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A novel truss formwork made from Casuarina wood

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THE AMERICAN
UNIVERSITY IN CAIRO

School of Sciences and Engineering

A novel truss formwork made from Casuarina wood

A Thesis Submitted to
Department of Construction Engineering

In partial fulfillment of the requirements for
The degree of Master of Science
in Construction Management

By
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Under the Supervision of

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May 2020

ABSTRACT

- University: American University in Cairo
- Thesis Title: A novel truss formwork made from Casuarina wood.
- Student Full Name: Moustafa Mohammed Osama Moustafa Ibrahim Hussein
- Name of Thesis Supervisors: Dr. Khaled Nassar and Dr. Mohamed Darwish
- Summary:

Wood is classified as one of the most common building materials due to its diverse nature. In Egypt, most of the wood used in different industries are imported from several places such as North America and Australia. Nowadays, Casuarina is considered one of the fast-growing trees in relatively arid countries like Egypt. The thesis aims to test the mechanical properties for the most two common species of Casuarina in Egypt, which are “Glauca” and “Cunninghamiana”. The thesis focused on testing both species for compression parallel to the grain, compression perpendicular to the grain, static bending tests while the tension parallel to the grain, tension perpendicular to the grain and cleavage tests were only tested on Glauca because Cunninghamiana was excluded after the first three tests due to the high variability in its results. The results of the mechanical tests showed that Casuarina Glauca was promising because it has the sufficient strength that could enable it to be used in construction applications.

A secondary scope in this thesis is to investigate the moisture content effect on the mechanical properties of both Casuarina species through testing both Casuarina species in three different moisture contents. Similar to the most types of wood reducing the moisture content improved the strength and the modulus of elasticity for all the mechanical tests.

The thesis also aims to design, manufacture and test a formwork truss made of Casuarina Glauca. Three trusses made of Casuarina Glauca were manufactured and tested under bending as structural application for a formwork beam and the results were promising and may achieve structural and economic gain for the wood industry in Egypt. A cost study comparing the Casuarina Glauca truss to the GT 24 truss produced by PERI company. The comparison was done by applying both trusses on a slab and calculating the number of units, the total weight and the total cost of each system. The results of the cost study have proven that the designed Casuarina truss to be a cost effective when compared to the GT 24 PERI formwork system.

Keywords: Wood, Mechanical Properties, Glauca, Cunninghamiana, Truss, Formwork

TABLE OF CONTENTS

CHAPTER 1 : INTRODUCTION 1

1.1. General 1
1.2. Background about Casuarina 3
1.3. Problem Statement 5
1.4. Objectives 5
1.5. Research Methodology 6
1.6. Thesis Organization 7

CHAPTER 2 : LITERATURE REVIEW 9

2.1 The wood use in the construction History 9
2.2 The wood from Trees to the end use 10
2.3 Timber as a structural material compared to other materials 12
2.4 Factors affecting the lifespan of timber in buildings 13
2.5 Different types of wood used in construction 14
2.6 Wood in Egypt 16
2.7 Formworks 19
  2.7.1 Introduction 19
  2.7.2 Form work systems 19
  2.7.3 Factors affecting the selection of formwork system 31
  2.7.4 The objectives to be considered when designing formwork 31
  2.7.5 Formwork materials 33
  2.7.6 Formwork Failures 35

CHAPTER 3: EXPERIMENTAL PROGRAM 36

3.1 Testing the mechanical properties 36
  3.1.1 Scope of Work: 36
  3.1.2 Sampling Procedures: 37
  3.1.3 Experimental program: 37
    3.1.3.1 Compression parallel to the grain test 37
    3.1.3.2 Compression Perpendicular to the Grain test 38

3.1.3.3 Static Bending test 39
3.1.3.4 Cleavage test 40
3.1.3.5 Tension parallel to the grain test 41
3.1.3.6 Tension Perpendicular to the grain test 43
3.1.3.7 Specific Gravity 44
3.1.4 Mechanical tests Results and discussion 46
3.1.4.1 Compression parallel to the grain test 46
3.1.4.2 Compression perpendicular to the grain test 49
3.1.4.3 Static bending test 52
3.1.4.4 Cleavage test 55
3.1.4.5 Tension parallel to the grain test 57
3.1.4.6 Tension perpendicular to the grain test 59
3.1.4.7 Specific Gravity 61
3.1.4.8 Ductility 63
3.1.5 Data correlation 65
3.2 INVESTIGATING THE MOISTURE CONTENT EFFECT ON THE MECHANICAL PROPERTIES 67
3.2.1 Scope of work 67
3.2.2 Sampling Procedures 67
3.2.3 Mechanical Tests 68
3.2.3.1 Compression parallel/perpendicular to the grain tests 68
3.2.3.2 Static bending test 69
3.2.3.3 Tension parallel to the grain test 69
3.2.4 Results and discussion 70
3.2.4.1 Compression parallel to the grain test 70
3.2.4.2 Compression perpendicular to the grain test 71
3.2.4.3 Static bending test 72
3.2.4.4 Tension parallel to the grain test 72

CHAPTER 4: TRUSS MODEL DESIGN & CONSTRUCTABILITY 75

4.1 INTRODUCTION 75
4.2 MODEL DESCRIPTION AND DESIGN 75

4.2.1 Model description 75
4.2.2 Model design 75
4.2.2.1 SAP analysis 77
4.2.2.2 Design of the connections 79
4.2.2.3 The design criteria 81
4.3 MODEL MANUFACTURING AND ASSEMBLY 81
4.3.1 Preparing the truss wooden members 81
4.3.2 Preparing the steel connections 84
4.3.3 The truss assembly 85
4.4 EXPERIMENTAL WORK 88
4.4.1 Description 88
4.4.2 Loading case 89
4.4.3 The Equipment used 89
4.4.4 Setting up the experiment 93
4.4.5 Experimental procedures 95
4.4.6 Results 95
4.4.6.1 Sample#1 96
4.4.6.2 Sample#2 97
4.4.6.3 Sample#3 98
4.4.7 Analysis and Discussion 99
4.4.8 Cost Study 100
4.4.8.1 Description 100
4.4.8.2 The total weight 102
4.4.8.3 Cost Comparison 103
CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS 104
REFERENCES 106

LIST OF FIGURES

Figure 1:Orthotropic axis of wood. (Stalnaker & Harris, 1997).. 1
Figure 2: Trees (A) Beech hardwood tree. (B) Pine softwood tree (Ramage et al.,2017).. 2
Figure 3: Dead and live knots in wood. (Kretschmann,2010) 3
Figure 4: Research Methodology Flow chart... 7
Figure 5: Tree cross-section. (Stalnaker & Harris, 1997).. 10
Figure 6: Wood treatment techniques (Ramage et al., 2017). 12
Figure 7: Casuarina trees planted in Egypt (Almahallawi, 2015).................................... 18
Figure 8: Forests plantation using treated sewage water locations in Egypt. (Almahallawi, 2015)... 19
Figure 9: Horizontal formwork systems. (Hanna,1999)... 20
Figure 10: The Conventional wood formwork system (Hurd,2005) 21
Figure 11: The Conventional metal formwork system (Ratay,1996) 22
Figure 12: The Joist slab forming system 23
Figure 13: The Dome forming system (http://geotoday.lt/uploads/catalogs/skydome.pdf) 24
Figure 14: Flying formwork system (Oberlender and Peurifoy, 2010) 25
Figure 15: The Flying formwork cycle (Oberlender and Peurifoy, 2010)....................... 26
Figure 16: The column mounted shoring system components (Hanna,1999) 27
Figure 17: The column mounted shoring system.. 27
Figure 18: Tunnel formwork system (Hanna,1999) 28
Figure 19: FAST falsework system (Darwish et.al,2018) 30
Figure 20: Formwork cost components (Hurd,2005) 31
Figure 21: Compression parallel to the grain test setup.. 38
Figure 22: Compression Perpendicular to the grain test setup 39
Figure 23: Static Bending test setup 40
Figure 24: Cleavage test setup 41
Figure 25: Tension Parallel to the grain test setup.. 42
Figure 26: Tension Perpendicular to the grain test setup.. 44
Figure 27: weighting the samples using a balance.. 45
Figure 28: Samples inside the oven to determine their dry weight.................................. 45

Figure 29: Compressive strength parallel to the grain results for Glauca samples........... 46
Figure 30 : Compressive strength parallel to the grain results for Cunninghamiana samples 46
Figure 31 : Shear failure 47
Figure 32 : Wedge split failure 47
Figure 33: Splitting failure.. 48
Figure 34: Stress-Strain curve sample for compression parallel to the Grain Test 49
Figure 35: Compressive strength perpendicular to the Grain Results for Glauca samples 50
Figure 36: Compressive strength perpendicular to the Grain Results for Cunninghamiana samples 50
Figure 37: Compression perpendicular to the grain sample after testing 51
Figure 38: Stress-Strain curve sample for compression perpendicular to the Grain Test 52
Figure 39: Bending Strength Results for Glauca samples 53
Figure 40: Bending Strength Results for Cunninghamiana samples 53
Figure 41: Simple tension failure.. 54
Figure 42: Cross grain tension failure... 54
Figure 43: Load-deflection curve sample for static bending test..................................... 55
Figure 44: Results for Cleavage test 56
Figure 45: Cleavage sample after failure 56
Figure 46: stress-strain curve for cleavage test sample 57
Figure 47: Tension parallel to the grain test results 57
Figure 48: Splintering tension failure 58
Figure 49: Stress-strain curve for tension parallel to the grain test sample 59
Figure 50: Tension perpendicular to the grain test results.. 59
Figure 51: Tension perpendicular to the grain failure specimen 60
Figure 52: Stress-strain curve for tension perpendicular to the grain test sample 60
Figure 53: Specific gravity results for Casuarina Glauca 62
Figure 54: Specific gravity results for Casuarina Cunninghamiana 63
Figure 55: Ductility results for Casuarina Glauca 64
Figure 56: Ductility results for Casuarina Cunninghamiana 64

Figure 57: Casuarina Glauca Average load – deformation curves at different moisture contents for compression parallel to the grain test. 71
Figure 58: Casuarina Glauca Average load – deformation curves at different moisture contents for static bending test 72
Figure 59: Casuarina Glauca Average load –extension curves at different moisture contents for tension parallel to the grain test. 73
Figure 60: Detailed design of the proposed Truss using AutoCAD. 76
Figure 61: Truss design on SAP 77
Figure 62: Normal distribution graph 78
Figure 63: Members axial forces on SAP 78
Figure 64: Connections distribution on the truss 79
Figure 65: The two types of screws used in connections........ 80
Figure 66: The procurement of the wood used in manufacturing the trusses........ 82
Figure 67: Cutting the wood samples into requires sizes using electric sow........ 83
Figure 68: Cleaning and smoothing the surface of the wooden members........ 84
Figure 69: Making the opening of the screws using a driller 85
Figure 70: Building the external members of the truss and connecting them 86
Figure 71: Connecting the inner diagonals of the truss 87
Figure 72: The truss final shape after connecting all the members 88
Figure 73: The electronic balance........ 89
Figure 74: The steel rods placed above the truss 90
Figure 75: The wooden beam that was used to distribute the load over the truss. 90
Figure 76: The load cell used in the test 91
Figure 77: The hydraulic pump........ 92
Figure 78: The LVDT used in the experiment........ 93
Figure 79: The supports used to support the truss 94
Figure 80: The truss is ready to begin the experiment........ 95
Figure 81: Sample #1 after testing........ 96
Figure 82: Sample #2 after testing........ 97
Figure 83: Sample #3 after testing........ 98

Figure 84: The allowable deflection plotted on the load-deflection curve for the three trusses 100
Figure 85: The GT 24 formwork girder (PERI,2016).. 100
Figure 86: The slab plan using Casuarina Glauca Girders 101
Figure 87: The slab plan using the GT 24 Girders.. 102

LIST OF TABLES

Table 1: Forests characteristic and Areas in Egypt. (FAO,2010). 16

Table 2: Comparing the different formwork systems. (Hanna,1999). 29

Table 3: Comparing different formwork materials. (Oberlender and Peurifoy, 2010). 34

Table 4: The most common formwork failures. (Hardipriono and Wang, 1986). 35

Table 5: Results of all tests of Casuarina Glauca 61

Table 6: Results of all tests of Casuarina Cunninghamiana 61

Table 7: Comparing Casuarina Glauca and Cunninghamiana to different types of wood. 65

Table 8: Pearson correlation results 66

Table 9: Casuarina Glauca results at different moisture contents.................................... 74

Table 10: Casuarina Cunninghamiana results at different moisture contents.................. 74

Table 11: Truss members dimensions... 76

Table 12: Comparing the member capacity to the Axial load on SAP. 79

Table 13: Results of sample # 1 96

Table 14: Results of sample # 2. 97

Table 15: Results of sample # 3 99

Table 16: The experimental work summary for the three trusses.................................... 99

Table 17: Comparing Casuarina Glauca girder to GT 24 girder 103

Chapter 1 : Introduction

1.1. General

Wood is a natural polymer composite material that has been used in the construction Industry for a long time (Zhao & Han, 2016). Wood consists mainly from three main elements which are cellulose, hemicellulose and lignin. (Siro and Plackett,2010). The properties of wood are subjected to many variations due to the presence of some imperfections such as knots, pocket, and pitches (Kisser et al. 1967). Wood is an orthotropic and inhomogeneous material which affects its properties across and along its length having more variation than other materials like steel but at the same time, it offers several unique features such as its low cost, renewability and high-quality sustainable construction (Harris & Van de Kuilen, 2016). Wood has three main mutually perpendicular directions which are tangential, radial and longitudinal. (Stalnaker & Harris, 1997). Figure (1) shows the orthotropic axes of wood.

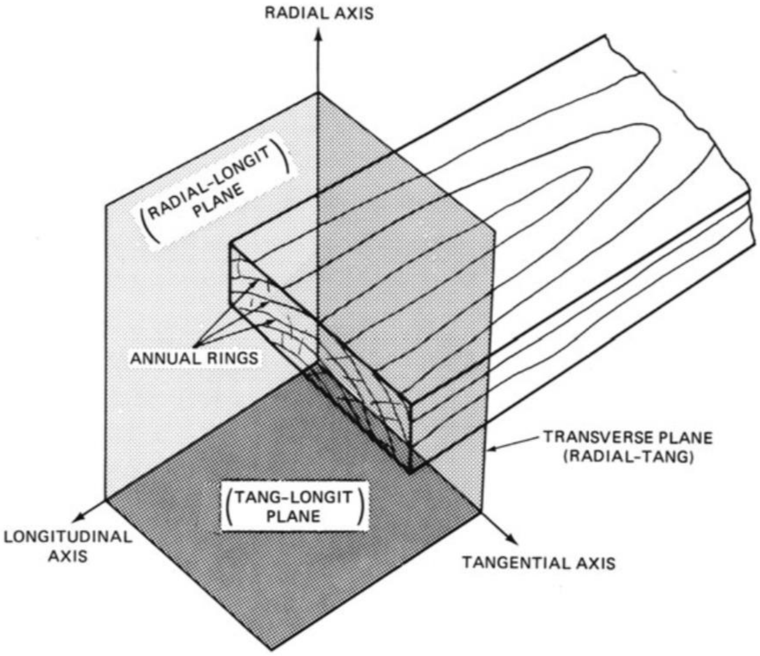


Figure 1:Orthotropic axis of wood. (Stalnaker & Harris, 1997)

Generally, wood can be classified into two main groups, softwoods and hardwoods (Stalnaker & Harris, 1997). Hardwoods is produced from a group of plants producing flowers and seeds called angiosperms while softwoods are produced from a group of plants producing uncovered seeds called gymnosperms. (Ramage et al., 2017) Hardwoods usually have higher density and slower growth rate than softwoods (Fridley, 2002). Softwoods include pine, larch, spruce, and hemlock while hardwoods include oak, birch, maple and beech (Kolb, 2008). Figure (2) shows a hardwood tree (Beech) vs a softwood tree (Pine).

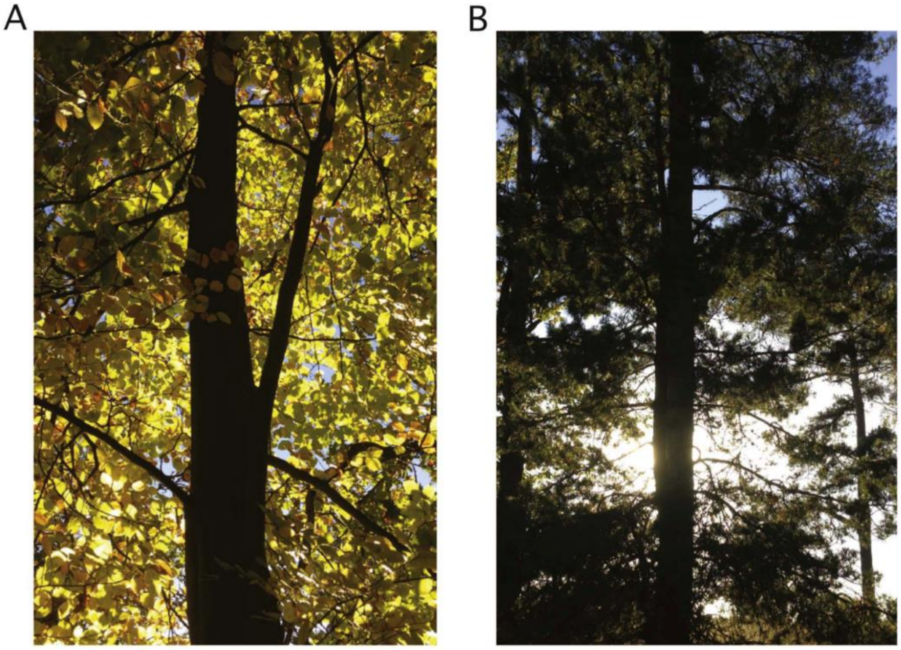


Figure 2: Trees (A) Beech hardwood tree. (B) Pine softwood tree (Ramage et al.,2017)

There are several factors affecting the strength of wood such as: a) Moisture content: which is inversely proportional with the wood strength, b) Density: several factors affect the density of wood such as temperature, humidity, position of the tree, soil and genetic characteristics, c) Load Duration Effect: It is very important to take into consideration the viscoelastic nature of wood, d) presence, size and location of several defects such as knots, compression wood cross grain, checks and decay will reduce the ultimate strength. (Kolb, 2008). The wood sections containing knots (Dead – live) will have lower mechanical properties than the knot free sections as the knots distort the grain direction leading to stress concentrations and the knot replace the clear wood. (kretschmann,2010) Figure (3) shows dead and live knots in wood.

Figure 3: Dead and live knots in wood. (Kretschmann,2010)

There are several reasons that lead to deterioration of wood such as exposure to sunlight and heat, attacks by insects and changes in moisture content. One of the major problems of using wood is the variability in its properties that may occur in different species, same species grown in different locations or even grown in the same location, so measuring the mechanical properties for any type of wood will need many samples from different trees to overcome this variation (Kolb, 2008).

1.2. Background about Casuarina

Casuarina wood is classified as a hardwood; Casuarina is a tree that consists of 17 species that was originally found in several locations such as Australia, Southeast Asia, Malaysia and New Caledonia (Brewbaker et al. 1990). Casuarina wood is a hard, heavy, dark red wood; which is commonly known as she-oak, river-oak, or Australian pine (Potgieter et al. 2013). The species of Casuarina are usually found in locations that lack nutrients. By the late 1852’s, Casuarina was first introduced in Australia then it was planted extensively in several parts of the world such as: China, India, Middle east, East Africa and southwestern united states (Zhang et al. 2006). The most common species planted in Egypt are Casuarina Equistifolia, Casuarina Cunninghamiana and Casuarina Glauca and a hybrid between the last two species (Brewbaker et al. 1990). The three types are differentiated through the branch of the Casuarina tree, as the pine needle branch of the Cunninghamiana is thin and less than 20 cm. The branches of the Glauca are thick and more than 20 cm and marked by 10-18 lengthwise ridge. Finally, the Equistifolia’s branches are also more than

20 cm and marked by a 6-8 lengthwise ridge (Zhong et al. 2013). They are used for different purposes such as windbreaks, firewood, charcoal, shelterbelts and its timber can be used in flooring due to its durability (Parrotta, 1993). In addition, it can be used in different construction purposes such as (beams, fences and poles), soil improvement due to their high nitrogen fixation abilities and it can be used in leather dying and fishing nets as the bark of Casuarina tree is rich of tannin material (Wilson & Johnson, 1989). One of the unique features of Casuarina is that it can grow in a very poor soil such as sandy and dry soils, soils with free drainage and soils that lack nutrients and tough climate conditions where the majority of other tree species cannot handle (Parrotta, 1993). Another impressive feature of Casuarina that it can grow on wastewater that contains a large number of contaminated micro-organisms and other deadly poisons such as arsenic and cyanide. (Sayed, 2003). Casuarina trees can adapt themselves in places with low fertility or high salinity (Zhong et al. 2013). Casuarina trees are characterized also by their high reproductive ability through the wind sprinkled seeds that can grow to form dense seedling banks (Wilson & Johnson, 1989). The disadvantages of Casuarina tree that it is not classified as a long-lived tree with an average age of 12 years while long-lived trees live beyond 50 years. Casuarina could be difficult to guarantee a long fire resistance duration without external protection; having an average charring rate of 0.60 mm/min (Fonseca, 2009). It is also characterized by its low coppicing ability and not always a good choice for carving as its heavy and hardwood (Parrotta, 1993).

Nowadays Casuarina is classified as one of the heavily grown trees in Egypt and a research program was established in 1975 to deduct the basic properties of Casuarina wood. According to a study done by (Brewbaker et al. 1990), Casuarina Equistifolia can be identified from Glauca and Cunninghamiana through the number of vessels per mm². The research program conducted the average fiber length for the Casuarina Glauca and Casuarina Cunninghamiana and their hybrid to be 0.97, 0.81 and 0.95 mm respectively. The Average Specific Gravity for the Casuarina Glauca and Casuarina Cunninghamiana and their hybrid were resulted to be 0.578, 0.528 and 0.509 respectively.

Meanwhile, the research performed on the mechanical properties and possible structural applications of Casuarina wood is scarce. The main objective of this thesis is to cover this research gap through studying the mechanical properties of Casuarina tree in order to rank it among the other types of hardwoods as no study was done on this type of wood and it was recommended by (Brewbaker et al. 1990) to direct some effort on studying the mechanical properties of Casuarina. The results from this thesis may be used in using Casuarina as a replacement for some common types of wood based on its mechanical properties and cost.

1.3. Problem Statement

Egypt is considered the biggest softwood importer in the middle east region as it imported more than 5,000,000 m^3 of softwood in 2015; that were used in different industries such as construction forming, scaffolding, furniture, roofing and manufacture of doors and windows. (ElShal, 2017) The amount of the foreign currency paid for the imported wood is so huge.

Casuarina is one of the most growing trees in Egypt that was classified by (FAO, 2010) the most important tree. Although Casuarina is used in Egypt for several purposes such as wind breaks, shelter belts, the mechanical properties of Casuarina was never tested before.

Using Casuarina in any of the wood industries can achieve economic and construction benefits and reduce the amount of the foreign currency needed to be paid for importing huge amounts of wood; to reduce the gap between wood production and consumption in the Egyptian market.

1.4. Objectives

The main objective of this thesis is to test the mechanical properties for two types of one of the most locally growing types of wood in Egypt (Casuarina Glauca and Casuarina Cunninghamiana) in order to use it as an alternative to the imported woods used in different industries, design and experimental test of formwork made of Casuarina Glauca as a structural use.

The main objective can be divided into the following:

1. Test the mechanical properties of both Casuarina species according to the ASTM standards.
2. Compare the mechanical properties of the Casuarina wood to the other types of hardwoods in order to rank it.

3. Investigating the moisture content effect on the mechanical properties of Casuarina wood.
4. Constructing a girder made of Casuarina Glauca and test it under bending as a structural application for a formwork beam.

1.5. Research Methodology

This section illustrates the methodology followed in conducting this research. Figure 4 shows a flow chart that describes every step in the research methodology starting with the introduction that briefly introduces wood and casuarina, then it is followed by the literature review that discusses the history of wood in construction and the different types of wood used in construction then a detailed literature about formworks. Then it is followed by an experimental program testing the mechanical properties of casuarina wood. Then it is followed by a model truss formwork construction and testing as a structural application for casuarina wood. then the experimental work conducted on this research and then conclusions and recommendations.

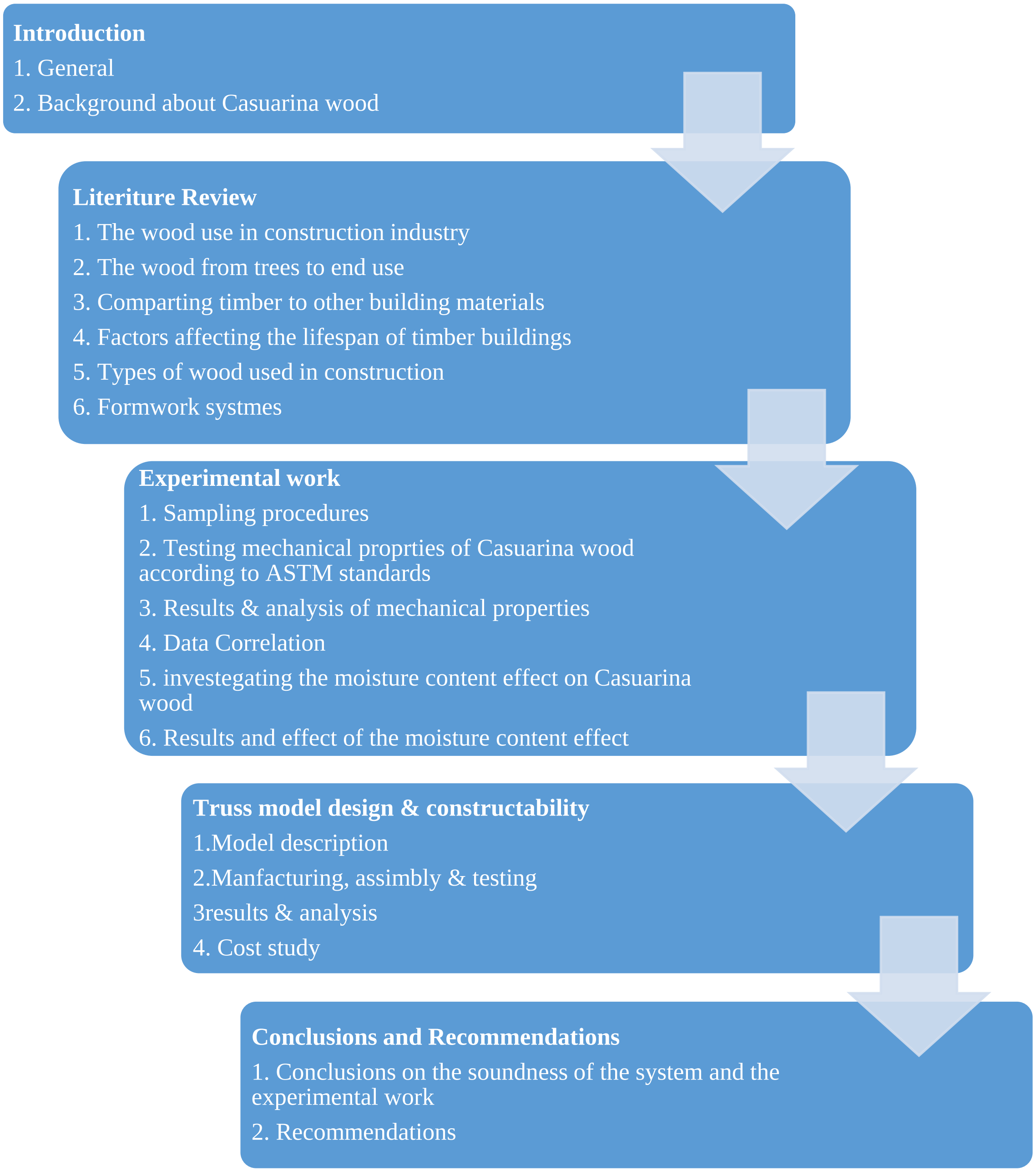


Figure 4: Research Methodology Flow chart

1.6. Thesis Organization

This thesis is organized into five chapters as illustrated below:

Chapter One: Introduction

This chapter provides a simple introduction to wood, wood classifications and the factors that affect the strength of wood followed by a background information about casuarina wood, the origin of casuarina and its characteristics. This chapter also states the problem statement, the thesis objectives, research methodology and thesis organization.

Chapter Two: Literature review

This chapter presents the literature review for this research which includes the history of wood in construction, the process of transforming the wood from trees to the end use, comparing the wood to the other building materials, the types of wood used in construction and the wood in Egypt. This chapter also discusses the different horizontal formwork systems, the objectives to be considered when designing formworks, the formwork different materials and the failure causes of formworks.

Chapter Three: Mechanical properties experimentation

In this chapter full experimental program was conducted to test the mechanical properties of both casuarina wood species according to the ASTM standards, comparing casuarina wood to the other hardwoods, testing the moisture content effect on the mechanical properties of wood and conducting a data correlation analysis.

Chapter Four: Casuarina truss design, manufacturing and experimentation

In this chapter a model truss formwork was constructed and tested as a structural application of casuarina wood

Chapter Five: Conclusion and Recommendations

It includes the conclusion from experimental work. It also presents the recommendations and the proposed future research related to this thesis.

