order to understand the truss behaviour and its responds ro changes in length, and load distribution. Additionally, the mechanics of materials also deals with the behaviours of materials under buckling loads, which is a critical consideration for safety in real-world applications. (Martinsson & Babuška, 2007)

Furthermore, the studies also consider the influence of fabrication errors and structural inaccuracies on the behaviour of Warren Truss, which is an important aspect of the design process. These studies show that the Warren truss is relatively insensitive to fabrication errors and structural inaccuracies, which allows for more efficient and cost-effective construction.

In summary, the theoretical background of the studies mentioned above is based on the principles of statics and mechanics of materials. The studies use these principles to understand the behaviours of a Warren truss under different loads and how the truss responds to changes in length. Additionally, the studies also consider the influence of fabrication errors and structural inaccuracies on the behaviour of Warren Truss.

2.3 Common Warren Truss Structures

Most of the Warren Trusses are used to construct bridges or used as a support in other buildings.

2.3.1 Kingston-Rhinecliff Bridge

Figure 2-1: Kingston Rhinecliff Bridge

Source: (Structurae, 2023)

The Kingston-Rhinecliff Bridge is a steel truss bridge that spans the Hudson River in New York, connecting the towns of Kingston and Rhinecliff. The bridge was built in 1957 and is 1,014 feet long, with a main span of 600 feet. It is a vital transportation link for the residents of the area, providing a connection between Route 199 on the west side of the river and Route 9 on the east side (Structurae, 2023).

The Brunsbuttel Viaduct is a testament to the remarkable engineering achievements of our time. Its combination of galvanized steel and subdivided Warren Truss design make it a bridge that is both durable and able to support heavy loads, ensuring its continued functionality for many years to come (Structurae, 2023).

2.3.2 Ulla Estuary Viaduct

Figure 2-2: Ulla Estuary-Viaduct

Source: (Millanes Mato *et al.*, 2015)

The Ulla Estuary Viaduct is a railway bridge that spans the Ulla Estuary in Galicia, Spain. The bridge is part of the Santiago de Compostela-Ferrol railway line and was built in the early 20th century. It is a steel structure that comprises several spans, with the longest one measuring approximately 250 meters (Structurae, 2023).

The bridge is made of steel-reinforced concrete composite, while it is a deck truss bridge combined with a warren type truss bridge design. The Warren truss envisaged in the design would consist in 15-m long modules in which the two lateral sets of nodes on the upper chord would be spaced 6m apart and the diagonal web members slanted at around 45° from the horizontal in the constant depth area; the sheet steel would form parallelograms 0.80m wide and 1.00m deep on the upper chords and diagonals and 0.80m wide and 1.20m deep in the bottom chord (Millanes Mato *et al.*, 2015). The cross-section shape resemble the Rectangular Hollow Section (RHS), however, it is not hollow and is made up of steel-reinforced concrete (Millanes Mato *et al.*, 2015).

2.3.3 Brunsbuttel Viaduct

Figure 2-3: Brunsbuttel Viaduct

Source: (Structurae, 2023)

The Brunsbuttel Viaduct is a railway bridge that spans the Kiel Canal in Germany. The bridge is part of the Hamburg-Altona-Kiel railway line and is one of the longest viaducts in Europe, measuring around 4,300 meters in length (Structurae, 2023).

The Brunsbuttel Viaduct is a bridge that spans the Kiel Canal in Germany. The viaduct is structurally composed of a prestressed concrete approach span and a steel middle span. The steel span is supported by Warren truss bridges, which provide additional stability and support to the structure. The combination of prestressed concrete and steel along with the Warren truss design creates a strong, durable and stable bridge that can withstand the demands of heavy railway traffic (Structurae, 2023).

2.3.4 Nigmiegen Railroad Bridge

Figure 2-4: Nigmiegen Railroad Bridge

Source: (Structurae, 2023)

The Nijmegen Railroad Bridge is a railway bridge that spans the Waal River in Nijmegen, Gelderland, Netherlands. The bridge is part of the Arnhem-Nijmegen railway line and connects the city of Nijmegen to other major cities in the Netherlands and Europe. The bridge was built in the late 19th century and is a steel truss bridge with multiple spans. The Nijmegen Railroad Bridge is an important transportation link for the region, connecting the cities of Arnhem and Nijmegen by rail (Structurae, 2023).

The Brunsbuttel Viaduct is not just any ordinary bridge, but a unique structure that stands out in its design and composition. The viaduct is a polygonal Warren truss bridge made entirely of steel, which adds to its strength and stability. The Warren truss design is renowned for its efficiency in transmitting loads, making it an ideal choice for heavy railway bridges. The use of steel in its construction also ensures durability and longevity, making the Brunsbuttel Viaduct a prime example of a well-engineered bridge (Structurae, 2023).

2.3.5 Wooden Warren Truss Hangar located at Canadian Forces Base

Figure 5: 34m long double-span Warren Truss

Source: (Locklin *et al.*, 2017)

This wooden Warren Truss hangar is located at Canadian Forces Base Greenwood, Nova Scotia, Canada. Typically, the hangars are made of strong, durable species of wood such as Douglas Fir or Southern Yellow Pine, and are designed to support significant loads while maintaining their structural integrity. There are several types of section connections used in wooden Warren truss hangers, including bolted connections and nail-laminated connections, The typical cross-sections used are sawn timber cross-sections (Locklin *et al.*, 2017).

2.4 Rationale and Relevance of Study

The rationale for the study above is to investigate the relationship between the change in length of a Warren truss and its structural behaviour. The length of a Warren truss is an important factor that affects its structural behaviour and performance. As the Warren truss is a commonly used structure in bridge construction, understanding the relationship between its length and structural behaviour is crucial for safe and efficient bridge design.

The relevance of the study is that it provides insight into how changes in the length of a Warren truss affect its structural behaviour and performance. This information can be used by engineers and designers to make informed decisions about the length of a Warren truss in a specific application, such as a bridge. By understanding how changes in the length of a Warren truss affect its structural behaviour and performance, engineers and designers can optimize the design of the truss to ensure its structural behaviour and performance. This in turn can improve the safety and efficiency of bridge construction and potentially reduce the cost of construction.

Additionally, these studies also provide a valuable contribution to the existing body of knowledge on Warren trusses and can be used as a reference for future research in this field.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The methodology section of this study outlines the methods used to achieve the research objectives, including the design of a Warren Truss model, selection of the connection and maximum length of the Warren Truss, and determination of the size of the Warren Truss. The research process will be illustrated using a flowchart, which will clearly show the steps involved in the study. The primary method used for the design and analysis of the Warren Truss is the manual calculation method, which involves applying the knowledge learned from the Structural Design 2 (SD2) and Theory of Structure (TOS) courses. The manual calculation method includes the use of the Method of Sections, which is more efficient than the Method of Joints, to calculate the internal reactions of the Warren Truss. Additionally, the Warren Truss will be modelled in the SAP2000 software, which is one of the most widely used structural design software in the industry, and internal reactions and checking will be performed by the software. This will allow for validation of the results obtained from the manual calculations, ensuring the accuracy and reliability of the results.

3.2 Methods Used

This study utilized two methods for analysis and design of the Warren Truss, manual calculations, and the utilization of the SAP 2000 software. The manual calculation method involves applying the knowledge learnt from the Structural Design 2 (SD2) and Theory of Structure (TOS) courses. The method used for calculating the internal reaction of the Warren Truss is the Method of Sections, as it is more efficient than the Method of Joints. The structural checking of the truss is done by referencing Eurocode 3: Design of Steel Structures – Part 1-1: General Rules and Rules for Buildings. The checking process includes verifying the internal reactions, tension, compression and torsional buckling of each member of the truss. These checking are based on clause 6.2.3, clause 6.2.4 and clause 6.3.1.1.

Additionally, the truss will be modelled in the SAP2000 software, which is one of the most widely used structural design software in the industry, and internal reactions and checking will be performed by the software. This will allow for validation of the results obtained from the manual calculations, ensuring the accuracy and reliability of the results.

