EMPIRICAL SHEAR FORCE CAPACITY AND STIFFNESS MODEL OF THE CROSS-FORMATION SCREW CONNECTIONS IN TIMBER– CONCRETE COMPOSITE STRUCTURES

MOHD KHAIRUL AKMAL BIN MD ZAHIR

SCHOOL OF CIVIL ENGINEERING

UNIVERSITI SAINS MALAYSIA

2022

EMPIRICAL SHEAR FORCE CAPACITY AND STIFFNESS MODEL OF THE CROSS-FORMATION SCREW CONNECTIONS IN TIMBER-CONCRETE COMPOSITE STRUCTURE

By

MOHD KHAIRUL AKMAL BIN MD ZAHIR

This dissertation is submitted to

UNIVERSITI SAINS MALAYSIA

As partial fulfilment of requirement for the degree of

BACHELOR OF CIVIL ENGINEERING (HONS.)
(CIVIL ENGINEERING)

School of Civil Engineering
Universiti Sains Malaysia

AUGUST 2022

Appendix A8

UNIVERSITI SAINS MALAYSIA

SCHOOL OF CIVIL ENGINEERING
ACADEMIC SESSION 2021/2022

FINAL YEAR PROJECT EAA492/6
DISSERTATION ENDORSEMENT FORM

Title: Empirical Shear Force Capacity and Stiffness Model of The Cross Formation Screw Connections in Timber- Concrete Composite Structure

Name of Student: Mohd Khairul Akmal Bin Md Zahir

I hereby declare that all corrections and comments made by the supervisor(s) and examiner have been taken into consideration and rectified accordingly.

Signature:

Date: 10/08/2022

Approved by:

(Signature of Supervisor)

Name of Supervisor: Dr. Mohd Amirul Bin Mohd Snin

Date: 10/8/2022

Approved by:

(Signature of Examiner)

Name of Examiner: DR. NOORHAZLINDA ABD RAHMAN
Lecturer
School of Civil Engineering
Engineering Campus
Universiti Sains Malaysia
14300 Nibong Tebal, Pulau Pinang
Tel: +604 599 6261
HP: +6012 503 1977

Date: 10.08.2022

ACKNOWLEDGEMENT

The completion of this thesis could not have been possible without the guidance of Dr. Mohd Amirul Mohd Snin, my beloved thesis supervisor. A debt gratitude is also owed to all the lecturers that involved in this subject. I received assistance from a large number of people and friends while working on this research project, and I would like to thank them all for their generosity. Finally, I want to express my gratitude to my family for supporting me throughout this project.

Last but not least, I would like to express my gratitude to those who could not be specifically named here but who nonetheless played a significant role in motivating me to take certain actions.

ABSTRAK

Sambungan antara dua bahan mempunyai kesan yang ketara terhadap kekakuan dan kapasiti daya ricih struktur Komposit Konkrit Kayu (TCC) apabila struktur berada dalam lenturan. Oleh kerana beberapa kekurangan dalam Eurocode 5 (EC5) dan kekuatan ramalan sedia ada dan model modulus slip sambungan skru, kerja ini telah dijalankan. Kegagalan untuk mengambil kira ciri-ciri tempatan skru yang tertanam dalam konkrit pada tingkah laku sambungan antara kayu dan konkrit adalah satu kecacatan dalam model ini. Selain itu, sementara Eurocode 5 kini memberikan panduan untuk menentukan kapasiti daya ricih sambungan yang diperbuat daripada kayu dan kayu, tidak ada panduan yang sama untuk sambungan yang diperbuat daripada kayu dan konkrit. Model kapasiti kekakuan dan daya ricih semasa telah dikaji semula. Didapati bahawa tiada penyelidikan telah dilakukan untuk mewujudkan kapasiti daya ricih dan model kekakuan berdasarkan skru pembentukan X dan mengambil sudut skru yang berbeza antara 0° dan 90° ke dalam pertimbangan. Dalam tesis ini, analisis Regresi Linear Pelbagai (MLR) digunakan untuk mencipta kapasiti daya ricih baru dan model kekakuan. Satu set 64 data dari penyelidikan sebelumnya digunakan untuk membandingkan kapasiti daya ricih baru dan model kekakuan dengan model dari Gelfi et al., 2002, Moshiri et al., 2014 dan Symons et al., 2010. Selepas menganalisis jarak engsel plastik dari antara muka antara konkrit dan kayu, l_c dan diameter skru, D dikenal pasti sebagai parameter yang mempengaruhi daya ricih. Untuk kekakuan tidak ada parameter yang mempengaruhi kekakuan. Kapasiti daya ricih empirikal baru yang diperoleh adalah $P_{max} = 4.481\ lc^{0.6784} D^{-0.0059}$.

ABSTRACT

The connection between the two materials has a significant impact on the stiffness and shear force capacity of Timber Concrete Composite (TCC) structures when they are in flexure. Due to some shortcomings in Eurocode 5 (EC5) and existing predictive strength and slip modulus models of screw connections, this work was undertaken. The failure to take into account the local characteristics of the screw embedded within the concrete on the behaviour of the connection between the timber and concrete is one flaw in these models. Additionally, while Eurocode 5 currently provides guidance for determining the shear force capacity of connections made of timber and timber, there is no similar guidance for connections made of wood and concrete. The current stiffness and shear force capacity model has been reinvestigated. It was discovered that no research had been done on creating a shear force capacity and stiffness model based on an X-formation screw and taking different screw angles between 0° and 90° into consideration. In this thesis, Multiple Linear Regression (MLR) analysis was used to create new shear force capacity and stiffness model. A set of 64 data from the previous research was used to compare the new shear force capacity and stiffness model with model from Gelfi et al., 2002), (Moshiri et al., 2014) and (Symons et al., 2010. After analysing the distance of plastic hinge from the interface between concrete and timber, l_c and screw diameter, D were identified as parameters that influenced shear force. For stiffness there was no parameter that influenced the stiffness. The new empirical shear force capacity obtained was $P_{max} = 4.481\ lc^{0.6784} D^{-0.0059}$.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