Chapter 2 : Literature review

2.1 The wood use in the construction History

2.1.1 Wood used in the construction of the ancient buildings

According to (Frazer,1980) wood have been used as a building material by the ancient Egyptian civilization and the area around the Mediterranean Sea. The Egyptians used the wood and the mud from the Nile river to build the first houses and to build the one room huts, then the ancient Egyptians started to use the bricks to build better houses not only for the durability of the bricks but also because in Egypt there were not any forests and wood was not available except from some trees such as palm and acacia. (Frazer,1980). At the time of Ramsis I and II the ancient Egyptians imported cedar wood to use it in the building for larger construction as the funeral temple.(Frazer,1980). It is believed there are other buildings in that era that were made from wood the Maya culture center. (Frazer,1980). The Sudanese of the Indian archipelago also used wood to build their houses. (Frazer,1980). The ancient Mediterranean also used imported cedar from northern Syria to build their public buildings (Frazer,1980). The ancient Scandinavians also used wood to build their huge temples. (Frazer,1980).

2.1.2 Wood used in construction during the middle ages

In the middle ages people relied on stone and other building materials more than wood due to the lack of knowledge of using wood and wood was only used for the buildings roofs and ceilings such as the Christian churches in Italy during the tenth century. (Waterhouse,1924). Many college halls in England also used timber roofs such as Wolsay hall (Jackson,1975) but the finest wooden roof was built during Richard IItime for the Westminster hall building (Warehouse,1924). An attractive use of wood in construction is the pilings of buildings in Venice that were built using more than 12,000 piles made of Elm wood and these piles were not destroyed by water. (Jackson,1975).

2.1.3 Wood used in construction from the Renaissance to the modern period

From the beginning of the renaissance period wood started to be used in the interior finishing and decorations instead of using it for ceilings and roofs. One example of the renaissance architecture is the cathedral of Mexico City that was built from marble and plaster while the wood was used for the interior finishing using cedar and mahogany wood. (Jackson,1975). In the past 70 years a lot of materials were introduced as building materials. Wood started to be used extensively in building houses especially in north America as the typical single house consisted of wooden floors, wooden partitions, plastered walls and ceilings, wood frames and more wood were used for paneling and slab doors. From the beginning of the 1990's wood started to be a common used structural material. In north America about 90% of the residential buildings are based of the lightwood frame construction and about 60% of the sawn wood were used structurally in 1994. (Jackson,1975). The use of wood was not limited to the residential buildings and it was used in more complex structures as the glulam roof trusses for the three winter Olympics stadiums in Norway in 1994. (Jackson,1975).

2.2 The wood from Trees to the end use

2.2.1 Wood structure

The trees have different growth rates which differ from one specie to another moreover the environment affect, the growth rate of the same specie and the wood properties of the tree. For example, the Sitka spruce tree can reach a height from 40-70 m in north America but in a milder condition as in the United Kingdom it reaches a height from 16-23 m but with a faster growth rate and a lower density of wood. (Moore et.al 2009). The wood from trees contain rings that reflect the growth rate of the tree and called annual rings. In the spring, the rapid growth happens and the wood produced is called Earlywood which consists of large cells and thinner walls allowing the water to pass through so its density is low. The next period is characterized by a slower growth rate with smaller cells and a higher density wood called latewood and the annual rings contain the early wood and the late wood. (Jagels,2006). Figure (5) shows a tree cross-section.

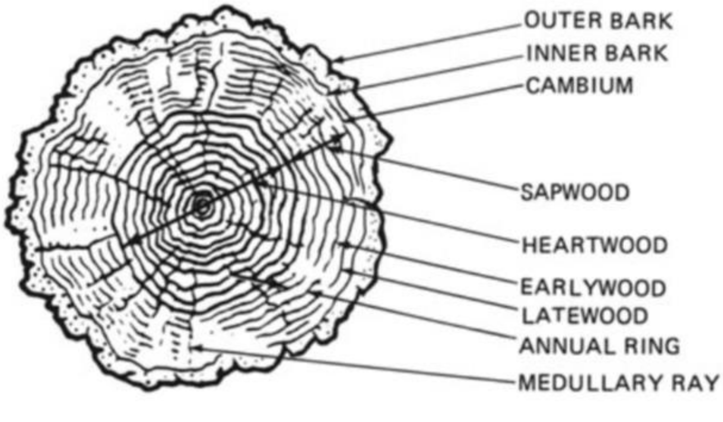


Figure 5: Tree cross-section. (Stalnaker & Harris, 1997).

2.2.2 Wood Processing

The wood processing is the most important process for using the timber produced from forests. The first step is to harvest the wood by cutting the trees, removing the branches, cutting the trunks in standard sizes for transportation. The wood from the harvesting step is called round-wood. (Ramage et al., 2017). It is well known that timber has a lot of variations even that the wood from the same species and sample may have different properties so in order to use the timber in structural and construction purposes there is an important step called strength grading must be done to strength class the timber. (Ramage et al., 2017). The strength grading has two types either visual or machine strength grading. The visual strength grading is done by visualizing the weak features such as knots, splits or deflections while the machine strength grading is done by feeding timber through a set of calibrated rollers to test some of its characteristics such as: stiffness and density, then the wood is classified according to a standard scale and sorted from the weakest to the strongest. (Ramage et al., 2017).

There are also structurally building materials called engineered timbers. The engineered timber is a wood composites from laminated timber and adhesives. The engineered timber has a higher durability and dimensional stability. The engineered timbers have a lot of families such as Glulam, cross laminated timber, structural veneer lumber and laminated veneer lumber. (Ramage et al., 2017).

2.2.3 Wood drying

Wood is a natural material that can be affected by fungi degradation so it has to be dried before using it especially in construction purposes. There are several ways to dry timber using a microwave or a solvent or using the supercritical Co2 drying or by using some techniques such as: kiln drying or convective drying which means providing controlled heating, circulation, humidification and ventilation inside an enclosed structure. (Ramage et al., 2017)

2.2.4 Wood treatment

Wood treatment is a very important step that must be done before using wood for construction purposes. Since wood is a natural material and it is not acceptable to degrade during using it in construction services so the durability of wood can be improved by physical or chemical treatments. (Ramage et al., 2017). Figure (6) shows the different techniques used for wood treatments.

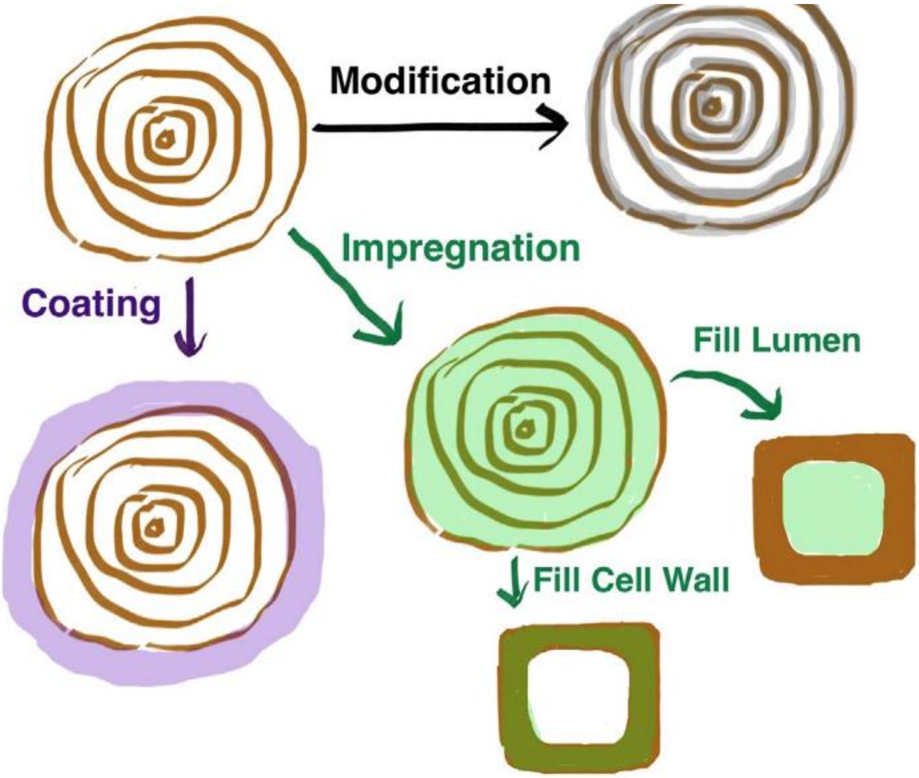


Figure 6: Wood treatment techniques (Ramage et al., 2017).

2.2.5 The wood flow map

The wood flow map shows the wood flow from its original source then the different processing processes to the end use product for different industries. This map facilitates the sustainable use of wood by showing where the wood products are used. (FAO,2015). The first segment of the map illustrates the forests classification, the second segment focuses on the collection and harvesting of the wood products from forests and the third segment shows the wood processing and how the primary wood from trees is transferred to end use products to be used in several industries.

2.3 Timber as a structural material compared to other materials

From the beginning of the 20th century timber started to be used as a building material. At the beginning, it was used in building the small buildings especially in Europe and north America. (Ramage et al., 2017). According to (Ramage et al., 2017) 20% of the new houses in the United Kingdom are built from timber and in Scotland it reaches 60%. Nowadays there are three main materials that are used in the construction of large structures which are: reinforced concrete, steel and timber.

Comparing timber to reinforced concrete we could find that both materials have almost the same strength parallel to the grain as the hardwood is slightly stronger and softwood is slightly weaker but still timber cannot be compared with the high strength concrete technologies in compression. Timber is less stiff than concrete and steel and has a lower density. (Ramage et al., 2017).

By the beginning of the past decade timber have been used in building high rise buildings but not any type of timber was used. The approach of using timber in high rise buildings was done using specifically the cross laminated timber. In case of the low-rise buildings, there are low forces to be resisted so the lateral loads are resisted by bending stresses in walls that form a vertical cantilever. (Ramage et al., 2017). Forming a core using this wall to increase its efficiency by loading the outer walls of the core in tension and compression. (Ramage et al., 2017). Another system can be used in case of a taller building as used in 14-storey building in Norway where the interior core Is replaced by a frame around the building to load all the member uniformly in tension and compression. (Ramage et al., 2017).

2.4 Factors affecting the lifespan of timber in buildings

2.4.1 Durability

One of the most critical factors that affect the wood durability is the decay by fungi and insects. (BSI,2015).

2.4.2 The fire resistance

Timber loses about 50% of its strength and stiffness when the temperature rises from 20 ^{o}c to 100 ^{o}c. (BSI,2015). At the same time timber still perform better at high temperatures than steel due to the presence of the char layer while steel has a high thermal conductivity which means it will quickly heat up. (UKTFA,2013). In the buildings using cross laminated timber this is done by assuming chars rate for timber then the cross section of the timber will remain after the given time. (Wells,2011).

2.4.3 End of life scenarios for wood

It is advisable that the wood used in construction sector to have more than 30 years of life span then the wood used in building can be reused as a wood plastic product. (Pearson, 2012). One application of the wood plastic products is the wood panels produced from high density polyethylene plastic waste. (Youssef et. Al, 2019)

2.5 Different types of wood used in construction

Softwoods

Cedar

Cedar wood is a reddish-brown wood that has a lot of characteristics that enables it to be used for the construction purposes. It is characterized by its light weight and the ability to resist insects and fungi attack in addition to its good density. Cedar is mainly used for wall coverings and landscapes. (Stalnaker & Harris, 1997).

Cypress

Cypress wood is characterized by its ability to resist the extreme wet conditions thus does not rot easily. Cypress wood is found mainly in north America and used in building construction decks. (Stalnaker & Harris, 1997).

Fir

Fir wood is one of the most types of wood used in construction. It is used to produce plywood, lumber and used in fencing. Quarter of the lumber production in north America is produced from the Douglas fir wood. Fir is a reddish-brown wood that is found in north and central of America, Europe and north Africa. It is characterized by its low resistivity to decay. (Stalnaker & Harris, 1997).

Hemlock

Hemlock is a light weight, average strength wood with a low resistivity to decay. Hemlock is find mainly in north America, Canada and England. It is not preferred to be used a lot in construction as it is full of knots but it still used in landscaping and as pulpwood in rail road construction and the construction of lumber, doors and subflooring. (Stalnaker & Harris, 1997).

Pine

Pine is a white wood that have been used expensively in construction as it is cheap, light in weight and resists swelling and shrinkage. Pine is found mainly in India and have been used in a lot of construction projects from craft to home construction. (Stalnaker & Harris, 1997).

Spruce

Spruce is a lightweight, strong and hardwood with low resistivity to decay. Spruce is found mainly in north America, Canada, Asia and Europe. There are more than 35 species of spruce wood and it is used mainly in the housing projects. (Stalnaker & Harris, 1997).

Hardwoods

Ash

Ash is a heavy hardwood that have high resistance to splintering and breaking under pressure. It is well known with its high strength and elasticity values. Ash wood is not expensive and its commonly used in building structural frames. (Stalnaker & Harris, 1997).

Balsa

Balsa is a light weight wood that can be shaped and glued easily in addition to its ability to absorb shocks and vibration. It is found mainly in north and south America. It is used to build structural models (such as bridges) in the design and testing phase. It is also characterized by its high strength although it has a relatively low density. (Stalnaker & Harris, 1997).

Beech

Beach is a heavy strong hardwood. It is not expensive and it is catheterized by its high resistance to splitting. It is commonly found in north America, Asia and Europe and used in plywood, flooring and in frames. (Stalnaker & Harris, 1997).

Oak

Oak is a strong, durable hardwood that resist the organic and insects decay and also has the ability to resist moisture. Oak is used mainly in building structural elements such as frames, trusses, beams and pillars and it is also used in flooring. Oak is commonly found in north Africa, Europe and Asia. (Stalnaker & Harris, 1997).

Maple

Maple is a strong hardwood with a fine texture and high durability. Maple is commonly found in north America, Europe, north Africa and India. Maple has high resistivity to splitting and shock and it is used mainly in the pathways construction and finishing. (Stalnaker & Harris, 1997).

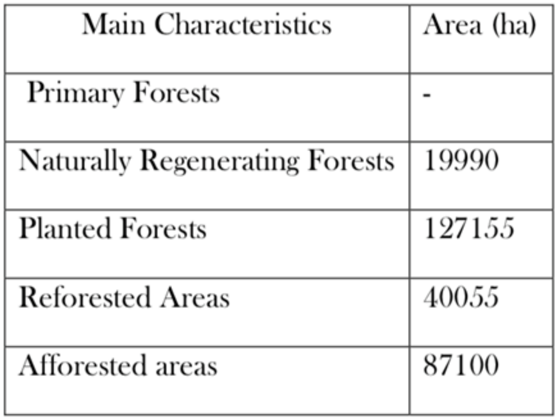
Elm

Elm is a strong hardwood and it is characterized by its wide variety of colors and its high resistivity to splitting. it is used mainly for flooring and landscaping. (Stalnaker & Harris, 1997).

2.6 Wood in Egypt

Due to the geographic location of Egypt and its climate there is no primary forests found. The forests in Egypt are regenerated occupying area of 19,990 Hectares and exists in two locations: The first location is Gebal Elba occupying area of 19,600 Hectares and the second location is called Mangroves and it is located in the red coast and occupying area of 390 Hectares. (FAO,2010). The growing trees and shrubs in the Egyptian forests is around 8,000,000 m3 producing around 268,000 m3 of the industrial wood production while the consumption is about 384,000 m3, so the difference in the demand is imported from outside. (FAO,2010). The consumption vs. the demand is a common problem in the majority of the wood products. The sawn wood production is around 2,000 m^3 while the consumption is about 1,465,000 m3, so again this gap is imported from outside. (FAO,2010). The planted trees can be classified into four main categories: Governmental or public farms, Public utilities, Plantation forests and Agroforestry systems. (FAO,2010). Table (1) summarizes the forests characteristics and areas in Egypt.

Table 1: Forests characteristic and Areas in Egypt. (FAO,2010).



Main Characteristics	Area (ha)
Primary Forests	-
Naturally Regenerating Forests	19990
Planted Forests	127155
Reforested Areas	40055
Afforested areas	87100

The imported planted trees in the plantation forests are Casuarina Glauca, Casuarina Cunninghamiana and Dalbergia Sisso. The trees in the Agroforestry systems is used mainly as a windbreak such as: Casuarina Glauca, Casuarina Cunninghamiana and Acacia Saligna. The most important trees of the public or the private utilities are Casuarina Glauca, Casuarina Cunninghamiana and Delonix Regia. (FAO,2010). Due to the weather conditions in Egypt where the rain is rare, the cost of tree planting is expensive in terms of irrigation system and land value, so it is so difficult for the individuals to pay for it in addition to using a fresh water for irrigation which is another problem. (FAO,2010).

In the past years, the interest of forest plantations has increased especially with using the treated sewage water for irrigation. The idea of using the treated sewage water has many benefits such as: there were a lot of difficulties in disposing it, increasing the number of forest plantations to be used and decreasing the gap between the wood production and consumption, thus reducing the amount of wood imported from outside. (FAO,2010)

According to the (FAO,2005) Casuarina tree with its two types Glauca and Cunninghamiana is considered the most important tree in Egypt for several reasons such as; its multipurpose, fast growing rate, suits the climate conditions in Egypt, it can be used as a wind breaks and shelterbelts, reduce the noise pollution in big cities and the most important fact about this tree that it overcomes a lot of soil difficulties (Salinity, drought and nutrients). (FAO,2005). There are several trees species that grow in Egypt but cannot be considered as promising as Casuarina such as: Eucalyptus Camaldulensis, Acacia Saligna, Cupressus Sepervirens, Khaya Senegalensis and Tamarix Aphylla. (FAO,2010). Figure (7) shows Casuarina tree in Egypt.

Figure 7: Casuarina trees planted in Egypt (Almahallawi, 2015)

Egypt started to use the treated sewage water in forests plantation in 1995. In 2000 the treated sewage water was 6.3 billion m3 and reached about 8.3 billion m3 in 2017. The disposal of such amount was so dangerous and risky to the environment and human especially that previously it was disposed in seas and rivers. The ministry of agriculture has established 24 forest plantations in different locations using the treated sewage water. The most common species planted in these forests are: Casuarina Glauca, Casuarina Cunninghamiana, Acacia Saligna and Salix Safsaf (FAO,2010). Figure (8) shows the location of the forests planted using treated sewage water in Egypt.

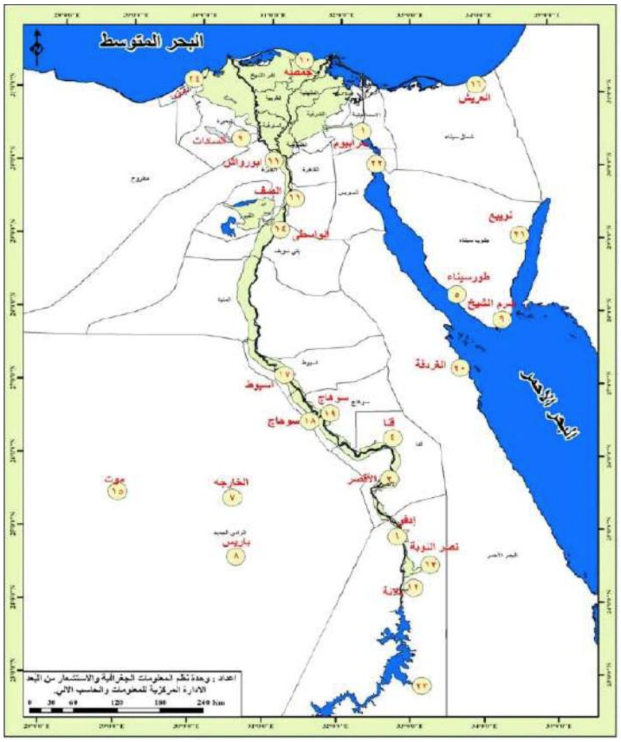


Figure 8: Forests plantation using treated sewage water locations in Egypt. (Almahallawi, 2015).

2.7 Formworks

2.7.1 Introduction

Formwork can be described as a temporary structure that is used to mold and support the fresh poured concrete to the desired shape and size and at the same time control its alignment. The formwork structure must be able to withstand the dead load of the concrete and reinforcing steel in addition to the live load of the labor and equipment without collapsing. The process of removing the formwork is called stripping so that it can be reused again. According to (Krawczyńska-Piechna, 2016) the cost of formwork ranges from 30-40 % of the cost of the concrete structure and from 60-70% of the construction time so any optimization in designing the formwork may be reflected as cost and/or time savings.

2.7.2 Form work systems

Formwork systems can be classified into two main categories: Horizontal formwork and Vertical Formwork system. The horizontal formwork system is used to form concrete elements which is placed horizontally such as slabs and the vertical formwork system is used to form concrete elements which is placed vertically such as columns. (Oberlender and Peurifoy, 2010). This thesis will focus on the horizontal formwork systems.

According to (Hanna, 1999) the horizontal formwork system is classified into two main groups: Hand set systems and Crane set systems. In the hand set systems, the formwork elements can be handed be one or two labors while in the crane set systems the formwork elements must be handed using a crane. The Hand set systems are the conventional wood system, conventional metal system, joist forming system and dome forming system. The crane set systems are the Flying formwork system, Column mounted shoring system and tunnel form work system. Figure (9) summarizes the horizontal formwork classification.

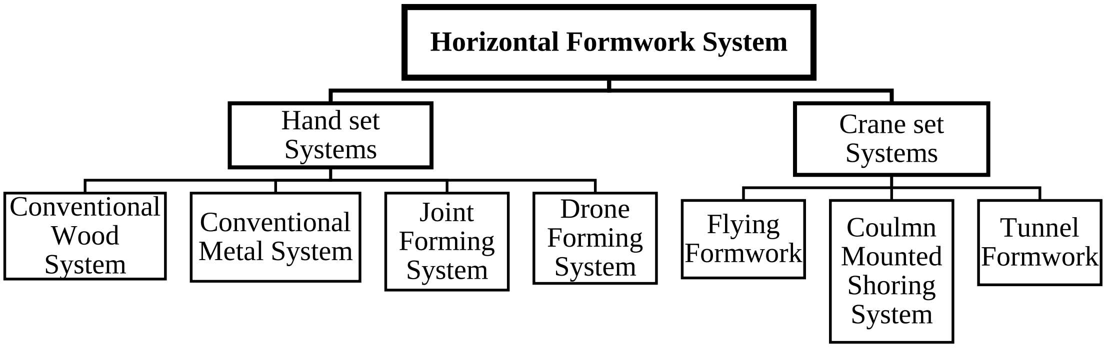


Figure 9: Horizontal formwork systems. (Hanna,1999).

The Conventional wood system

It is the most common type used formwork system and it consists of four main elements which are Sheathing, Joists, Stringers and shores in addition to the lateral bracing. The sheathing material is usually made of plywood or lumber and it acts as a mold shaping the concrete. The joists are the horizontal members that support the decking system and transfer the load to the stringers. The stringers are the horizontal members placed perpendicular to the joists. The role of the stringers is to support the joists and transfer the load into the shores. The shores are the vertical posts that supports the joists, stringers and the decking system and transfer the load into the ground through resting on a heavy timber call mudsill. The last element is the lateral bracing of the system which is used to withstand the lateral loads such as the wind and increase the capacity of the shores by decreasing the unsupported length. (Nawy, 2008). The Conventional wood formwork system is shown in figure (10).

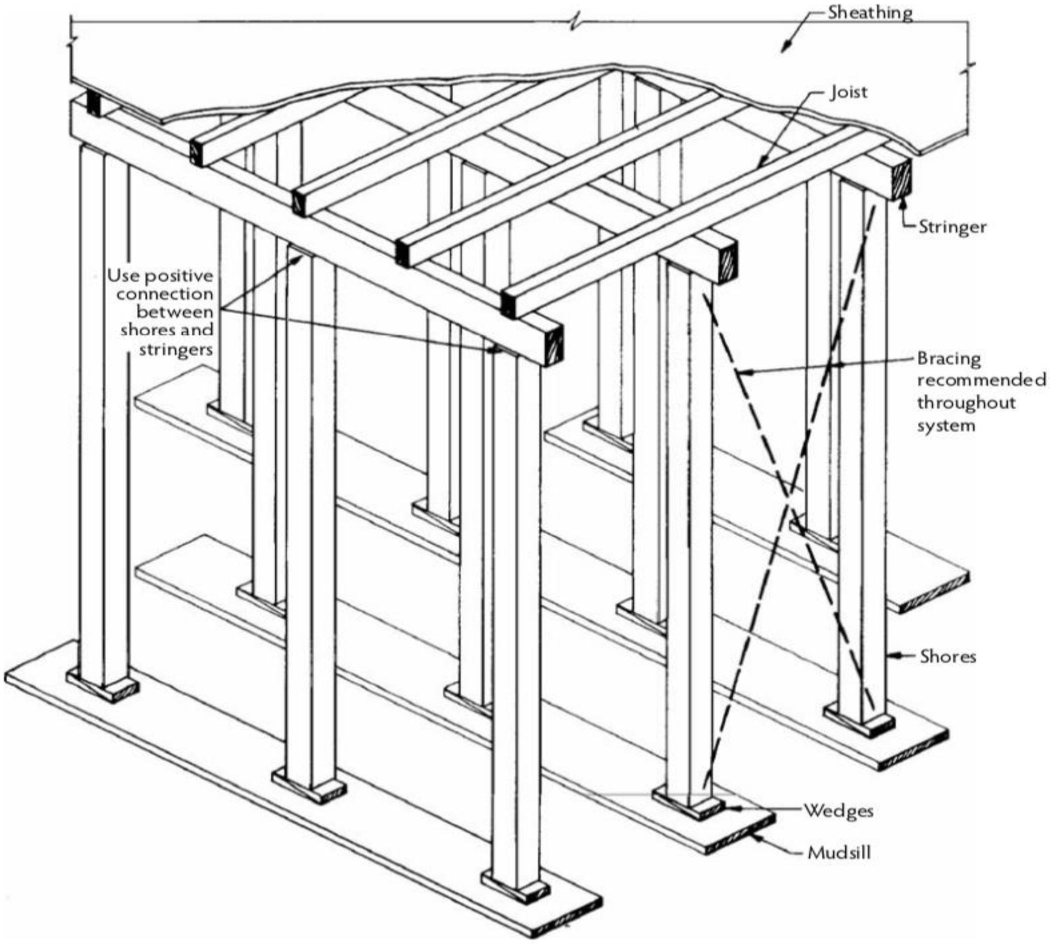


Figure 10: The Conventional wood formwork system (Hurd,2005)

The Conventional metal system

The formwork elements of the conventional metal system are similar to the conventional wood system but different materials are used. There are two types of the conventional metal system, In the first type the joists are made of wood or laminated wood and the stringers are made of steel while the shores are made of aluminum props. In the second type of the conventional metal system the joists and stringers are made of steel while Aluminum scaffolding or steel is used for the shores. (Hanna,1999). The Conventional metal system is shown in figure (11).