3.3 Flowchart

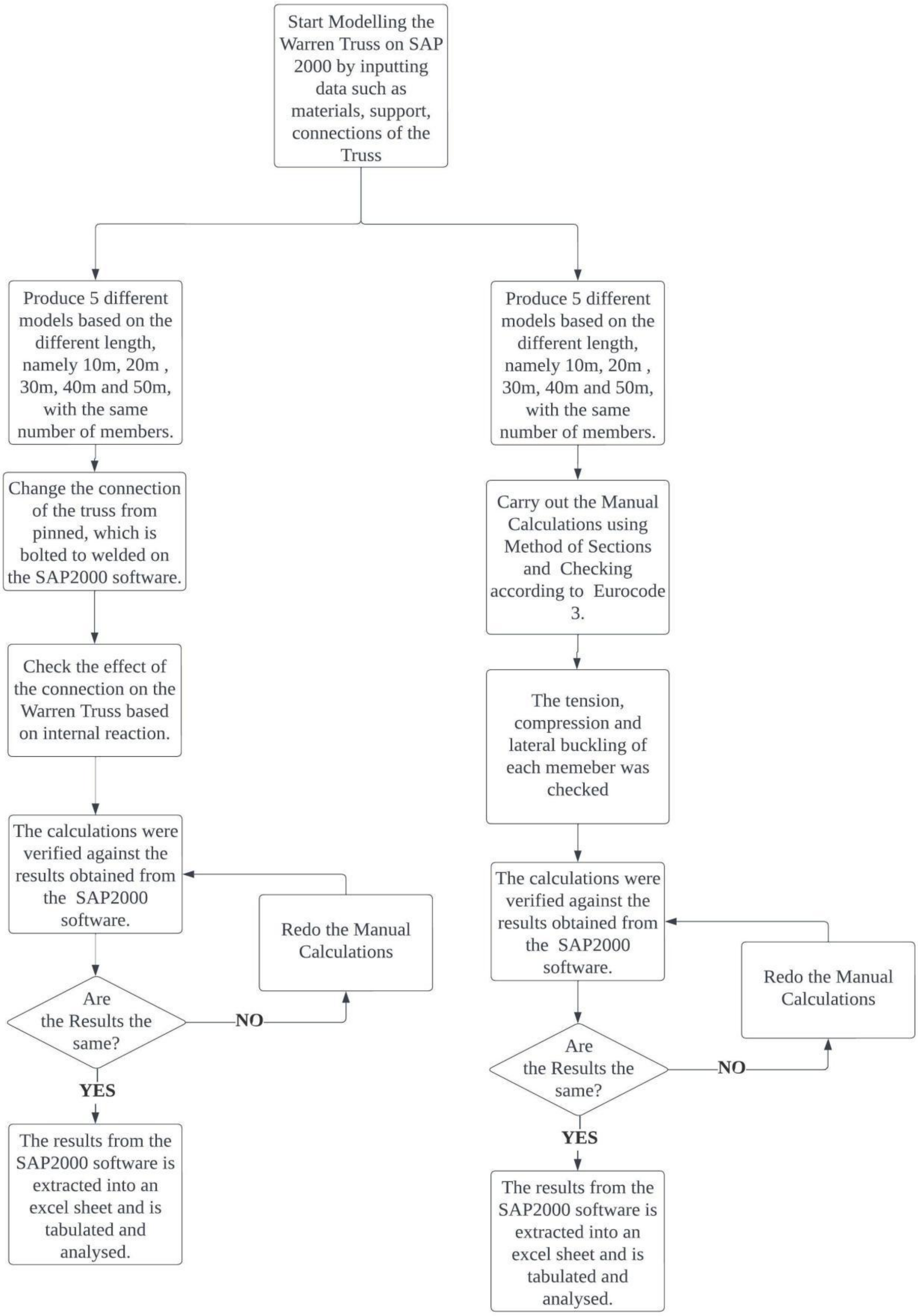


Figure 3-1: Flowchart of Methodology

3.4 Setting Up

Five models will be prepared to undergo the investigation. The first model (Model A) will have the span of 10m, the second model (Model B) is 20m and the consequent models will have an increment of 10m until the last model (Model E) which has the span of 50m as shown in Table 1.

Table 1: Warren Truss Models

Model	**Length**
A	10 m
B	20 m
C	30 m
D	40 m
E	50 m

According to the Malaysia National Annex to Eurocode 1: Actions on Structures – Part 1-1 : general actions – densities, self-weight, imposed loads for buildings, the imposed load acting on the roof is taken as $0\,\text{kN/m}^2$, due to the fact that the roof designed is a flat roof.The figure below shows the references made and their respective tables,

Table 2: Table 6.10 - Imposed loads on roof of category H

Roof	qk [kN/m^2]	Qk [kN]
Category H	0,00 $\text{kN/m}^2$to 1,0kN/m^2	0.9 kN to 1,5 kN

Source: (*Eurocode 1: Actions on Structures - Part 1-1: General Actions - Densities, Self-Weight, Imposed Loads for Buildings Malaysian Standard, 1991*)

Table 3: Table NA7. Imposed loads on roofs not accessible except for normal maintenance and repair

Roof slope, α (degrees)	qk [kN/m^2]	Qk [kN]
$\alpha \leq 30°$	0.25	0.9
$30° \leq \alpha \leq 60°$	0.25[(60-α)/30}	
$\alpha \geq 60°$	0	

Source: (*Malaysia National Annex to Eurocode 3: Design of Steel Structures -Part 1-1: General Rules and Rules for Buildings Malaysian Standard, n.d.*)

The steel grade is taken as S275 as it is common practice in Malaysia to use steel grade of this calibre for roofing. At the same time, the section chosen for this truss is the I- section from the table of properties, the dimensions are 203x133x25. The results obtained by manual calculations and from the SAP 2000 software will be tabulated and categorized according to the position of each individual member. The categories will be top chord, bottom chord and web members.

3.5 Model Design

The proposed Warren Truss model consist of 18 members, with 4 members forming the top chords, 5 members forming the bottom chords and 10 web members in between the top chords and bottom chords as illustrated in Figure 3.2. The model is drawn in the SAP2000 software and will be used for checking and analysing results.

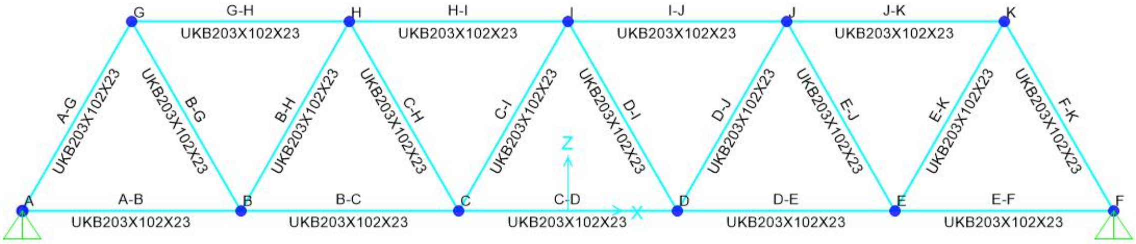


Figure 3-2: Example of a Warren Truss Model

3.6 Manual Calculation

The manual calculation methods will be carried out as follows

Table 4:Steps to carry out manual calculation

Position	Steps			
	Section Classification	Compression Resistance	Tension Resistance	Flexural Buckling
Top Chord	1	2	x	3
Bottom Chord	1	2	2	3
Web Member	1	2	2	3

The section classification method will involve Table 3.1: Nominal values of yield strength f_y and ultimate tensile strength f_u for hot rolled structural steel.

Table 5: Nominal values of yield strength f_y and ultimate tensile strength f_u for hot rolled structural steel

Standard Steel Grade	Nominal thickness of the element t [mm]	
	t ≤ 40 mm	
	f_y [N/mm^2]	f_u [N/mm^2]
EN 10025-2		
S 275	275	430

Source: (*Eurocode 3: Design of Steel Structures -Part 1-1: General Rules and Rules for Buildings, 1993*)

From table 5, the value of f_y and f_u can be obtained. After this, the table of classification will be used, which is table 5.2, Sheet 1 and Sheet 2, where the web and flange of the section chosen will be classified according to the mentioned table. For reference, the web is the part subjected to bending, while the flange is the part subjected to compression. Shown below are the equation used for the flange and web for classification.

Web

$c/t = 9\varepsilon$

Flange

$c/t = 72\varepsilon$

where $\varepsilon = \sqrt{235/f_y}$

After classifying the web and flange, the class of the section can be obtained. The sections can fall into the Class 1 category, Class 2 category or the Class 3 category.

For each category, there will be different methods to carry out the relevant checking. In this study, the section is found to be in the Class 1 category. Therefore, the checking for tension, compression and buckling resistance will be as follows,

For Tension, according to clause 6.2.3

The design plastic resistance of the gross cross-section is,

$$N_{pl,\,Rd} = \frac{Af_y}{\gamma_{M0}}$$

Where,

A= area of cross section
f_y= yield strength
γ_{M0}= 1.0 from 6.1 NOTE 2B

The value obtained from the equation above will be substituted into the equation below,

$$\frac{N_{Ed}}{N_{t,Rd}} \leq 1.0$$

Where,

N_{Ed} = Design Value of Tension Force
$N_{t,Rd}$ = The value obtained from $N_{pl,\,Rd}$

If the value of $\frac{N_{Ed}}{N_{t,Rd}}$ exceeds 1.0, that means that the member of the truss is not suitable to carry the tension exerted on it, or in layman terms, not safe for construction and use.