TCC	Timber- Concrete Composite
MLR	Multiple Linear Regression
ANOVA	Analysis of Variance
LVL	Laminated Veneer Lumber
PSL	Parallel Strand Lumber
CLT	Cross- Laminated Timber
CHS	Circular Hollow Sections
UCS	Universal Column Sections
HSP	Horizontal Steel Plate
PSP	Perforated Steel Plate
TSP	“T” Steel Plate
HBV	Holz- Beton- Verbund

LIST OF NOMENCLATURES

A_t	cross-sectional area of timber
A_c	cross-sectional area of concrete
A_s	cross-sectional area of fastener
a	distance of load in four-point bending test from edge of span
D	diameter of the fastener
F_v	shear force capacity in Eurocode 5
$f_{y,\,s}$	yield stress of stud in Gelfi et al.'s model
L_c	fastener length embedded within the concrete
L_t	embedded length of screw within timber
L_{span}	length of the beam
L_s	length of screw
l_c	effective length of concrete
l_t	effective length fastener in timber
P_{max}	maximum shear force capacity
σ_t	timber normal stress
σ_c	concrete normal stress
$\sigma_{y(s)}$	yield strength of the fastener
$\sigma_{y(B)}$	flexural strength of the beam member
σ_m	bending stress in fastener
k_p	foundation moduli of timber parallel
k_t	foundation moduli of timber transverse
E_s	Young's modulus of screw
$\boldsymbol{I}_s$	moment inertia of screw
f_{hc}	concrete bearing resistance

f_{hw} wood bearing resistance

M_y stud plastic moment

L_c minimum stud total lengths embedded in concrete

Lw minimum stud total lengths embedded in wood

l_c concrete effective length

l_w wood effective length

CHAPTER 1

INTRODUCTION

1.1 Introduction

Members of timber-concrete composite (TCC) structures are typically horizontal members that can withstand uniaxial bending while accepting unidirectional loads. To achieve a combined effect, the timber and concrete pieces of the TCC element are connected using one of several types of connectors (Dias A et al., 2018). Timber is typically placed below the elements where tensile stress is anticipated and concrete is placed above where compressive stress is generated because concrete has almost no tensile strength (Meena R et al., 2014). Additionally, there are TCC wall systems and inverted TCC structural components with concrete on the underside (Fortuna et al., 2017).

Timber-concrete composite structures have reportedly been used in Europe for the past 50 years, particularly in new construction and renovation of old timber floors (Natterer et al., 1996). A concrete slab and a timber joist are both components of a TCC building. Different types of shear connectors may be related to the upper concrete flange and the timber joist. In this instance, the timber fibre is in tension while the concrete is under compression force. These two materials' superiority is fully tapped into by the TCC structure. Due to their stiffness and strength, TCC structures perform well under dead loads, earthquakes, and fire (Skinner et al., 2014). TCC structures are significantly more energy-efficient than concrete ones, and because wood is a carbon store, a carbon sequestration mechanism can significantly reduce CO_2 emissions (Rodrigues et al., 2013).

Environmental protection is becoming more and more important in China, where it is also likely that TCC use will grow significantly. It is crucial to use connectors in the composite structure that are sturdy and stiff enough to withstand the shear force (Yeoh et al., 2011). Dowels, screw or stud connectors, notches cut in the wood and filled with concrete, and other types of connectors have all been developed. Mascia and Soriano (2004) investigated the properties of TCC using numerical simulations and experimental analysis of the stiffness of joints between timber and concrete that use dowel-type fasteners. The load-carrying capacity of timber-concrete joints made with dowel-type fasteners was examined by (Dias et al., 2007). The long-term mechanical behaviour of timber-to-concrete joints made with dowel-type fasteners was discussed by (Van de Kuilen & Dias, 2011). TCC structures have been the subject of experimental study (Grantham et al., 2004), but no appropriate theoretical equation has been provided. The literature and codes that are currently available in Europe and North America should be checked in order to provide guidance for the design of TCC using Chinese timber because there hasn't been much research on TCC in China.

1.2 Problem Statement

The goal of this study was to identify the critical parameters needed to recommend the published EC5 and screw connection predictive strength and slip modulus models. The problem with those models is that they do not take into account how the local characteristics of the screw embedded in the concrete will affect the connection between the timber and concrete.

In the first version of EC5 approved by CEN (2004) for the serviceability limit state, Clause 7.1 of Part 1-1 permits calculation of the slip modulus of a timber-concrete composite connection to be doubled that of a timber-timber connection, for which a power law formula based on timber material density is provided. This clause assumes that local deformations within the concrete side of the connection are minimal.

The slip stiffness of the connections should be considered to be 2/3 of that at serviceability for the ultimate limit state, according to clause 2.2.2(2) of EC5. Additionally, the accounting for friction and adhesion between the timber and concrete in the timber-concrete composite connection is prohibited by EC5 clause 5.3 (2).

The mechanical characteristics of screw-based timber-concrete composite shear connectors have not been predicted by many prior studies, it should be noted. On a 2-D elastic foundation with minimal concrete deformation, Symons et al. (2010a) presented a model for calculating the slip moduli of inclined screw timber-concrete composite connections. Moshiri et al. (2014a) have developed a predictive model for the strength of screw connections in crossed or X-formations, where the screws resist shear tension and shear compression stresses while the concrete is unaffected. Symons et al. (2010b) presented an upper bound plastic collapse predictive model for screw connection strength if the screws behave perfectly plastically and that the concrete is unaffected. Gelfi et al. (2002) proposed a strength and stiffness model for screw connections installed in a 90° formation. The effective length of the screw had an impact on the embedment strength of the screw within the concrete (Gelfi et al., 2002). So, most of the researchers do not include various types of angles in their research and a new study on new shear force and stiffness must be done for various types of angles.

1.3 Aim and Objectives

This study is aimed to develop empirical model of shear force capacity of the screw connection in Timber- Concrete Composite. In order to achieve this aim, several objectives are outlined below:

1. To analyse the database by using statistical analysis tool (Microsoft Excel)

2. To investigate the effect of material properties of screw connections, timber to concrete on the shear force capacity
3. To propose prediction model of shear force capacity of the screw connection in Timber- Concrete Composite.