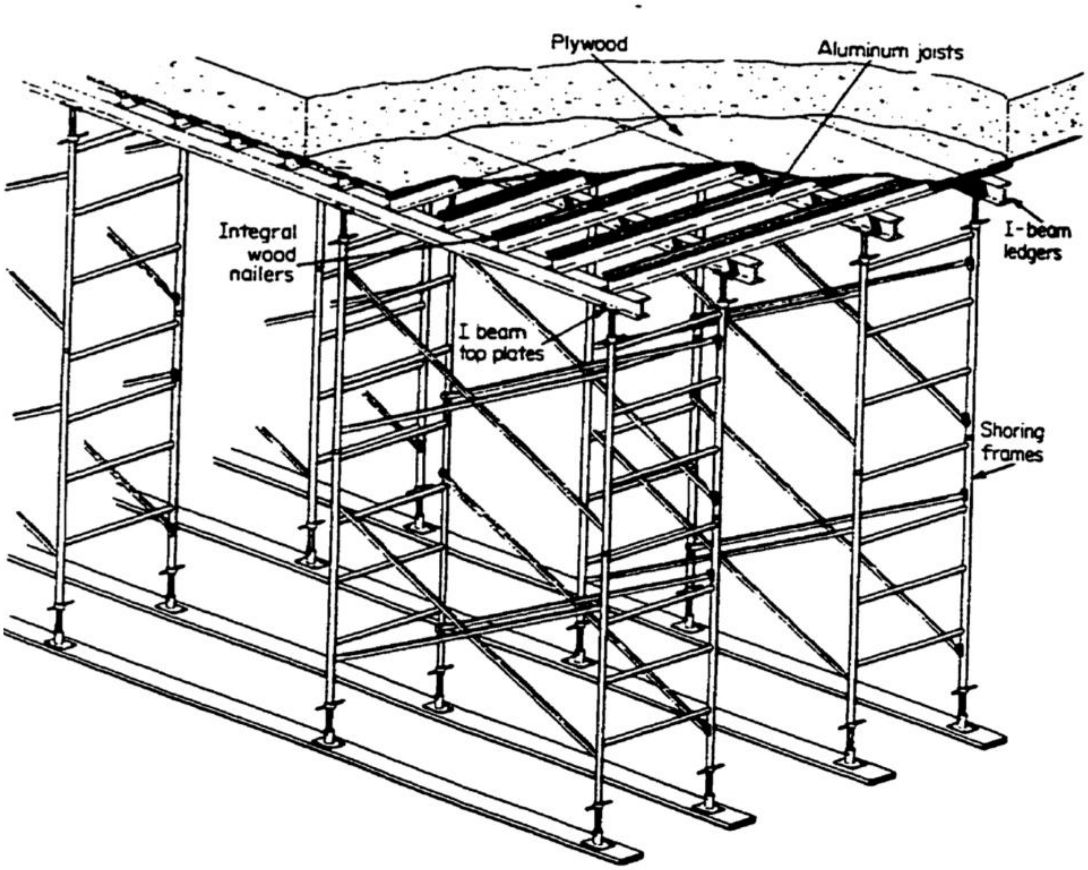


Figure 11: The Conventional metal formwork system (Ratay,1996)

Joist slab forming system

The joist slab forming system is used for the one-way joist slabs. The joist slab consists of spaced joists that are uniformly spaced in one direction with maximum distance 75mm and thin cast in place slab. The one-way joist slab is formed by steel pans which is supported by a support member. The support member is supported on a perimeter member which transfer the load to the shoring system. (Nawy,2008). The joist slab forming system is shown in figure (12)

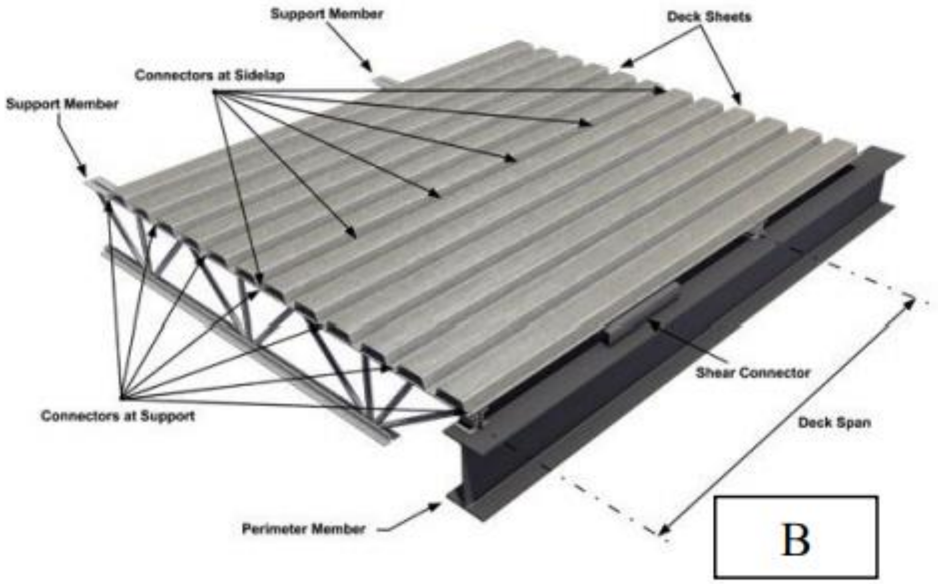


Figure 12: The Joist slab forming system
(https://www.pinterest.com/pin/558587160019674402/)

Dome forming system

The dome forming system is used usually for the construction of the waffle slab or the two-way joist slab. The formwork system can be either made of metal or wood while the sheathing is made of steel domes. The dome system is available in 2ft and 3ft standard sizes. (Oberlender and Peurifoy, 2010). The Dome forming system is shown in figure (13)

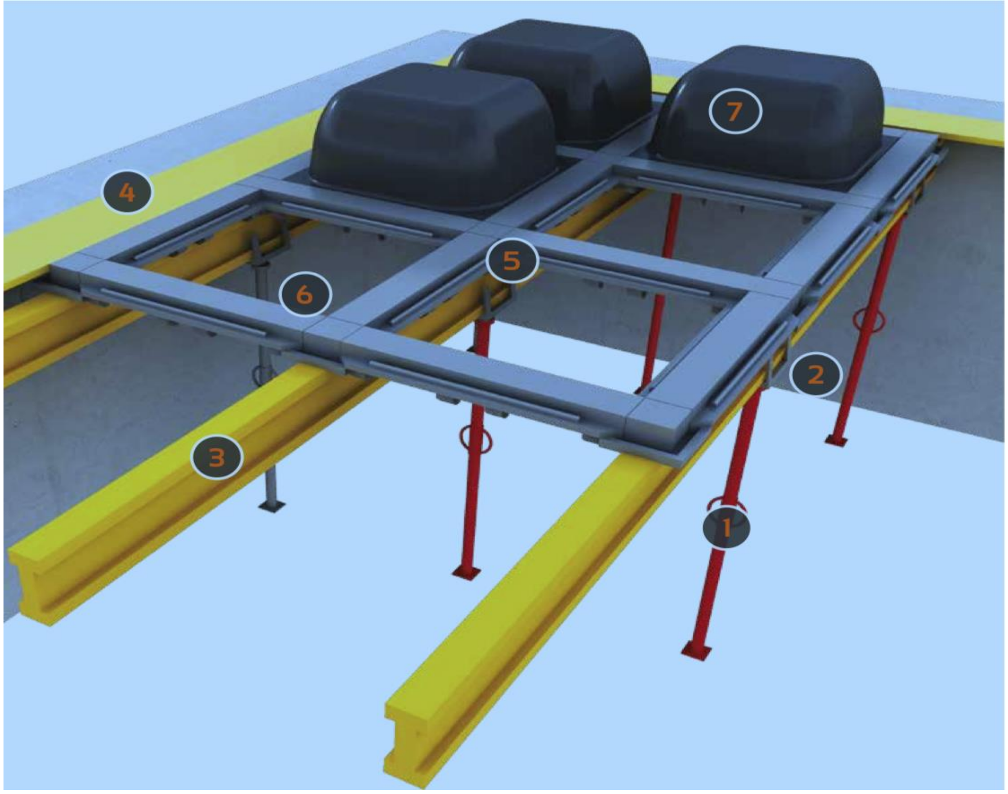


Figure 13: The Dome forming system (http://geotoday.lt/uploads/catalogs/skydome.pdf)

Flying formwork

The flying formwork or the table formwork is considered as an advanced type of formworks that is used to reduce the labor cost resulting from erecting and removing the formworks especially in the high-rise buildings and offer quick installation for construction. This type of formworks can fly from floor to floor using a crane so it is named as a flying formwork. The flying formwork consists of a plywood or ply-form sheathing panels. The sheathing is supported by aluminum joists. The joists can be either I-beam or symmetrically wide top and bottom flanges. The sheathing and joists are supported on aluminum trusses that have adjustable vertical extension legs in order to support the trusses and transfer the load into the ground. (Hanna,1999). The flying formwork system is shown in figure (14).

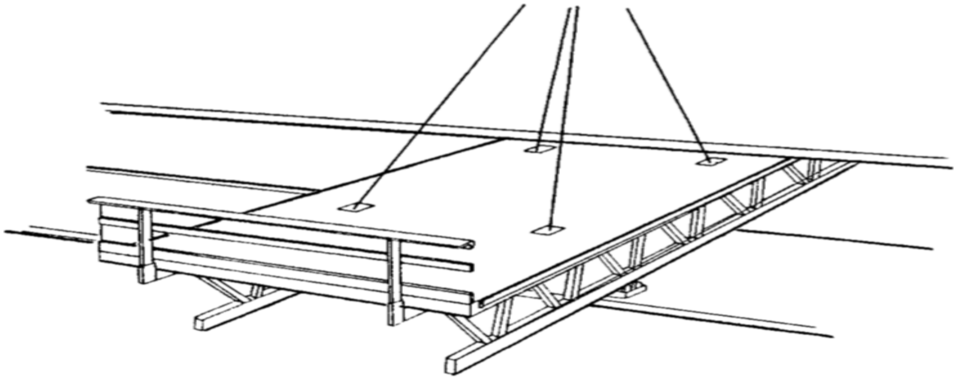
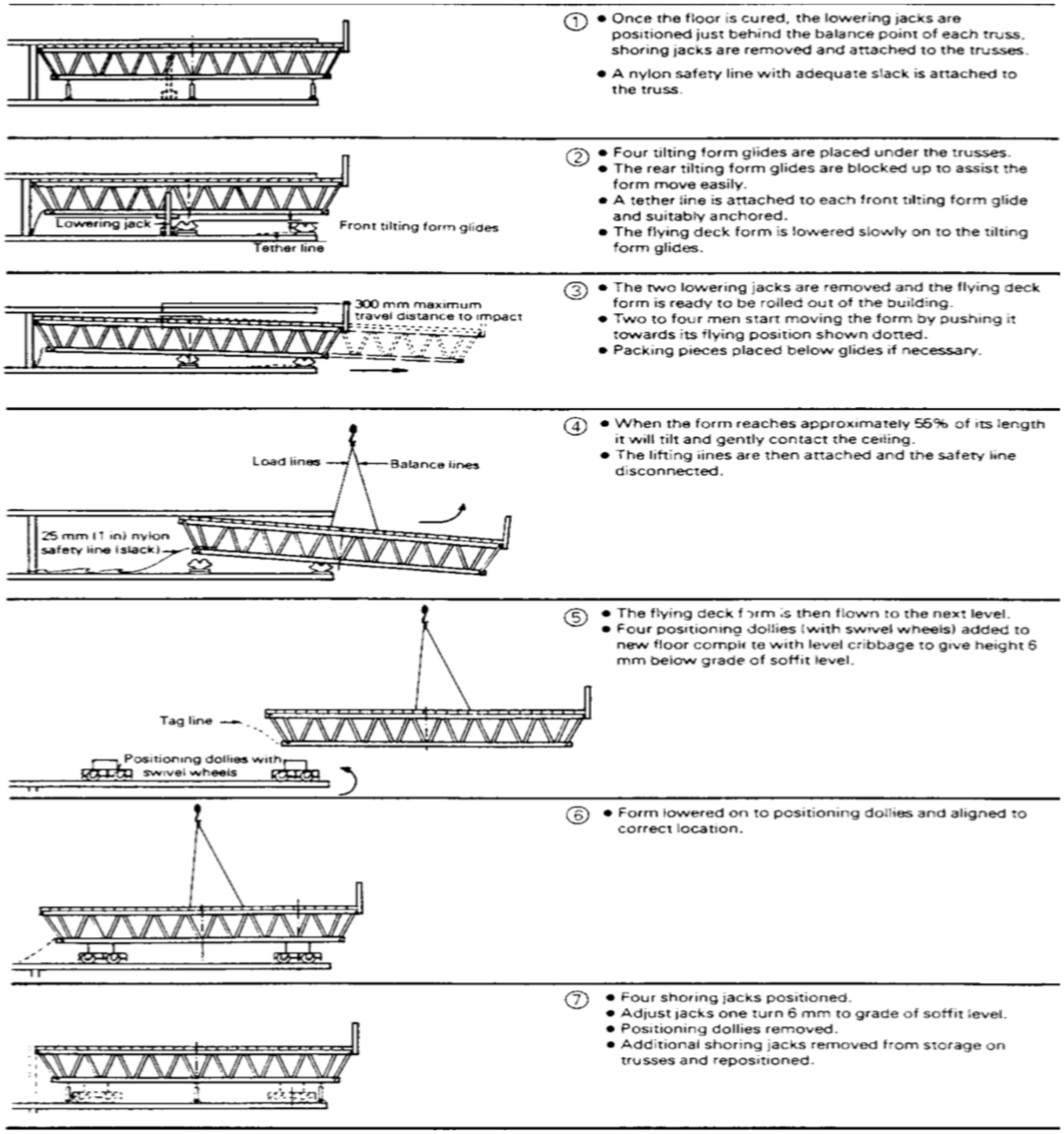


Figure 14: Flying formwork system (Oberlender and Peurifoy, 2010)

The cycle of the flying formwork consists of six steps. The first step is the assembly of the form at the ground level then lifting the formwork system to the required level using a crane. The second step is placing the formwork to its exact location using moveable dollies. The third step is placing the formwork assembly under the new slab and adjusting its height then fastened the system with the similar modules. The fourth step is when the concrete maintains the desired strength the form assembly system is lowered down using hydraulic jacks placed under the formwork system. The fifth step is to tilt and pull out the formwork system to the slab edge using the movable dollies. The sixth step is tilting the formwork system then raising it to the upper floor to be used again. (Hanna,1999), The cycle of the flying formwork is shown in figure (15).



①
- Once the floor is cured, the lowering jacks are positioned just behind the balance point of each truss, shoring jacks are removed and attached to the trusses.
- A nylon safety line with adequate slack is attached to the truss.

②
- Four tilting form glides are placed under the trusses.
- The rear tilting form glides are blocked up to assist the form move easily.
- A tether line is attached to each front tilting form glide and suitably anchored.
- The flying deck form is lowered slowly on to the tilting form glides.

③
- The two lowering jacks are removed and the flying deck form is ready to be rolled out of the building.
- Two to four men start moving the form by pushing it towards its flying position shown dotted.
- Packing pieces placed below glides if necessary.

④
- When the form reaches approximately 55% of its length it will tilt and gently contact the ceiling.
- The lifting lines are then attached and the safety line disconnected.

⑤
- The flying deck form is then flown to the next level.
- Four positioning dollies (with swivel wheels) added to new floor complete with level cribbage to give height 6 mm below grade of soffit level.

⑥
- Form lowered on to positioning dollies and aligned to correct location.

⑦
- Four shoring jacks positioned.
- Adjust jacks one turn 6 mm to grade of soffit level.
- Positioning dollies removed.
- Additional shoring jacks removed from storage on trusses and repositioned.

Figure 15: The Flying formwork cycle (Oberlender and Peurifoy, 2010)

Column mounted shoring system

The column mounted shoring system consists of two main components: A deck panel and a column or wall mounted bracket system. Figure (16) shows the main components of the column mounted shoring system. The deck panel consists of plywood sheathing supported by a system of wooden joists and a nailer type open stringer to allow the wooden section to be inserted into the open web. The joists and stringers are supported on a truss system steel I-beams which run all the sides of the deck panel. The I-beam rests on column mounted jacks anchored in the concrete columns so no shoring is needed in this system as shown in figure (17).

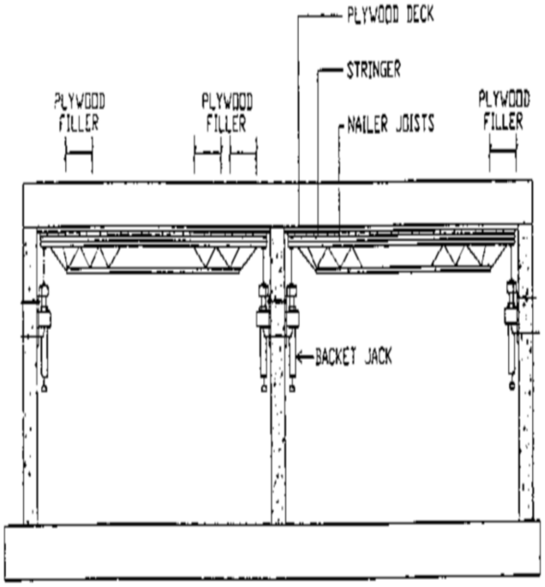


Figure 16: The column mounted shoring system components (Hanna,1999)

Figure 17: The column mounted shoring system (https://www.formwork-exchange.com/index.php?option=com_content&view=article&id=161:60a-50k-and-70k-jacks&catid=55:60-flying-column-mounted-shoring&Itemid=168)

The cycle of the column mounted shoring system consists of three steps; The assembly of the deck panel, positioning of the deck panel and stripping the deck panel. The deck panel is either assembled at the site or preassembled in factory. The assembly of the deck panel is done by bolting the trusses to the flange I-beam then the wooden joists are placed and attached to the joists. The positioning of the deck panel starts by lifting the deck panel with a crane and lowering it to a pre-marked elevation on the face of the column or the wall then the deck panel is rested on a bracket jack system. The positioning of the deck panel ends by adding some fillers to fill the gab above the concrete columns. The stripping of the deck panel starts after the concrete maintains enough strength to support its own weight. The stripping process begins by lowering the jack system then pulling out the deck panel using the crane to be used again for the next floor. (hanna,1999)

Tunnel formwork system

The tunnel formwork system is used in the buildings with repeated architectural details such as rooms. The main function of using this system is it allows the vertical and horizontal elements (walls and slabs) to be casted at the same time thus achieving time and cost saving. The tunnel formwork consists of five components. The first component is a deck steel panel that form the ceiling and the floor of each module. The second component is wall steel panel that form the walls between the adjacent modules. The third component is a stiffer deck called the waler and waler splices used to reduce the deflection resulted from the concrete lateral pressure. The fourth component of the tunnel formwork system is a diagonal strut assembly used to keep the walls and floor perpendicular and also used as an additional support for the floor slab. The fifth component is a wall tie between forms of two adjacent tunnels to keep the forms in place while placing the concrete. The last component of the tunnel formwork system is wheel jack assembly to allow the labor to move the form before being pulled by the crane. (Hanna,1999). Figure (18) shows the tunnel formwork system.

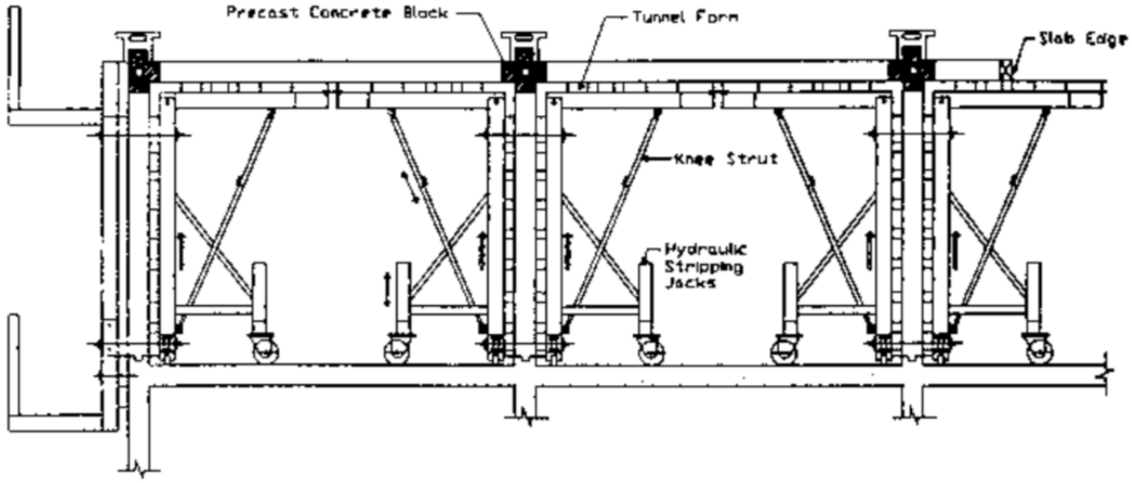


Figure 18: Tunnel formwork system (Hanna,1999)

In a nut shell, a comparison between the different formwork systems is shown in table (2).

Table 2: Comparing the different formwork systems. (Hanna,1999).

Point of Comparison	**Conventional Wood Formwork**	**Conventional Metal System**	**Flying Formwork**	**Column Mounted Formwork**	**Tunnel Formwork**
Labor Cost	High Labor Cost About 30-40% of concrete slab cost(labor intensive system)	Medium Labor cost Achieve cost reduction about 30% compared to conventional wood formwork	Low Labor Cost Fabrication is done one time at ground level then low number of labor needed for stripping & re-installation	High Labor Cost Almost the same labor cost requirements for the conventional wood formwork	Medium Labor Cost Cost can be reduced using skilled foreman that turns less expensive unskilled labors into skilled tunnel operators
Waste	High Waste (around 5% from a single use of formwork)	Low Waste	Low Waste (as assembling & stripping are not required)	Very Low Waste	Low Waste
No. of reuses	Limited (from 5-6 reuses)	Medium (higher number of reuses compared to conventional wood formwork)	High	Very High	Very High (from 500-1000 reuses)
Spans	Limited Spans	Large Spans due to the light weight & strength capacity of its components	Large Spans due to the light weight & strength capacity of its components	Large Spans & High Independent system	Medium Spans & the height ranges from 2.29 m to 3.04 m
Flexibility	Very High	Very High	Medium (as this system cannot be used for flat slab with drop panels)	Medium (especially when there is not many models available)	High (especially when several modules are available)
Initial cost	Low	Medium	High	High	Very High (considered the most expensive horizontal formwork system)
Crane dependency	Very Low	Very Low	High	Very High	High
Limitations	Labor Intensive System	Labor Intensive System & there is a chemical problem resulted from chemical reaction between aluminum & concrete.	**1.** In windy conditions, flying formwork handling is difficult. **2.** Cannot be used for flat slab with drop panels.	This system require a crane service in terms of capacity & space around the building.	**1.** This system suits only buildings with repetitive rooms. **2.** Very high initial cost.

Funicular arched steel truss (FAST) false-work system

The FAST falsework system follows the concept of the funicular arched steel truss. The arch of the funicular truss has an intermediate hinge in the midpoint and hinged at the two supports. (Darwish et.al,2018). In the FAST system, the upper chord acts as a beam that transfer the uniform load to the vertical members. The FAST system consists of two steel trusses connected by a bracing, when the pump starts pouring the concrete on the top of one of the trusses, the other truss unit will not be subjected to the same load until the pump starts pouring the concrete directly on the top of it. (Darwish et.al,2018). The are several advantages for using the FAST falsework system according to a real-life application of a falsework system that was developed by (Darwish et.al,2018). The achievements were: The fast erection process which takes around nine minutes only to assembly a falsework system that consists of two trusses connected with a bracing, the lightweight of the FAST system was another achievement that result in a cost reduction in terms of the material cost and the labor cost due to reducing the total weight of the system, the FAST requires a limited space to be stored and allow more space for material storage and labor movement underneath it and finally the FAST system is an environmentally friendly system due to its low Co_2 emissions and few hazardous waste. Figure (19) shows a FAST falsework system that was experimentally tested by (Darwish et.al,2018).

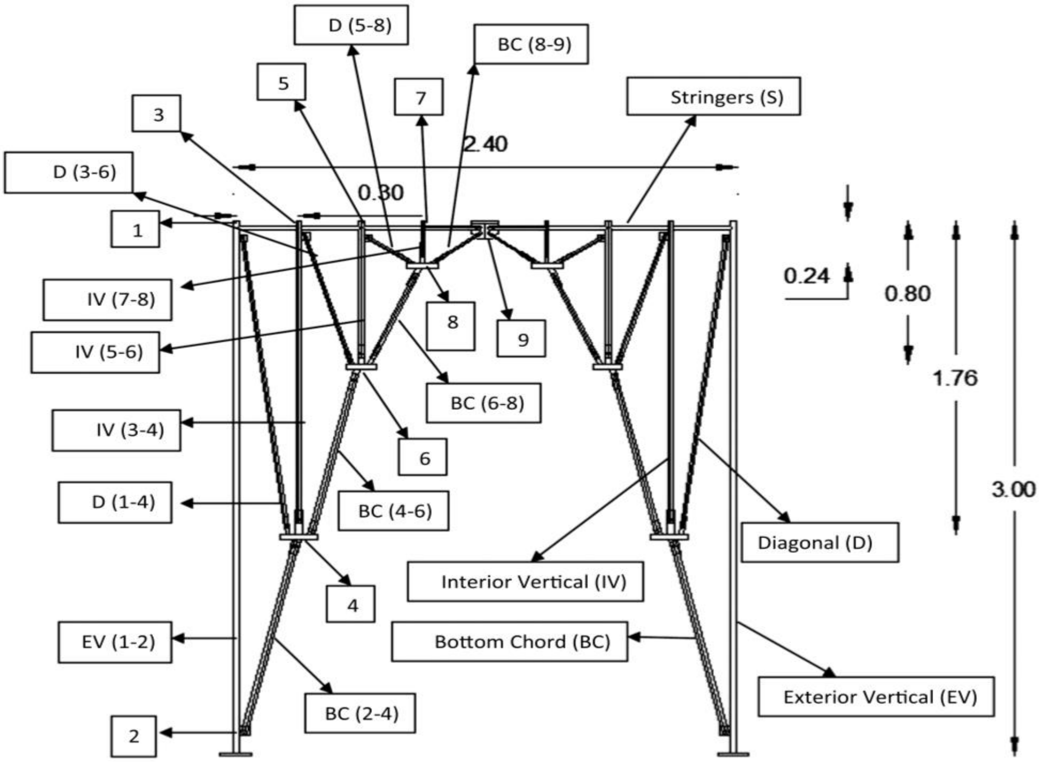


Figure 19: FAST falsework system (Darwish et.al,2018)

2.7.3 Factors affecting the selection of formwork system

There are several factors that affect the selection of appropriate formwork system. According to (Hanna,1999), the factors affect the selection of the formwork system are the supporting organization, local conditions, Job specification and building design.

2.7.4 The objectives to be considered when designing formwork

There are four main objectives to be considered when designing the formwork:

2.7.4.1 Economy

Economy is one of the most important factors that should be taken into consideration for the concrete formwork design. The economy of the formwork is divided into several factors: The cost of the formwork materials, the cost of the labor that build, erect and remove the forms and the cost of the equipment handling the formwork. The economy of the formwork should also include the concrete placing process (mixing, transporting, plumping and placing). The number of reuses of the formwork and its salvage value is also an important thing especially for the forms that has high initial cost. The designer should determine in advance the formwork system, materials and methods to be used to achieve the most economical benefit. The forms must be simple in the assembly and disassembly process and to be built efficiently to achieve construction cost saving or time reduction or both. (Hurd,2005). Figure (20) shows the formwork cost components in a typical concrete construction.

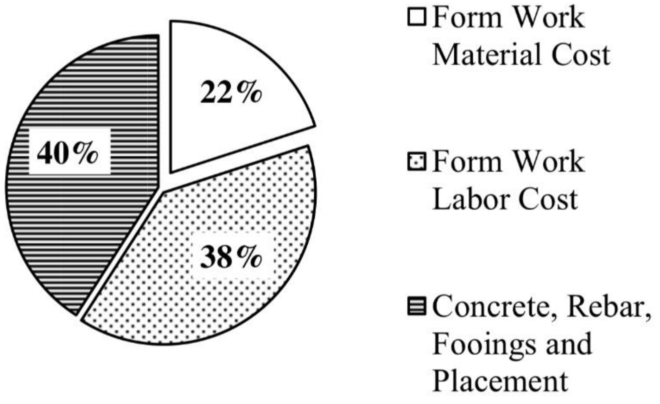


Figure 20: Formwork cost components (Hurd,2005)

2.7.4.2 Quality

The quality of the resulted concrete on forms is usually affected by the efficiency of the labor and the used formwork materials. The concrete formwork may lead to some concrete problems such as dusting, stains and discoloration, also there is the deformed concrete surface caused by the deformed formworks that were reused a lot of times or caused by the inadequate support of the formwork. The final shape of the formwork in contact with the concrete should be arranged and jointed to produce a concrete surface with good appearance. In some cases, to satisfy some surface finishing requirements a special form lining may be done. (Hurd,2005).

2.7.4.3 Safety

Formwork labors are subjected to unsafe and risky working environment. The failure of the concrete formwork may lead to injuries, damages and in some cases deaths, so the safety is an important factor for both the workers and the structure. According to Hadipriono and Wang (1986) more than 50% of the concrete structure failures are related to the formwork failure. The responsibility of the concrete formwork safety is on the designer. The designer should determine the loads applied on the formwork, do a job conditions analysis and select the formwork system that suits the job. Contractors should do a calculation check on the design to ensure the safety of the formwork and the labor should do the assembly and erection of the formwork according to the design so the formwork safety is a common responsibility between all parties. The formwork safety can be achieved through three factors. The first factor is the strength which means that the formwork is designed to withstands the applied load and the lateral pressure from the fresh poured concrete in addition to the labor and the equipment without collapsing. The second factor is that the used formwork materials are sound in terms of the size, durability, quality and quantity. The third factor is to avoid or at least limit the deflection to the allowable. (Hardipriono and Wang, 1986).

2.7.4.4 Speed and time

Speed in construction can be defined in different ways. It can be measured through the number of floors erected in days or weeks. It can be defined as the number of concrete millimeters poured per hour. As defined before the shores are the vertical members supporting the recently poured concrete until the concrete gain the designed strength while the reshoring takes place after removing the shoring to avoid any defection for the cured concrete, so this may result in blocking several floors and by default affecting the progress of any construction activity. Faster removal of shoring and reshoring may be achieved by fast formwork cycle from the erection to the stripping.

2.7.5 Formwork materials

There are different materials that can be used as a formwork. The choice of the material is mainly based in the economy and the purpose of the structure to be built. The formwork materials are timber, plywood, steel, aluminum, plastics and fabric. The formwork may be built from one material or a hybrid between more than one material. The formwork used material must fulfill some requirements such as: the strength and to be able to withstand all the loads, minimize the deflection, swelling and shrinkage as much as possible, does not interact with concrete, easy and fast in stripping and provide smooth surface, the cost and the number of reuses should satisfy the economical purpose. (Oberlender and Peurifoy, 2010). Table (3) compares the different formwork materials

Table 3: Comparing different formwork materials. (Oberlender and Peurifoy, 2010).

Point of Comparison	**Timber**	**Plywood**	**Steel**	**Aluminum**	**Plastics**	**Fabric**
Pros	1. Can be cut & shaped easily 2. Light weight 3. Relatively cheap 4. Easy in assembly& disassembly 5. Does not require skilled labor	1. Can be cut & shaped easily 2. Light weight 3. Higher number of reuses compared to timber 4. Provides smooth finish so it reduces the finishing cost 5. Available in large size sheets to reduce the formwork construction time 6. Eliminate the joint marks	1.Stronger than wooden formworks with better durability 2. High number of reuses 3. Provides smooth finish 4. Fast & easy in installing & dismantling 5. Does not shrink or wrap	1. Strong & Light weight 2. Easy in assembly& disassembly 3. Walls & slabs can be casted at the same time 4. High number of reuses	1.High durability 2. Light weight 3. High resistance to water 4. High number of reuses 5. Damaged plastic sheets can be recycled & used in manufacturing new sheets	1. The lightest in weight compared to other materials 2. Waterproof 3. Does not interact with concrete 4. Economical 5. Easy to be removed after the concrete hardened
Cons	1. Limited number of reuses 2. The strength of the concrete may be affected in case of using dry timber 3. Timber may swell, shrink or wrap	1. More expensive compared to timber 2. The plywood sheets may bend & fail to withstand the concrete weight if the proper section is not provided	1. Expensive 2. Limited size & shapes 3. Heavy in weight & require equipment for lifting 4. Corrosion may happen in case of periodic contact with water	1. Sometimes the light sections may deflect at maximum load 2. Cannot be used for structures having a lot of architectural details 3. Affected chemically by wet concrete	1. Cannot handle high loads compared to other materials 2. High cost 3. Cannot handle heat & humidity	1. Require very skilled labor
Applications	Used as bracing material	Used as sheathing, decking & lining	Heavy structures such as dams & bridges	- Flying forms use Aluminum truss - Aluminum is used in building monolithic crack free structures	Structures with complicated shapes	Used in complicated Architectural shapes

2.7.6 Formwork Failures

The formwork failure can be caused by different reasons such as the stripping and shore removal, the excessive loads and the human error. The formwork failure causes can be classified into three main categories: Enabling causes, triggering causes and procedural causes. The enabling causes are the events related to the defects in the design or the construction of the false-work. The triggering causes are the events that could lead to a false-work collapse. The procedural causes are the hidden events lead to either the enabling or the triggering causes. (Hardipriono and Wang, 1986). Table (4) summarizes the false-work failure causes.