On the other hand, for members that experience compression, the steps taken for checking is similar. However, it differs from tension only in terms of the direction of the force. Shown below are the equations used for the checking of compression members.

For Compression, according to clause 6.2.4

The design plastic resistance of the cross-sections for uniform compression, $N_{c,Rd}$, should be determined as follows

$$N_{c,Rd} = \frac{Af_y}{\gamma_{M0}} \text{ for class 1, 2 and 3 cross-sections}$$

Where,

A= area of cross section

f_y= yield strength

γ_{M0}= 1.0 from 6.1 NOTE 2B in the Eurocode 3: Design of Steel Structures – Part 1-1: General Rules and Rules for Buildings

The value obtained from the equation above will be substituted into the equation below,

$$\frac{N_{Ed}}{N_{c,Rd}} \leq 1.0$$

/Where,

N_{Ed} = Design Value of Compression Force
$N_{c,\,Rd}$ = The value obtained from $N_{c,\,Rd}$

If the value of $\frac{N_{Ed}}{N_{c,Rd}}$ exceeds 1.0, that means that the member of the truss is not suitable to carry the compression exerted on it, or in layman terms, not safe for construction and use.

Lastly, for the flexural buckling resistance of the members, the checking reference will be in accordance with the buckling resistance of member stated in clause 6.3. The steps taken are as follows,

Step 1

$$\varepsilon = \sqrt{\frac{235}{f_y}}\,(f_y\ in\ N/mm^2)$$

Step 2

$$\lambda_1 = \pi\sqrt{\frac{E}{f_y}} = 93{,}9\varepsilon$$

Step 3

$$\lambda_{y-y} = \pi\sqrt{\frac{Af_y}{N_{cr}}} = \frac{L_{cr}}{i_{y-y}}\ \frac{1}{\lambda_1}$$

$$\lambda_{z-z} = \pi\sqrt{\frac{Af_y}{N_{cr}}} = \frac{L_{cr}}{i_{z-z}}\ \frac{1}{\lambda_1}$$

Where,

i= radius of gyration (obtained from the Table of Properties)

Since there are 2 radius of gyration values. Therefore, the value of λ will be in y-y and z-z.

L_{cr} is taken in accordance with Annex BB [informative] – Buckling of components of building structures, clause BB.1.1.2, as stated, L_{cr} of I or H section chord members can be taken as 0,9 L for in-plane buckling.

Step 4

$\lambda_{eff,y} = 0{,}50 + 0{,}7\lambda_y$ for buckling about y-y axis

/

$\lambda_{eff,z} = 0{,}50 + 0{,}7\lambda_z$ for buckling about z-z axis

Where,

λ is as defined in clause 6.3.1.2.

Step 5

Table 6: Table 6.1 Imperfection Factor for Buckling Curves

Buckling curve	a_0	a	b	c	d
Imperfection factor,α	0,13	0,21	0,34	0,49	0,76

(*Eurocode 3: Design of Steel Structures -Part 1-1: General Rules and Rules for Buildings, 1993*)

From table 6.2, the imperfection factor will be obtained by comparing the steel grade to the limits stated in the table. In this study. Once the limits are determined, the imperfection factor, α, will be obtained from table 6.1.

Step 6

$$\Phi_{y-y} = 0,5\left[1 + \alpha(\lambda - 0,2) + \lambda^2_{y-y}\right]$$

$$\Phi_{z-z} = 0,5\left[1 + \alpha(\lambda - 0,2) + \lambda^2_{z-z}\right]$$

Where,

$$\lambda_{y-y} = \pi\sqrt{\frac{Af_y}{N_{cr}}} = \frac{L_{cr}}{i_{y-y}}\frac{1}{\lambda_1}$$

$$\lambda_{z-z} = \pi\sqrt{\frac{Af_y}{N_{cr}}} = \frac{L_{cr}}{i_{z-z}}\frac{1}{\lambda_1}$$

α is an imperfection factor

Step 7

$$\chi_{y-y} = \frac{1}{\Phi_{y-y} + \sqrt{\Phi_{y-y}^{2} - \lambda^{2}}} \text{ but } \chi \leq 1{,}0$$

$$\chi_{z-z} = \frac{1}{\Phi_{z-z} + \sqrt{\Phi_{z-z}^{2} - \lambda^{2}}} \text{ but } \chi \leq 1{,}0$$

Substitute the value obtained in step 6 into step 7.

Step 8

$N_{b,Rd\,(y-y)} = \frac{\chi_{y-y}\, A\, f_y}{\gamma_{M1}}$ for class 1, 2 and 3 cross-sections

$N_{b,Rd\,(z-z)} = \frac{\chi_{z-z}\, A\, f_y}{\gamma_{M1}}$ for class 1, 2 and 3 cross-sections

The design resistance of a buckling member should be taken as above

where χ is the reduction factor for the relevant buckling mode

Step 9

$$\frac{N_{Ed}}{N_{b,Rd\,(y-y)}} \leq 1.0$$

$$\frac{N_{Ed}}{N_{b,Rd\,(z-z)}} \leq 1.0$$

Where,

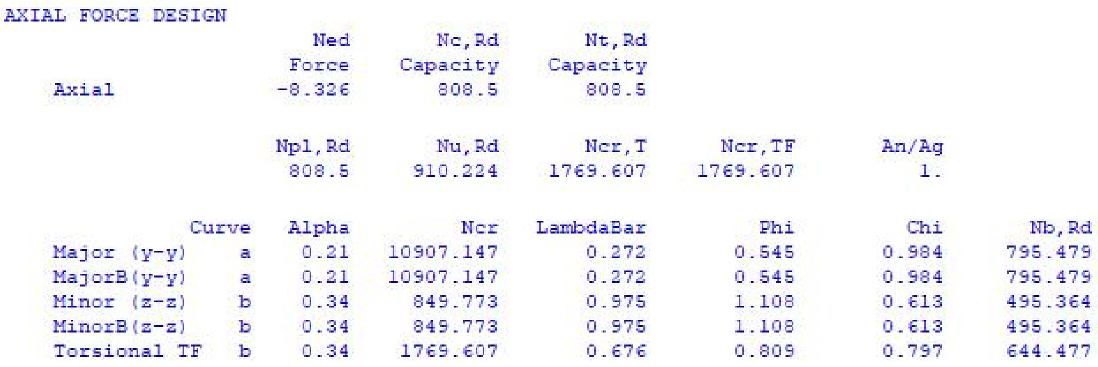
N_{Ed} = Design Value of Compression Force

A compression member should be verified against buckling as above

3.7 SAP2000 Software

Modelling a Warren Truss in the SAP 2000 software involves creating a 3D model of the truss using the software's built-in modelling tools. This includes inputting the dimensions of the truss such as height and length, as well as the properties of the materials used for the members. Once the model is created, the software can be used to apply loads to the truss, simulating the actual conditions of the structure.

To extract the internal reactions of each individual member of the truss, the software provides the option to perform a static analysis on the model. This analysis calculates the forces acting on each member of the truss, including the internal axial, shear and bending forces. These results can be viewed in the form of diagrams, such as a force-displacement or moment-rotation diagram, which shows the distribution of forces and moments within the truss. Additionally, the software can also be used to check for deflection, torsional and buckling of each member. This feature has enabled the students to carry out their studies to ensure that the structure is safe, stable, and efficient. Figure 3.2 shows the value that is obtained from the SAP2000 software that will be used for checking.



```
AXIAL FORCE DESIGN
                         Ned       Nc,Rd       Nt,Rd
                       Force    Capacity    Capacity
    Axial             -8.326       808.5       808.5

                      Npl,Rd       Nu,Rd       Ncr,T      Ncr,TF       An/Ag
                       808.5     910.224    1769.607    1769.607          1.

               Curve   Alpha         Ncr   LambdaBar         Phi         Chi       Nb,Rd
    Major (y-y)    a    0.21   10907.147       0.272       0.545       0.984     795.479
    MajorB(y-y)    a    0.21   10907.147       0.272       0.545       0.984     795.479
    Minor (z-z)    b    0.34     849.773       0.975       1.108       0.613     495.364
    MinorB(z-z)    b    0.34     849.773       0.975       1.108       0.613     495.364
    Torsional TF   b    0.34    1769.607       0.676       0.809       0.797     644.477
```

Figure 3-3 The table that will be used for checking

The values such as $N_{t,Rd}$, $N_{c,Rd}$ and $N_{b,Rd}$ will be used to cross-check the value obtained from the manual calculation.