1.4 Limitation of Study

This study focuses on the short-term behaviour of screw connections in timber-concrete composite structures. Dynamic, cyclic, and long-term effects and behaviours under fire and fluctuating moisture conditions have not been taken into account. Timber-concrete composite joints with screw arrangements that cause the screws to behave only in shear compression are not taken into account in this study.

1.5 Research Method

Samples of data are taken from previously published works. Statistical analysis is used to analyse the data. As a result, the value of shear force capacity was influenced by the effects of material properties. Finally, this study suggests a prediction model for the cross-formation screw connections in Timber-Concrete Composite Structure empirical shear force capacity model.

1.6 Outline of The Research

This thesis is divided into five chapters. Chapter 1 covered the introduction of timber composite structures. This chapter also clarifies the limitations of the current design models for concrete-timber composite structures. The objective of the study is to create a trustworthy model for predicting the mechanical characteristics of connections in composite structures made of concrete and timber.

1.6.1 Chapter 2 – Literature Review

The literature review begins by describing the history of the use of timber-concrete composite systems in different nations. The various connection systems used in a composite timber-concrete system are discussed. There is also a discussion of the design model for screw connection strength, which is based on earlier research. The most recent iteration of the EC5 design code is also covered in this chapter. The most recent stiffness and strength design models for composites made of concrete and wood are also discussed.

1.6.2 Chapter 3 – Research Methodology

This chapter discussed the process for extracting data from earlier research papers. The necessary data for analysis were all discussed in this chapter. This chapter also covered how to access the data. A table with all the data from the previous research paper organised by parameter and source is then presented.

1.6.3 Chapter 4 – Results and Discussion

This chapter discusses the creation of new empirical models of shear force capacity and connection stiffness using information from previously published work. The empirical shear force capacity model for the X-formation screw connection was created using Microsoft Excel. In this chapter, the Linear Regression Method (MLR) used to analyse the data while also developing an empirical model of shear force capacity and stiffness in relation.

1.6.4 Chapter 5 – Conclusion and Recommendations

The entire thesis is summarised in the thesis' final chapter, which also makes recommendations for additional studies to enhance the design process for composite structures made of wood and concrete.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews earlier research on timber-concrete composite (TCC) structures. TCC has been increasingly used as a structural system ever since. The various types of engineered wood, their differences, and their applications in TCC structures are covered in this chapter. Further investigation is done into the composite action of wood and concrete. Explanations of the various connection systems used in TCC that are based on prior research are provided in the following section of the discussion.

The slip modulus and shear connector strength are the main topics in the TCC section on connection system design. An overview of the EC5 timber composite design comes first in this discussion. The development of a predictive model of connection strength and slip modulus in TCC structures and the work of several researchers, including Symon et al., 2010a and Symon et al., 2010b, are discussed. Finally, conclusions that support the goals of the study are reached after reviewing earlier TCC structure research.

2.2 History

TCC structures, in particular TCC bridges, are said to have first appeared in the 1930s in the USA during a time of a shortage of steel that forced construction companies to use alternative structural materials (Richart and Williams, 1943). TCC bridges were already widely used in the USA by the following decade (Duwadi and Ritter, 1997). TCC structures were first used in Australia and New Zealand to build bridges in the 1950s. TCC bridges were, however, generally disregarded until quite recently. TCC bridges did not actually start to appear in Europe until the beginning of the 1990s, for example, in

Finland, Switzerland, France, Germany, and Austria (Pischl and Schickhofer, 1993). After nearly going out of use for a while, there has recently been a resurgence of interest in timber bridges in general and TCC bridges in particular in the USA (Wacker and Smith, 2001). Due to their innovative or distinctive features, many TCC bridges have been studied. A thorough review of this kind of bridges is still lacking, though. For working engineers or research projects, such a review can serve as a crucial foundation.

TCC systems were first implemented in Europe after World War II due to a lack of steel for concrete reinforcement (Van der Linden, 1999). In order to connect concrete slabs and wooden joists, Muller (1922) developed a system of nails and steel braces. A floor system that uses a timber layer beneath a concrete layer and relies on steel I and Z sections as shear connectors was also introduced by Schaub in 1939. In 1960, TCCs were installed on existing ceilings in Bratislava, Slovakia, using nails as shear connectors (Postulka, 1983). No significant deflection was discovered during the project's evaluation during its use in the following years, from 1975 to 1988 (Postulka, 1997). In addition to the development of various fasteners, analysis, and design methodologies for the application of TCC systems, intensive research on these topics was started in Germany in the mid-1980s (Steinberg and Faust, 2003). Around 1930, steel connectors between wood and concrete were first used in the USA at the University of Oregon (Benitez, 2008).

Most of the buildings constructed in the Persian Gulf (which has salty airflow) were made of reinforced concrete. Corrosion on the steel reinforcement caused by this environment has made structural concrete less effective. The contractors have chosen to use TCC structures to address the issue (Ahmadi & Saka, 1993).

2.3 Engineered Timber in Construction

Because of advancements in timber technology, construction materials that are more rigid and durable are being created. TCC structures have been developing more frequently in the construction industry (Yeoh et al., 2011). Engineered wood production technology has advanced as its use has increased globally (Beskitt, 2016).

2.3.1 Engineered Timber

Strong solid wood, glulam, and laminated veneer lumber (LVL), which are all types of structural timber, are becoming more and more popular in terms of use and application as well as in the field of research. The industry has improved over time as a result of its many applications, including large trusses, glulam beams, arches, and engineered multi-story projects.

Research on engineered wood focuses more on the use of composite materials, such as fiber-reinforced plastic (FRP) composites, for reinforcing wood, fire protection, and wood preservatives, as well as glulam and LVL as structural elements (M.Z. Jumaat, 2001).

Glulam was the engineered wood that was first introduced to Europe in the early 1890s. This style of engineered consists of several parallel layers that range in thickness from 40 to 45 millimetres and are typically made of spruce and larch wood species. Sebastian et al. (2016) stated that the glulam typically has defects (such as knots) that could reduce its strength.