Table 4: The most common formwork failures. (Hardipriono and Wang, 1986).

Causes Of Failure		
(a) Triggering Cause of Failure	**(b) Enabling Causes of Failure**	**(c) Procedural Causes of Failure**
• Heavy rain causing falsework foundation slippage • Strong river current causing falsework foundation slippage • Strong wind • Fire • Failure of equipment for moving formwork • Effects of formwork component failure • Concentrated load due to improper prestressing operation • Concentrated load due to construction material • Other imposed loads • Impact loads from concrete debris and other effects during concreting • Impact load from construction equipment/vehicles • Vibration from nearby equipment/vehicles or excavation work • Effect of improper/premature falsework removal • Other causes or not available	• Inadequate falsework cross-bracing/lacing • Inadequate falsework component Inadequate falsework connection • Inadequate falsework foundation Inadequate falsework design Insufficient number of shoring • Inadequate reshoring • Failure of movable falsework/formwork components Improper installation/ maintenance of construction equipment • Failure of permanent structure component • Inadequate soil foundation Inadequate design/construction of permanent structure • Other causes or not available	• Inadequate review of falsework design/construction • Lack of inspection of falsework/formwork during concreting • Improper concrete test prior to removing falsework/formwork Employment of inexperienced/inadequately trained workmen • Inadequate communication between parties involved • Change of falsework design concept during construction • Other causes or not available

Chapter 3: Experimental Program

3.1 Testing the mechanical properties

3.1.1 Scope of Work:

The Scope of the experimental program is to test the mechanical properties of the two most common types of Casuarina wood in Egypt, Casuarina Glauca and Casuarina Cunninghamiana. The tests were static bending, compression parallel to the grain, compression perpendicular to the grain, cleavage, tension parallel to the grain, tension perpendicular to the grain and density.

All the mechanical tests were performed according to ASTM D143 (ASTM,2014) standard test methods for small clear specimens of timber, ASTM D2555 (ASTM,2017) standard practice for establishing clear wood strength values, ASTM D2915 (ASTM,2017) standard practice for sampling and data-analysis for structural wood and wood-based products and ASTM D2395 (ASTM,2017) Standard Test Methods for Density and Specific Gravity (Relative Density) of Wood and Wood-Based Materials.

All the specimens were dried in dry air to reach an approximate constant weight before testing, and when testing the temperature of the specimens shall be 20 ˚C +3˚C. All the tested specimens were dried in an oven to a moisture content approximately 20% which was measured using a moisture meter. All the tests were done according to the primary method or secondary method specified by ASTM. The primary method mainly suggests a specimen cross section of 50 x 50 mm, whereas the secondary method mainly suggests a specimen cross section of 25 x 25 mm. In general, it is better to use the primary method as it uses a larger cross section and the larger specimens adopt a larger number of growth rings reducing the variability between results of early wood and late wood. All the tests were done using the primary method except for the static bending test due to the difficulty of obtaining the cross-section requirements with the available mechanical testing machine (MTS).

Each test was performed on 15 specimens of Casuarina Glauca and 15 specimens of Casuarina Cunninghamiana; calculating mean value, standard deviation, coefficient of variation, then applying the resulted values on the equation of the ASTM D2915 to determine whether the 15 samples were enough or the variation was high and more samples were needed then calculating the additional samples required. The results from each test were compared with the values of other commercial species of wood enabling the ranking the Casuarina wood among other species of hardwoods.

3.1.2 Sampling Procedures:

The sampling procedures were done according to ASTM D2915. For every test, 15 samples from each species were tested as a preliminary assumption for the first 3 tests (before excluding Casuarina Cunninghamiana from the rest of the tests due to its poor results), then the mean, standard deviation and coefficient of variation were calculated, and then the sample size rechecked. If the sample size was not sufficient, the number of additional samples required was calculated and they were tested, then the sample size rechecked. The parameter used in determining the number of samples in all the tests is the modulus of elasticity (E). Generally, the wood samples for all tests were taken from farmed trees, not forest trees, that were delivered from more than one tree then cut and shaped according to the ASTM requirements for every test.

3.1.3 Experimental program:

3.1.3.1 Compression parallel to the grain test

Objective:

The main objective of the compression parallel to the grain test is to determine the ultimate compressive strength longitudinal to the axis for the two types of Casuarina wood: Casuarina Glauca and Casuarina Cunninghamiana and calculate the modulus of elasticity within that direction. The Test was carried out using the MTS machine according to ASTM D143.

Procedures:

According to ASTM D143, the test requires a specimen with dimensions of 50 x 50 x 200 mm and the displacement rate of the movable crosshead to be 0.03 mm/min. The test starts by applying the load to the specimen continuously till the specimen fails or the compressive strength of the specimen exceeds the elastic limit. According to ASTM D143, the load- compression curves shall be taken over a central gage not exceeding 150 mm. After the specimen fails, the load-deflection readings are recorded by the MTS machine and are used to draw the stress-strain curve in order to get the ultimate strength, modulus of elasticity (E) in compression for each sample and the average of all samples. It is important to classify the compressive failure according to the shape of the fractured surface. The compression parallel to the grain specimen and the test setup are shown in Figure (21).

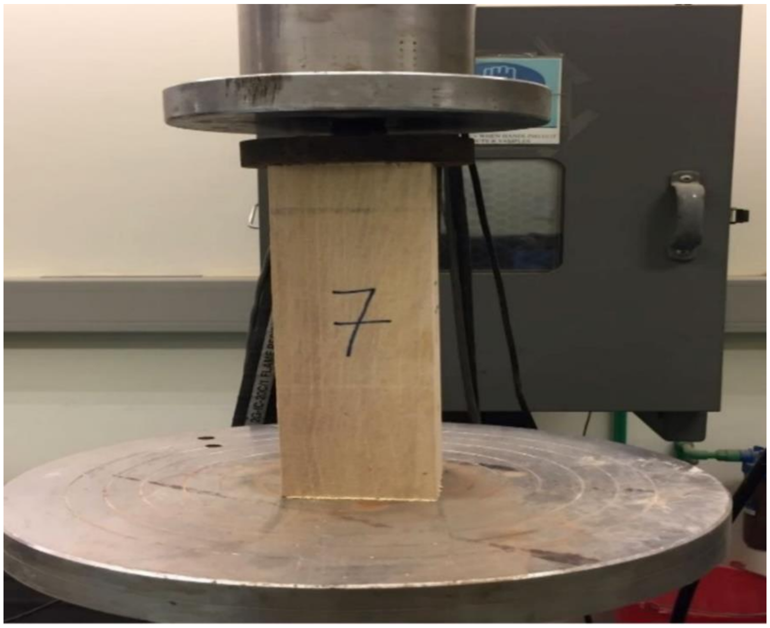


Figure 21: Compression parallel to the grain test setup

3.1.3.2 Compression Perpendicular to the Grain test

Objective:

The main objective of the compression perpendicular to the grain test was to determine the values of compressive strength perpendicular to the grain and the associated value for the compression perpendicular to the grain modulus of elasticity for the two types of Casuarina wood: Casuarina Glauca and Casuarina Cunninghamiana. It is important to test the wood behavior in the compression perpendicular to the grain and compare it to the compression parallel to the grain especially for beams and joints that are supported on certain areas and should maintain high values of compressive strength in the perpendicular direction. The test was carried out using the MTS machine according to ASTM D143.

Procedures:

According to ASTM D143, the test requires specimen with dimensions of 50 x 50 x 150 mm and a displacement rate of the movable crosshead to be 0.305 mm/min. The test starts by applying the load on a metal bearing plate that is placed across the upper surface of the specimen. According to ASTM D143, the test shall be continued until the deflection equals 2.5mm. Load-deflection curves were plotted and used to draw the stress strain-curve for each sample. All the samples are weighted and had their moisture content measured immediately before testing. The compression perpendicular to the grain specimen and the test setup are shown in Figure (22).

Figure 22: Compression Perpendicular to the grain test setup

3.1.3.3 Static Bending test

Objective:

The main objective of the static bending test is to determine the bending strength, the associated value for the modulus of elasticity and assess the ductility for the two types of Casuarina wood: Casuarina Glauca and Casuarina Cunninghamiana. The test was carried out using the MTS machine according to ASTM D143.

Procedures:

According to ASTM D143, the test requires primary specimens with dimensions of 50 x 50 x 760 mm, but due to the span limitations of the used MTS machine, the secondary specimen’s dimensions of 25 x 35 x 410 mm were used. The loading span should be 360 mm and the rate of displacement was 1.3 mm/min. The test begins by applying center loading on a bearing block placed on the center of the specimen so that the load is transmitted to the surface of the specimen through the block as shown in Figure (23). The test is continued until the specimen fails to withstand a load of 222 N or the deflection reaches 76 mm. The load-deflection curve for each sample was plotted and a stress-strain curve is deducted from it to calculate the modulus of rupture for each sample. It is important to classify the failure type for each sample according to the shape of the fractured surface.

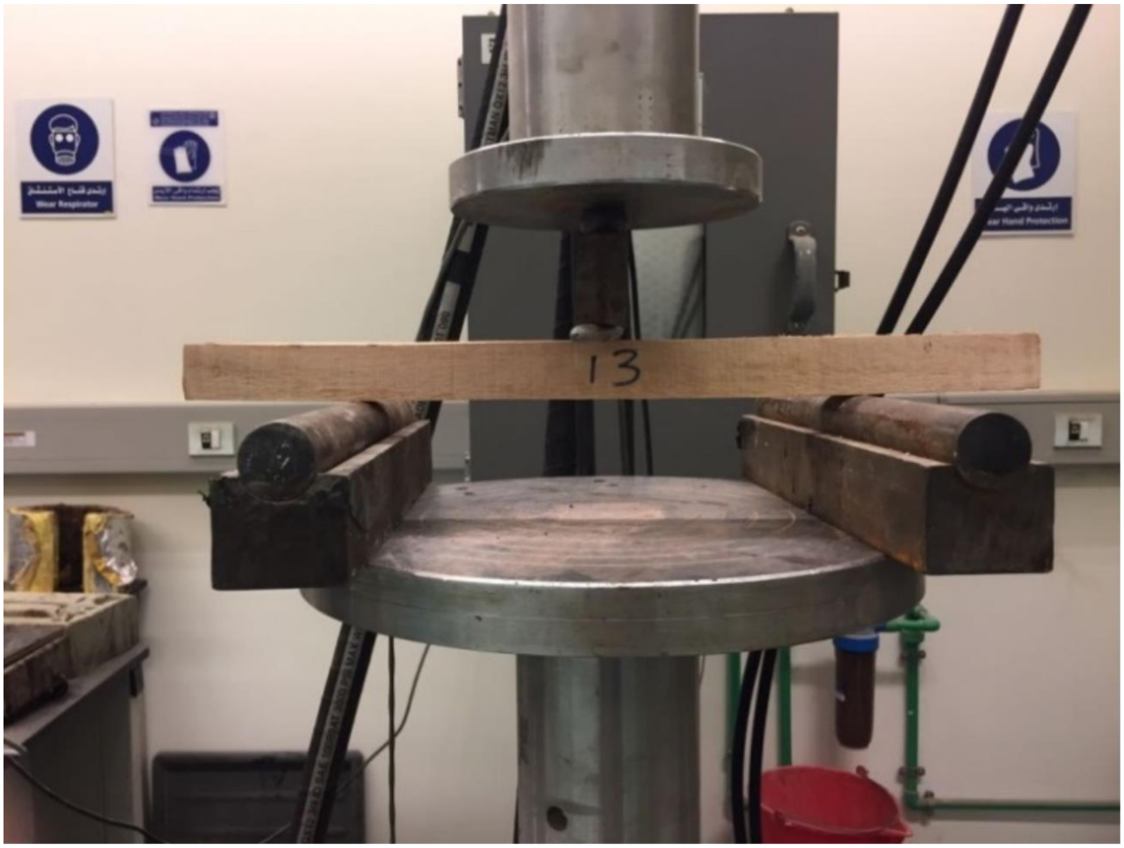


Figure 23: Static Bending test setup

3.1.3.4 Cleavage test

Objective:

The main objective of the cleavage test is to measure the Casuarina's wood resistance to splitting. The cleavage test is one of the tensile tests that is used to test the tensile failure mode that the standard tensile tests (Tension parallel to the grain and Tension perpendicular to the Grain) cannot define. The test was carried out using Universal testing machine according to ASTM D143.

Procedures:

According to ASTM D143, the test requires primary specimens with dimensions of 50 x 50 x 95 mm with a groove shaped on one side of the specimen. The cleavage specimen is grasped by grips that are fixed in the universal testing machine during testing. These grips were designed and manufactured according to the specifications of ASTM D143 before testing. After the Specimen is shaped and held by the grips, a tensile load of 2.5 mm/min is applied with a constant rate of motion for the movable crosshead until the specimen fails; the maximum strength reached is the load of failure. The cleavage Specimen and the test setup are shown in Figure (24).

Figure 24: Cleavage test setup

3.1.3.5 Tension parallel to the grain test

Objective:

The main objective of the tension parallel to the grain test was to determine the tensile strength and the associated value for the tension parallel to the grain modulus of elasticity of the two types of Casuarina wood. The importance of the tension parallel to the grain property is that it is considered the most important property of wood and its value is expected to be correlated with that of the modulus of rupture. The test was carried out using the universal testing machine according to ASTM D143.

Procedures:

According to ASTM D143, the specimen has to be grasped by grips that are fixed in the universal testing machine during the testing. These grips were designed and manufactured according to the specifications of ASTM D143 before testing. After the specimen was shaped and held by the grips, a tensile load of 1 mm/min was applied with a constant rate of motion for the movable crosshead then deformation was measured using 50 mm central gage length to record the load-deflection readings till the specimen failed. The shape of failure must be sketched on the data sheet for a full description of the specimen and its failure as mentioned in ASTM D143. The tension parallel to the grain specimen and the test setup are shown in Figure (25).

Figure 25: Tension Parallel to the grain test setup

3.1.3.6 Tension Perpendicular to the grain test

Objective:

The main objective of the tension perpendicular to the grain test was to study the behavior of the two types of Casuarina wood when loaded with an axial tensile load and record the maximum tensile strength. The value of ultimate strength for the tension perpendicular to the grain direction is typically lower than the strength in the parallel to the grain direction for all types of wood. The test was carried out using a universal testing machine according to ASTM D143.

Procedures:

According to ASTM D143, the test requires primary specimens with dimensions of 50 x 50 x 63 mm, with a groove shaped on both sides of the specimen. The specimen is grasped by grips that are fixed in the universal testing machine during the testing. These grips were designed and manufactured according to the specifications of ASTM D143 before testing. After the specimen is shaped and held by the grips, a tensile load of 2.5 mm/min is applied with a constant rate of motion of the movable crosshead until the specimen fails, the maximum is recorded. The shape of failure must be sketched on the data sheet. The tension perpendicular to the grain Specimen and the test setup are shown in Figure (26).

Figure 26: Tension Perpendicular to the grain test setup

3.1.3.7 Specific Gravity

Objective:

The specific gravity or the relative density is a very important property of wood as it gives a clear identification about the density of the material. The main objective is to calculate the specific gravity of the two types of Casuarina wood. The process of calculating the specific gravity was done according to ASTM D2395.

Procedures:

According to ASTM D2395, the specific gravity was calculated using Method A-Volume by measurement. The samples dimensions were 50 x 50 x 150 mm. The samples were numbered, weighted to get their green weight using a balance as shown in figure (27) and the volume of each specimen is calculated measuring the length, width and the thickness using a meter. The moisture content was measured for each sample using a moisture meter. The samples were dried using an oven to determine their dry weight as shown in figure (28).

Figure 27: weighting the samples using a balance

Figure 28: Samples inside the oven to determine their dry weight

3.1.4 Mechanical tests Results and discussion

3.1.4.1 Compression parallel to the grain test

After testing the 15 samples of Glauca and Cunninghamiana, the average compressive strength parallel to the grain for Casuarina Glauca was 32.2 N/mm2 while the average compressive strength for Casuarina Cunninghamiana was 11.4 N/mm2. The average compression parallel to the grain modulus of elasticity (E) For Casuarina Glauca was 5083.1 N/mm2, and that of Casuarina Cunninghamiana was 1728.9 N/mm2. The results for Casuarina Glauca and Cunnunghamiana are summarized in Tables 5 & 6 respectively. Comparing the two types with each other it's clear that the Glauca is much stronger than the Cunninghamiana. The results for Compressive strength parallel to the grain for Glauca and Cunninghamiana are shown in Figures (29) and Figure (30) respectively.

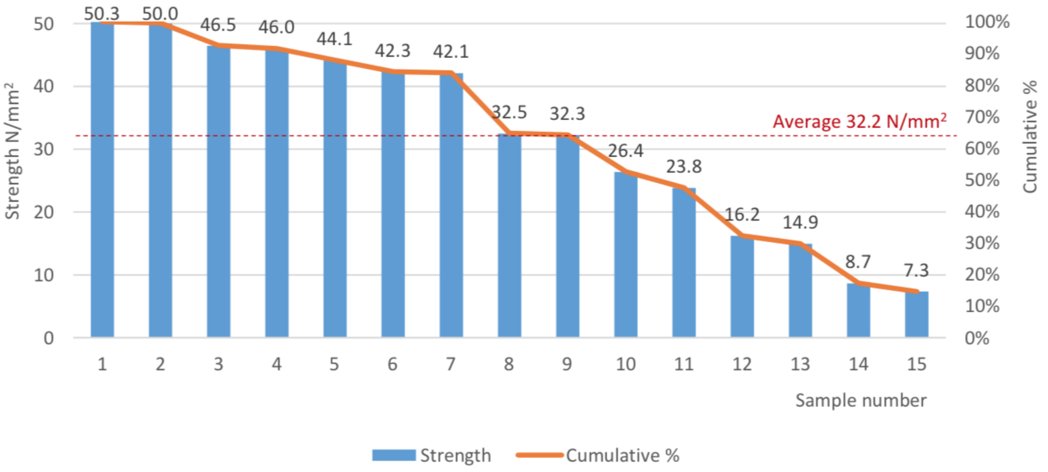


Figure 29: Compressive strength parallel to the grain results for Glauca samples

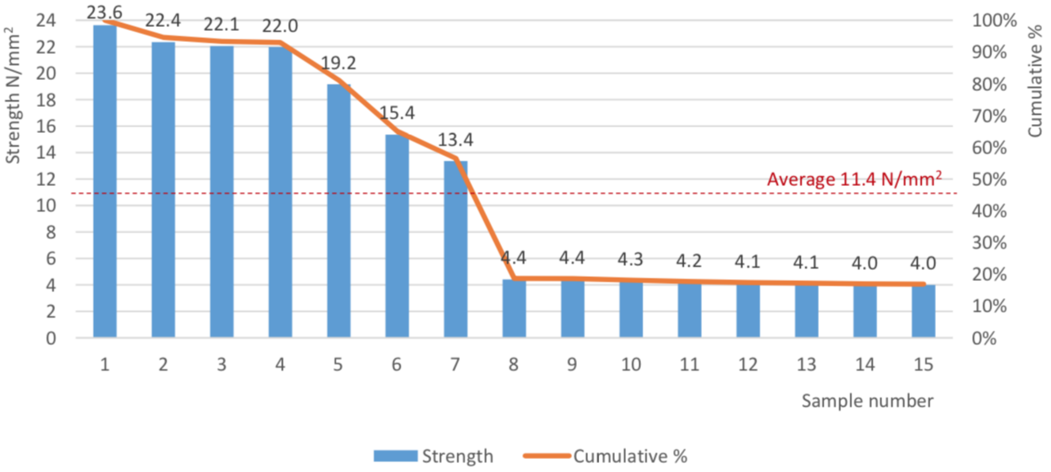


Figure 30 : Compressive strength parallel to the grain results for Cunninghamiana samples

According to ASTM D143, the failure shapes expected from this test are shearing, compression and shearing parallel to the grain, splitting, wedge split, crushing and end-rolling. The types of failure occurred for Casuarina Glauca were either shearing as shown in Figure (31) or wedge split as shown in Figure (32). The common failure type for Casuarina Cunninghamiana was splitting as shown in Figure (33), which matches with the results that show Cunninghamiana much weaker than Glauca.

Figure 31 : Shear failure

Figure 32 : Wedge split failure

Figure 33: Splitting failure

It is important to determine whether the samples tested are sufficient or if the variance was large and more samples need to be tested. This is determined according to ASTM D2915 using:

$$n = (\frac{t}{\alpha} CV)^2 \qquad (1)$$

Where:

n = sample size.

CV is the coefficient of variation=standard deviation of specimen values/mean value.

α is an estimate of precision =0.05 assuming confidence intervals 95%.

t = value of t statistic from table 1 in ASTM D295

Applying Eq. (1) to Glauca, the number of samples required was 14.9 so 15 samples were enough, whereas the number of samples required for Cunninghamiana was 26.5 which meant that additional 12 samples needed to be tested, which indicated the large variation in Cunninghamiana.

Because Casuarina is considered a hardwood and a type of oak, its properties can be compared with those of similar hardwoods. According to ASTM D2555, the average compressive strength parallel to the grain of various types of red oak varies from 20.7 to 31.9 N/mm^2, that of various types of white oak varies from 22.7 to 37.4 N/mm^2, and that of balsam which is one of the hardwoods has a value of 11.7 N/mm^2. Based on the previous results it is obvious that Casuarina Glauca has a relatively high compressive strength parallel to the grain of 32.2 N/mm^2, compared with other hardwoods, whereas it is so difficult to rank Casuarina Cunninghamiana because it has a very low average compressive strength parallel to the grain compared with other hardwoods. A sample stress-strain curve is shown in Figure (34).

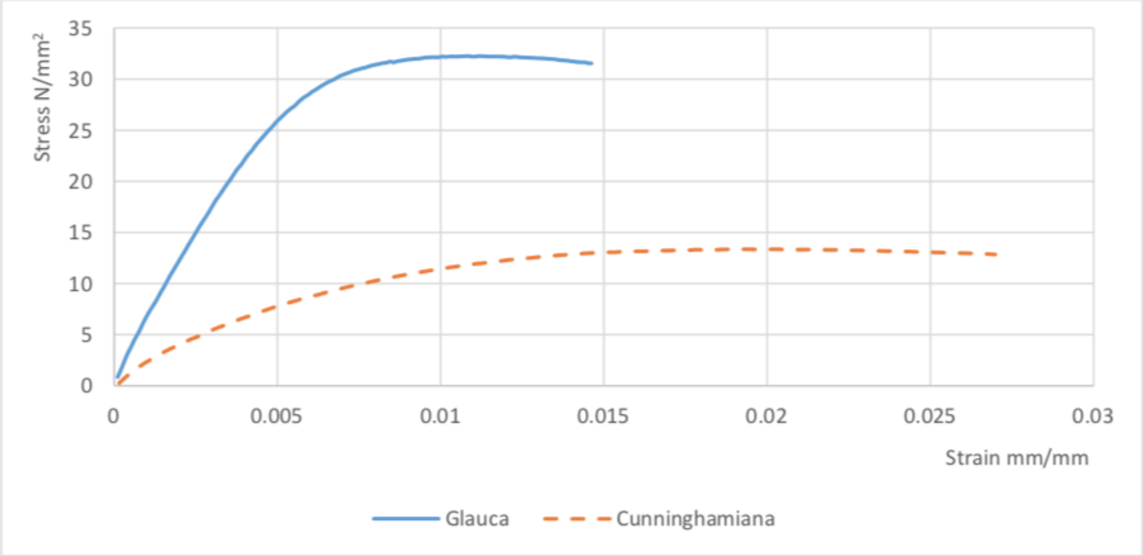


Figure 34: Stress-Strain curve sample for compression parallel to the Grain Test

3.1.4.2 Compression perpendicular to the grain test

Testing the 15 samples of Glauca and Cunninghamiana, showed that the average compressive strength perpendicular to the grain of Casuarina Glauca was 7.4 N/mm2, whereas the average compressive strength of Casuarina Cunninghamiana was 4.9 N/mm2. The average compression perpendicular to the grain modulus of elasticity (E) of Casuarina Glauca was 172.2 N/mm2 and 87.3 N/mm2 for Casuarina Cunninghamiana. The results for Casuarina Glauca and Cunnunghamiana are summarized in Table 5 & 6 respectively. Comparing the two types with each other it’s clear that the Glauca is still much stronger than the Cunninghamiana. The results for compressive strength perpendicular to the grain for Glauca and Cunninghamiana are shown in Figure (35) and Figure (36) respectively.

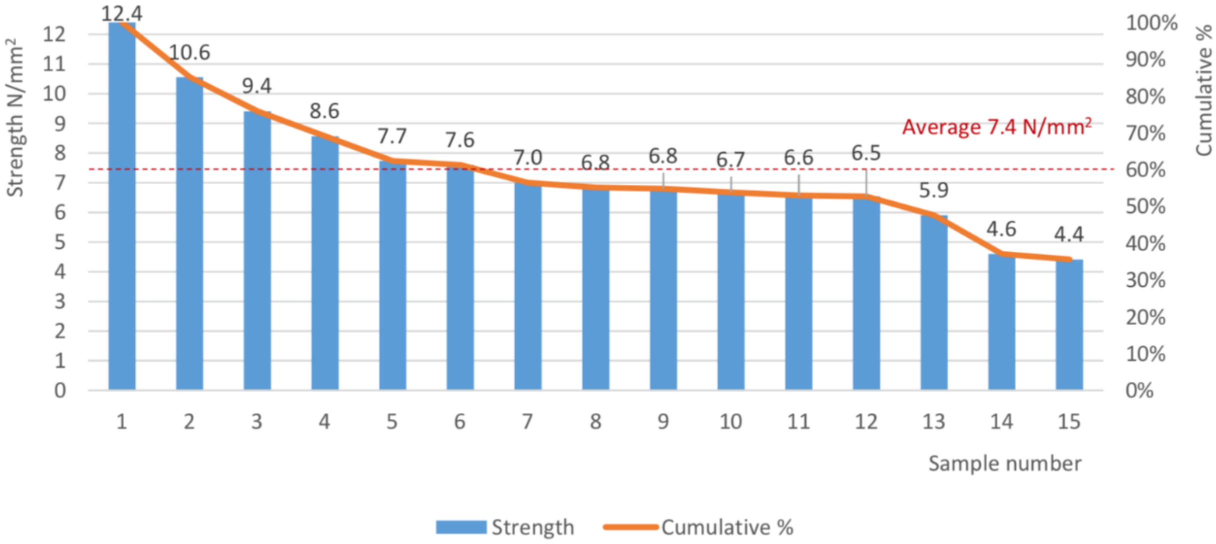


Figure 35: Compressive strength perpendicular to the Grain Results for Glauca samples

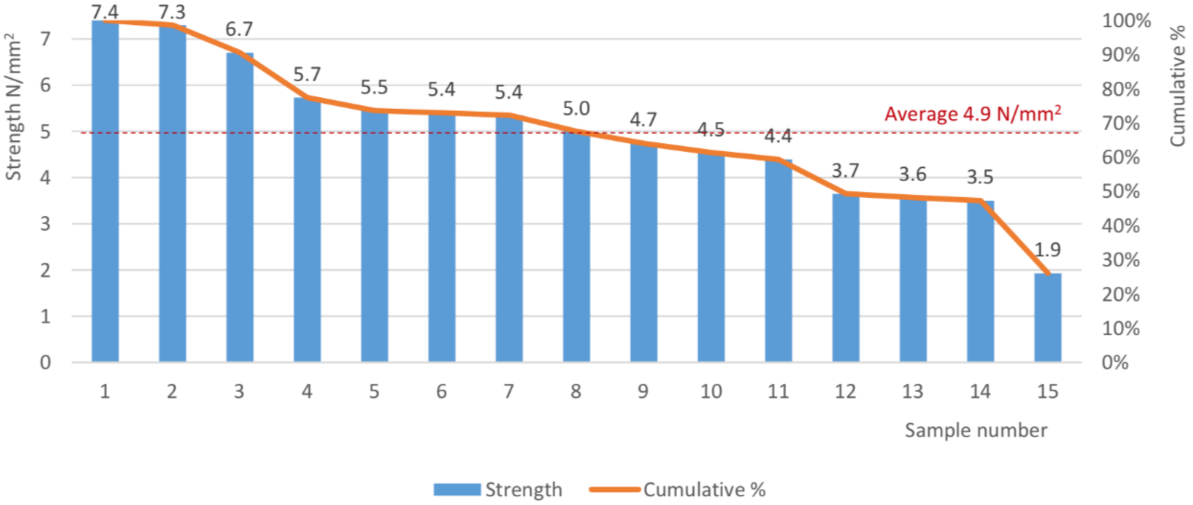


Figure 36: Compressive strength perpendicular to the Grain Results for Cunninghamiana samples

According to ASTM D143, this test shall be stopped after the deflection reaches 2.5 mm and does not require the failure of the specimen, so the ultimate strength in this case does not reflect the strength of the wood to withstand the compressive load but only refers to the maximum load equivalent to 2.5 mm deflection. A Sample of Glauca after being tested is shown in Figure (37).