The data extracted is then transferred into an excel sheet and tabulated for analysis and discussion. The SAP 2000 software can only be accessed at the computer laboratory as it is a licensed product procured by University Malaysia Pahang (UMP) and only can be accessed usually during office hours, it is imperative to note that the students are under the advisor's supervision during the time spent using the SAP 2000 software.

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Introduction

This chapter presents the results and discussion of the study on the optimal design of Warren Truss based on a fixed number of members with different lengths, and the effect of bolting and welding on the truss. The results of the manual calculations and the utilization of the SAP 2000 software are presented and compared to determine the structural efficiency of the Warren Truss under different design scenarios. The discussion section delves into the implications of these findings for the design and construction of Warren Truss structures and how they align with existing literature in the field. Overall, this chapter provides a comprehensive analysis of the Warren Truss design and serves as a valuable resource for engineers and practitioners in the field of structural design.

4.2 Results

In this section, the results of the study on the optimal design of Warren Truss based on a fixed number of members with different lengths and the effect of bolting and welding on the truss will be presented and discussed. The results obtained from the manual calculations and the utilization of the SAP 2000 software are analysed and compared to determine the structural efficiency of each model. The internal reactions, compression, tension, and lateral buckling of the bottom chord, top chord, and web members for each model are tabulated and presented in a clear and organized manner. The results of the software model checking, and the values used to check the manual calculations are also included to provide a comprehensive understanding of the analysis and design process.

For internal reaction, the -ve value represents members that undergoes compression, while the +ve value represents members that undergo tension. In this study, an indicator system is used to represent the results of the structural checking of the Warren Truss models. The indicator system uses three different colors to indicate the level of compliance with the Eurocode 3 standards for structural design.

A red indicator represents a value above 1, which means that the member in question did not pass the checking criteria according to Eurocode 3. This indicates that the member is not suitable for use in the truss structure and that further investigation or redesign is required.

An orange indicator represents a value between 1 and 0.9, which means that the member is approaching the limits of the Eurocode 3 standards. This indicates that the member is still suitable for use in the truss structure, but it may be necessary to monitor it closely or consider alternative design options to ensure that it remains within the limits of the standards.

A blue indicator represents a value less than 0.5, which means that the member has passed the checking criteria according to Eurocode 3. This indicates that the member is suitable for use in the truss structure and that it is unlikely to be a cause for concern.

Model A (10m)

Table 7: Results of Model A

POSITION	MEMBER	INTERNAL REACTION (KN)	COMPRESSION	TENSION	BUCKLING Y-Y	BUCKLING Z-Z
Bottom Chords	A-B	-2.1	0.003		0.003	0.004
	B-C	1.0		0.001	0.001	0.002
	C-D	2.1		0.003	0.003	0.004
	D-E	1.0		0.001	0.001	0.002
	E-F	-2.1	0.003		0.003	0.004
Top Chords	G-H	-4.1	0.005		0.005	0.008
	H-I	-6.2	0.008		0.008	0.012
	I-J	-6.2	0.008		0.008	0.012
	J-K	-4.1	0.005		0.005	0.008
Web Members	A-G	-4.7	0.006		0.006	0.009
	B-G	3.7		0.005	0.005	0.008
	B-H	-2.7	0.003		0.003	0.005
	C-H	1.7		0.002	0.002	0.003
	C-I	-0.7	0.001		0.001	0.001
	D-I	-0.7	0.001		0.001	0.001
	D-J	1.7		0.002	0.002	0.003
	E-J	-2.7	0.003		0.003	0.005
	E-K	3.7		0.005	0.005	0.008
	F-K	-4.7	0.006		0.006	0.009

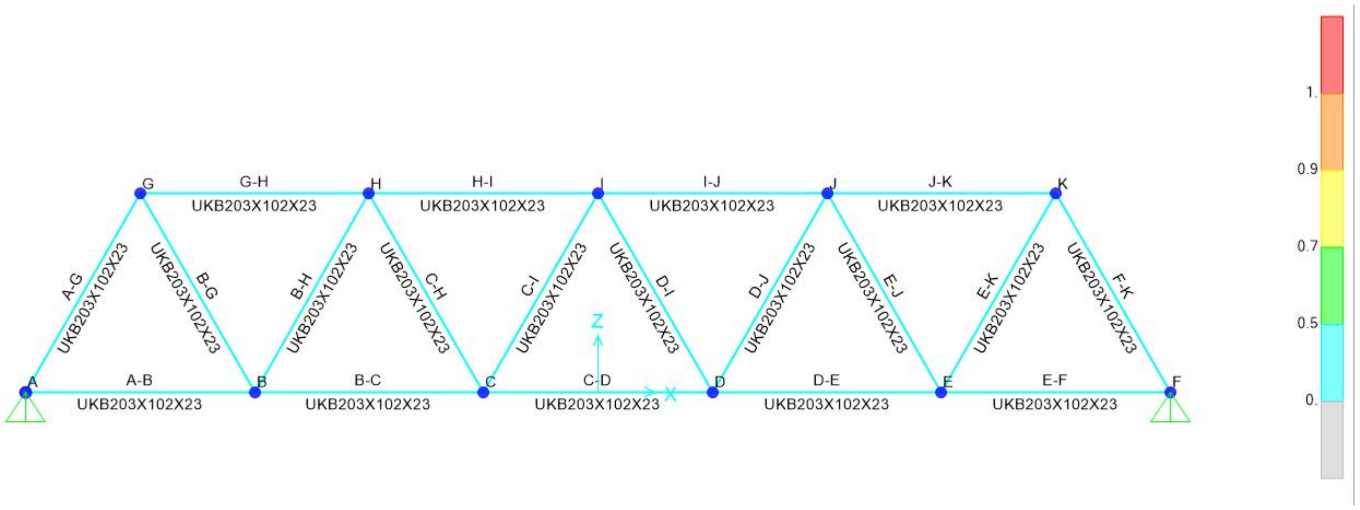
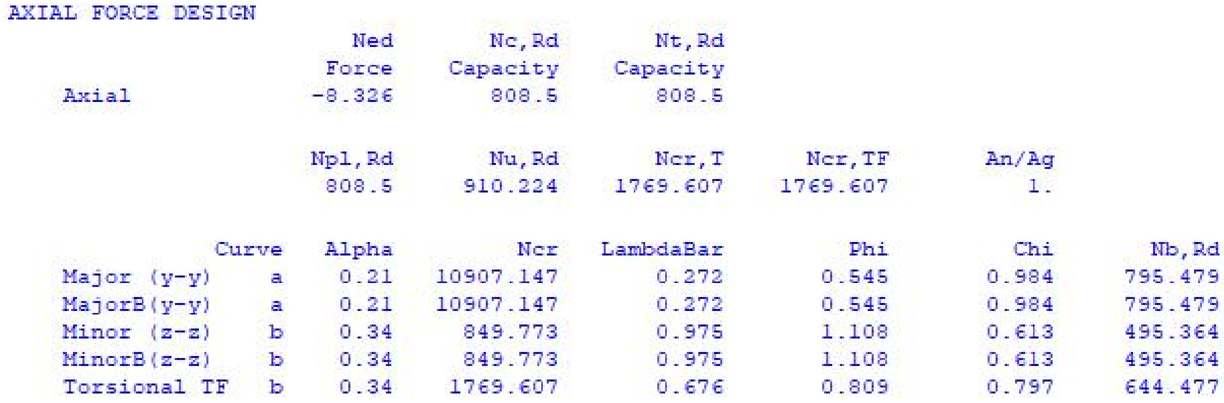


Figure 4-1: SAP2000 software checking for Model A



```
AXIAL FORCE DESIGN
                        Ned         Nc,Rd        Nt,Rd
                      Force      Capacity     Capacity
   Axial             -8.326         808.5        808.5

                     Npl,Rd         Nu,Rd        Ncr,T       Ncr,TF        An/Ag
                      808.5       910.224     1769.607     1769.607           1.

                Curve    Alpha           Ncr    LambdaBar          Phi          Chi        Nb,Rd
   Major (y-y)      a     0.21     10907.147        0.272        0.545        0.984      795.479
   MajorB(y-y)      a     0.21     10907.147        0.272        0.545        0.984      795.479
   Minor (z-z)      b     0.34       849.773        0.975        1.108        0.613      495.364
   MinorB(z-z)      b     0.34       849.773        0.975        1.108        0.613      495.364
   Torsional TF     b     0.34      1769.607        0.676        0.809        0.797      644.477
```