The layers of Glulam are glued together under pressure with the laminates' grain running parallel to the section's longitudinal axis, as shown in Figure 2 (Moddy & Hernandez, 1997). Cross laminated timber (CLT) is another type of engineered wood that is currently widely used throughout the world. Due to improved operational efficiency, product approvals, and marketing and distribution channels, the use of CLT in construction has significantly increased since 2000 (Mohammad et al., 2012). Applying CLT to mid-rise and high-rise buildings and using its easier handling during construction have made the European experience with it positive (Gagnon et al., 2013). As shown in Figure 3, CLT panels are constructed by stacking several layers of lumber boards, typically made of spruce. At least three layers of board should be glued together to create CLT panels (Mohammad et al., 2012).

A different type of engineered wood known as laminated veneer lumber (LVL), which has more consistency in its material properties and fewer flaws, is produced by the machine and has a lamination of 4mm thickness as shown in Figure 4. In fact, LVL began to be applied structurally in the United States in 1978. (Youngquist, 1985). However, softwood species like Douglas-fir and pine were used to make the types of wood used in the production of LVL (Vlosky et al., 1994). The use of hardwood LVL joists as structural applications have not been the subject of a lot of research. The majority of LVL hardwood is used in the manufacture of furniture. Sebastian et al. (2016) and Boccardo et al. (2014) conducted two recent studies on the use of LVL hardwood in structural applications for simply supported and indeterminate beams, respectively.

2.3.2 Comparison Between All Engineered Timber

Smaller cross-sections are feasible with LVL hardwood (Baubuche), which results in significant material savings due to its high strength and stiffness (Pollmeier, 2016b). LVL hardwood requires smaller timber widths than other types of engineered wood to achieve comparable bending strength, shear strength, compressive strength, tensile strength, and modulus elasticity. To achieve the same bending strength as solid wood with a 200mm width, for instance, LVL hardwood only required a 57mm width.

2.3.3 Application of Engineered Timber in TCC Structures

A sample of 75 TCC bridges served as the basis for the current analysis. Balogh et al. (2012) stated that there are more than 100 TCC bridges in existence worldwide, and the researcher believes that this sample is representative of all these bridges.

TCC solutions for bridge construction were promoted by the University of Washington in the USA. This project's objective was to use a combination of wood and concrete to make bridges that would

1. less expensive than reinforced concrete bridges
2. more durable than timber bridges, and
3. easy to construct without the need for specialised tools.

Soon, construction spread to other American states, including Oregon and Delaware, where some are still in use and require little upkeep.

TCC bridges were only constructed in Brazil in South America, though other nations like Chile and Argentina have also looked into them (Cárdenas et al., 2010). Under a research programme on timber bridges sponsored by the University of So Paulo, TCC bridges were built in Brazil for local roads (Calil Jr, 2006). This program's main objective was to create short span bridges with

1. a competitive cost and
2. a durability that could be positively compared with that of other structural materials.

The overall success of these bridges suggests that there may be a market for TCC bridges in Brazil, especially for auxiliary or secondary roads (Soriano & Mascia 2009).

Nolan (2009) stated that the first TCC bridges in Oceania were likely constructed by the US army in the 1950s. They represented a significant technological advance over the locally well-established timber bridges (Yttrup, 2009). Recently, research initiatives were started by forest authorities to encourage the building of TCC short span bridges using regional roundwood species. As a result, for instance, a specific chapter was added to the Timber Bridge Manual with support from the Australian Roads and Traffic Authority of New South Wales (RTA-NSW).

The "Nordic Timber Bridge Project," a comprehensive research initiative of Finland and the Scandinavian countries, encouraged the construction of TCC bridges in Northern Europe, specifically Finland. This project aimed to promote the building of wooden bridges as an alternative to steel and reinforced concrete ones. Given that Finland had constructed the first TCC bridge in the area prior to the Project's launch, the Finnish team was in charge of the sub-project on the specific subject of TCC bridges (Aasheim, 2000).

TCC bridges are extremely uncommon throughout Southern Europe, as well as other parts of the world. Only two have been found which are one in Italy and one in Portugal (Dias et al., 2011). The lack of knowledge about this structural solution among engineers and architects has undoubtedly hindered the introduction of TCC bridges in some construction markets (Rodrigues et al., 2010).

Figure 2.1 organises the sample of TCC bridges gathered by construction date, showing that more than 85% of them were built in the last twenty years, and more than 50% were built between 2000 and 2010.

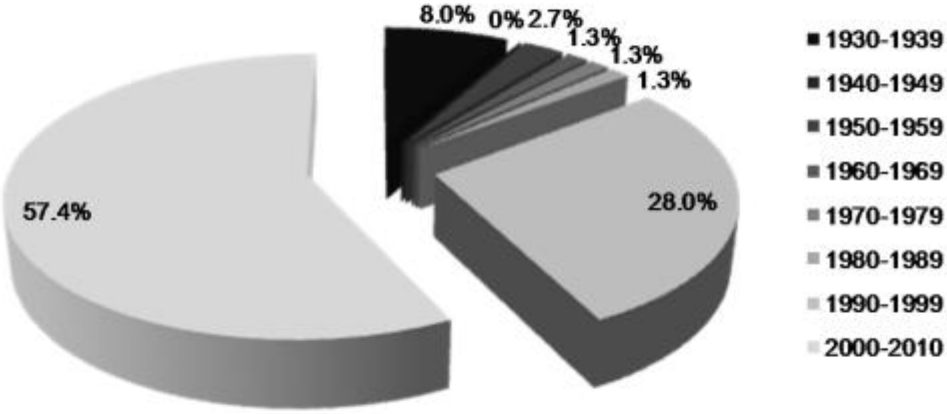

Figure 2.1: Construction date of the TCC bridges considered in this study (adopted from (Rodrigues et al., 2013))