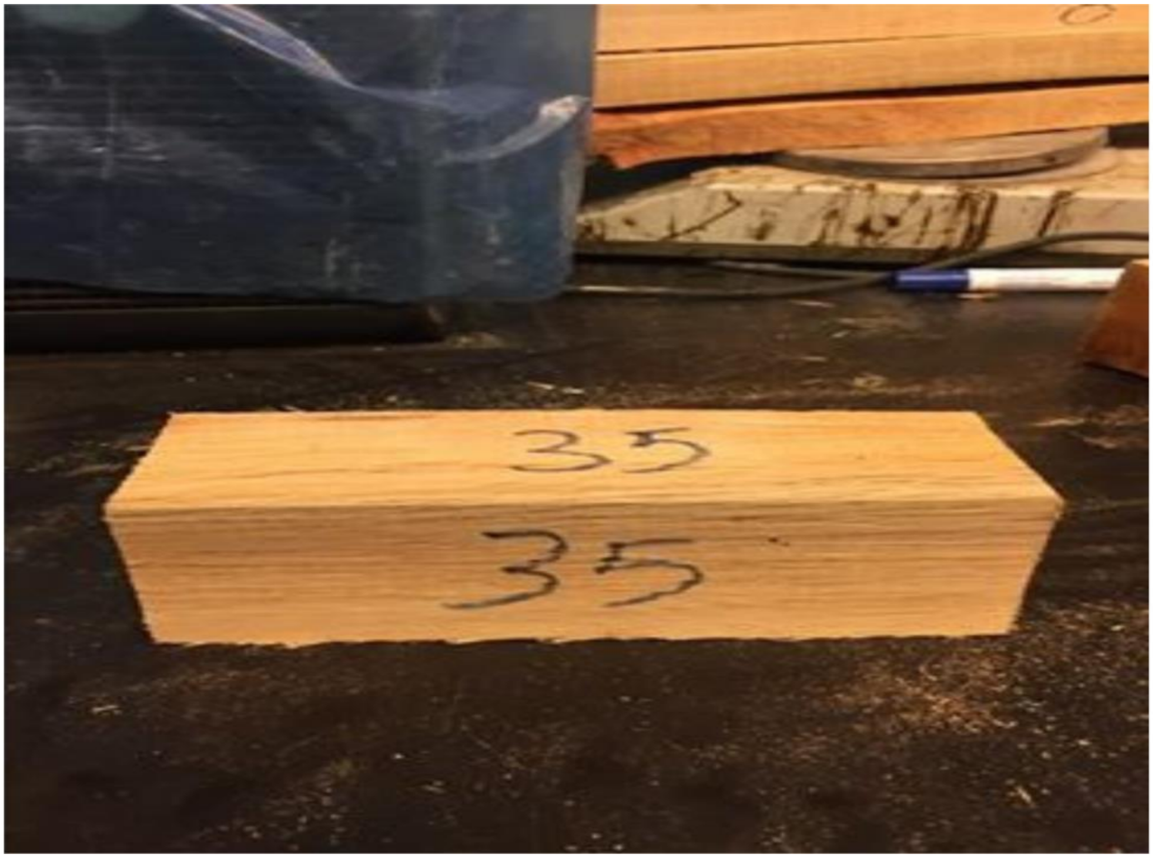


Figure 37: Compression perpendicular to the grain sample after testing

Applying Eq. (1) in ASTM D2915 to check the number of samples tested, the number of samples required for Glauca was 16.55 so two additional samples were tested; the same equation was applied, and it was determined 17 samples were enough. The number of samples required for Cunninghamiana was 135.7, which mean 121 additional samples needed to be tested. This large number showed the large variations in Cunninghamiana, which subsequently led to its exclusion from the rest of the mechanical tests and continuing the research on Glauca only as a material like Cunninghamiana with such extreme variability is not supposed to be used within any structural applications.

According to ASTM D2555, the average compressive strength perpendicular to the grain of the various types of Red oak varies from 6.3 to 9.4 N/mm2, and that for various types of white oak varies from 6.1 to 8.7 N/mm2. Comparing the average compressive strength perpendicular to the grain of Glauca with that of the different types of oak, the average compressive strength 7.4 N/mm2 is within the same range of strength as the similar types of wood, whereas Cunninghamiana with an average compressive strength 5.0

N/mm2, ranked as a below average compressive strength compared with similar types of wood. A sample for the stress-strain curve is shown in Figure (38).

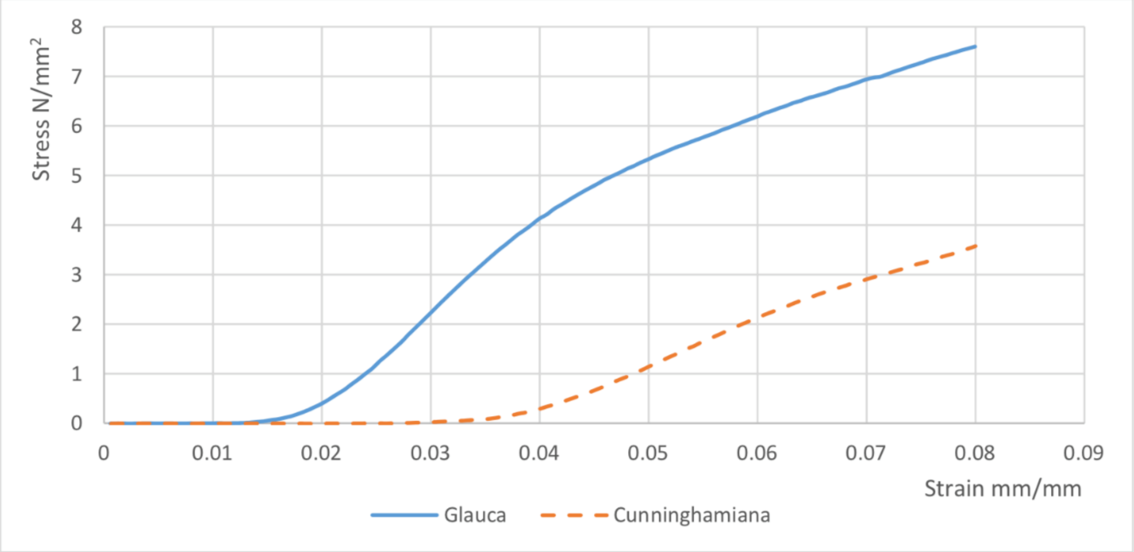


Figure 38: Stress-Strain curve sample for compression perpendicular to the Grain Test

3.1.4.3 Static bending test

After testing the 15 samples of Glauca and Cunninghamiana, the results showed that the average bending strength (modulus of rupture) for Casuarina Glauca was 62.1 N/mm2, whereas the average bending strength for Casuarina Cunninghamiana was 32.4 N/mm2. The average (E) of Casuarina Glauca was 8,418 N/mm2 and that of Casuarina Cunninghamiana was 4,193 N/mm2. The results for Casuarina Glauca and Cunnunghamiana are summarized in Tables 5 & 6 respectively. Glauca was much stronger than the Cunninghamiana. The results for bending strength of Glauca and Cunninghamiana are shown in Figures (39) and (40) respectively.

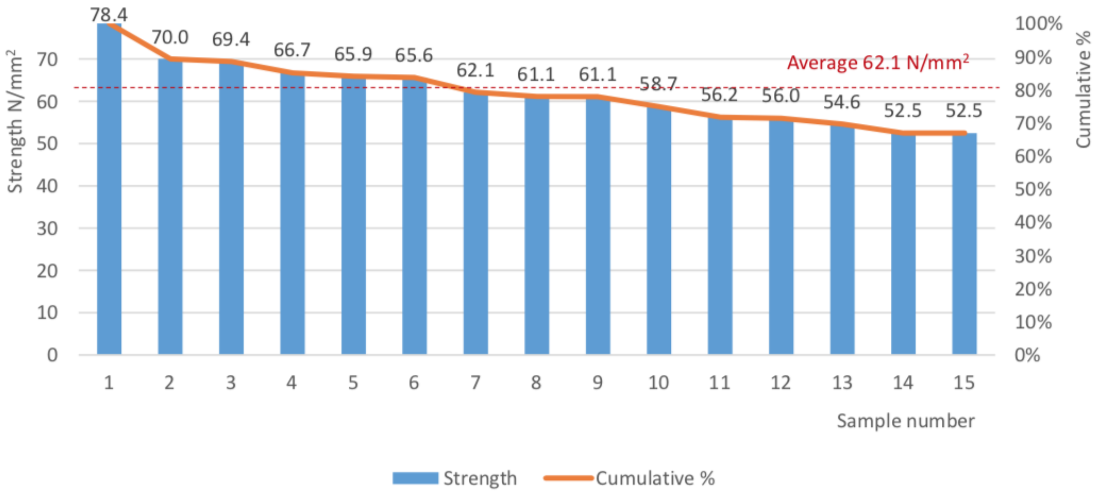


Figure 39: Bending Strength Results for Glauca samples

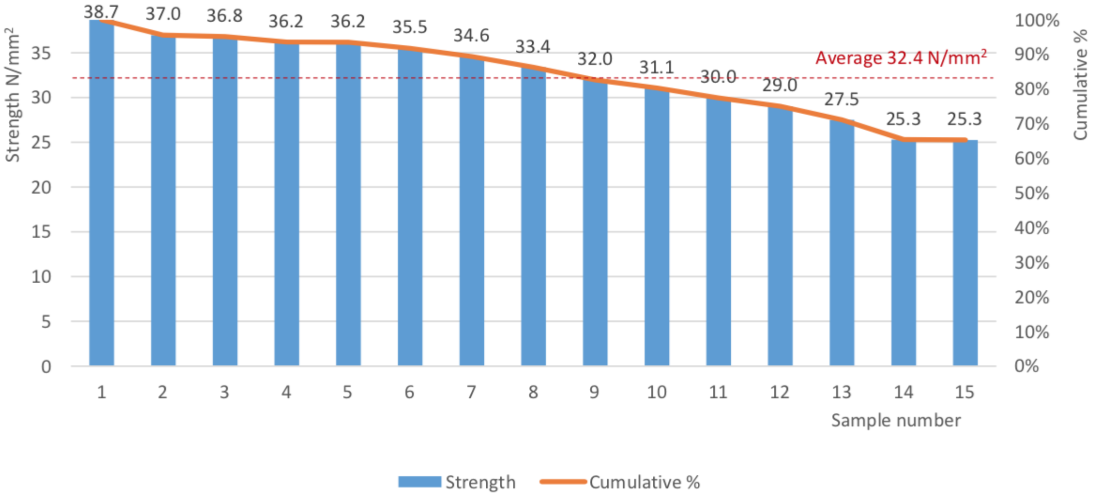


Figure 40: Bending Strength Results for Cunninghamiana samples

According to ASTM D143, the failure shapes expected from this test are simple tension, cross grain tension, splintering tension, brash tension, compression and horizontal shear. The types of failure for both species of Casuarina Glauca were either simple tension as shown in Figure (41) or cross grain tension as shown in Figure (42).

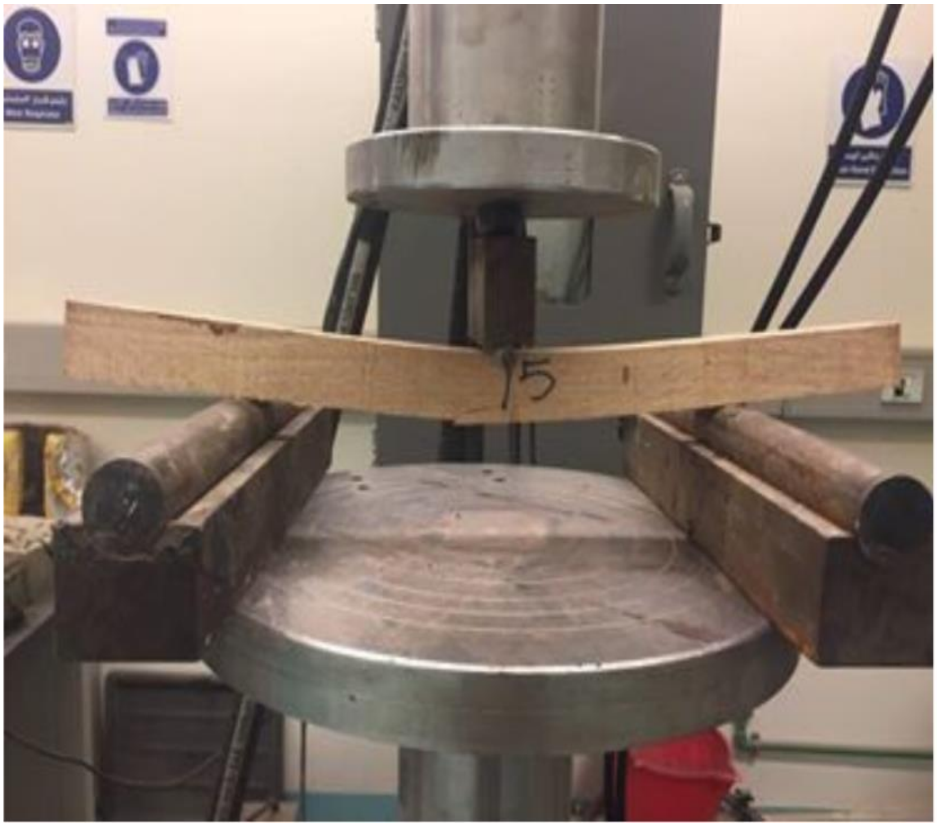


Figure 41: Simple tension failure

Figure 42: Cross grain tension failure

Applying Eq. (1) in ASTM D2915 to check the number of samples tested, the number of samples required for Glauca was 15 so no additional samples were required, because the preliminary assumption of 15 samples was enough. The number of samples required for Cunninghamiana was 31.1 which meant that 17 additional samples needed to be tested; this large number shows the large variations in the Cunninghamiana which subsequently led to its exclusion and continuing the research on Glauca only.

According to ASTM D2555, the average bending Strength (modulus of rupture) of the various types of Red oak varies from 51.0 to 74.8 N/mm2; that of the various types of white oak varies from 49.5 to 68.0 N/mm2; and that of balsam, which is a hardwood is 95.6 N/mm2. Comparing the average bending strength of Glauca with the different types of oak, the average bending strength 62.1 N/mm2, is considered a very high strength for wood in general, not only hardwoods, whereas Cunninghamiana with an average bending strength of 32.4 N/mm2, is ranked as an average bending strength compared with similar types of wood. A sample for load-deflection curve is shown in Figure (43).

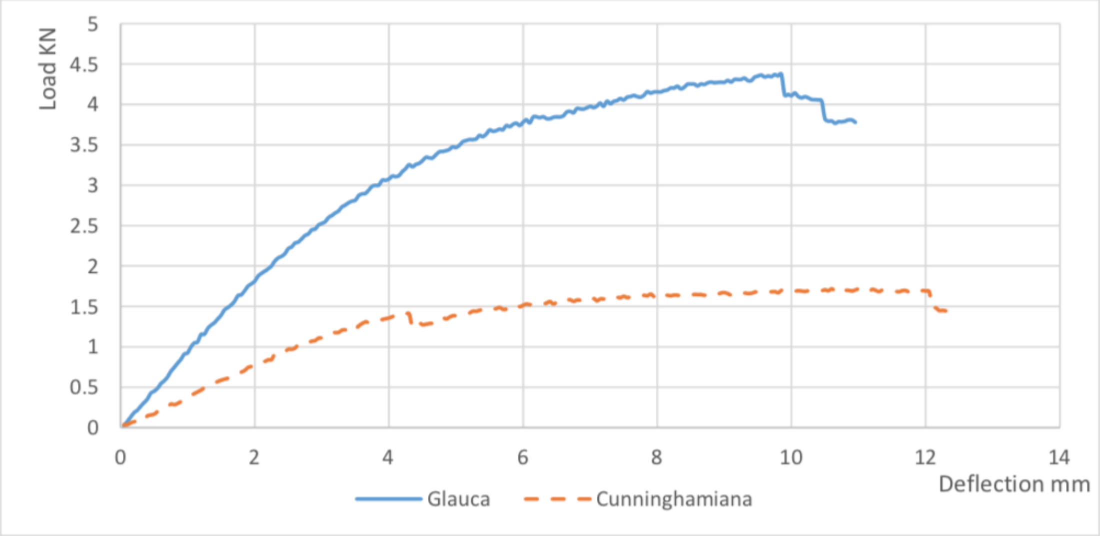


Figure 43: Load-deflection curve sample for static bending test

From the previous results for the first three tests, it is clear that Casuarina Cunninghamiana showed inconsistent performance and its results had a large variation that required large number of samples to be tested to cover the high standard deviation so it was excluded from the subsequent tests and the experimental program continued using only Casuarina Glauca.

3.1.4.4 Cleavage test

After Cleavage testing the 15 samples of Casuarina Glauca, the average strength for Casuarina Glauca in cleavage test is 0.8 N/mm2. The average cleavage modulus of elasticity (E) for Casuarina Glauca was 28.6 N/mm2. The results of Casuarina Glauca are summarized in table 5. The results for cleavage test strength for Glauca are shown in Figure (44).

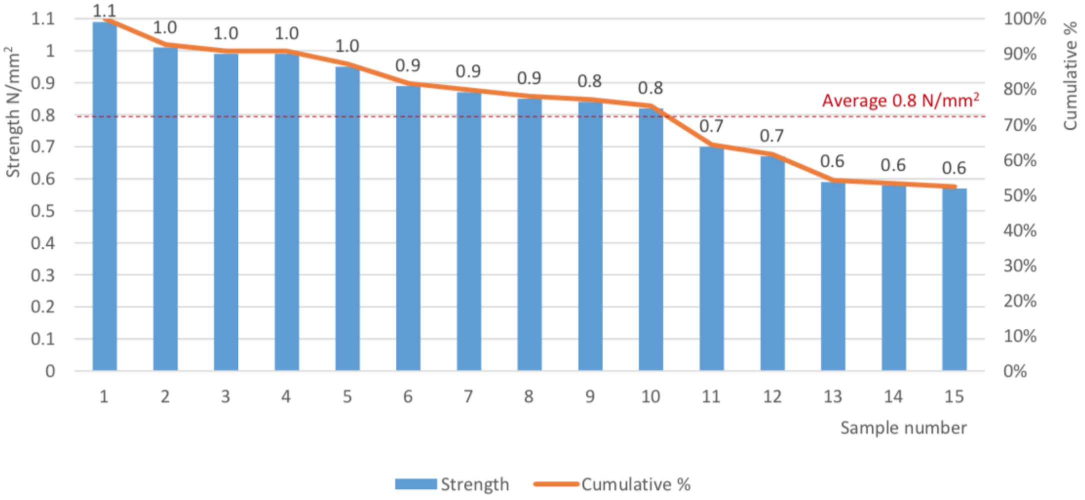


Figure 44: Results for Cleavage test

The failure shape for the cleavage sample after failure is shown in Figure (45).

Figure 45: Cleavage sample after failure

Applying Eq. (1) in ASTM D2915 to check the number of samples tested, the number of samples required for Casuarina Glauca was 13.9, so no additional samples were needed, beacuse 15 samples were enough. Comparing the results for cleavage test with other types of wood was not possible because ASTM does not mention the results for cleavage test for wood. A sample stress-strain curve for Casuarina Glauca is shown in Figure (46).

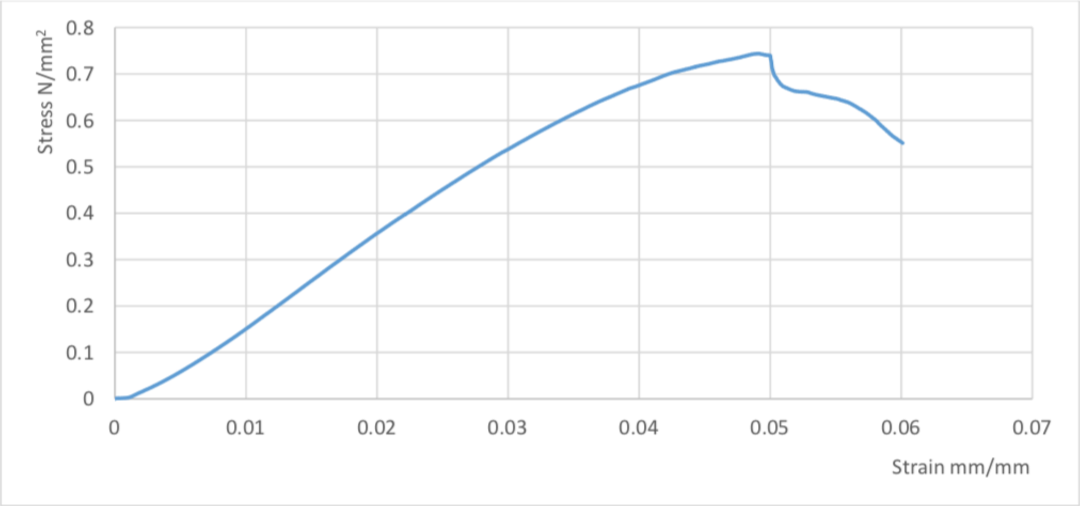


Figure 46: stress-strain curve for cleavage test sample

3.1.4.5 Tension parallel to the grain test

After testing the 15 samples of Glauca, the average tensile strength parallel to the grain of Casuarina Glauca is 162.9 N/mm2. The average tension parallel to the grain modulus of elasticity (E) of Casuarina Glauca was 716.4 N/mm2. The results for tensile strength parallel to the grain of Casuarina Glauca are summarized in table 5 and shown in Figure (47).

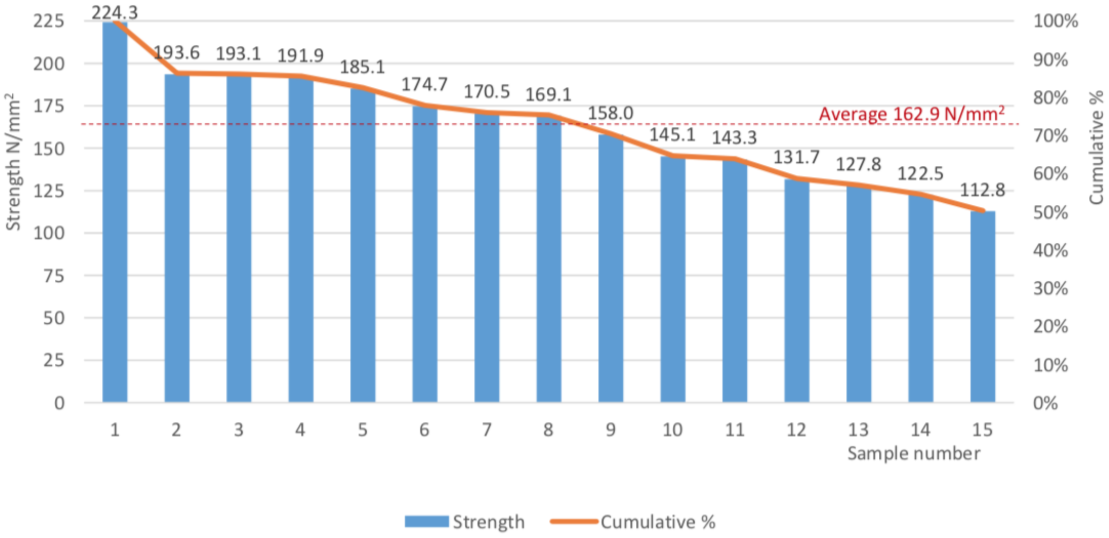


Figure 47: Tension parallel to the grain test results

According to ASTM D143, the failure shapes expected from this test are splintering tension, combined tension and shear, shear and brittle tension. The types of failure for Casuarina Glauca was splintering tension as shown in Figure (48).

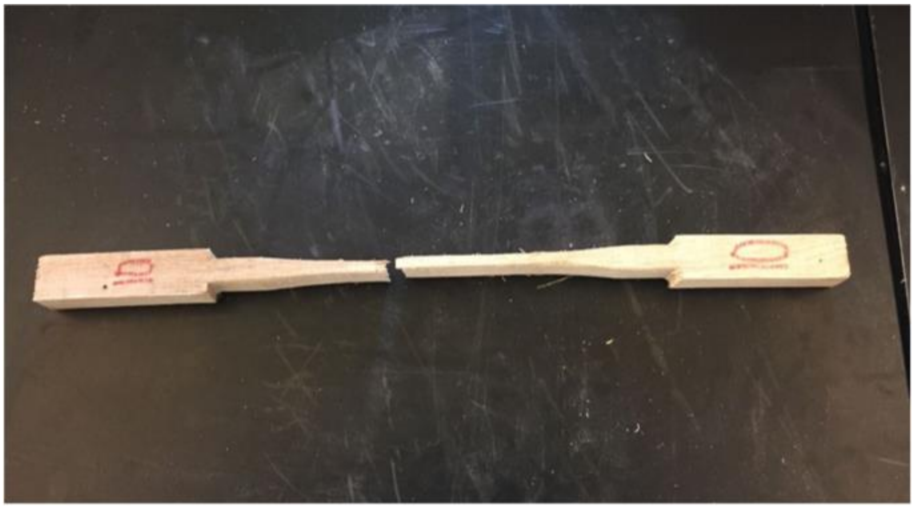


Figure 48: Splintering tension failure

Applying Eq. (1) in ASTM D2915 to check the number of samples tested, the number of samples required for Casuarina Glauca was 14.9, so No additional samples were needed because 15 Samples were enough.

According to ASTM D2555, the average tensile strength parallel to the grain of the various types of oak varies from 78.0 N/mm2 to 112.0 N/mm2, and that for the various types of hardwood in general varies from 51.0 to 121.0 N/mm2. The average tensile strength parallel to the grain of Glauca, 163.0 N/mm2, was high compared with that of similar types of hardwoods. Although the average tensile strength parallel to the grain was high, the average (E) in this test seems to be low compared with the average (E) from the bending or the compression parallel to the grain tests. This is because the (E) is calculated based on the elastic zone only from the stress-strain curve (slope of stress-strain curve, so the value was quite low, whereas if it was calculated based on the maximum load and the extension at the break, the result of the (E) would be much higher. A sample for the stress-strain curve for Casuarina Glauca is shown in Figure (49).

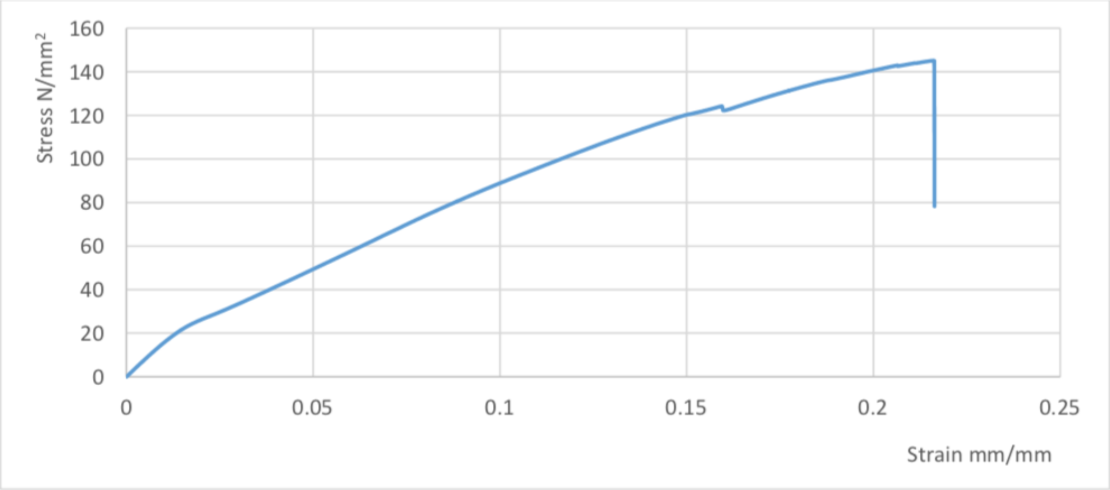


Figure 49: Stress-strain curve for tension parallel to the grain test sample

3.1.4.6 Tension perpendicular to the grain test

After testing the 15 samples of Glauca, the average tensile strength perpendicular to the grain of Casuarina Glauca was 5.9 N/mm2. The average tension perpendicular to the grain modulus of elasticity (E) for Casuarina Glauca was 176.9 N/mm 2.

The results of Casuarina Glauca are summarized in table 5 and shown in Figure (50).