Figure 4-2: Checking values obtained from SAP2000 software for Model A

Model B (20m)

Table 8: Results of Model B

POSITION	MEMBER	INTERNAL REACTION (KN)	COMPRESSION	TENSION	BUCKLING Y-Y	BUCKLING Z-Z
Bottom Chords	A-B	-6.305	0.01	-0.01	0.01	0.11
	B-C	3.162	0.00	0.00	0.00	0.06
	C-D	6.287	-0.01	0.01	0.01	0.11
	D-E	3.162	0.00	0.00	0.00	0.06
	E-F	-6.305	0.01	-0.01	0.01	0.11
Top Chords	G-H	-12.48	0.02	-0.02	0.02	0.22
	H-I	-18.717	0.02	-0.02	0.03	0.33
	I-J	-18.717	0.02	-0.02	0.03	0.33
	J-K	-12.48	0.02	-0.02	0.02	0.22
Web Members	A-G	-14.105	0.02	-0.02	0.02	0.25
	B-G	11.665	-0.01	0.01	0.02	0.20
	B-H	-8.399	0.01	-0.01	0.01	0.15
	C-H	5.245	-0.01	0.01	0.01	0.09
	C-I	-2.153	0.00	0.00	0.00	0.04
	D-I	-2.153	0.00	0.00	0.00	0.04
	D-J	5.245	-0.01	0.01	0.01	0.09
	E-J	-8.399	0.01	-0.01	0.01	0.15
	E-K	11.665	-0.01	0.01	0.02	0.20
	F-K	-14.105	0.02	-0.02	0.02	0.25

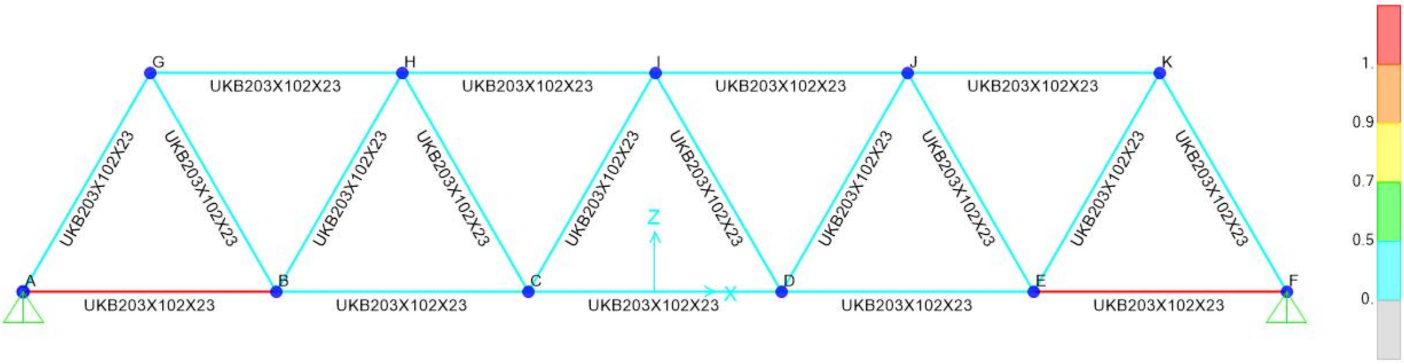
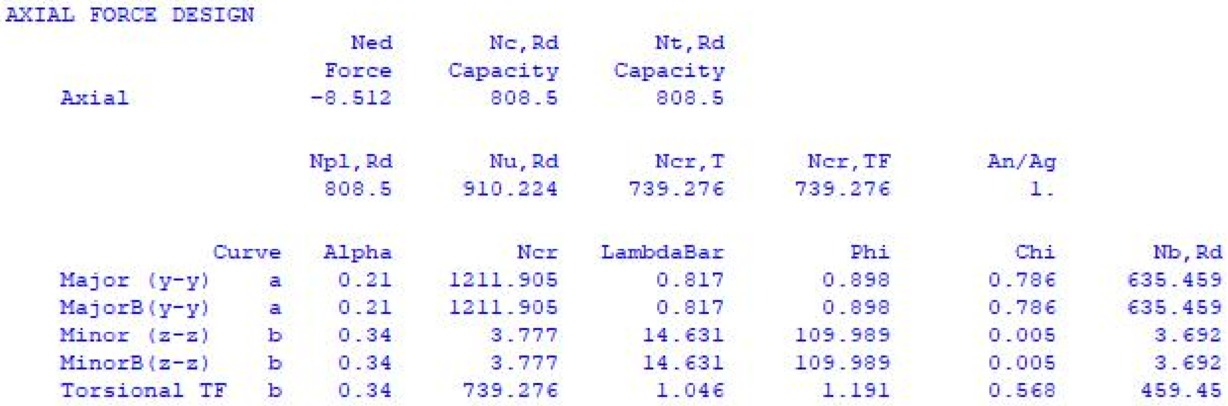


Figure 4-3: SAP2000 software checking for Model B



```
AXIAL FORCE DESIGN
                         Ned        Nc,Rd        Nt,Rd
                       Force     Capacity     Capacity
    Axial             -8.512        808.5        808.5

                     Npl,Rd        Nu,Rd       Ncr,T       Ncr,TF        An/Ag
                      808.5      910.224     739.276      739.276           1.

               Curve   Alpha          Ncr   LambdaBar          Phi          Chi        Nb,Rd
    Major (y-y)    a    0.21     1211.905       0.817        0.898        0.786      635.459
    MajorB(y-y)    a    0.21     1211.905       0.817        0.898        0.786      635.459
    Minor (z-z)    b    0.34        3.777      14.631      109.989        0.005        3.692
    MinorB(z-z)    b    0.34        3.777      14.631      109.989        0.005        3.692
    Torsional TF   b    0.34      739.276       1.046        1.191        0.568       459.45
```

Figure 4-4: Checking values obtained from the SAP2000 software for Model B

Model C (30m)

Table 9: Results of Model C

POSITION	MEMBER	INTERNAL REACTION (KN)	COMPRESSION	TENSION	BUCKLING Y-Y	BUCKLING Z-Z
Bottom Chords	A-B	-8.417	0.010		0.017	0.172
	B-C	4.222		0.005	0.009	0.086
	C-D	8.39		0.010	0.017	0.172
	D-E	4.222		0.005	0.009	0.086
	E-F	-8.417	0.010		0.017	0.172
Top Chords	G-H	-16.652	0.021		0.034	0.341
	H-I	-24.973	0.031		0.051	0.512
	I-J	-24.973	0.031		0.051	0.512
	J-K	-16.652	0.021		0.034	0.341
Web Members	A-G	-18.819	0.023		0.039	0.386
	B-G	15.593		0.019	0.032	0.319
	B-H	-11.221	0.014		0.023	0.230
	C-H	7.007		0.009	0.014	0.144
	C-I	-2.872	0.004		0.006	0.059
	D-I	-2.872	0.004		0.006	0.059
	D-J	7.007		0.009	0.014	0.144
	E-J	-11.221	0.014		0.023	0.230
	E-K	15.593		0.019	0.032	0.319
	F-K	-18.819	0.023		0.039	0.386