Obinna (2020) asserts that engineered wood products are becoming more prevalent in structural engineering. High-rise timber structures have been built all over the world in the last 10 years as a result of enhanced engineered wood products. In addition, when compared to concrete and steel, lumber has been recognised as the most environmentally benign building material (Obinna, 2020). According to the Structural Timber Engineering Bulletin, the range of EWPs for structural applications has significantly expanded as a result of the increased availability of materials like laminated veneer lumber (LVL), parallel strand lumber (PSL), laminated strand lumber (LSL), prefabricated I-beams, metal web joists, and "massive" or cross-laminated timber (CLT). Laminating and glueing are the most typical processes for producing engineered timber products that are utilised in high-rise timber constructions (Tupenaite et al., 2019). These are some examples of the products:

1. Glued Laminated Timber (Glulam)
2. Cross Laminated Timber (CLT)
3. Laminated Veneer Lumber (LVL)

A structural member known as glued laminated timber (glulam) is created by joining several graded timber laminations with their grains running perpendicular to the section's longitudinal axis. Glulam is the oldest glued structural product (over 100 years). It is constructed of lumber layers (2x3 to 2x12), which are pre-finger-jointed, planned, and longitudinally glued with structural adhesives resistant to moisture. A variety of structural forms can be produced using straight or curved members laminated horizontally or vertically. Smaller laminations may be required where sections that are tightly curved or vertically laminated are required. Typically, laminates are either 25mm or 45mm thick. Glulam is used to construct portal frames, bridges, beams, columns, trusses, and other substantial structural components.

Cross laminated timber (CLT), a structural wood product, is made of at least three cross-bonded layers of wood with thicknesses ranging from 6 to 45 mm. These layers are adhered together in a press that applies pressure to the entire surface area of the panel. CLT is a solid engineered wood panel that has been around for about 15 years. It is made of cross-angled wood boards that are glued together. CLT panels usually have an odd number of layers (3,5,7,9), each of which may vary in thickness but are symmetrically arranged around the middle layer, with the grain directions of adjacent layers at right angles to one another.

Compared to traditional softwood wall framing and joisted floor constructions, CLT offers some structural advantages that include the following:

1. Superior acoustic properties.
2. Large axial and flexural load-bearing capacity when used as a wall or slab.
3. High in-plane shear strength when used as a shear wall.
4. Fire resistance characteristics for exposed applications.

CLT can be used to create floor slabs, roofs, beams, columns, load-bearing walls, and shear walls. Up to 20 metres of material can be produced with thicknesses ranging from 50 to 300 millimetres. You can get a width of up to 4.800 m with CLT.

Laminate veneer lumber is created by bonding together thin vertical softwood veneers with grains that are parallel to the longitudinal axis of the section under heat and pressure (LVL). To increase dimensional stability, cross grain veneers are occasionally used. Structural composite lumber is one type of LVL. It has a higher allowable stress than glulam and is less likely to warp, twist, bow, or shrink than conventional lumber because of its composite construction. LVL is frequently used to withstand flexural, axial, or a combination of both loads in high-load applications. There are components for panels, beams, and columns. It can be used to create edges, beams, walls, and other kinds of structures.

2.4 Connection Systems in TCC Structures

The connection system is a crucial part of any composite beam structure. There have been numerous studies done on various connection system types. In this section, the connection systems used in TCC are described.

In the 1940s and 1970s, studies on connection systems appropriate for TCC bridge construction were conducted. However, over the past few years, there has been a significant increase in research on this subject, and numerous connection systems specifically for bridge construction are currently being studied in various locations around the world. These investigations involve testing TCC connection systems in shear and, frequently, bending tests on prototype TCC beam or panel designs using such connection systems.

Metal fasteners, notches in the wood, or a combination of the two can be used as connectors. The use of gluing technology in connection systems used for bridges or other structures has recently been the subject of research by some authors. Connectors can be classified as discrete or continuous depending on how they are distributed spatially.

The most widely used discrete connection systems use metal fasteners. Mascia and Soriano (2004) examined the mechanical performance of nail- and screw-based connection systems (Figures 2.2a, b), respectively, and came to the conclusion that nails offer a satisfactory and effective connection that is quicker to install and less expensive than screws. In order to reduce stress concentration around the screws, Astori et al. (2007) investigated the use of screws in conjunction with steel springs (Figure 2.2c). They discovered that these methods were suitable for bridge applications. A study at the University of So Paulo (Molina & Calil Jr., 2008) looked at connection systems using dowels fastened in holes drilled at a 90^{o} angle to the grain of the wood (Figure 2.2d). Bentez (2000) investigated two additional types of discrete connection systems with metal fasteners at the University of New South Wales in Australia: universal column sections (UCS) and circular hollow sections with screws (CHS) (Figure 2.2e, f). Both have demonstrated a high degree of stiffness and load-bearing capacity. A stiff connection was also created by Simon et al. (2008) from the Bauhaus-Universität Weimar in Germany. It consists of welded studs on the concrete side and a horizontal steel plate (HSP) inserted into the wood (Figure 2.2g). There were two different designs for this connector that were looked at: the first had two studs that were welded to steel plates that were 2 and 3 cm thick, while the second had four studs and a 5-cm trapezoidal rim inside the timber that was welded to a plate that was 2 cm thick on the concrete side. The load-bearing capacity of the connector was increased by increasing the thickness of the plate from 2 to 3 cm. For greater thicknesses, no load increase, however, was confirmed. While the other specimens displayed brittle fracture, the specimens with two studs displayed ductile deformation. Rebars can be used to create X-connectors (Figure 2.2h), which are composed of rebars placed crosswise and glued into 45^{o} inclined holes drilled in wood. Aldi and Kuhlmann (2010) investigated the possibility of doing this. The load-bearing capacity, slip modulus, and ductility of these connections have all been very acceptable. Using rebars of two different diameters that were glued into holes in wood that were drilled at a 45^{o} to the grain of the wood, Miotto and Dias (2008) investigated connection systems (Figure 2.2i). The efficiency of this connection system performed quite well, with the diameter of the rebars having an impact on the stiffness of the connections. This investigation included a connection system that involved inserting and adhering a perforated steel plate (PSP) into the wood (Figure 2.2j). This connection system showed a brittle fracture even though it was stiffer than the connection with rebars. Helsinki University of Technology created a similar connection method known as a "T" steel plate with an end plate (TSP) (Figure 2.2k). Comparing its mechanical behaviours indoors and outdoors revealed that, as a result of weathering, it becomes brittle and loses an average of 84% of its load-bearing capacity.