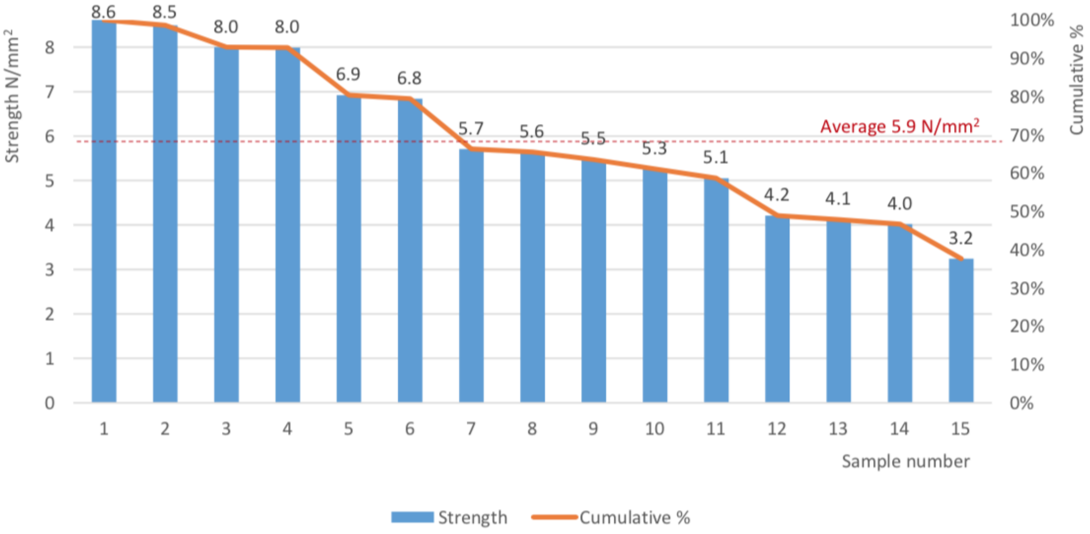


Figure 50: Tension perpendicular to the grain test results

According to ASTM D143, the failure shapes expected from this test are tension failure of early wood, shearing along a growth ring, tension failure of wood rays. The types of failure occurred for Casuarina Glauca were tension failure of early wood as shown in Figure (51).

Figure 51: Tension perpendicular to the grain failure specimen

Applying Eq. (1) in ASTM D2915 to check the number of samples tested, the number of samples required for Casuarina Glauca was 12.7, so no additional samples were needed because 15 samples were enough.

According to ASTM D2555, the average tensile strength perpendicular to the grain of the various types of oak varies from 4.6 to 6.5 N/mm2, and that of the various types of hardwood in general varies from 3.4 to 6.4 N/mm2. The average tensile strength perpendicular to the grain of Glauca was 6.0 N/mm2, which is high compared with that of similar types of hardwoods. A sample for the stress-strain curve for Casuarina Glauca is shown in Figure (52).

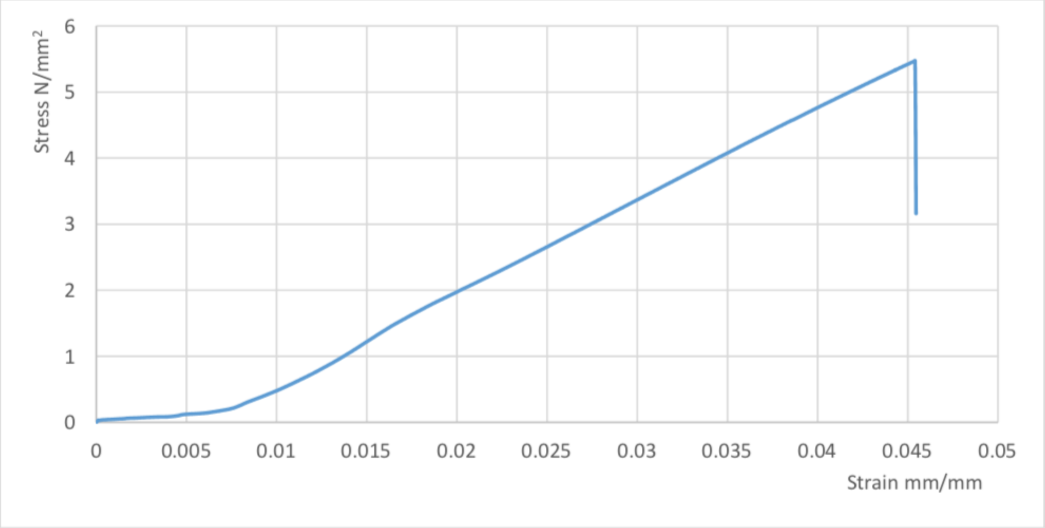


Figure 52: Stress-strain curve for tension perpendicular to the grain test sample

Tables 5 and 6 summarize the results of the modulus of Elasticity, strength, standard deviation, coefficient of variance and the number of samples tested for all the tests for Casuarina Glauca, Cunninghamiana respectively.

Table 5: Results of all tests of Casuarina Glauca

Test	E (N/mm^2)			Strength (N/mm^2)			Standard Deviation	CV	No of Samples Tested
	E max	E min	E Average	Max Strength	Min Strength	Average Stress			
Compression Parallel to the Grain	5619.1	4119.2	5083.06	50.248	7.339	32.219	450.887	0.089	15
Compression Perpendicular to the Grain	201.71	150.16	172.18	12.4	4.41	7.44	16.330	0.095	17
Static Bending	9,830	7,003	8,418	78.4	52.48	62.06	807.147	0.090	15
Tension Parallel to the Grain	876.89	631.5	716.44	224.32	112.83	162.9	68.901	0.090	15
Tension Perpendicular to the Grain	201.15	147.78	176.98	8.61	3.24	5.97	14.817	0.084	15
Cleavage	33.73	23.87	28.53	1.09	0.57	0.827	2.486	0.087	15

Table 6: Results of all tests of Casuarina Cunninghamiana

Test	E (N/mm^2)			Strength (N/mm^2)			Standard Deviation	CV	No of Samples Tested
	E max	E min	E Average	Max Strength	Min Strength	Average Stress			
Compression Parallel to the Grain	2040.7	1373.7	1728.85	23.63	4	11.43	212.335	0.122	15
Compression Perpendicular to the Grain	131.02	21.334	87.27	7.4	1.93	4.98	25.665	0.294	15
Static Bending	5,428	3,541	4,193	38.68	25.25	32.36	647.305	0.154	15

3.1.4.7 Specific Gravity

The specific gravity was calculated for both species (Glauca and Cunninghamiana) based on the green volume basis. 15 samples from each specie were used to calculate the specific gravity. The specific gravity was calculated according to ASTM 2395 using:

$$S_b = \frac{K*m_0}{V_{max}} \qquad (2)$$

$$m_0 = \frac{m_M}{1+0.01\,M} \qquad (3)$$

Where:

S_b = Basic specific gravity.

K= Constant determined by units used to measure mass and volume (K=1cm^3/gm).

m_0 = Oven dry mass of specimen.

V_{max}= Green volume of specimen.

m_M = Initial mass of specimen.

M= Moisture content of specimen at the time of test, percent.

The average specific gravity of Casuarina Glauca was 0.63, whereas the average specific gravity of Casuarina Cunninghamiana was 0.50. According to ASTM D2555, the average specific gravity of the various types of oak varies from 0.56 to 0.64, and that for the various types of hardwood in general varies from 0.48 to 0.81 N/mm2. Comparing the results of both Casuarina species to the hardwoods, the average specific gravity of Casuarina Glauca=0.63 was high which mean it is a high-density wood and Casuarina Cunninghamiana's specific gravity = 0.50 was an average which mean it is a medium density wood. The Specific gravity values are summarized in Figures (53) and (54).

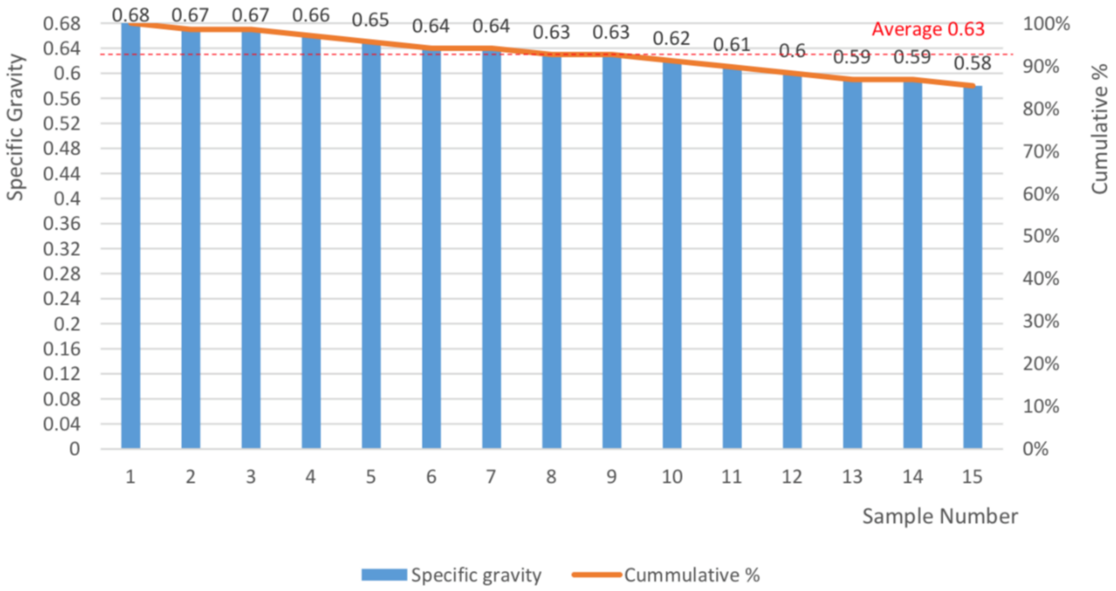


Figure 53: Specific gravity results for Casuarina Glauca

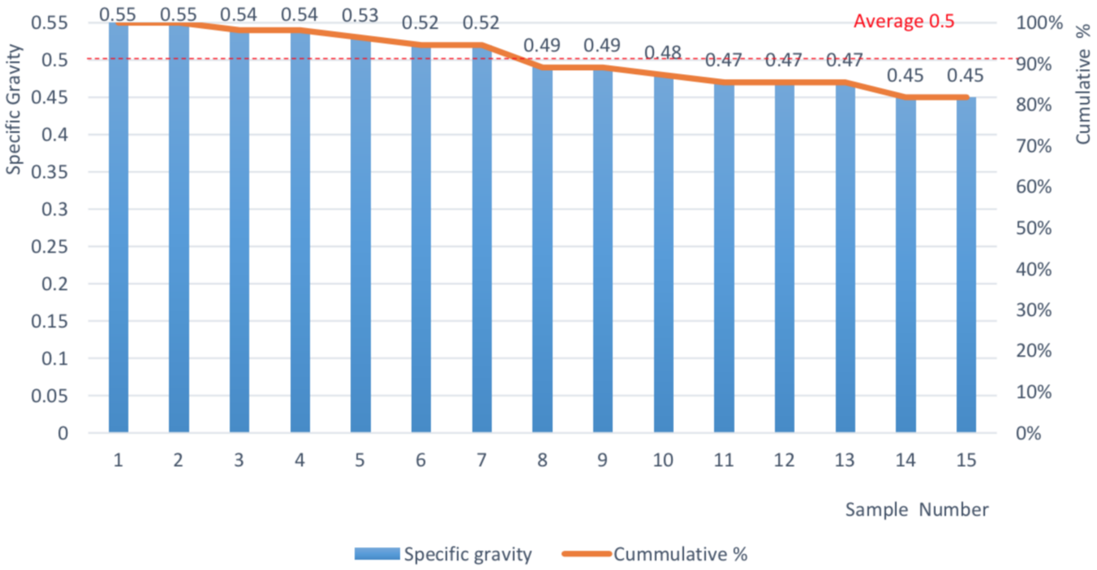


Figure 54: Specific gravity results for Casuarina Cunninghamiana

3.1.4.8 Ductility

In all tests covered in this research, the ductility was assessed by comparing the maximum deformation of Glauca and Cunninghamiana for each test, drawing the stress-strain curves and calculating the modulus of elasticity.

The Ductility was calculated in terms of permanent deformation at ultimate stress (σ_u) and elastic deformation at the same stress for both species (Glauca and Cunninghamiana). The ductility was calculated according to the Euro code 8 (CEN, 2005):

$$Ds_{ue} = \frac{\varepsilon_{pu}}{\varepsilon_{eu}} = \frac{\varepsilon_{pu}}{\sigma_u/E} \qquad (4)$$

Where:

Ds_{ue} = Ductility based on and permanent and elastic strain at ultimate load limit.

ε_{pu} = Permanent strain at ultimate load limit

ε_{eu} = Strain at ultimate load limit

σ_u = Normal stress at ultimate load

E = Modulus of Elasticity

The average ductility for Casuarina Glauca was 1.12, whereas the average ductility for Casuarina Cunninghamiana was 0.78. The previous results show that Casuarina Glauca is more ductile than Casuarina Cunninghamiana. The Ductility results are summarized in Figures (55) and (56).

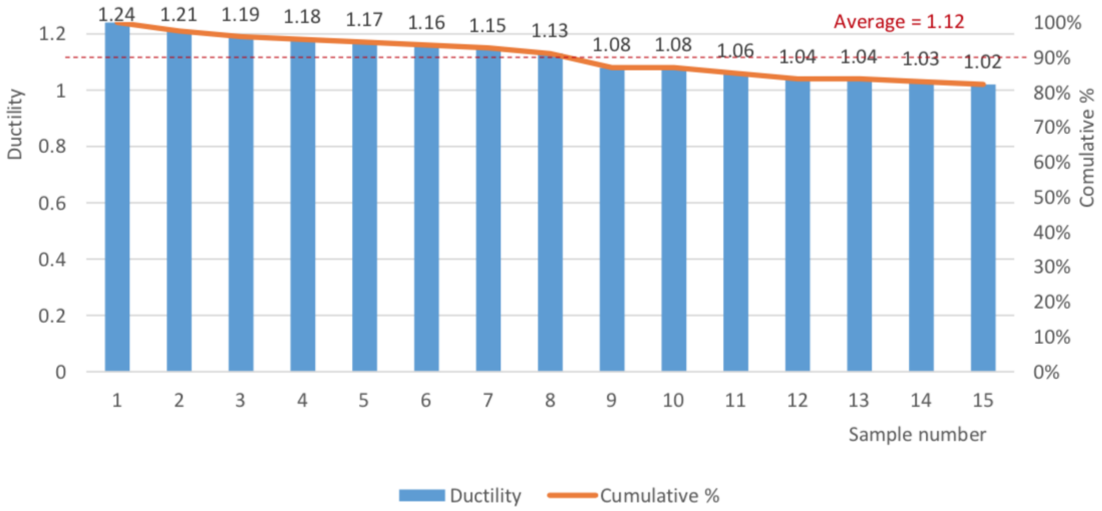


Figure 55: Ductility results for Casuarina Glauca

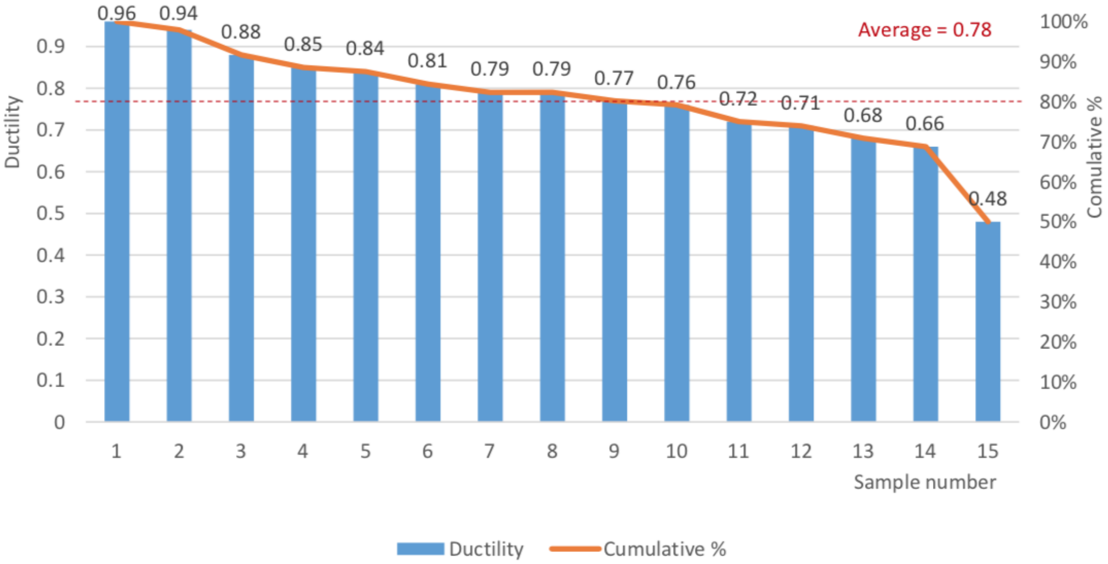


Figure 56: Ductility results for Casuarina Cunninghamiana

By the end of the mechanical testing, it was important to compare the results of Casuarina Glauca and Cunninghamiana to several types of softwoods and hardwoods in order to rank Casuarina among the different types of wood. As shown in table (7) The values of Casuarina Glauca were the highest in almost all the tests while Casuarina Cunninghamiana has an average strength values.

Table 7: Comparing Casuarina Glauca and Cunninghamiana to different types of wood.

Property	Casuarina		Hardwoods				Softwoods			
	Glauca	Cunn.	Red Oak	White Oak	Hickory	Maple	Cedar	Fir	Pine	Hemlock
Compressive strength parallel to the grain (N/mm^2)	**32.2**	**11.4**	**22.0**	**26.3**	**30.2**	**22.5**	**19.8**	**17.0**	**18.4**	**20.5**
Compressive strength perpendicular to the grain (N/mm^2)	**7.4**	**4.9**	6.5	7.2	6.6	3.4	2.4	1.3	2.0	2.5
Bending strength (N/mm^2)	**62.1**	**32.4**	59.2	60.2	**72.6**	52.7	39.9	35.9	37.6.	43.7
Tensile strength parallel to the grain (N/mm^2)	**163.0**	**-**	112.0	78.0	88.3	108.2	62.1	86.5	76.4	89.6
Tensile strength perpendicular to the grain (N/mm2)	**5.9**	**-**	5.1	5.2	5.4	4.3	1.7	1.8	2.0	2.0
Specific Gravity	**0.63**	**0.50**	0.57	0.62	**0.63**	0.50	0.36	0.31	0.39	0.41

3.1.5 Data correlation

The Data correlation analysis was done using Pearson correlation method, which studies the strength and the linear relationship between two variables through the Pearson correlation coefficient **(r)**. The **(r)** value ranges from -1 to 1, where the sign refers to the direction of the relationship and the value refers to the strength of the relationship.

If the value of r = 0, then there is no relationship between the variables. If the value of r = +1 then the two variables have a perfectly positive linear relationship. If the value of r = -1 then the two variables have a perfectly negative linear relationship.

The Pearson correlation was used to measure the correlation between each test and another based on the strength. The resulting strength from each test was listed and then each test is correlated to another regardless of the sample size or description. Only Casuarina Glauca samples were used as it was tested for all tests. The Pearson correlation coefficient was calculated for two sets of data (strength values of two tests) to study whether the strength values from the two tests were correlated or not. The results of the correlation analysis were:

1) Static bending and compression parallel to the grain: r= +0.30, which means that the two tests have a weak positive correlation.

2) Static bending and compression perpendicular to the grain: r= -0.05, which means that the two tests have no correlation.
3) Static bending and tension parallel to the grain: r= +0.5, which means that the two tests have a moderate positive correlation.
4) Static bending and tension perpendicular to the grain: r= +0.12, which means that the two tests have a weak positive correlation.
5) Tension parallel to the grain and compression parallel to the grain: r= +0.40, which means that the two tests have a weak positive correlation.
6) Tension parallel to the grain and tension perpendicular to the grain: r= +0.34, which means that the two tests have a weak positive correlation.
7) Tension perpendicular to the grain and compression perpendicular to the grain: r= 0.00, which means that the two tests have no correlation.
8) Compression parallel to the grain and compression perpendicular to the grain: r= 0.00, which means that the two tests have no correlation.

From the previously mentioned results, it is clear that the highest correlation was recorded between the tension parallel to the grain test and static bending test which matched the results, because all the bending samples failed in the tension side, whereas some other tests had no correlation with each other. Table (8) summarizes the Pearson correlation results for all the tests.

Table 8: Pearson correlation results

Pearson Correlation by Strength		
Tests	**r**	**Correlation Result**
Tension parallel to the Grain / Tension Perpendicular to the Grain	0.34	Weak positive Correlation
Compression parallel to the Grain / Compression Perpendicular to the Grain	0.00	No Correlation
Tension parallel to the Grain / Static Bending	0.50	Moderate positive Correlation
Compression parallel to the Grain / Static Bending	0.30	Weak positive Correlation
Tension parallel to the Grain / Compression parallel to the Grain	0.4	Weak positive Correlation
Tension perpendicular to the Grain / Compression perpendicular to the Grain	0.00	No Correlation
Tension perpendicular to the Grain / Static Bending	0.12	Weak positive Correlation
Compression perpendicular to the Grain / Static Bending	-0.05	No Correlation

Comparing the above results with another study done on five types of wood which are: Red pine, Larch, Pitch pine, Cedar and Cypress (Kim & Kug, 2011). The study used a different correlation technique rather than Pearson correlation. The results from that study showed that the tension test in more than one type of wood achieved its highest correlation with the static bending test (correlation coefficient=0.88). The compression test also still achieved high correlation with the tension test (correlation coefficient=0.87), whereas the compression test achieved moderate correlation with the static bending tests (correlation coefficient=0.60). The results from this study match the correlation results of done on other species of Casuarina wood.

3.2 Investigating the moisture content effect on the mechanical properties

3.2.1 Scope of work

The experimental program for this study is based on testing 10 samples from Casuarina Glauca and 10 samples from Casuarina Cunninghamiana in three different moisture contents, the first one is when the specimens have just arrived without any drying (approximately 60%), the second moisture content is after partially drying the specimens to 40% and the third one is after drying the specimens to 20%. Before testing, all the samples were dried in the oven and the moisture content was measured using a moisture meter.

Small clear samples are subjected to compression parallel to the grain, compression perpendicular to the grain, tension parallel to the grain and static bending tests. Load-deformation curves were obtained and drawn to evaluate the mechanical properties for both species then the modulus of rupture, bending strength, modulus of elasticity in tension parallel to the grain, tensile strength parallel to the grain, modulus of elasticity in compression parallel and perpendicular to the grain and compressive strength parallel and perpendicular to the grain were obtained.

All the mechanical tests were performed according to the standards of ASTM D143, ASTM D2555 and ASTM D2915.

3.2.2 Sampling Procedures

The Sampling procedures were done according to ASTM D2915. For every test, 10 samples from each specie were tested as a preliminary assumption for each moisture content level, then the mean, standard deviation and coefficient of variation are calculated, and then sample size is being checked. If the sample size was not sufficient, the number of additional samples is calculated and tested then the sample size will be checked again. The parameter used in determining the number of samples in all the tests is the modulus of elasticity (MOE). Generally, the wood samples for all tests were taken from farm trees and not Forrest trees that were delivered from more than one tree then cut and shaped according to the ASTM requirements for every test.

3.2.3 Mechanical Tests

3.2.3.1 Compression parallel/perpendicular to the grain tests

The Compression parallel to the grain and the compression perpendicular to the grain tests were done according ASTM D143 using the mechanical testing machine for 10 samples from each specie (Casuarina Glauca and Casuarina Cunninghamiana under 3 different moisture contents (60%, 40%, 20%) the load -deflection curves and the stress-strain curves are drawn to be used to determine the compressive strength according to equation 5 and the compressive modulus of elasticity (MOE) according to equation 6 as follows:

$$\text{The compressive strength} = \frac{P}{A} \qquad (5)$$

Where:

P = maximum load achieved during test (N).

A = cross sectional area of the test sample (mm^2).

The compressive modulus of elasticity was calculated according to equation 6 as follows:

$$\text{E(compression)} = \frac{P / A_0}{\Delta L / L_0} \qquad (6)$$

Where:

E(compression) = Compressive modulus of elasticity

P=load at linear zone of load-deformation curve (N)

A_0 = cross sectional area of the sample (mm2)

ΔL = deformation at linear zone of load- deformation curve (mm)

L_0 = extensometer gage length (mm).

3.2.3.2 Static bending test

The static bending test was done according ASTM D143 using the mechanical testing machine for 10 samples from each specie (Casuarina Glauca and Casuarina Cunninghamiana under 3 different moisture contents (60%, 40%, 20%) the load -deflection curves and the stress- strain curves are drawn to be used to determine the modulus of rupture (bending strength) according to equation 7 and the modulus of elasticity in bending according to equation 8 as follows:

$$MOR = \left(\frac{3PL^2}{2bh^2}\right) \qquad (7)$$

Where:

MOR = Modulus of rupture (N/mm^2).

P = Maximum load achieved during the bending test (N).

L = span (mm).

b = sample width (mm).

h = sample height (mm).

$$MOE = \left(\frac{\Delta FL^3}{4bh^3\Delta d}\right) \qquad (8)$$

MOE = Modulus of elasticity in bending (N/mm^2)

ΔF = load at linear zone of load-deformation curve (N)

L = span (mm); b = sample width (mm)

h = sample height (mm)

Δd = deformation at linear zone of load- deformation curve (mm).

3.2.3.3 Tension parallel to the grain test

The tension parallel to the grain test was done according ASTM D143 using the mechanical testing machine for 10 samples from each specie (Casuarina Glauca and Casuarina Cunninghamiana under 3 different moisture contents (60%, 40%, 20%) the load -deflection curves and the stress- strain curves are drawn to be used to determine the tensile strength according to equation 9 and the tensile modulus of elasticity according to equation 10 as follows:

$$\text{The Tensile strength} = \frac{P}{A} \qquad (9)$$

Where:

P = maximum load achieved during test (N).

A = cross sectional area of the test sample (mm^2).

The Tensile modulus of elasticity was calculated according to equation 6 as follows:

$$E(\text{Tension}) = \frac{P / A_0}{\Delta L / L_0} \qquad (10)$$

Where:

E(compression) = Tensile modulus of elasticity

P=load at linear zone of load-deformation curve (N)

A_0 = cross sectional area of the sample (mm2)

ΔL = deformation at linear zone of load- deformation curve (mm)

L_0 = extensometer gage length (mm).

3.2.4 Results and discussion

3.2.4.1 Compression parallel to the grain test

After testing 10 specimens from Casuarina Glauca and 10 specimens from Casuarina Cunninghamiana, the compression parallel to the grain test results for both species showed that the highest compressive strength was recorded at moisture content (MC) 20%.

The average compressive strength parallel to the grain for Casuarina Glauca results were 32.4 N/mm2, 22.2 N/mm2 and 13.2 N/mm2 achieved by MC 20%, MC 40% and MC 60% respectively. The previous results show that reducing the moisture content by 20% improves the average compressive strength by approximately 46%. A sample for load-deformation curve for different moisture content samples for Casuarina Glauca are shown in Figure (57).

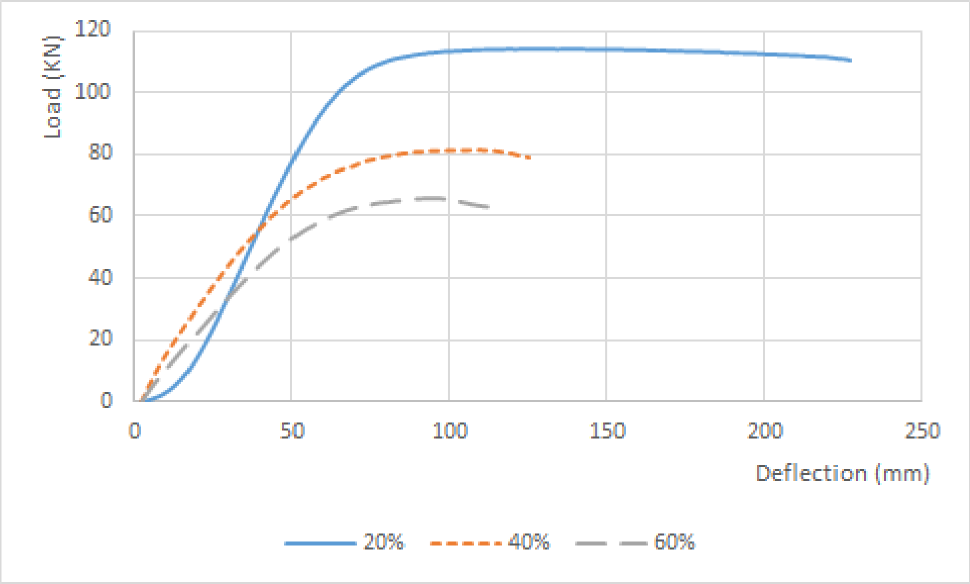


Figure 57: Casuarina Glauca Average load – deformation curves at different moisture contents for compression parallel to the grain test.

The average compressive strength parallel to the grain for Casuarina Cunninghamiana results were 13.3 N/mm2, 7.6 N/mm2and 4.6 N/mm2 achieved by MC 20%, MC 40% and MC 60% respectively. The previous results show that reducing the moisture content by 20% improves the average compressive strength by approximately 75%.

The results of compression parallel to the grain test are shown in tables (8) & (9).

3.2.4.2 Compression perpendicular to the grain test

After testing 10 specimens from Casuarina Glauca and 10 specimens from Casuarina Cunninghamiana, the compression perpendicular to the grain test results for both species showed that the highest compressive strength was recorded at moisture content (MC) 20%.

The average compressive strength perpendicular to the grain for Casuarina Glauca results were 7.5 N/mm2, 6.6 N/mm2 and4.4 N/mm2 achieved by MC 20%, MC 40% and MC 60% respectively. The previous results show that reducing the moisture content by 20% improves the average compressive strength by approximately 14%.

The average compressive strength perpendicular to the grain for Casuarina Cunninghamiana results were 5.4 N/mm2, 3.6 N/mm2and 1.9 N/mm2 achieved by MC 20%, MC 40% and MC 60% respectively. The previous results show that reducing the moisture content by 20% improves the average compressive strength by approximately 50%.

3.2.4.3 Static bending test

After testing 10 specimens from Casuarina Glauca and 10 specimens from Casuarina Cunninghamiana, the static bending test results for both species showed that the highest bending strength (Modulus of rupture) was recorded at moisture content (MC) 20%.