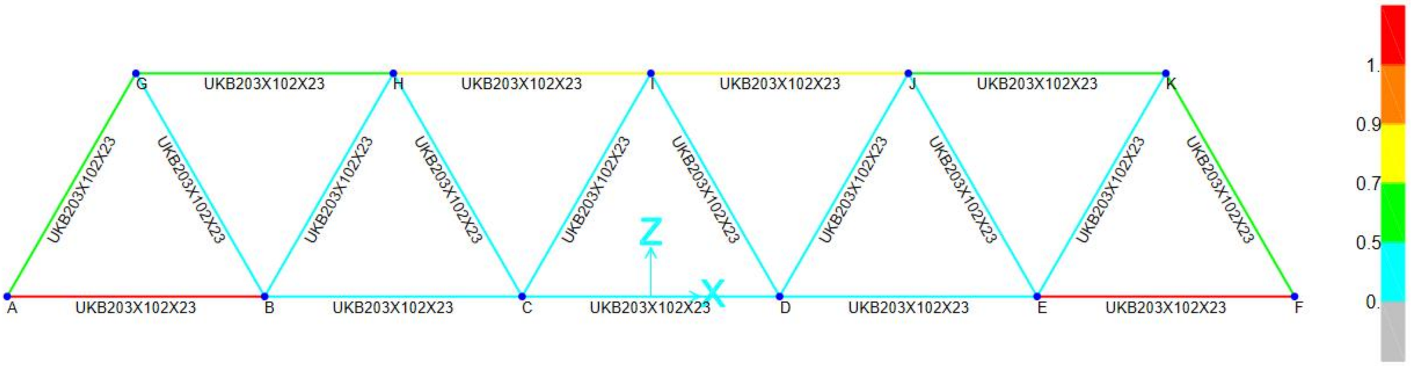
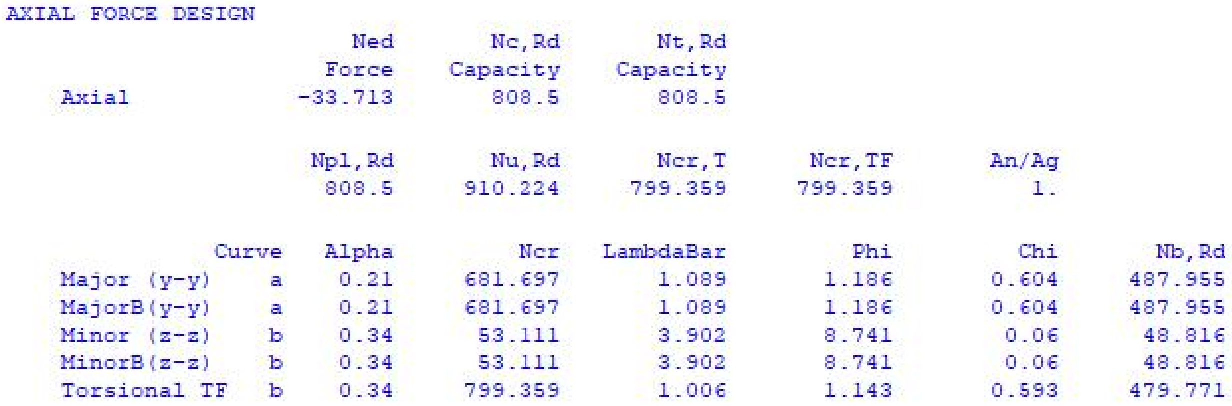


Figure 4-5: SAP2000 software checking for Model C



```
AXIAL FORCE DESIGN
                        Ned         Nc,Rd        Nt,Rd
                      Force      Capacity     Capacity
   Axial            -33.713         808.5        808.5

                     Npl,Rd         Nu,Rd        Ncr,T       Ncr,TF        An/Ag
                      808.5       910.224      799.359      799.359           1.

                Curve   Alpha          Ncr    LambdaBar          Phi          Chi        Nb,Rd
   Major (y-y)     a     0.21      681.697        1.089        1.186        0.604      487.955
   MajorB(y-y)     a     0.21      681.697        1.089        1.186        0.604      487.955
   Minor (z-z)     b     0.34       53.111        3.902        8.741         0.06       48.816
   MinorB(z-z)     b     0.34       53.111        3.902        8.741         0.06       48.816
   Torsional TF    b     0.34      799.359        1.006        1.143        0.593      479.771
```

Figure 4-6: Checking values obtained from the SAP2000 software for Model C

Model D (40m)

Table 10: Results of Model D

POSITION	MEMBER	INTERNAL REACTION (KN)	COMPRESSION	TENSION	BUCKLING Y-Y	BUCKLING Z-Z
Bottom Chords	A-B	-10.527	0.013	-0.013	0.030	0.331
	B-C	5.281		0.007	0.015	0.166
	C-D	10.492		0.013	0.030	0.330
	D-E	5.281		0.007	0.015	0.166
	E-F	-10.527	0.013		0.030	0.331
Top Chords	G-H	-20.821	0.026		0.059	0.655
	H-I	-31.226	0.039		0.088	0.983
	I-J	-31.226	0.039		0.088	0.983
	J-K	-20.821	0.026		0.059	0.655
Web Memebrs	A-G	-23.531	0.029		0.067	0.740
	B-G	19.516		0.024	0.055	0.614
	B-H	-14.039	0.017		0.040	0.442
	C-H	8.767		0.011	0.025	0.276
	C-I	-3.59	0.004		0.010	0.113
	D-I	-3.59	0.004		0.010	0.113
	D-J	8.767		0.011	0.025	0.276
	E-J	-14.039	0.017		0.040	0.442
	E-K	19.516		0.024	0.055	0.614
	F-K	-23.531	0.029		0.067	0.740

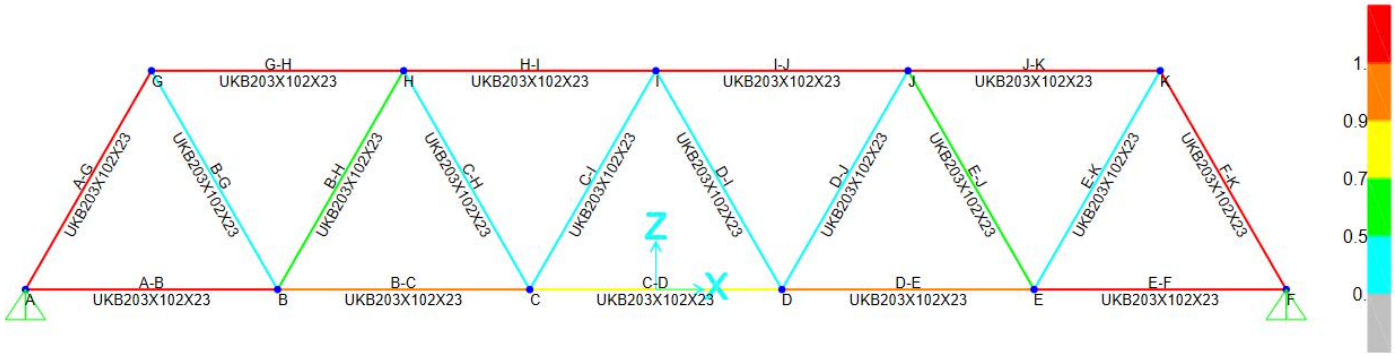
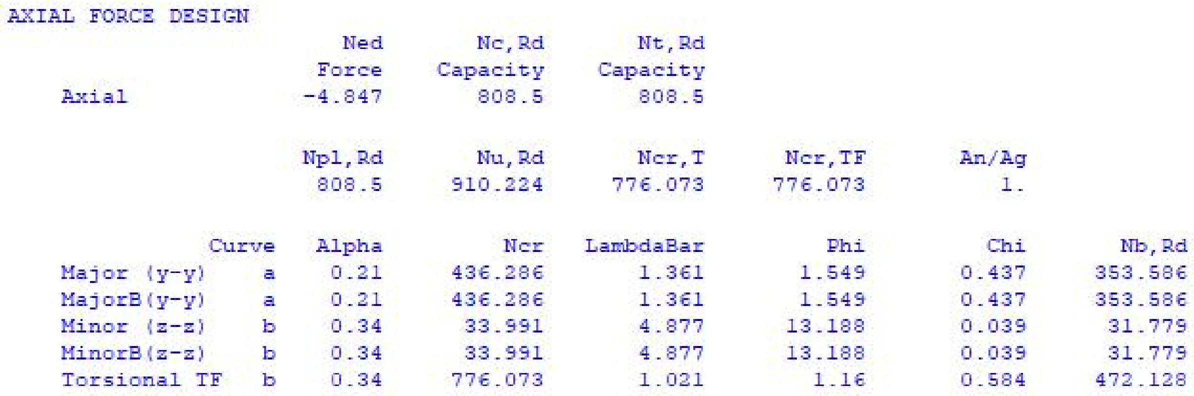


Figure 4-7: SAP2000 software checking for Model D



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AXIAL FORCE DESIGN
                         Ned       Nc,Rd       Nt,Rd
                       Force    Capacity    Capacity
   Axial              -4.847       808.5       808.5

                      Npl,Rd       Nu,Rd      Ncr,T      Ncr,TF      An/Ag
                       808.5     910.224    776.073     776.073         1.