Discrete connection systems with metal fasteners are frequently used in conjunction with notch-cut timber beams, which are filled with concrete during the pouring process. Rebars that were glued into holes in wood that were drilled at a 45-degree angle to the grain and combined with notches were tested. (Figure 2.2l). These specimens' mechanical characteristics were much better than those of comparable specimens without notches. Furthermore, using these notches is advised due to how simple and inexpensive it is to produce them. Yttrup (2009) combined notches and dowels (Figure 2.2m) and compared this connection system to one using only timber notches or just dowels, coming to the conclusion that the combination of the two is the most efficient. Other tests were conducted on connection systems that only used notches. In this instance, Dhrer and Rautenstrauch (2006b) testing of the grooved connection (Figure 2.2n) revealed a satisfactory mechanical behaviour, including ductile failure. With the exception of the mode of failure, which was brittle and caused by a crack that appeared between the concrete notch and the upper edge of the timber, this connection was also studied at the University of Stuttgart in Germany (Aldi & Kuhlmann 2010), confirming the earlier satisfactory results.

Metal plates or other continuous connection systems can also be used. At the University of Wiesbaden in Germany, Bathon et al. (2006b) looked into the HBV connector that was mentioned when describing the support systems (Figure 2.2o). They examined specimens with one, two, and three rows of metal plates and came to the conclusion that the group effect increases the connection system's stiffness and strength. Failure always happened at the metal plates, indicating that the connection exhibited ductile behaviour.

The third category of connection systems is glued connections, which present a continuous distribution, distributing the shear forces evenly across the timber-concrete interface and preventing the localised stress concentrations that are unavoidable with discrete connections. Additionally, glued connections guarantee a rigid connection between the two materials, i.e., no slip is seen at the point where they meet. Conversely, glued connections increase the risk of brittle failure.

Using a "wet" production method in which fresh concrete is poured onto still-wet adhesive, Brunner et al. (2007) investigated the behaviours of glued connections. Rodrigues et al. (2013) came to the conclusion that despite the confirmation of the excellent mechanical characteristics previously mentioned, the use of "wet" glued connections is still not advised because it is challenging to ensure an adequate thickness of the glue layer, particularly in the concrete pouring areas. The assembly of the wood beams to a precast concrete slab is a more frequent use of glued connections (Ben Mekki & Toutlemonde, 2011). The issue of the glue layer thickness is avoided by this "dry" glued connection, but it can only be used with prefabricated TCC structures.

The double shear test was used by Sebastian et al. (2016) to examine hardwood-concrete specimens. The 4 mm thick laminations of beech species were used to create the hardwood for that study. Fully threaded (FT) and partially threaded (PT) screws were used to create shear connectors. Each type of screw was installed into the wood joist in an X pattern. Screws were driven into the joist at a 45-degree angle in the X layout for double shear specimens as depicted in Figure 3. Then, after the prior side had dried out, 32 N/mm2 concrete was poured on one side of the timber surface, and then on the other. The stiffness of specimens connected with FT screws was found to be 20% higher than partially threaded screws in double shear compression testing. The longitudinal shear force of FT screws was, however, about 20% less than that of partially threaded screws at 39 kN. The mechanics of full-scale externally indeterminate hardwood-concrete composite beams were also studied by Sebastian et al. (2016). In this study, FT and PT screws were used to compare the connection behaviours within composite beams. As shown in Figure 4, the screws were inserted into the wood joists in X pairs at a 45-degree angle before pouring concrete with a compressive strength of 32.7 N/mm2. Compared to the TCC beam with PT screws, which failed at 125kN, the TCC beam with PT screw connections failed at a much higher load of 170kN.

In an experimental study, Shrestha et al. (2012) investigated epoxy-bonded shear connections for TCC with and without mechanical fasteners. LVL hardwood joists and a concrete slab were used to construct a set of ten shear test specimens. In five of the specimens, epoxy was used to bond the joist and slab together, and in the remaining five, a long coach screw was inserted through the concrete slab and into the joist before the epoxy was used to seal the timber-concrete joint.

The testing's findings showed that notch-type connections and epoxy-bonded wood-to-concrete connections had comparable stiffness and strength. The ductility of an epoxy-bonded connection was improved by the addition of metal fasteners. The brittle failure mode typical of epoxy-bonded connections was avoided. According to the failed specimens, failure in all connections was concentrated in the LVL or concrete next to the interface, with no signs of interface failure.

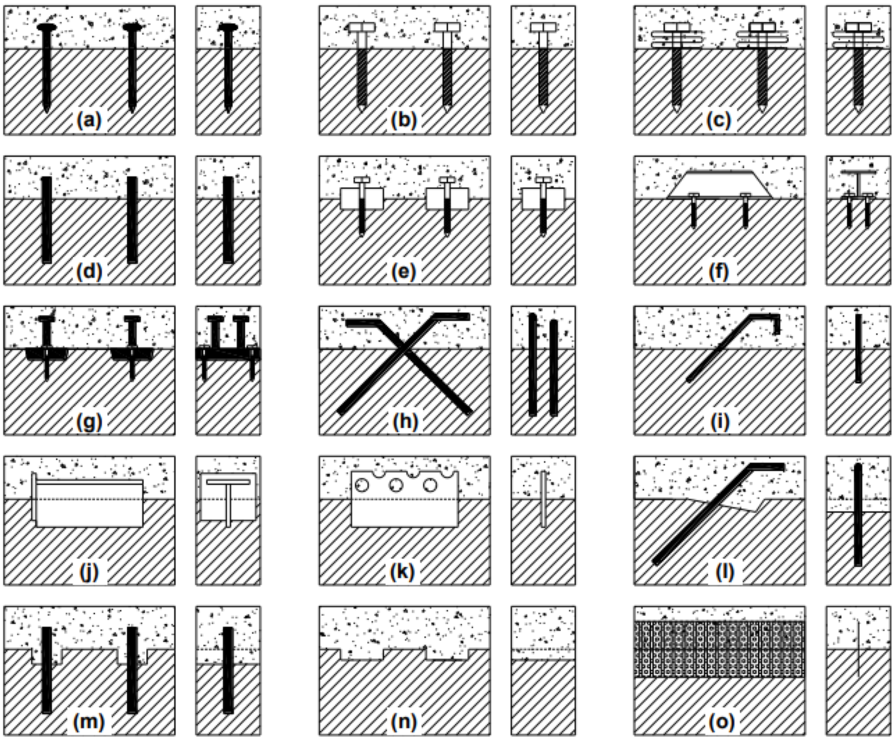

Figure 2.2: Connection systems

Table 2.1 Description of the Type of Connection in Timber Concrete Composite Structures