The average modulus of rupture for Casuarina Glauca results were 63.7 N/mm2, 51.2 N/mm2 and 48.6N/mm2 achieved by MC 20%, MC 40% and MC 60% respectively. The previous results show that reducing the moisture content by 20% improves the average modulus of rupture by approximately 24%. A sample for load-deformation curve for different moisture content samples for Casuarina Glauca are shown in Figure (58).

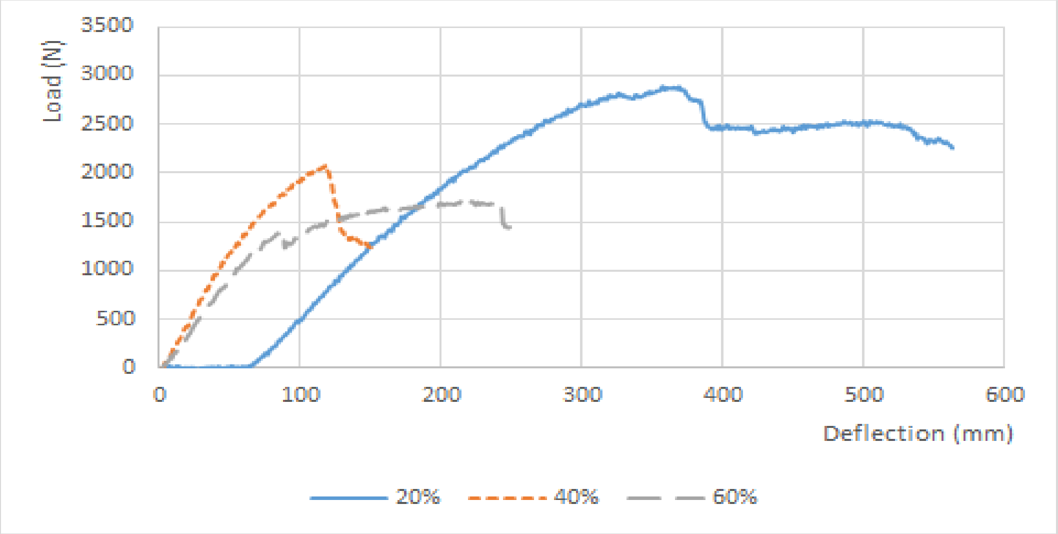


Figure 58: Casuarina Glauca Average load – deformation curves at different moisture contents for static bending test

The average modulus of rupture for Casuarina Cunninghamiana results were 44.7 N/mm2, 34.5 N/mm2 and 25.4N/mm2 achieved by MC 20%, MC 40% and MC 60% respectively. The previous results show that reducing the moisture content by 20% improves the average modulus of rupture by approximately 29%. The results of static bending test are shown in tables (8) & (9).

3.2.4.4 Tension parallel to the grain test

After testing 10 specimens from Casuarina Glauca and 10 specimens from Casuarina Cunninghamiana, the tension parallel to the grain test results for both species showed that the highest tensile strength was recorded at moisture content (MC) 20%.

The average tensile strength parallel to the grain for Casuarina Glauca results were 166.3 N/mm2, 123.8 N/mm2 and 107.4N/mm2 achieved by MC 20%, MC 40% and MC

60% respectively. The previous results show that reducing the moisture content by 20% improves the average tensile strength by approximately 34%. A sample for load-extension curve for different moisture content samples for Casuarina Glauca are shown in Figure (59).

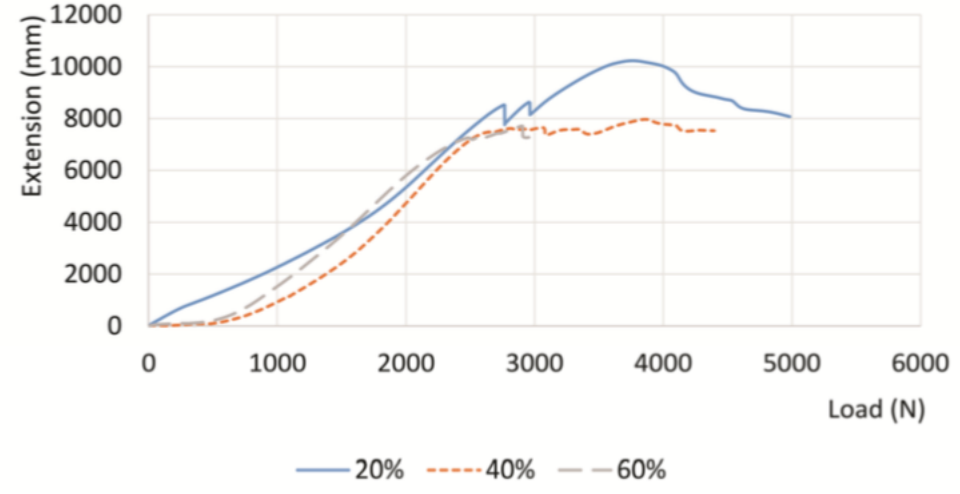


Figure 59: Casuarina Glauca Average load –extension curves at different moisture contents for tension parallel to the grain test.

The average tensile strength parallel to the grain for Casuarina Cunninghamiana results were 161.2 N/mm2, 152.6 N/mm2and 38.4 N/mm2 achieved by MC 20%, MC 40% and MC 60% respectively. The previous results show that reducing the moisture content by 20% improves the average tensile strength by approximately 6%.

The results of tension parallel to the grain test are shown in tables (9) & (10).

Table 9: Casuarina Glauca results at different moisture contents

Test	Property	Moisture content %			SD	CV	# of samples tested
		20%	40%	60%			
Compression Parallel to the grain	MOE (N/mm2)	5144.3	4857	4647.9	464.1	0.09	10
	strength (N/mm2)	32.4	22.2	13.2			
Compression Perpendicular to the grain	MOE (N/mm2)	183.7	163.3	150.2	15.2	0.083	10
	strength (N/mm2)	7.5	6.6	4.4			
Static Bending	MOE (N/mm2)	8517.3	7188.3	6254.7	655.1	0.08	10
	strength (N/mm2)	63.7	51.2	48.6			
Tension Parallel to the grain	MOE (N/mm2)	755.8	620.4	592.8	57.8	0.077	10
	strength (N/mm2)	166.3	123.8	107.4			

Table 10: Casuarina Cunninghamiana results at different moisture contents

Test	Property	Moisture content %			SD	CV	# of samples tested
		20%	40%	60%			
Compression Parallel to the grain	MOE (N/mm2)	1851.5	1591.7	1356	156.5	0.085	10
	strength (N/mm2)	13.3	7.6	4.6			
Compression Perpendicular to the grain	MOE (N/mm2)	111	98.2	21.3	7.8	0.088	10
	strength (N/mm2)	5.4	3.6	1.9			
Static Bending	MOE (N/mm2)	4322.9	4151.2	4115.4	373.6	0.09	10
	strength (N/mm2)	36.7	31.5	25.4			
Tension Parallel to the grain	MOE (N/mm2)	662	605.9	574.4	50.2	0.079	10
	strength (N/mm2)	143.8	112.6	100.4			

Chapter 4: Truss model design & constructability

4.1 Introduction

This chapter focuses on designing, manufacturing and testing a formwork girder made of Casuarina Glauca that can be used on the construction of slab formworks. The first section in this chapter is the model description and the design criteria that were followed in designing the truss. The second section in this chapter is the truss manufacturing and assembly process. The third section in this chapter is the experimental testing of the truss followed by the results and discussion. The last section of this chapter is a comparison between the manufactured girder and the GT 24 Formwork girder produced by PERI company.

4.2 Model description and design

4.2.1 Model description

The model developed in this thesis is a wooden K-truss made of casuarina Glauca that covers a span of 2.2 meters and a height of 0.35 meters. This span was chosen specifically to compare the results of the manufactured girder with a well-known commercially formwork girder produced by PERI company which is the GT 24 formwork girder. The significance of designing such a model using Casuarina Glauca wood is very important as it will be a major achievement if it succeeded due to the major cost savings compared to the other alternatives available in the formwork market.

The Truss model manufactured in this thesis will be similar to the GT 24 girder in terms of the span and height but the shape of the truss system and the connections used to connect the wooden members are completely different as well as the type of wood used to build the truss.

4.2.2 Model design

The methodology followed in producing such a model started with analyzing the properties and choose the shape of the truss model. The chosen truss shape was a K-truss, as the K-truss has a lot of advantages such as reducing the compression on the vertical members and can achieve material and cost reduction if designed efficiently. The design was executed on the AutoCAD as shown in figure (60). Table (11) summarizes the dimensions of each member in the truss.

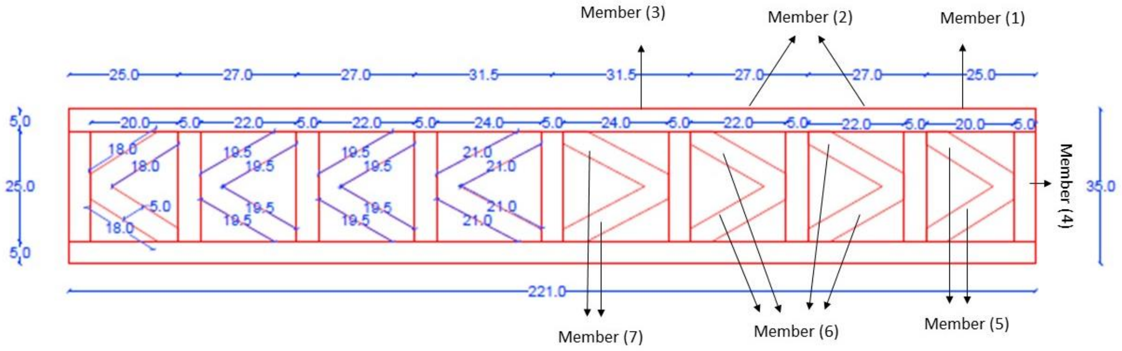


Figure 60: Detailed design of the proposed Truss using AutoCAD.

Table 11: Truss members dimensions

	Member No.	Dimensions (cm)			No. of members in truss
		Length	Width	Depth	
Upper and Lower Chords	(1)	25	5	3.5	4
	(2)	27	5	3.5	8
	(3)	31.5	5	3.5	4
Vertical Members	(4)	25	5	3.5	9
Diagonal Members	(5)	18	5	3.5	4
	(6)	19.5	5	3.5	8
	(7)	21	5	3.5	4

After drawing the model using the AutoCAD, the model was drawn on SAP in order to test the functioning of such a model as shown in figure (61). The design load was based on assuming the slab thickness of the slab to be poured above the truss to be 0.32 meters, the Joists spacing to be 0.8 meters, the concrete unit weight to be 2.5 tons per cubic meters. The resulted load from the previous assumptions was 1 ton per meter run, so the design load that was applied in the SAP model as a distributed load on the upper chord was 1 ton per meter run.

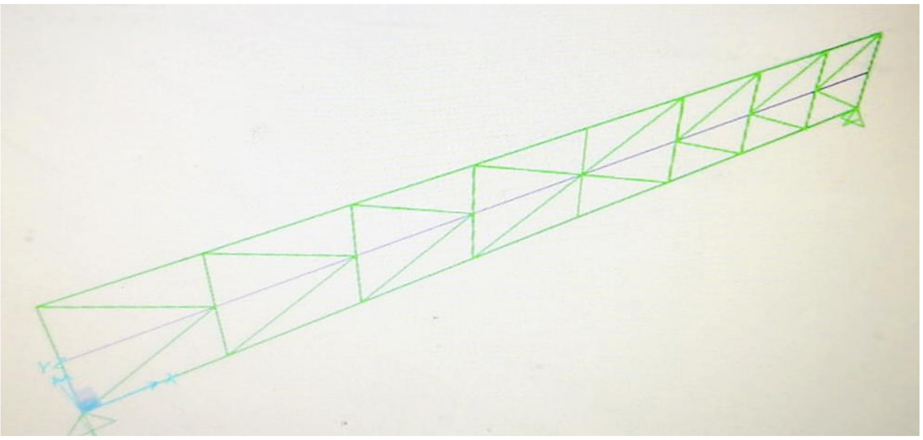


Figure 61: Truss design on SAP

4.2.2.1 SAP analysis

In order to run the sap model, there was an important step that must be done which is identifying the material which is the Casuarina Glauca. To identify the Casuarina Glauca, the results from the mechanical tests were used such as the specific gravity, the compressive modulus of elasticity for the members subjected to compressive forces and the tensile modulus of elasticity for the members subjected to the tension forces.

According to statistics and as shown in figure (62), moving one standard deviation from the mean covers 68% of the data in the normal model and moving two standard deviations covers around 95% of the data, so as a factor of safety and to overcome any variability in the wood, the mechanical properties that were entered in the SAP model was moving to standard deviations from the average value.

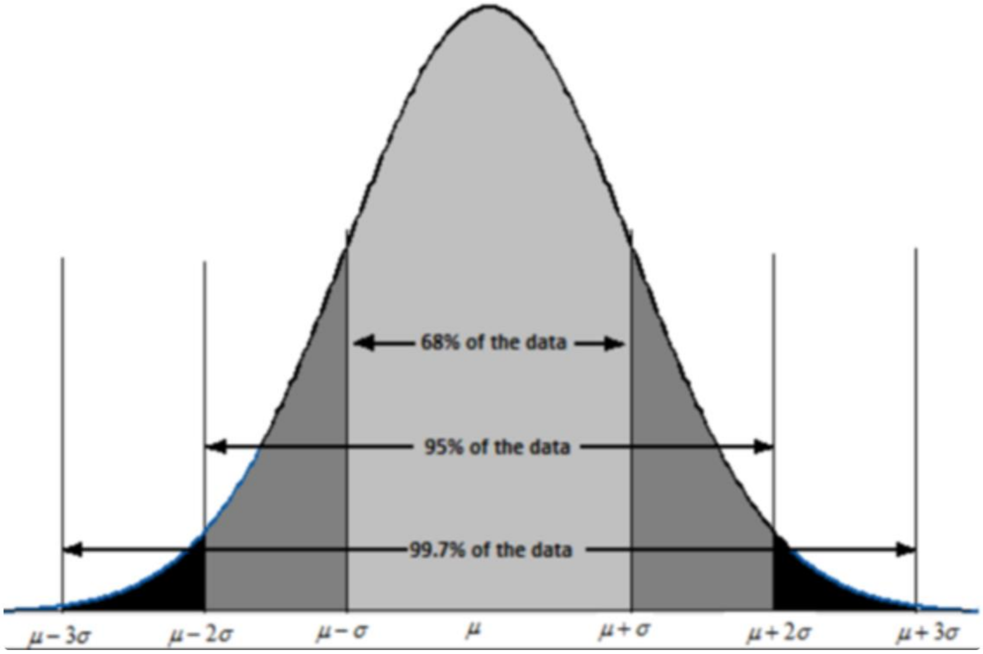


Figure 62: Normal distribution graph

In order to validate the design model, it was important to compare the allowable member forces with the axial forces resulted from the SAP model to make sure that the design is valid. The allowable member capacity was calculated according to Euler's equation and compared to the resulted axial forces in each member as shown in table (12). Figure (63) shows the load analysis from the SAP.

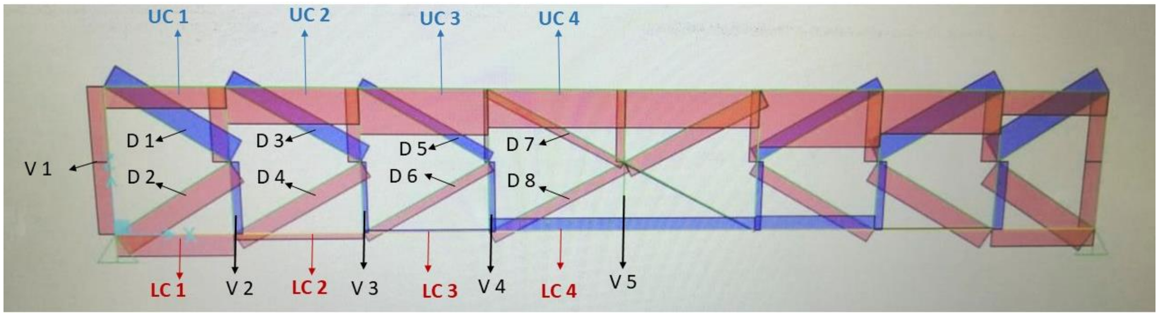


Figure 63: Members axial forces on SAP

Table 12: Comparing the member capacity to the Axial load on SAP.

Member	Member Capacity (Ton)	Axial Load (Ton)
UC 1	0.96	0.38
UC 2	1.04	0.47
UC 3	1.04	0.82
UC 4	1.13	0.63
LC 1	0.96	0.81
LC 2	1.04	0.25
LC 3	1.04	0.07
LC 4	1.13	0.46
V 1	0.86	0.57
V 2	0.86	0.32
V 3	0.86	0.18
V 4	0.86	0.2
V 5	0.86	0.18
D 1	1.00	0.84
D 2	1.00	0.84
D 3	0.88	0.64
D 4	0.88	0.64
D 5	0.88	0.37
D 6	0.88	0.37
D 7	0.62	0.29
D 8	0.62	0.44

4.2.2.2 Design of the connections

There are several materials that can be used in the connections such as steel, aluminum, wood plastic composites or even glue. In this thesis steel plates were used to connect the wooden members of the truss. The steel plates were 2mm thickness as recommended by (Mahmoud et.al, 2019), as the results of the 0.5mm, 1mm thickness plates were not satisfactory and has some problems. Two types of steel plates were used to connect the members of the truss, either (6cm*6cm) or (4cm*6cm) steel plate that were repeated symmetrically along the whole truss as shown in figure (64).

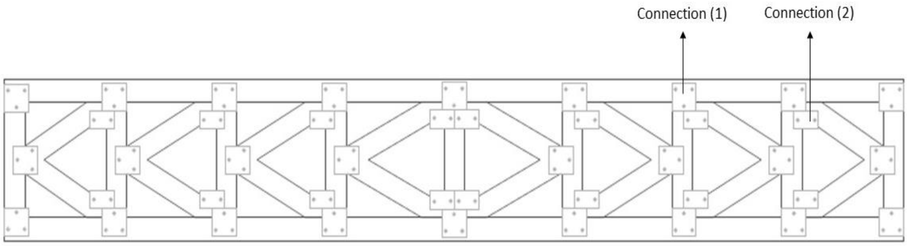


Figure 64: Connections distribution on the truss

After trying several types of screws in the steel connections, the common problem was the screw failure in wood, as Casuarina Glauca is a very hardwood. After several trials, two types of Screws succeeded to penetrate the wood without failing or cracking the wood members. The two types of screws used were size#8 tapered head screw that was used in the (6cm*6cm) connection and size#6 bugle shape screw that was used in the (4cm*6cm) connection. Figure (65) shows the two types of screws used.

Figure 65: The two types of screws used in connections.
(https://woodworkingformeremortals.com/types-screws-use-woodworking-basics)

4.2.2.2.1 Manual Calculations

The manual calculations analyzed the types of failure that might occur in the connections. The first expected failure was the screw shear failure. The screw shear failure capacity was checked according to (Mahmoud et.al,2019) Equation 11 as follows:

$$R_s = (0.6 * F_{us}) * A_s * n \qquad (11)$$

Where:

R_s =Screw shear capacity.

F_{us} = The ultimate screw shear strength.

A_s= Area of the screw.

N= Number of screws.

The second expected failure was the bearing failure on the plate and it was checked according to (Mahmoud et.al,2019) Equation 12 as follows:

$$R_{b=} \, d*t*(\alpha*F_u) \qquad (12)$$

Where:

R_b= Bearing plate capacity.

D= The diameter of the screw.

T= plate thickness.

α= Factor determined according to the used edge distance.

4.2.2.3 The design criteria

The design criteria for the manufactured truss is to achieve the strength and deflection requirements.

The model will achieve the strength by maintain the design load (1 Ton per meter run) and the equivalent deflection which was calculated according to Equation 13:

$$D = \frac{L}{270} \qquad (13)$$

Where:

D= Allowable deflection at the design load.

L= Span of the truss.

4.3 Model manufacturing and assembly

4.3.1 Preparing the truss wooden members

After determining the dimensions of the girder as mentioned in the model design section, a detailed shop drawing for each member in the truss before starting the manufacturing process. Three trusses will be manufactured and tested so the amount of wood required to manufacture one truss was calculated in order to calculate the total amount of wood required to build the three trusses made of casuarina Glauca wood. Figure (66) shows the procurement of Casuarina Glauca wood that will be used in manufacturing the three trusses.

Figure 66: The procurement of the wood used in manufacturing the trusses

The first step in the manufacturing process is to cut all the members of the truss according to the shop drawings prepared in advance. All the exterior members, the interior vertical members and the inner diagonals were cut into the required sizes using electric sow as shown in figure (67).

Figure 67: Cutting the wood samples into requires sizes using electric sow

After cutting the members into the required sizes it is very important to smoothen and clean the surface of the wood as mentioned in the literature review that the wood used in formworks should have a smooth surface so that the concrete does not stick during pouring the concrete. Figure (68) shows the machine used to clean up and smoothen the surface of the wood. By the end of the cleaning process the wooden members are ready to be used to form the truss.

Figure 68: Cleaning and smoothing the surface of the wooden members

4.3.2 Preparing the steel connections

Before using the steel plates as a connection, it has to be prepared. First of all, the locations of the screws are marked on the steel plated using a marker, then a driller is used to make the opening of the screw as shown in figure (69).

Figure 69: Making the opening of the screws using a driller

4.3.3 The truss assembly

The Assembly of the truss begins with building the external members of the truss and connecting them to each other as shown in figure (70).

Figure 70: Building the external members of the truss and connecting them

Then the inner diagonals are inserted and connected as shown in figure (71).

Figure 71: Connecting the inner diagonals of the truss

The process of connecting any two or more members starts by placing the steel connection in its design position, then the wooden member is drilled using the driller through the opening that were done during preparing the steel plates in order to insert the screw, then the screw is fastened using a driller. Figure (72) shows the truss after connecting all the members.

Figure 72: The truss final shape after connecting all the members

It is very important to calculate the assembly time to construct one truss. The time taken by a carpenter to prepare the steel connections, construct one truss was around 45 minutes which is considered a relatively short time especially when the truss is built by only one carpenter using noncomplex building materials so the assembly time of one truss can be considered a good outcome. The assembly time can also decrease by adding a non-skilled assistant to the carpenter where it might reach 30 minutes.

4.4 Experimental work

4.4.1 Description

The experimental work of this thesis includes testing three manufactured trusses using casuarina Glauca wood. The samples will act as a formwork girder made of Casuarina Glauca which was never used before in structure applications. The scope of the experimental work is to test each of the three trusses under bending till failure in order to determine the maximum load and deflection resulted from loading the truss.

4.4.2 Loading case

There are several loading cases that the truss may be subjected to in a real-life application such as the loading during construction, loading during transportation and the loading during pouring the concrete. The loading case in the experimental work will be the loading during pouring the concrete only and neglecting the effect of the other types of loads.

4.4.3 The Equipment used

Electronic Balance

As shown in figure (73), The electronic balance was used to weight the samples before testing and weight the wooden beam that was placed above the truss samples.

Figure 73: The electronic balance

Wooden beam and steel rods

In order to simulate the behavior of a distributed load on the truss, the load was applied on a wooden beam above the truss sample. Steel rods were placed at each joint and the wooden beam was placed above the steel rods. Figure (74) shows the steel rods placed on the truss and figure (75) shows the wooden beam used.

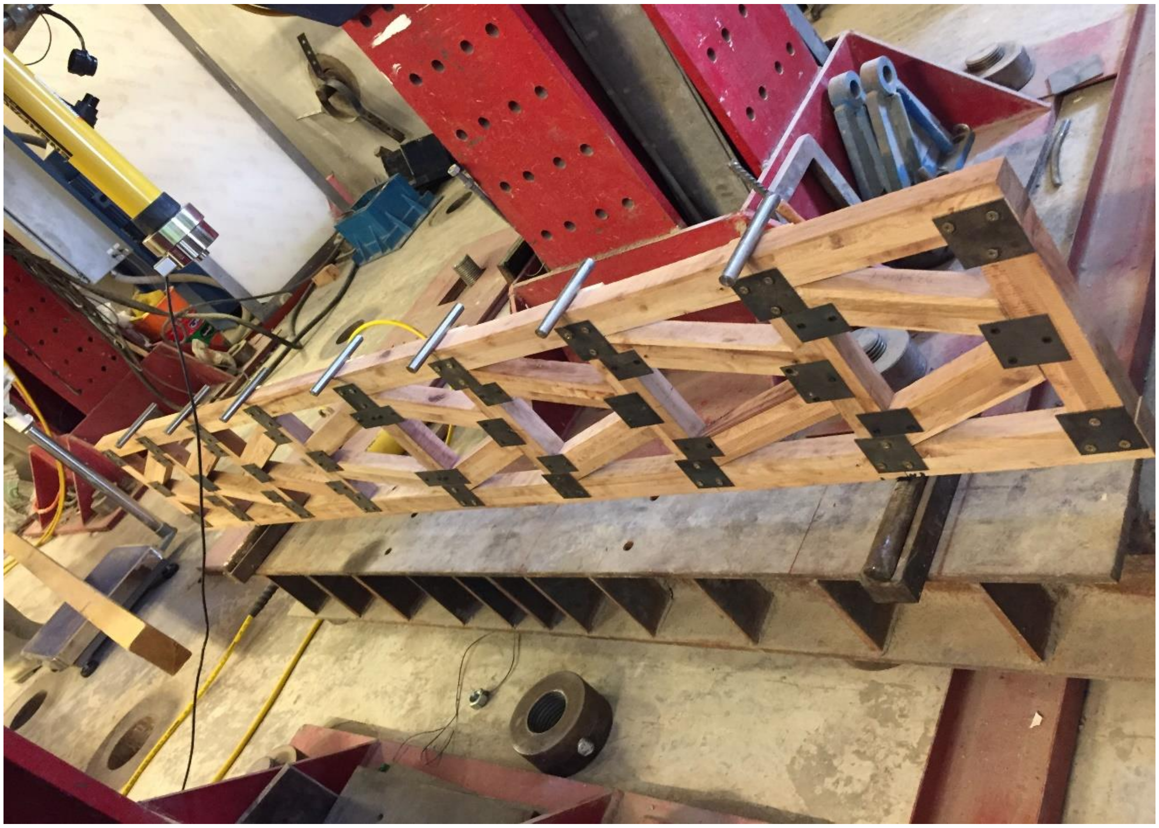


Figure 74: The steel rods placed above the truss

Figure 75: The wooden beam that was used to distribute the load over the truss.

The Load cell

The load cell is the device used to apply the load on the truss. The load is applied manually in this test using a hydraulic pump to control the sensitivity range of the loads applied (Load control). The capacity of the load cell used in this test is 10 Tons. The specimen must be placed under the load directly to avoid any eccentricity. Figure (76) shows the load cell used in the experiment.

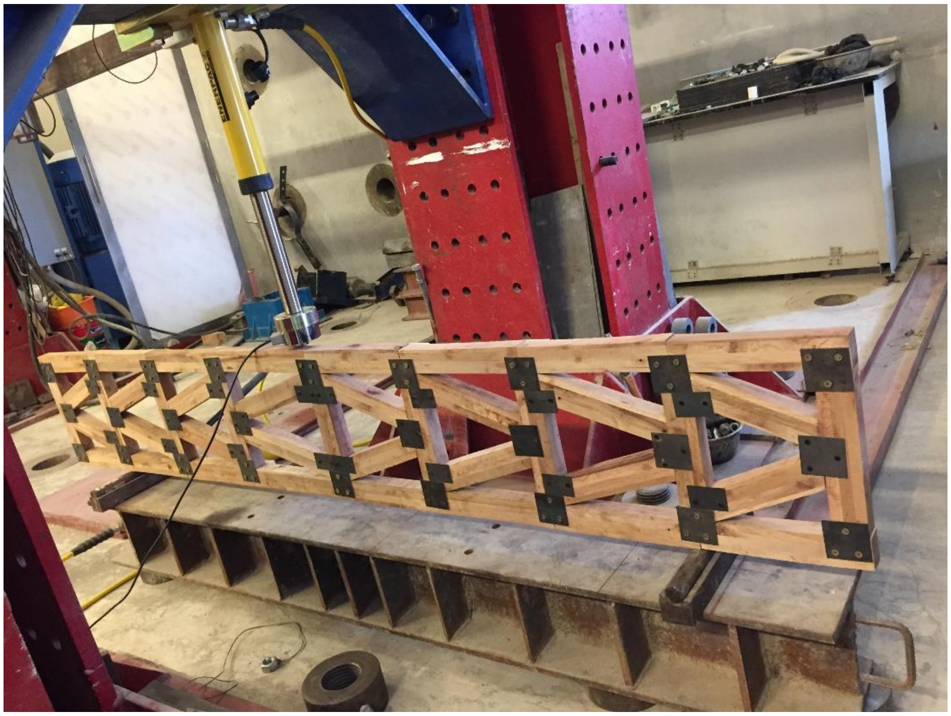


Figure 76: The load cell used in the test

The hydraulic pump

The hydraulic pump is the device that transmits the load applied by the load cell on the specimen. The hydraulic pump is operated by a technician that apply the load in increments. The failure load was expected to be 1 ton so it is important to use the hydraulic pump in order to increase the load by small increments. The hydraulic pump is connected to the load cell through a hose that transmits the load with every pressure through the jack. Figure (77) shows the hydraulic pump.

Figure 77: The hydraulic pump

Linear variable differential transformer (LVDT)

The LVDT is the device used to measure the displacement. The LVDT has two parts, the first part is a magnetic base and the second part is a wired needle connected to a reading device. The needle transforms electronic signals that represents the deflection happened into the reading device. In this experiment 3 LVDT's were used to record the deflection during the test. Figure (78) shows the LVDT used in the experiment.