                Curve  Alpha         Ncr  LambdaBar        Phi        Chi      Nb,Rd
   Major (y-y)    a     0.21     436.286      1.361      1.549      0.437    353.586
   MajorB(y-y)    a     0.21     436.286      1.361      1.549      0.437    353.586
   Minor (z-z)    b     0.34      33.991      4.877     13.188      0.039     31.779
   MinorB(z-z)    b     0.34      33.991      4.877     13.188      0.039     31.779
   Torsional TF   b     0.34     776.073      1.021       1.16      0.584    472.128
```

Figure 4-8:Checking values obtained from the SAP2000 software for Model D

Model E (50m)

Table 11: Results of Model E

POSITION	MEMBER	INTERNAL REACTION (KN)	COMPRESSION	TENSION	BUCKLING Y-Y	BUCKLING Z-Z
Bottom Chords	A-B	-12.636	0.016		0.049	0.566
	B-C	6.34		0.008	0.024	0.284
	C-D	12.593		0.016	0.048	0.564
	D-E	6.34		0.008	0.024	0.284
	E-F	-12.636	0.016		0.049	0.566
Top Chords	G-H	-24.99	0.031		0.096	1.120
	H-I	-37.477	0.046		0.144	1.679
	I-J	-37.477	0.046		0.144	1.679
	J-K	-24.99	0.031		0.096	1.120
Web Members	A-G	-28.242	0.035		0.109	1.265
	B-G	23.434		0.029	0.090	1.050
	B-H	-16.855	0.021		0.065	0.755
	C-H	10.525		0.013	0.041	0.472
	C-I	-4.308	0.005		0.017	0.193
	D-I	-4.308	0.005		0.017	0.193
	D-J	10.525		0.013	0.041	0.472
	E-J	-16.855	0.021		0.065	0.755
	E-K	23.434		0.029	0.090	1.050
	F-K	-28.242	0.035		0.109	1.265

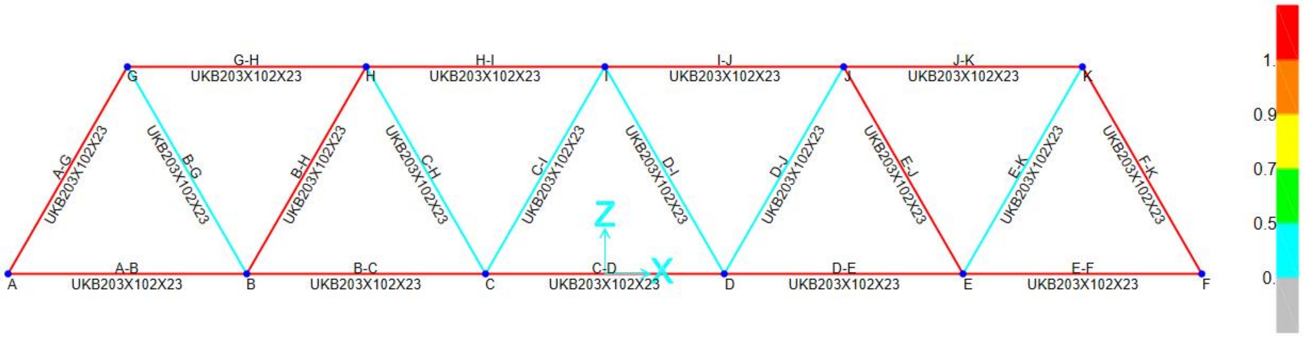
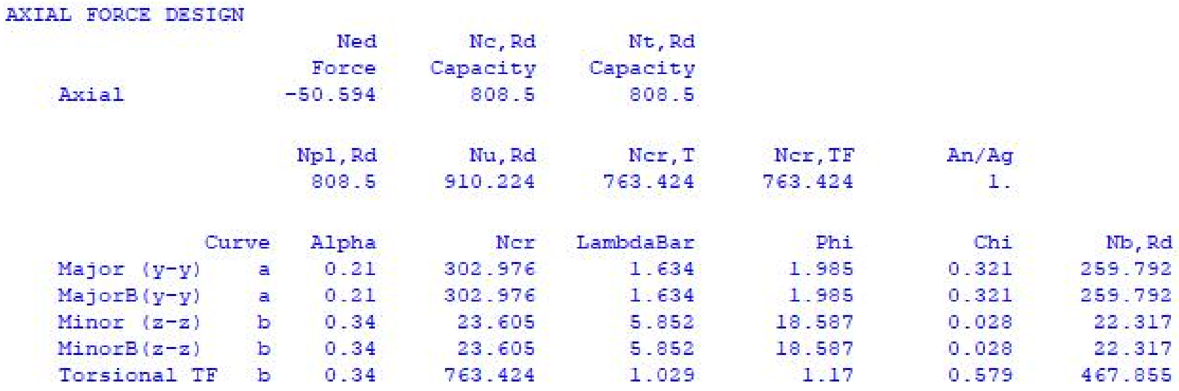


Figure 4-9: SAP2000 software checking for Model E



```
AXIAL FORCE DESIGN
                          Ned        Nc,Rd       Nt,Rd
                        Force     Capacity    Capacity
   Axial              -50.594        808.5       808.5

                       Npl,Rd        Nu,Rd      Ncr,T      Ncr,TF       An/Ag
                        808.5      910.224    763.424     763.424          1.

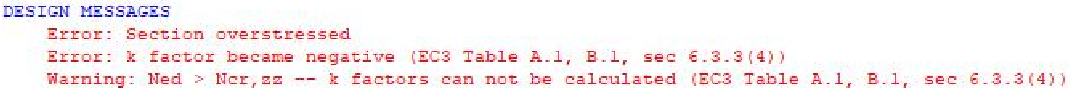
                 Curve  Alpha          Ncr  LambdaBar         Phi         Chi       Nb,Rd
   Major (y-y)      a    0.21      302.976      1.634       1.985       0.321     259.792
   MajorB(y-y)      a    0.21      302.976      1.634       1.985       0.321     259.792
   Minor (z-z)      b    0.34       23.605      5.852      18.587       0.028      22.317
   MinorB(z-z)      b    0.34       23.605      5.852      18.587       0.028      22.317
   Torsional TF     b    0.34      763.424      1.029        1.17       0.579     467.855
```

Figure 4-10:Checking values obtained from the SAP2000 software for Model E

4.3 Analysis of Results

Based on the results of the study, it can be observed that the design of the Warren trusses, when analysed according to the axial forces design checking criteria outlined in Eurocode 3, generally meet the standards set forth by the code. However, it was found that Model E, with a length of 50m, did not fully comply with the Eurocode standards. This can be attributed to the fact that, as the span of the truss increases, the individual members become weaker and are more susceptible to lateral buckling. As the length of the truss increases from Model A to Model E, the value of the ratio of design value to design resistance (V/Rd) also increases, approaching the threshold of 1.0, which is indicative of an unsafe structure.

Despite this, it should be noted that all members of the truss, across all models, met the tension and compression checking criteria outlined in Eurocode 3. However, it was observed that certain members of the truss, starting from Model B onwards, failed to meet the standards set forth in clause 6.3.3.4 of Eurocode 3, which pertains to uniform members in bending and axial compression. These members were identified as failing based on the SAP2000 software's indicator system, which uses colour coding (red, orange, blue, yellow, green) to indicate the degree of compliance with the code. In this case, red indicates that the member did not pass the checking criteria according to Eurocode 3. However, it should be noted that these members were not identified as failing based on the manual calculations carried out in this study and, as such, these results should be considered with caution.