Label	**Description**
a	Nails
b	Screws
c	Screws + Springs
d	Dowels
e	Circular Hollow Sections (CHS) + Screws
f	Universal column sections (UCS)
g	horizontal steel plate (HSP) + studs
h	X- connector
i	rebars
j	Perforated steel plate (PSP)
k	"T" steel plate (TSP)
l	rebars + notches
m	dowels + notches
n	grooved connection
o	Holz-Beton-Verbund (HBV) connector

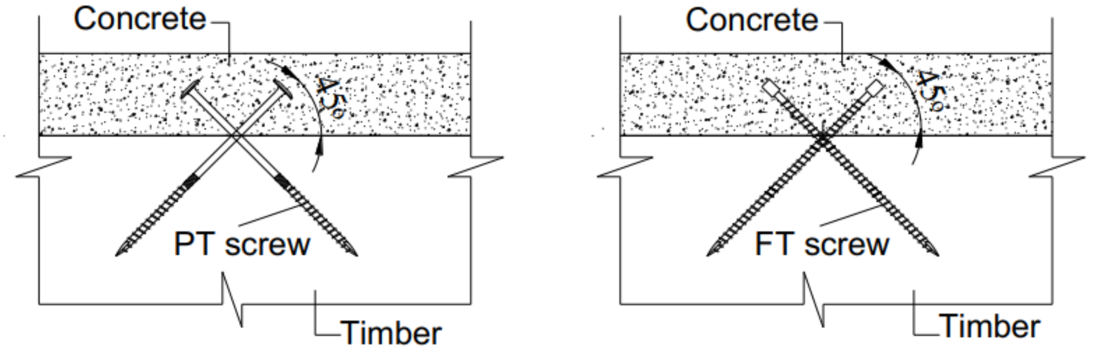

Figure 2.3: Inclined screw connections adopted from (Bin and Snin, 2021)

Figure 2.4: Fully threaded screws fitted at ±45° on timber joist (Sebastian, et al., 2016)

2.5 Composite Action in TCC Structures

The bonding between two distinct elements in TCC structures must be discussed. Monteiro et al. (2015) emphasized that a good connection system requires that the efficiency of the connection between two elements be guaranteed. While the timber helps to resist tensile stress, the concrete in the TCC system typically behaves well in compression. The stiffness and strength of these existing wood joists can be increased by casting concrete as a composite on wood components like joists (Parisi & Piazza, 2007).

Because it makes use of the tension and compression resistances of concrete and timber, respectively, the TCC structure is more effective. The tensile resistance of wood can be equalled to that of steel in conventional reinforced concrete by using a concrete layer on top of the wood (Kuhlmann & Schanzlin, 2008). To transfer longitudinal shear, prevent relative movement (slip) between the two elements (concrete and timber), and prevent vertical separation, particularly at high loads, a variety of shear connectors are used in TCC structures. There cannot be any composite, partial composite, or full composite interactions between timber and concrete (Zakaria et al., 1986). In fact, the full composite action is considered when two elements are fastened together with epoxy, whereas partial interaction occurs when the elements are joined together with other types of fasteners, like mechanical ones. If there are no composite actions, there is no connection between timber and concrete.

In any composite beam, the shear connector is necessary to prevent significant deflection and deformation and to increase the stiffness of the connection between the two materials (Garuckas & Bareisis, 2003). A composite beam with full composite action will typically have a higher design moment capacity and second moment of area than a non-composite beam (Hilti, 2017).

2.5.1 Full Composite Action

Complete interaction is the connection between two elements without any slippage or movement along the interface direction, as depicted in Figure 2.5. Conclusion: The glued joint, glued joint with screw, steel mesh, and steel tube with notch and screw are the shear connectors that will permit full composite action. However, compared to mechanical fasteners, these techniques are more expensive, and all these connector types are more challenging to install.