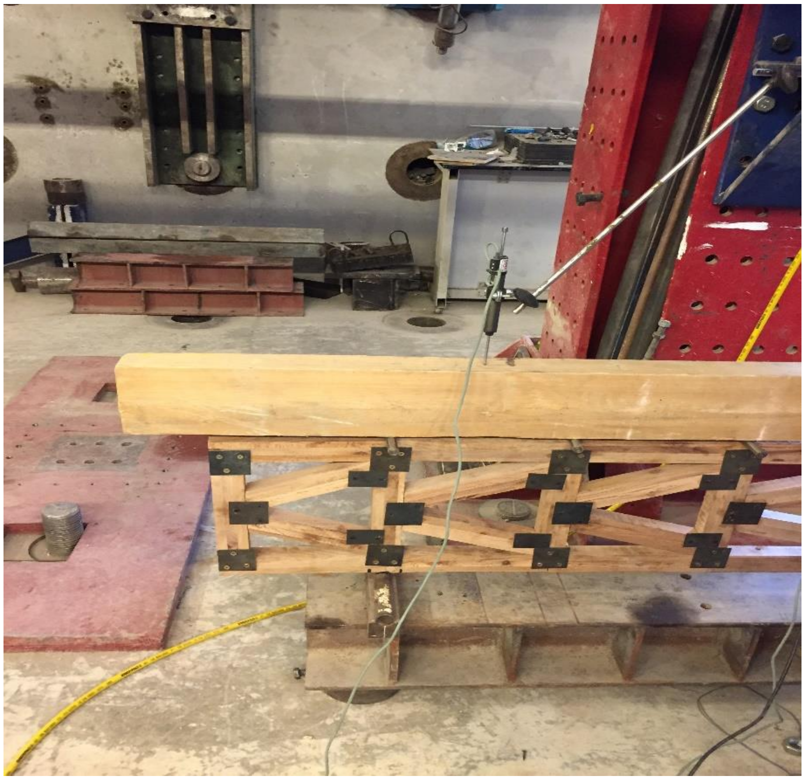


Figure 78: The LVDT used in the experiment

Laptop

The Laptop is connected to the load cell and the LVDT's. It is used to record the load from the load cell and the equivalent deflection from the electronic signals of the LVDT's using a special software.

Digital Camera

A Digital camera was used to live record the experiment.

4.4.4 Setting up the experiment

The first step is to prepare the sample and using the electronic balance determine the weight of the sample and the wooden beam placed over it which was 12.5 KG. The second step is to place the sample on two supports as shown in figure (79).

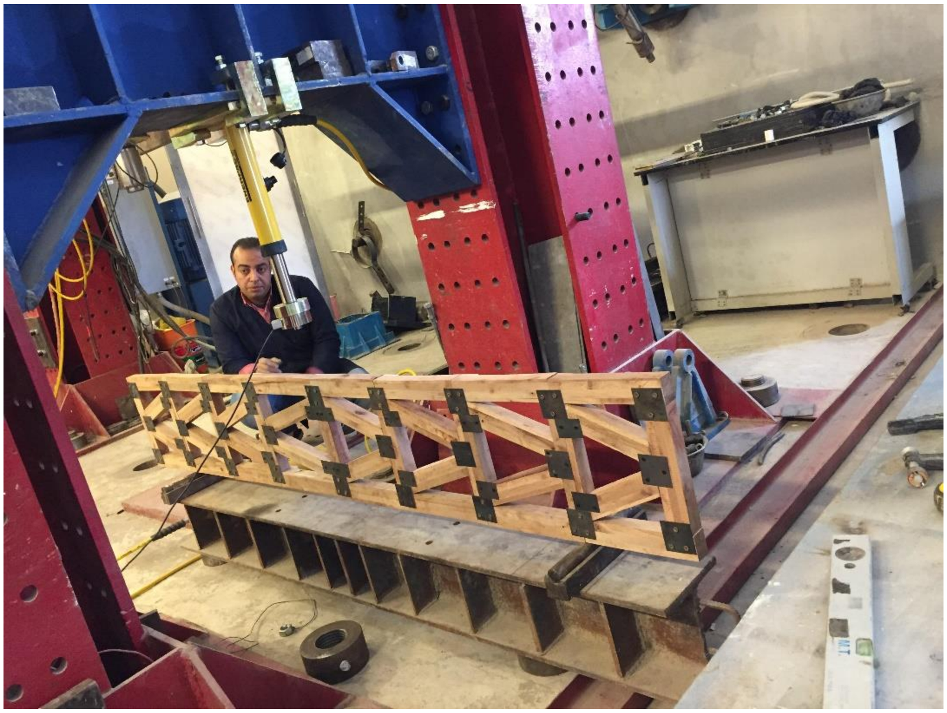


Figure 79: The supports used to support the truss

The third step is to start distributing the steel rods at each joint of the truss in order to place the wooden beam over it. The fourth step is to place the wooden beam above the sample and to make sure that it is symmetrically placed to ensure that the load is uniformly distributed on the truss. The last step is to put the LVDT's at the points to measure the deflection and connect the hydraulic pump. In this experiment 3 LVDT's were distributed at the center of the truss and on the second horizontal member from each end. Figure (80) shows the experiment ready for testing.

Figure 80: The truss is ready to begin the experiment

4.4.5 Experimental procedures

a. Before starting the loading of the truss, the technician must make sure that all the LVDT’s are calibrated and checks the deflection reading.
b. The technician starts applying the load in increments using the hydraulic pump.
c. The deflection readings are recorded from the electric signals sent by the LVDT’s and the load readings are recorded from the load cell using a special software on the laptop.
d. The experiment continues by increasing the load using the jack of the hydraulic pump till the specimen fails.
e. After the failure, the load is released from the hydraulic pump.
f. A live video and photos are recorded during the whole experiment using a digital camera.

4.4.6 Results

After testing the three trusses, the load readings and the deflection readings for the three LVDT’s were produced in excel sheets. The results of each sample are as follows:

4.4.6.1 Sample#1

In the first sample, the maximum recorded load was 1094.97 Kg. This load represents only the load applied only from the load cell. After adding the load of the wooden beam which was 12.5 Kg, therefore the total load applied on sample#1 was 1107.47 Kg.

The maximum deflection was recorded by the middle LVDT which recorded 13.1 mm, followed by the right LVDT which recorded a deflection of 8.84 mm followed by the left LVDT which recorded a deflection of 8.4 mm.

As shown in figure (81) The truss experienced an out of plane buckling while none of the members were subjected to any deformation or cracks and none of the connections or the screws failed. Table (13) summarizes the results of Sample#1.

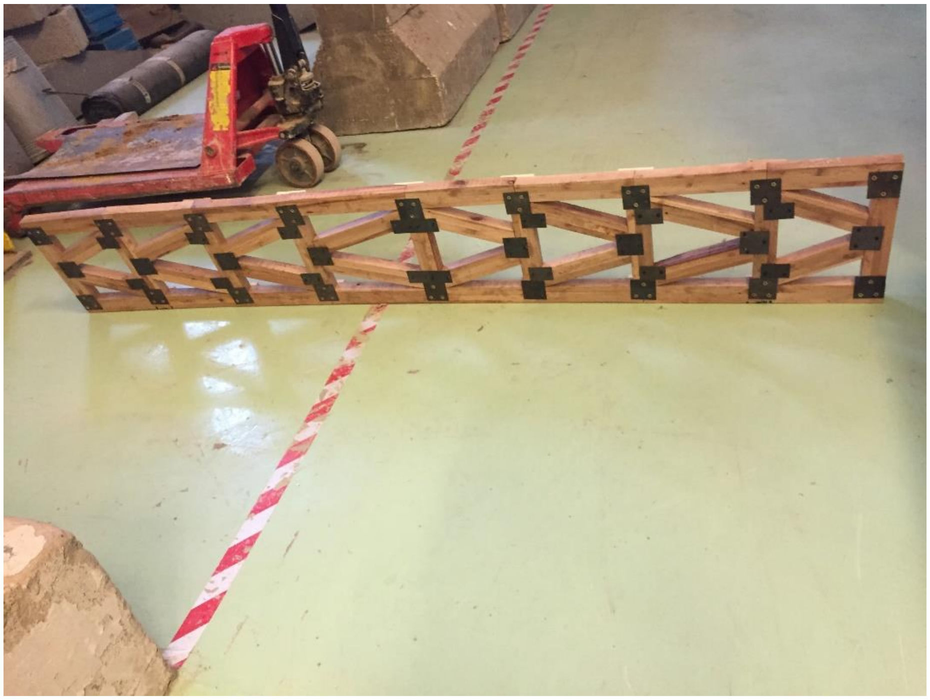


Figure 81: Sample #1 after testing

Table 13: Results of sample # 1

Sample 1 (W= 18.0 kg)				
Name	Load (kg)	LVDT Right (mm)	LVDT Left (mm)	LVDT MID (mm)
Max Value	1107.47	8.843	8.4	13.1
Min Value	0	-0.0411	0.041	-0.041
Average Value	644.34	3.648	3.125	5.82

4.4.6.2 Sample#2

In the first sample, the maximum recorded load was 1184.94 Kg. This load represents only the load applied only from the load cell. After adding the load of the wooden beam which was 12.5 Kg, therefore the total load applied on sample#2 was 1197.44 Kg.

The maximum deflection was recorded by the left LVDT which recorded 12.66 mm, followed by the middle LVDT which recorded a deflection of 12.42 mm followed by the right LVDT which recorded a deflection of 6.44 mm.

As shown in figure (82) The truss experienced an out of plane buckling while none of the members were subjected to any deformation or cracks and none of the connections or the screws failed. Table (14) summarizes the results of Sample#2.

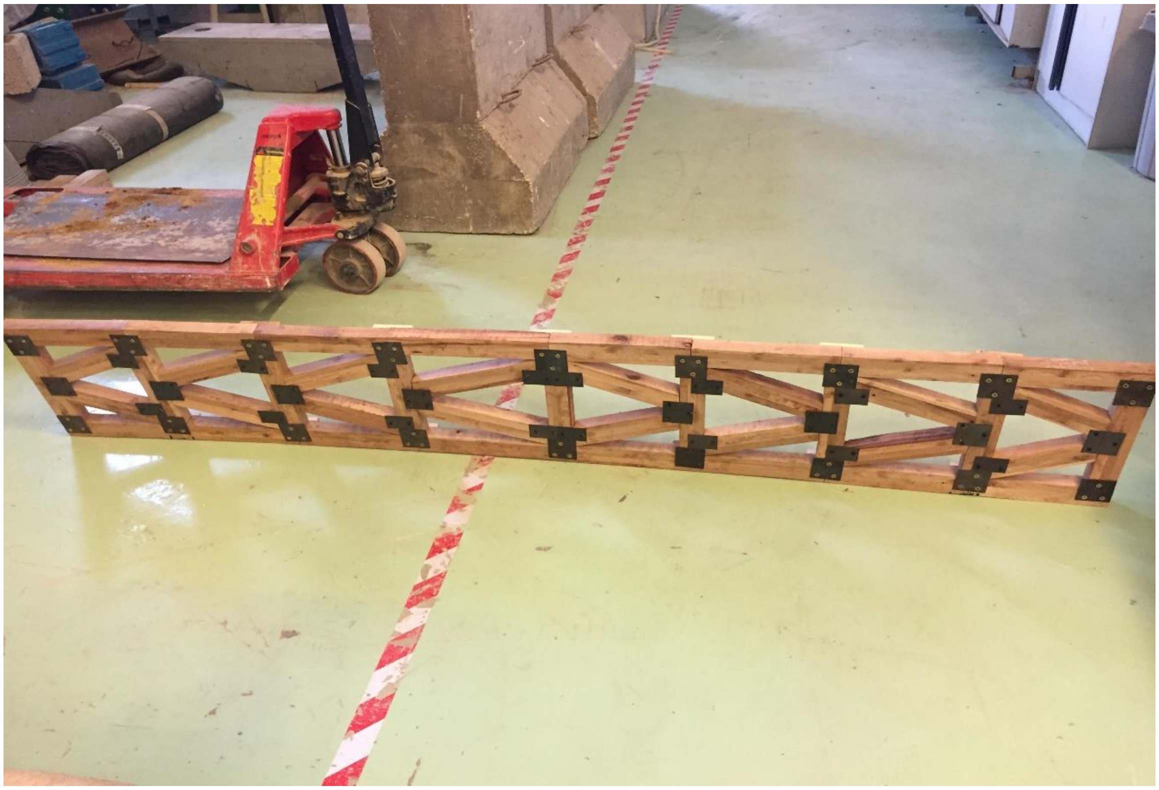


Figure 82: Sample #2 after testing

Table 14: Results of sample # 2.

Sample 2 (W= 18.36 kg)				
Name	Load (kg)	LVDT Right (mm)	LVDT Left (mm)	LVDT MID (mm)
Max Value	1197.44	6.44	12.66	12.424
Min Value	0	-0.0823	-0.1028	0.0205
Average Value	682.25	3.023	2.765	5.476

4.4.6.3 Sample#3

In the first sample, the maximum recorded load was 1209.94 Kg. This load represents only the load applied only from the load cell. After adding the load of the wooden beam which was 12.5 Kg, therefore the total load applied on sample#3 was 1222.44 Kg.

The maximum deflection was recorded by the middle LVDT which recorded 12.178 mm, followed by the right LVDT which recorded a deflection of 8.23 mm followed by the right LVDT which recorded a deflection of 7.36 mm.

As shown in figure (83) The truss experienced an out of plane buckling while none of the members were subjected to any deformation or cracks and none of the connections or the screws failed. Table (15) summarizes the results of Sample#3.

Figure 83: Sample #3 after testing

Table 15: Results of sample # 3

Sample 3 (W=18.55 kg)				
Name	Load (kg)	LVDT Right (mm)	LVDT Left (mm)	LVDT MID (mm)
Max Value	1222.44	8.23	7.363	12.1778
Min Value	0	0	0.514	0.575
Average Value	694.33	2.788	3.265	5.450

4.4.7 Analysis and Discussion

The design criteria were to satisfy the design load (1 ton) and the equivalent deflection according to equation 13. None of the three trusses failed but they experienced out of plane buckling due to the absence of bracing system. The three samples were able to achieve more than the design load before they buckled, which can be considered as an important outcome for this model and shows the strength of Casuarina Glauca wood. Table (16) summarizes the experimental work summary for the three trusses.

Table 16: The experimental work summary for the three trusses

Sample No.	Design load	Failure load	Failure reason
1	1 Ton	1.1 Ton	Out of plane buckling
2	1 Ton	1.2 Ton	Out of plane buckling
3	1 Ton	1.22 Ton	Out of plane buckling

According to equation 13, the allowable deflection was calculated = 8.3 mm. After testing the three

trusses, the three samples were able to satisfy the allowable design deflection as the first sample recorded deflection at the middle LVDT = 8.3 mm, the second sample recorded deflection at the middle LVDT= 8.2 mm and the third sample recorded deflection at the middle LVDT = 7.6mm. Figure (84) shows the allowable deflection on the load-deflection curve for the three trusses.

According to the previous mentioned results the three truss samples made of Casuarina Glauca were able to satisfy the strength and the deflection that were previously designed.

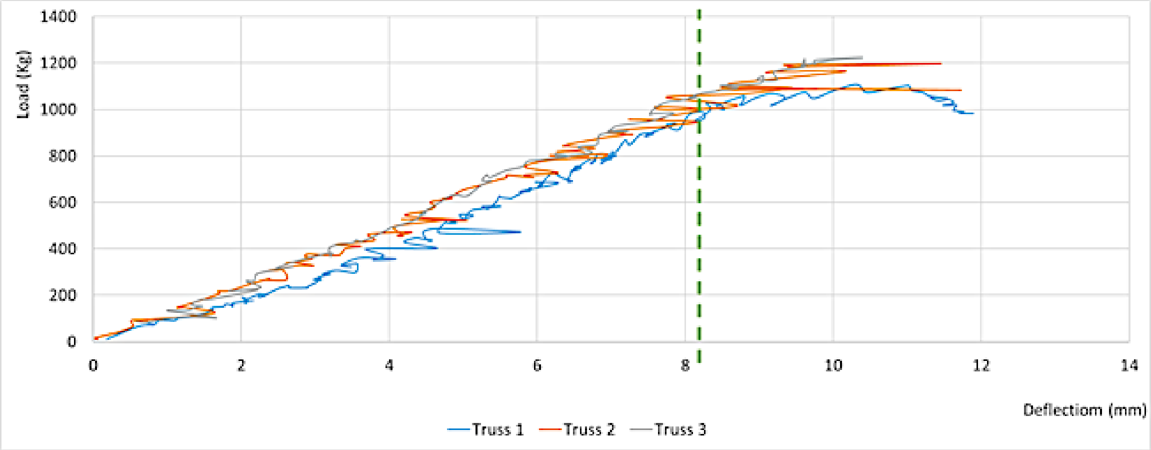


Figure 84: The allowable deflection plotted on the load-deflection curve for the three trusses

4.4.8 Cost Study

4.4.8.1 Description

In this section, the designed Casuarina Glauca girder will be applied on a slab that has an area of 10 m x 9.6 m (96 m2) and compared to the GT 24 girder produced by PERI formwork company as shown in figure (85).

Figure 85: The GT 24 formwork girder (PERI,2016).

The comparison between the two girders will be in terms of the number of units required to cover the slab area and the cost of using each type. According to (PERI,2016) the GT 24 girder is available in different spans ranging from 0.9 to 6 meters but the one chosen in this study will be the 2.4 meters length model.

As shown in figure (86), The Casuarina Glauca girder with the length of each line representing the span of the girder which is 2.3 meters, the number of girders required to cover the slab area is 52 girders and the distance between each girder is 0.8 meters as designed.

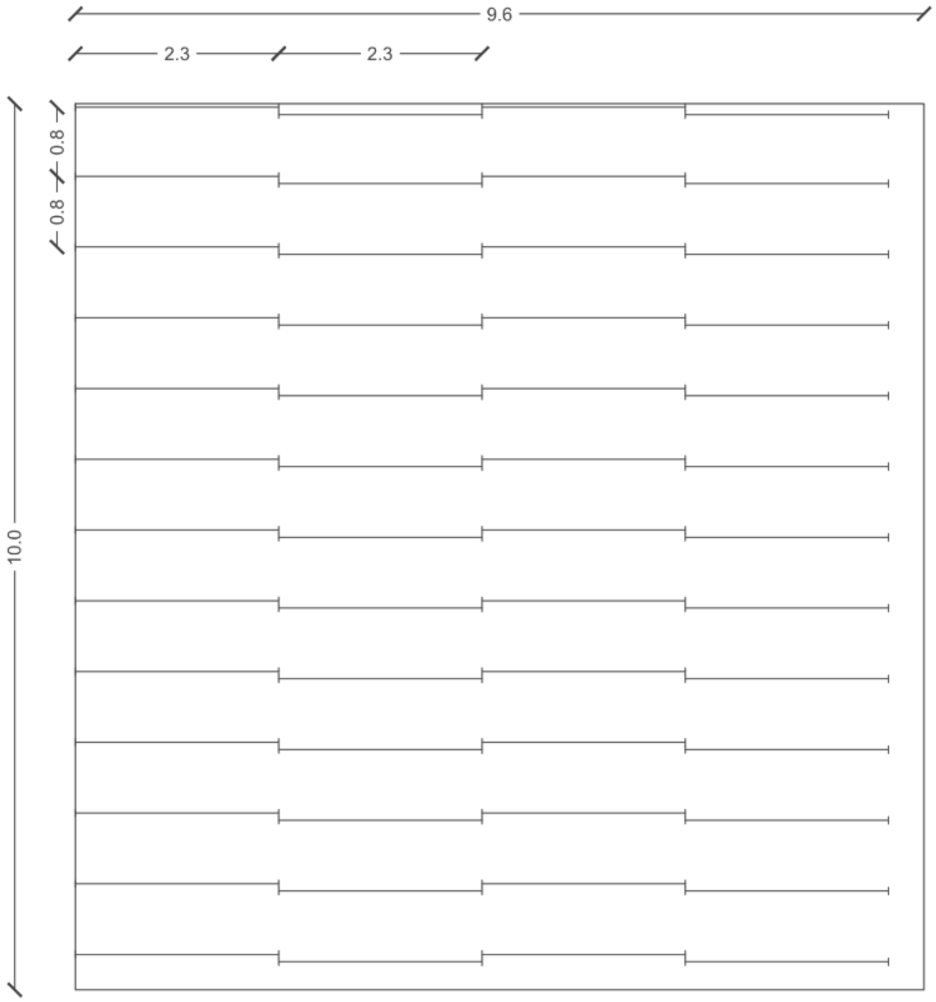


Figure 86: The slab plan using Casuarina Glauca Girders

On the other side as shown in figure (87), representing the GT 24 girders occupying the slab area, the length of each line representing the girder span which is 2.4 meters, the number of girders required to cover the slab area is 64 girders and the distance between them is 0.6 meters as used by PERI design tables. (PERI,2016).

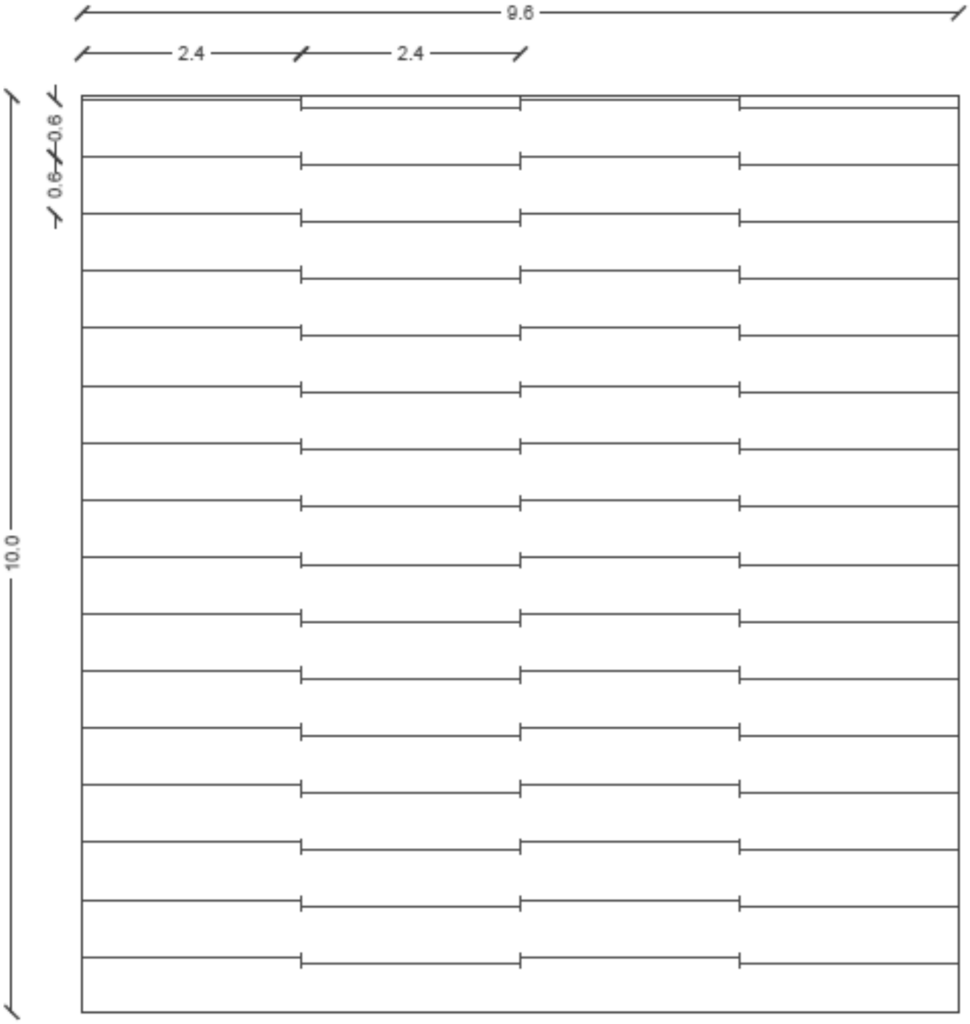


Figure 87: The slab plan using the GT 24 Girders.

4.4.8.2 The total weight

The average weight of the Casuarina Glauca designed girder was 18.3 Kg, while the average weight of the GT 24 girder is 14.2 Kg (PERI,2016). The total weight of the 52 Casuarina Glauca girders to cover the slab area will be 951.6 Kg, while the total weight of the 64 GT 24 girders to cover the slab area 937.2 Kg. Although the number of the GT 24 girders is more than the Casuarina Glauca girders, the total weight of the GT 24 was less than the Casuarina Glauca girders for two reasons; the steel plates used in connecting the members of the Casuarina glauca girders, also the pine wood used in the GT 24 girder is much lighter than Casuarina Glauca.

4.4.8.3 Cost Comparison

Calculating the cost of producing 1 Casuarina Glauca girder is divided into three parts; The cost of the Casuarina Glauca wood, the cost of the steel connections and the screws and the cost of the labor (Carpenter) used to cut the wood members, prepare the steel connections and connect the truss. The cost of 1 m3 of Casuarina Glauca is around 300 LE. The cost of the wood used to build one unit of Casuarina Glauca girder reaches around 25-30 LE. The cost of the steel plates connections and the screws used to build a single girder is around 95 LE. The cost of the carpenter that will connect the members and drill the steel plates is around 150 LE/unit, Therefore the total cost of producing a single truss made of Casuarina Glauca wood is 225 LE/unit. In case of producing large number of units the total cost per unit is will be lowered due to the mass production rates.

According to (PERI,2016), the total cost of the GT 24 girder is around 1500 LE/unit. The cost is relatively high as the pine wood used in the GT 24 girder costs around 1800 LE/m3, in addition to the finger joint details for the connections of the girder which is one of PERI’s trademarks.

Applying the total cost of each girder on the design slab (10 m x 9.6 m), the total cost of the 52 Casuarina Glauca girders is 11,700 LE while the total cost of the 64 GT 24 girders is 96,000 LE. The difference in the total cost is huge as the total cost of the Casuarina Glauca girders to cover the slab area is around 0.1 the total cost of the GT 24 girders. According to (PERI,2016) the Permissible bearing load of the GT 24 girder is 2.8 ton, while the Casuarina Glauca girder was able to withstand a 1.1 Ton load and failed due to buckling. Table (17) summarizes the comparison between the Casuarina Glauca girder and the GT 24 girder covering a slab of 96 m2 area.

Table 17: Comparing Casuarina Glauca girder to GT 24 girder

Point of comparison	Casuarina Glauca girders	GT 24 girders
No. of units	52	64
Total weight of units	951.6 Kg	937.2 Kg
Total cost of units	11,700 LE	96,000 LE

Chapter 5 Conclusions and Recommendations

In the light of the materials used, the procedures followed, as well as the other parameters, the following conclusions can be stated:

1) The results of the mechanical and physical properties of Casuarina wood in this thesis contributes in providing basic guidelines for any future works that includes using Casuarina wood.
2) Based on the results of the mechanical tests in this thesis; Casuarina Glauca has higher strength in tension parallel to the grain, Tension perpendicular to the grain, Cleavage and static bending and compression parallel to the grain test than most of the hardwoods. The previously mentioned results are a good indication for using Casuarina Glauca as a replacement for the common types of wood used in construction formworks.
3) Due to the high variability and inconsistency in its results, Casuarina Cunninghamiana was excluded from the rest of the experimental tests after the first three tests. The results of Casuarina Cunninghamiana was not satisfying compared to the different types of hardwoods.
4) Based on the data correlation analysis, the highest correlation was found between tension parallel to the grain and static bending tests, which match with the results of the static bending test as all the bending samples failed in the tension side.
5) Similar to the diffuse porous wood, the effect of moisture content on the mechanical properties of Casuarina Glauca and Casuarina Cunninghamiana was studied on small clear wood samples. Reducing the moisture content level was found to be effectively increasing the strength and the modulus of elasticity for compression parallel to the grain, compression perpendicular to the grain and static bending while the tension parallel to the grain test was found to be the least effected test by changing the moisture content level.
6) The designed truss model using Casuarina Glauca wood were able to achieve good results in terms of the strength and the deflection which shows that Casuarina Glauca wood can be used in structural applications such as formworks and scaffolding.
7) Although the wood from Casuarina tree is not available in long pieces (more than two meters), the design of the Casuarina Glauca girder was utilized into a number of small

members instead of one continuous member as designed in the GT 24 girder and the results were able to maintain the design strength and deflection criteria.

8) The construction of the proposed truss model does not require skilled labor or complicated materials and can be manufactured in a very short time.

9) The strength of Casuarina Glauca might not be the highest among the different types of wood used as a formwork material or in structural purposes but compared to its price and availability and the results from this thesis it can be considered so promising type of wood.

10) The designed Casuarina Glauca system was proven to be cost effective when compared to the GT 24 PERI formwork system and at the same time maintain the strength requirements.

Recommendations

Increasing the stiffness of the system

The truss samples were able to achieve the strength and the deflection without failing but experienced an out of plane buckling due to the absence of bracing system. This issue can be resolved by bracing two trusses and loading them as a one unit which will allow to experience the maximum failure load for the truss.

Full scale prototype to be tested

This is very important to test the soundness of the system to be integrated with a formwork system such as the funicular arched steel truss system and to experience real site conditions such as pouring concrete on site, the handling of the labor, the weather conditions, all these conditions will definitely test the durability of such a system.

Trying different types of connections

The steel plates connections were able to withstand the strength but increased the total truss weight. Trying different types of connections such as the finger joint connection will decrease the truss weight and improve its durability.

Using Casuarina in different industries in Egypt

The results from the mechanical properties discussed in this thesis opens the door for using Casuarina wood in Egypt in the construction industry such as formworks, scaffolding and roofing or in other industries such as the manufacture of wood, doors and furniture.

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