```
DESIGN MESSAGES
    Error: Section overstressed
    Error: k factor became negative (EC3 Table A.1, B.1, sec 6.3.3(4))
    Warning: Ned > Ncr,zz -- k factors can not be calculated (EC3 Table A.1, B.1, sec 6.3.3(4))
```

Figure 4-11: Part that failed according to SAP2000 software

4.4 Improvements Made to the Trusses

For each model that does not meet the checking standards set by the Warren Truss, a new model with the same length but new cross-section size is made in order to ensure that the Warren Truss. Through the Trial and Error Method, the improved Warren Truss is identified, with the criteria of the indicators being at the colour blue, which is below 0.5. This improvements are made to show that the solution to a fixed number of members but with a longer span length can be safe if the sections are replaced and changed with the appropriate sections. The improvements made are shown below: However, for Models D and E, despite using the largest I-section available, the model still does not comply with the standard set in the Eurocode 3.

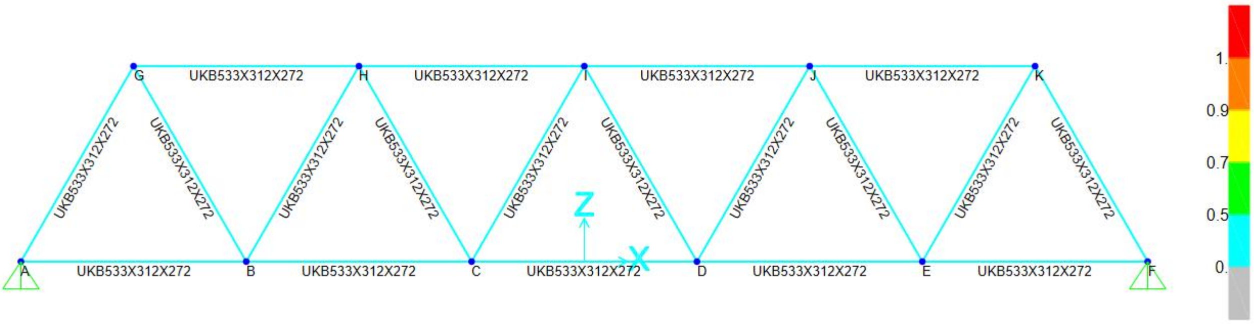


Figure 4-12: Model B (533x312x272)

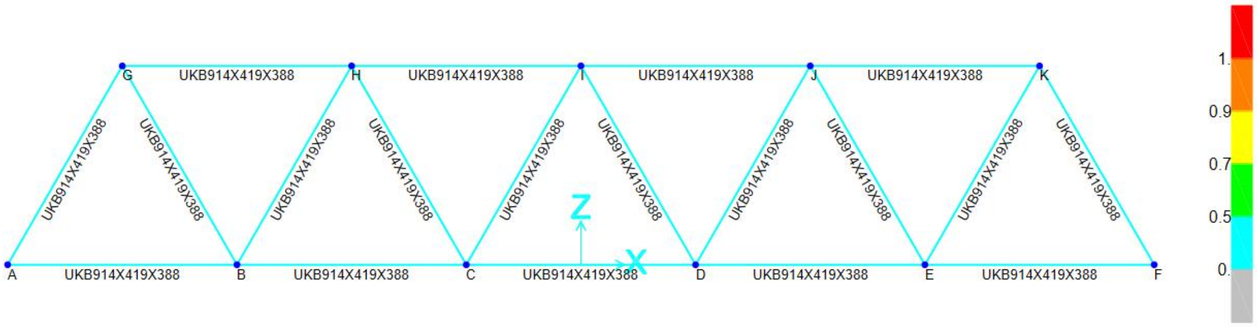


Figure 4-13: Model C (914x419x388)

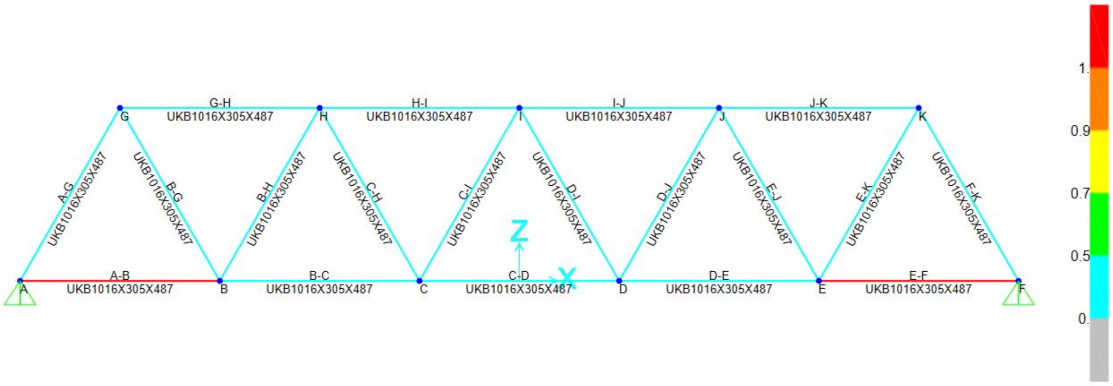


Figure 4-14: Model D (1016x305x487)

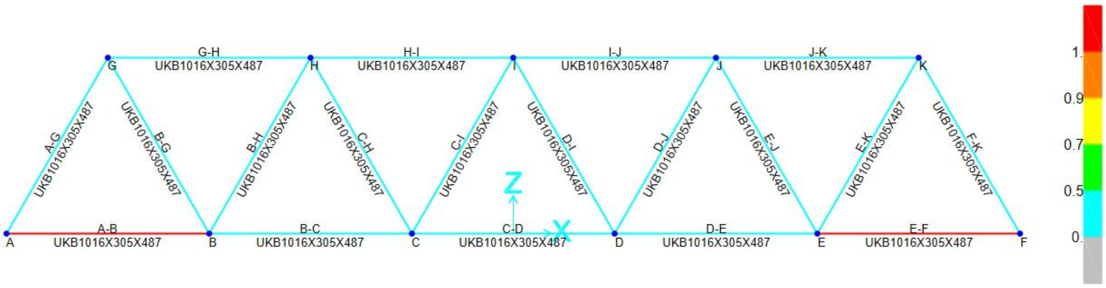


Figure 4-15: Model E (1016x305x487)

4.5 Comparison of Results in between Manual Calculation Results and SAP2000 Software Results

This section will show the comparison of manual calculation results and SAP2000 software results for the Model A (10m), it can be seen that there is a small difference between both results. The comparison of the two methods demonstrates the reliability of the software in accurately predicting the structural efficiency of the Warren Truss. It also highlights the importance of using both manual calculations and software in the design process, as it provides a more comprehensive analysis and reduces the risk of errors. However, it should be noted that the use of software does not replace the need for manual calculations, as it is still necessary to understand the underlying principles and assumptions behind the calculations. Additionally, manual calculations provide a check on the software results, ensuring the validity and accuracy of the results.

Table 12: Result Comparison in between Manual Calculation SAP2000 Software Results for Model A

POSITION	MEMBER	INTERNAL REACTION (KN)	SAP2000 SOFTWARE				MANUAL CALCULATION			
			COMPRESSION	TENSION	BUCKLING Y-Y	BUCKLING Z-Z	COMPRESSION	TENSION	BUCKLING Y-Y	BUCKLING Z-Z
Bottom Chords	A-B	-2.1	0.003		0.003	0.004	0.003		0.003	0.003
	B-C	1.0		0.001	0.001	0.002		0.001	0.001	0.001
	C-D	2.1		0.003	0.003	0.004		0.003	0.003	0.003
Top Chords	G-H	-4.1	0.005		0.005	0.008	0.005		0.006	0.006
	H-I	-6.2	0.008		0.008	0.012	0.008		0.008	0.009
Web Members	A-G	-4.7	0.006		0.006	0.009	0.006		0.006	0.007
	B-G	3.7		0.005	0.005	0.008		0.005	0.005	0.005

	B-H	-2.7	0.003		0.003	0.005	0.003		0.004	0.004
	C-H	1.7		0.002	0.002	0.003		0.002	0.002	0.002
	C-I	-0.7	0.001		0.001	0.001	0.001		0.001	0.001

CHAPTER 5

CONCLUSION

5.1 Introduction

In this chapter, we will present the conclusions and recommendations derived from our study on the optimal design of Warren Truss based on a fixed number of members with different lengths, and the effect of bolting and welding on the truss. The conclusion will summarize the findings of the manual calculations and the utilization of the SAP 2000 software, and the recommendation section will provide suggestions for further research and practical applications in the field of structural design. Overall, this chapter will provide a comprehensive summary of the study and its implications for the design and construction of Warren Truss structures.

5.2 Conclusion

In conclusion, the study aimed to evaluate the design of Warren trusses in terms of axial forces design checking according to the Eurocode 3 standards. The results of the study have shown that all models, ranging from Model A to Model E, have passed the standard set by Eurocode 3 with the exception of Model E with a length of 50m. The failure of Model E can be attributed to the increase in span length, which resulted in the individual members being weaker in terms of lateral buckling. The study also found that all members of the trusses met the standard for tension and compression checking set by Eurocode 3. However, SAP2000 indicators for certain members of the Warren Truss began showing red at the beginning of Model B until Model E, which can be attributed to the failure of the members based on clause 6.3.3.4 of Eurocode 3. Despite this, it was found that this parameter was not used to determine the failure of the members of the Warren Truss and thus, these results were ignored. Based on the findings of this study, recommendations will be provided on how to improve the design of Warren trusses to ensure compliance with Eurocode 3 standards.

On the other hand, bolted connection and welded connections did not affect the Warren Truss in a significant way as the internal reaction, tension, compression and lateral buckling was not affected at all even if the connections were changed.

5.3 Recommendation

Based on the results of this study, it is recommended that future designs of Warren Truss structures consider the effect of span length on the structural efficiency of the truss. It is also recommended that the use of bolting and welding as a method of joint connection be further explored to determine its effectiveness in increasing the structural efficiency of the truss. Additionally, it is suggested that further research be conducted on the effect of different types of welding on the structural efficiency of the Warren Truss. Furthermore, it is recommended that the use of software such as SAP2000 be integrated into the design process to accurately predict the performance of the truss under different loading conditions. Overall, it is suggested that a comprehensive approach be taken when designing Warren Truss structures in order to ensure their structural efficiency and safety.

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