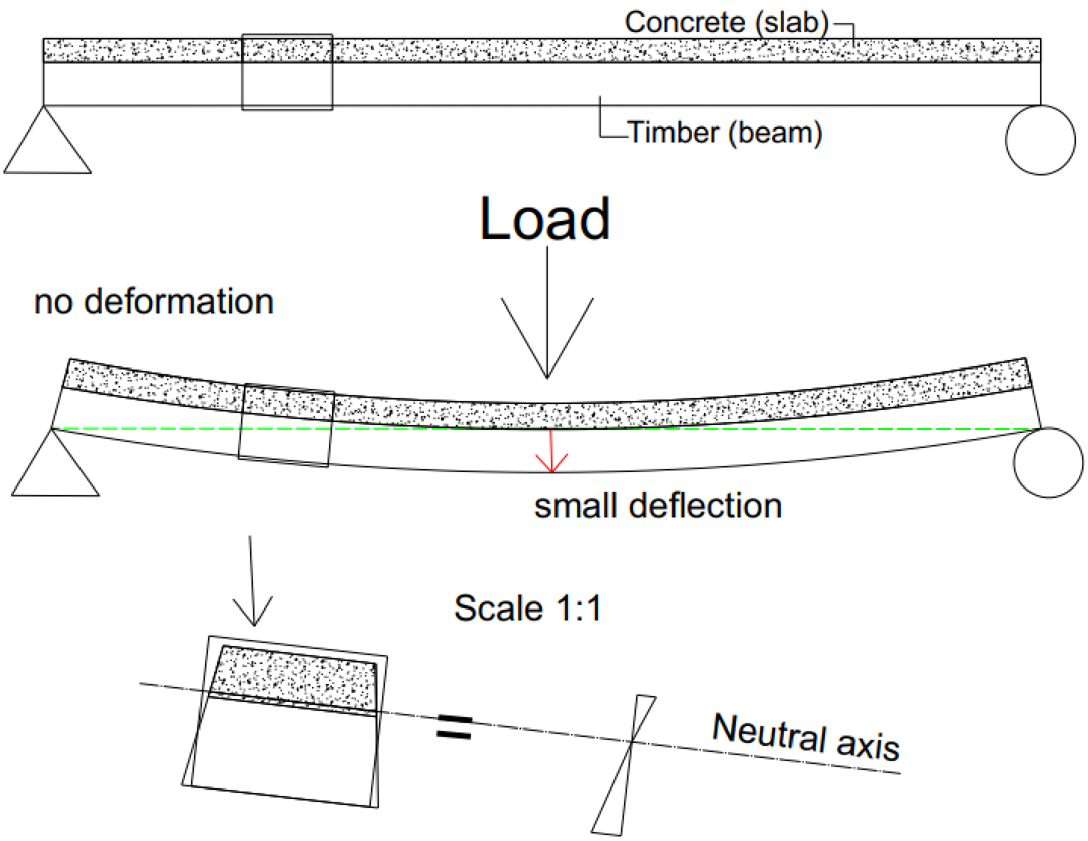

Figure 2.5: Full composite action adopted from Ballerini et al. (2002)

2.5.2 Partial Composite Action

On the other hand, mechanical fasteners like steel screws and nails have many advantages over epoxy and can speed up installation. On the other hand, this kind of connection causes some minor shear deformation and moderate deflection. In Figure 2.6, a partial composite action with small deformation and medium deflection is produced by connectors like inclined screws, notches, nail plates, and bent steel connections. Although inclined screws, notches, nail plates, and bent steel connections have more stiffness and less slip than hardwood fasteners, they can also be categorised as shear connectors that function as partial composites.

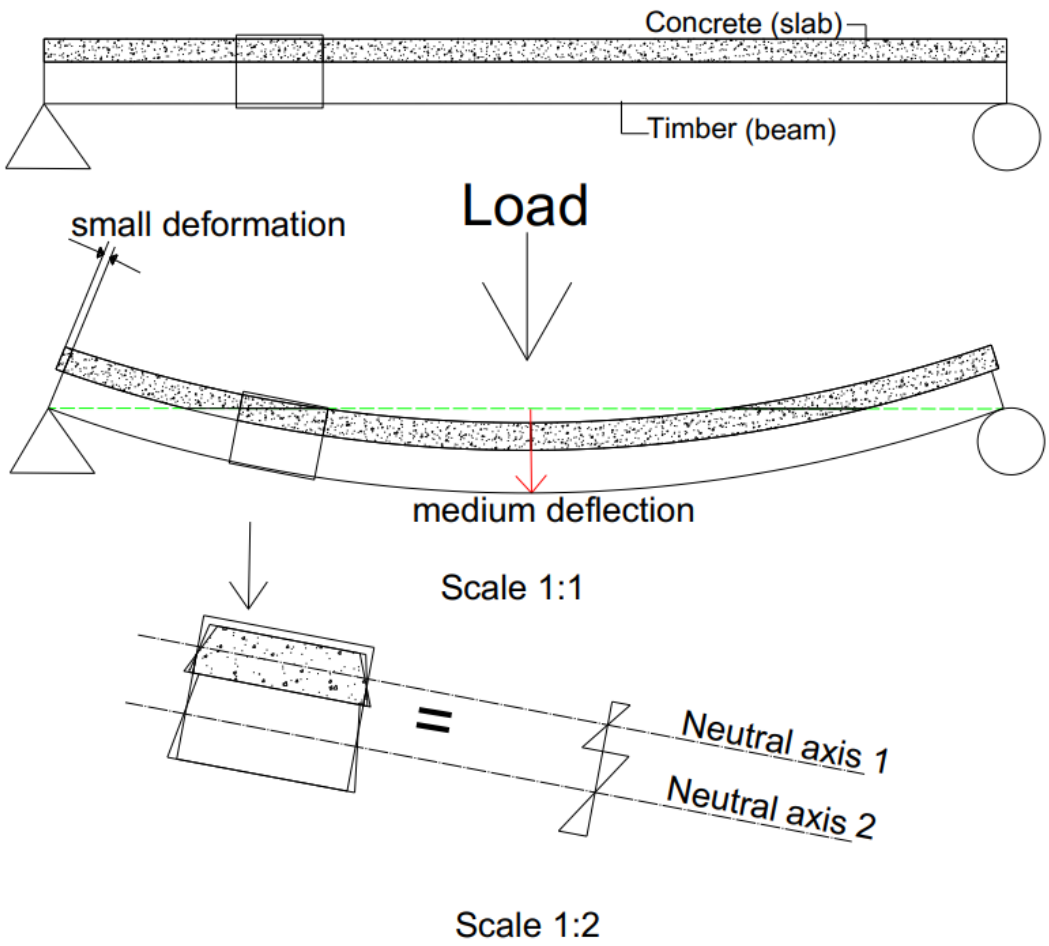

Figure 2.6: Partial composite action adopted from Ballerini et al. (2002)

2.6 Design of Timber Concrete Composite Structure According to Eurocode 5

Slip may happen at the interface when mechanical fasteners, like screws, are used to connect wood and concrete during shear. The entire composite section is not compatible with the presumption (compatibility) that plane sections will stay plane (Persaud & Symons, 2006). When loads are applied to the slab, the shear connectors will transfer those loads to the joist. Slip and shear stress between the two composite elements should be considered when designing the structure.

2.7 Slip Modulus of Connection in Timber Concrete Composite Structure

When designing a TCC structure, it's crucial to take the slip modulus, also known as connection stiffness, into account. As was covered in the previous section, the slip